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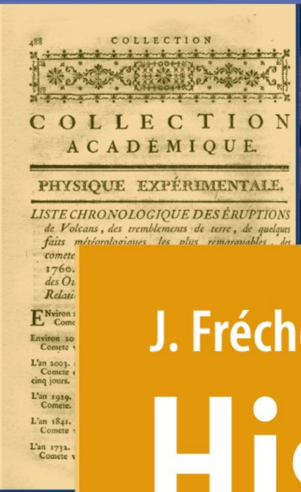
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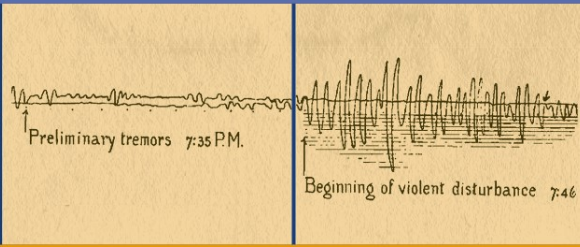

J. Fréchet · M. Meghraoui · M. Stucchi (Eds.)

Historical Seismology

Interdisciplinary Studies of Past and Recent Earthquakes

Springer

Historical Seismology

Modern Approaches in Solid Earth Sciences

VOLUME 2

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Historical Seismology

Interdisciplinary Studies of Past and Recent Earthquakes

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Cover illustration: (*left*) First page of Guéneau de Montbeillard's chronological list of earthquakes, volcanic eruptions, and other natural phenomena, in Collection Académique, vol 6, Paris 1761 (see the papers by Ambraseys and by Fréchet in this volume). Photograph by J. Fréchet.

(*center*) The Romanesque basilica of San Zeno Maggiore (Verona, Northern Italy), dedicated to the 4th century A.D. bishop Saint Zeno, contains some 14-15th cent. frescoes narrating his life. The top-right corner of one panel (photo) was used by a Veronese as a blackboard to carve the news of an earthquake felt there, with these words: "Al 25 febraro 1695 fú il teremoto grande" (On 25 February 1695 there was a great earthquake). Photograph courtesy of F. Galadini.

(*right*) Scanned seismogram of the 17 August 1906 Valparaiso (Chile) earthquake, as recorded by the N-S component of a Bosch-Omori seismograph at Albany (NY, USA) (see the paper by Lee and Benson in this volume). Figure courtesy of W.H.K. Lee and the SeismoArchives project.

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Jean Vogt 1929–2005 in memoriam

Jean Vogt at Cape Sounion (Greece), September 1994
(photographer: Pierre Alexandre)

Preface

In the last three decades, the historical earthquake investigation became an outstanding source of information in seismology. The rigorous interpretation of known or newly discovered historical documents from public and private archives, including military and religious documents, press reports, correspondences, publications, etc., brings new light on the effect of past earthquakes and contributes to the assessment of their characteristics. Historical documents are nowadays examined in the frame of modern methodologies and new approaches applied in the study of individual earthquakes. Jean Vogt was a precursor in this work, and devoted his life to the retrieval and critical evaluation of such documents and to the constant reappraisal of historical events. His biography (herein) shows that he left an invaluable heritage for reassessing the seismic history of France and the Mediterranean region.

Recent publications on the seismicity of tectonically active regions show the use of an increasing number of historical earthquake data, damage descriptions and intensity distribution, from which valuable earthquake parameters can be determined. Therefore, this volume entitled "*Historical Seismology – Interdisciplinary Studies of Past and Recent Earthquakes*" is based on different scientific contributions that document the state-of-the-art and new methodological approaches – namely from early historical accounts to the quantification of early seismograms – in the historical earthquake investigation.

The idea of this volume came after a 1-day colloquium on the theme "The Historical Seismology, From the Archive to the Waveform" organized in September 2005 at the Institut de Physique du Globe of Strasbourg with 40 participants and 13 contributions of different authors involved in the research field of historical seismology. The meeting was a tribute to Jean Vogt and generated a lively discussion on the main recent advances and future of historical seismology.

The volume includes 20 contributions subdivided in four main sections: I – Introduction: Jean Vogt Heritage, Learning from the Past; II – Reappraisal of Historical Earthquake Information; III – Case Studies, New Data and Critical Analysis; IV – Quantifying Historical Earthquakes: Effects, Intensity, Magnitude, Seismograms. The volume includes two posthumous articles of Jean Vogt and covers all fields related to historical seismology that may help students and young researchers and individual scientists from different disciplines – such as history, seismology, engineering, geology and geophysics – to understand the potential of historical earthquake data.

The introductory part (Part I) deals with the main scientific contributions of Jean Vogt to the historical seismology. A biography describes the principal steps of his professional life and interaction with worldwide institutions and peers. A significant article prepared by Jean Vogt on a critical evaluation of the Trinidad historical seismicity follows and describes his method of investigation. This method was developed in collaboration with different experienced scientists, including Nicholas Ambraseys who shared most of his points of view and provides a critical overview with interesting remarks on the historical earthquake catalogues in the Eastern Mediterranean regions.

The reappraisal of historical earthquake information and catalogues (Part II) includes critical analysis of structured lists of earthquakes and their parametric characteristics. Individual earthquakes as well as catalogues are taken into account and examined in the light of new research of historical documents and the occurrence of recent earthquakes. The seismically active areas concerned by the reappraisal include the Ionian Islands, the intraplate Europe in France, the Eastern Pyrenees in Spain, as well as North Africa and the Italian Peninsula.

Case studies of historical earthquake investigation and their critical analysis (Part III) represent a fundamental aspect of the historical seismology. For this purpose, five specific examples of historical earthquakes in the United Kingdom, Belgian Ardennes, the Swiss Alps, the Italian Peninsula, and the re-evaluation of the 1755 Lisbon earthquake document the effect of historical events and allow the determination of their seismic parameters.

The quantification of historical earthquakes (Part IV) shows how the study of recent individual seismic events and the use of early seismograph recordings may contribute to assess earthquake parameters for catalogues. Comparisons between damage areas and assigned intensities of large or moderate instrumental earthquakes may serve as a calibration for historical earthquakes that occurred in seismically active zones in Northern Algeria, French Alps or Eastern-Central North America. Intensity scales, attenuation relationships, threshold magnitudes and the study of seismic waveforms of non-digitally recorded earthquakes provide us with the scaling laws and empirical relations that quantify the relationships between different seismic parameters of instrumental and non-instrumental earthquakes. The compilation of parametric catalogues and related problems reflect the multidisciplinary approach which contributes to this volume.

Strasbourg, Milano

Julien Fréchet
Mustapha Meghraoui
Massimiliano Stucchi (Editors)

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The preparation of this volume could not be possible without the peer reviewing and we are grateful to our colleagues Paola Albini, Pierre Alexandre, Nicholas N. Ambraseys, Kuvvet Atakan, William Bakun, Josep Batlló, Mourad Bezzeghoud, Jean Bonnin, Romano Camassi, Thierry Camelbeeck, Michel Cara, Bernard Dost, Monika Gisler, Gregory Good, Gottfried Grünthal, Christa Hammerl, Assia Harbi, Klaus Hinzen, Vasiliki Kouskouna, Willie Lee, Agnès Levret, Dieter Mayer-Rosa, Alberto Michelini, Roger Musson, Carlos Oliveira, Luis Rivera, Johannes Schweitzer, Annie Souriau, Daniel Stich, François Thouvenot.

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Part II Reappraisal of Historical Earthquake Information

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* English text can be found at: http://www.springer.com/earthsciences/geophysics/book/978-1-4020-8221-4.

Part III Case Studies, New Data and Critical Analysis

Part IV Quantifying Historical Earthquakes: Effects, Intensity, Magnitude, Seismograms

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Part I

Introduction: Jean Vogt Heritage, Learning from the Past

Jean Vogt 1929–2005: His Life as a Seismologist, Geologist, Geographer, and Historian

J. Fréchet and P. Albini

Abstract Jean Vogt was born in 1929 in Strasbourg (France), where he attended primary and secondary school. At the University of Strasbourg, he graduated in Geography, and majored in Geomorphology. His professor was the geographer Jean Tricart, who taught him the importance of both geological field work and archive investigation.

In 1955 he joined the French West-Africa Geological Service and later the French Bureau for Geology and Mines (BRGM). Along the following 20 years he lived as a "geological" globetrotter in a number of countries, dispensing his time between the field and the archives. In these years, he was concerned mainly with mining geology, geomorphology, superficial deposits, and landslides.

This unique experience led him in 1975 to the responsibility of the "Seismo-Tectonic Project", the BRGM project in relation with the French nuclear power programme. From 1975 to 1984, he gave a substantial impulse to the study of French historical earthquakes, and since then he visited almost every public archive in France, and several major archives and libraries in Europe and abroad. He took care at the same time of the follow-up of macroseismic studies of present-day earthquakes. After he retired in 1984, he continued on a personal basis his investigations of historical earthquakes, in Europe, the Middle East, North Africa, and the Caribbean area.

Alongside and for about 50 years, Jean Vogt investigated uninterruptedly the agrarian history of Northeastern France and Southwestern Germany. He published in scientific journals and in local learned societies bulletins more than 500 notes and articles devoted to a variety of subjects, such as soil erosion, agriculture, cattle trade, and social conflicts.

Jean Vogt died on 5 June 2005 in Strasbourg. His scientific legacy consists of a wealth of published papers, manuscripts, documentation related to history and seismology, awaiting to be further exploited, as he would have done.

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J. Fréchet et al. (eds.), *Historical Seismology*,

Keywords Jean Vogt · biography · historical seismology · earthquake catalogues

1 Strasbourg 1929–1951

Jean Emile Auguste Vogt was born on 13 March 1929 in Strasbourg, Alsace (France), in a Protestant family, eldest of two brothers. His family had roots in Northern Alsace and in nearby Southern Palatinate. He attended primary and secondary school in Strasbourg where his father served in the fiscal services. He used to go during holidays to his grandparents' home town, Wissembourg in Northern Alsace; he would later recall with humour that his ancestors in this city owned a match factory, which led him sometimes to be deliberately inflammatory (Boehler 2005; Vogt 1997). During World War II, from 1940 to 1944, Alsace being *de facto* annexed by Germany, the schools were totally Germanized. This allowed Jean Vogt to master the German language, including the unusual German handwritten script (this Sütterlin script, in use until the mid-20th century, was similar to the old Gothic or Fraktur handwritten scripts). These circumstances were determinative in letting him become later an expert of German archives.

At the University of Strasbourg, he graduated in 1951 in Geography (Vogt 1951), a discipline considered then as belonging to the humanities. The Strasbourg school of geography was led by several young and dynamic teachers, including Jean Dresch (specialized on North Africa), Pierre Monbeig (specialized on Brazil and South America), and the geomorphologist Jean Tricart. They adhered to the new geography development, partly of Marxist inspiration. Under their influence, especially that of Tricart, Jean Vogt discovered the power of combining field work and archive investigation (Vogt J 1999). Between 1952 and 1954, he published not less than nine articles on various topics such as geomorphology, soil erosion, and agrarian history. In his work on soil erosion and agricultural techniques (Vogt 1953), he presented the results of extensive research in several state archive depositories in France, Luxembourg, and in three German towns (Speier, Wertheim, Donaueschingen). This early performance demonstrated the ability of Jean Vogt to explore historical archives in order to enlighten numerous geographical or geological problems. The French Strasbourg Geographical Institute was founded in 1919 by Henri Baulig (Masutti 2002), and it succeeded to the German Geographisches Seminar, created by Georg Gerland in 1875, followed by Karl Sapper in 1910 (Vogt H 1999). Sapper and Baulig were both geomorphologists, and the Strasbourg Geographic Institute developed as a world leader in this field. Gerland considered Seismology as a branch of Geography; this led him to the foundation of the German Central Seismological Station in Strasbourg in 1899, and more importantly to the foundation of the International Seismological Association in 1904. Thus, interestingly enough, when Jean Vogt moved to the field of seismology in 1975, he followed the same path as his predecessor Georg Gerland.

2 Saarbrücken, Strasbourg 1951–1955

In fall 1951, J. Vogt moved to Saarbrücken, the capital of the present German Saar state, where he was appointed as *Assistant* with the European Saarland University for the next two years. [The University had been recently created by the French administration, since Saar was a protectorate under French control since 1945. France and the Federal Republic of Germany (West Germany) developed in the early 50s a plan to establish an independent Saar state,[1] thought to become ultimately the centre of the new political Europe. But a plebiscite in Saar rejected it in October 1955, and Saar joined the Federal Republic of Germany in January 1957.] After one year performing military service in Tunisia and in Nancy (France), he returned in October 1954 to the Geographical Institute in Strasbourg. There, he was appointed by the French National Centre for Scientific Research (CNRS) as *Stagiaire de recherche* (Research Trainee). During this first professional period, he developed further his analysis of historical soil erosion, which he decided to be the subject of the thesis he planned to prepare in the next years. At the same time, he explored a few new geographical themes oriented towards the American continent (Canada, Cuba, Porto-Rico). His work on Canadian hydrocarbons was the first sign of his next move towards the geological and mineral industry.

3 Western Africa 1955–1960

In May 1955 Jean Vogt put an end to his promising domestic academic career; he chose instead the adventurous life of a field geologist in the overseas. He joined the *Direction Fédérale des Mines et de la Géologie de l'Afrique Occidentale Française* (DFMG) based in Dakar, Senegal. (Soon after, in 1957, the Department was renamed as *Service de Géologie et de Prospection Minière* (SGPM).) Indeed, after WWII France decided to develop its mining industry in its overseas territories. The geological development of French Sub-Saharan Africa was strongly sustained by the new *Bureau Minier de la France d'Outre-Mer* (BUMIFOM) created in 1948. Pre-existing Geology and Mines Departments in Federal French Western Africa (AOF) and Federal French Equatorial Africa (AEF) were reinforced. Their geological services were in charge of geological mapping and preliminary wide-area mineral prospecting, while the services of mines were in charge of permitting and mines exploitation. The BUMIFOM worked in between, performing detailed prospecting of previously inferred mineral deposits. Hundreds of young Frenchmen left the mainland and headed for these remote and exciting territories searching for gold, diamonds, and other attractive minerals (Legoux and Marelle 1991).

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[1] Saar was disputed between France and Germany for several centuries. It was under French administration during three periods, simplifying: French *Département* 1792–1814, French administration under control of the League of Nations 1920–1935, French Protectorate 1945–1956.

Table 1 Geological missions of Jean Vogt from 1955 to 1960 (list not exhaustive)

1955 Senegal (Djifère); Western Mali (Kenieba)
1956 Senegal (Lompoul); Côte d'Ivoire
1957 Western Mali (Mandingue Plateau), French Guiana, Curaçao
1958 Benin (Cotonou)
1958–1960 Niger
1959 Northern Benin (Alibori and Mekrou basins)
1959 Côte d'Ivoire (Lobo); Guinea (Beyla); Western Mali (Kenieba)
1960 Niger; Western Mali (medium Bagoé)

Jean Vogt was in no case a geologist, but his education and expertise as a geographer, and specifically as a geomorphologist, made him very useful for the prospecting and reconnaissance missions of the AOF Geological Service. AOF was a federation of eight Western African territories: Mauritania, Senegal, Mali (as French Sudan), Guinea, Côte d'Ivoire, Niger, Burkina Faso (as Upper Volta), and Benin (as Dahomey). In the next years, he performed numerous geological missions in AOF, often in very crude conditions. He spent usually several months on the field, often alone or with one or more indigenous workers, travelling either on foot, or with various means of transport ranging from pirogues to planes. From his notes and reports, we can list but a few of these prospectings (Table 1). During these years he continued to be supported by Tricart and was still listed by the CNRS as *Stagiaire* without salary, until the end of 1959.

4 Globetrotter with the BRGM 1960–1974

By the end of 1960, after 2 years of rapid political evolution, the twelve territories that belonged to French Western Africa and French Equatorial Africa had become independent states, as well as the two former German colonies of Togo and Cameroon under French protectorate since 1919, and as Madagascar. The process had begun when a new constitution was voted in 1958, in France and overseas, as a consequence of the civil war in the then French Algeria. The constitution created the *Communauté Française*, promoting the French African territories to autonomous republics. One country, Guinea, voted against the constitution and became independent four days later, on 2 October 1958. The evolution was from then on very rapid, and between January and November 1960 all the aforementioned countries accessed to independence, thus putting an end to the French Empire-Union-Community (its three successive statutes) in Africa. Anticipating the coming independences, a new French central geological service was created on 23 October 1959, the *Bureau de Recherches Géologiques et Minières* (BRGM), which joined together the BUMIFOM (Overseas), the BRGGM[2] (France), the BRMA[3] (Algeria) and the BMG[4]

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[2] *Bureau de Recherches Géologiques, Géophysiques et Minières.*

[3] *Bureau de Recherches Minières de l'Algérie.*

[4] *Bureau Minier Guyanais.*

Table 2 Geological missions of Jean Vogt from 1960 to 1974 (list not exhaustive)

1960 France (Brittany, Limousin)
1961 Gabon; Republic of the Congo (Kouyi Plateau)
1961 Niger; Algeria (Laouni, Southern Hoggar)
1962 Niger (Aïr); Gabon (Makongonio);
1964 Cameroon (Adamaoua); Madagascar
1965 Madagascar
1965 Burkina Faso (Black Volta and Comoë); USA (Wyoming and Colorado)
1966 Burkina Faso (Comoë, Lobi); Western Cameroon
1967 Burkina Faso – Côte d'Ivoire; Senegal
1968 Côte d'Ivoire (Séguéla); Burkina Faso; Saudi Arabia
1970 Malaysia
1974 New-Caledonia
Undated: Australia, Brazil, Fiji, etc.

(French Guiana). In 1960, the personnel of the disappearing SGPM, including Jean Vogt, joined the BRGM.

This was the start of a new period for Vogt. During the next 15 years, he travelled tirelessly for the BRGM throughout the five continents, mixing field work, archive depositories and libraries visits, and scientific meetings participations (Table 2). He extended his geomorphological skills acquired in AOF to several countries worldwide where he performed numerous geological missions. He married in 1961, and had two daughters. The family was first based in Algeria, then in Strasbourg, and eventually moved in 1967 to Orleans, the city hosting the headquarters of BRGM. Sadly, his wife died there accidentally in the late 70s.

Vogt worked on many geological subjects. Not only did he investigate several geomorphological problems, as erosion surfaces, alluviums, including the famous stone-line (Vogt and Vincent 1966), but he also studied several ore deposits (diamond, gold, nickel, sulphur, uranium) and the mineral industry.

The French Geologic Mapping Service (*Service de la Carte Géologique*), created in 1868 under the direction of the Ministry of Industry, was mainly under the influence of the School of Mines (*Ecole des Mines*) and of the University. In 1968, it became a service of the BRGM. In the following years, Jean Vogt played a key role in the renovation of the Service, initiating several developments on the cartography of quaternary and superficial formations (Vincent 2005).

Surprisingly enough, during all these years, Vogt did not refrain from his hobby research, the agrarian history of Alsace and surrounding regions. In Saarbrücken, in 1951, he started to work on a thesis whose subject was the historical erosion of soils. Though his departure for Africa in 1954 put a temporary end to this project, from then on he spent his vacations and free time to develop and extend this theme as a personal research. This eventually allowed him to defend a thesis (Vogt 1963) in Strasbourg on the agrarian history of the Rhine region. From 1951 to 1974 he visited numerous European archives and libraries and published more than 100 notes related to this research, mainly in the journals of regional learned societies (Fréchet 2007). He continued this research his life away and is now considered one of the best connoisseurs of rural history of Alsace and beyond (Boehler 2002, 2005). From

1975 to 2005 he published an additional number of more than 450 notes on a large range of subjects, such as historical soil erosion, rotation of crops, tenure, farming, cattle trade, rural life, and social conflicts.

5 The Seismo-Tectonic Project 1975–1984

During the years preceding 1975, Jean Vogt developed interest into the field of geological hazard, as he developed with Pierre Vincent the project of a database of landslides and related hazard. In 1975 the concern about safety of the French nuclear industry gave birth to the French Seismo-Tectonic Mapping Project (*Projet de la Carte Sismotectonique de la France*). The *Projet* was a joint operation of the French electricity company EDF,[5] the French atomic energy commission CEA,[6] and the BRGM, and was primarily destined to evaluate the seismic risk in the vicinity of nuclear power plants. Jean Vogt was promoted as director of the programme. As a first step, a pilot study was performed in Provence (Southeastern France). The BRGM was in charge of the project and contracted with Professor Jean Pierre Rothé, the former director of IPGS.[7] Jean Pierre Rothé and even more his father Edmond, founder of IPGS in 1919, had developed a seismic catalogue of France including a historical earthquake database and the macroseismic enquiries of the BCSF[8] conducted since 1921. Rothé was asked to provide a catalogue for each *département*,[9] first of Provence, and in 1976–77 for the rest of France.

Vogt found out that the *fichier Rothé* (the Rothé file) for historical earthquakes was based much too exclusively on the 19th century Perrey's catalogues without further analysis of the original sources. Based on his rich expertise on archives, he realized quickly that an extensive search of sources was necessary. In few years, he and a small number of highly competent collaborators, in particular Bernard Cadiot and Jean Delaunay, performed a huge gleaning of original and new sources. All major French archive depositories (one per *département*) and libraries were visited in the years 1976–77, a quite remarkable achievement in such a short time. Scrutiny of thousands of archive documents, periodicals and newspapers led to a completely renewed knowledge of the historical earthquakes in France. They set up the foundations of the new historical earthquake database, which later gave birth to the Sirene database, a subset of which is now available on Internet (Sis-France 2008). The relations between Vogt and Rothé became quickly difficult and ended into a breaking off. The countless new documents accumulated in the course of the *Projet* were stored in hundreds of boxes into Jean Vogt's so called *armoire normande* (actually Alsatian) in his Orleans office. The main results of the

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[5] *Electricité de France*.

[6] *Commissariat à l'Energie Atomique*.

[7] *Institut de Physique du Globe de Strasbourg*.

[8] *Bureau Central Sismologique Français*, IPGS, Strasbourg.

[9] France is divided into 96 *départements*.

Projet Sismotectonique were published in a book (Vogt 1979) that will remain as a milestone for French and European historical earthquake investigation.

The seismo-tectonic map of France at a scale of 1/1,000,000 appeared 2 years later (Vogt and Godefroy 1981). As a consequence of the successful seismo-tectonic project, the BRGM took over the BCSF the responsibility of the French macroseismic enquiries in 1978. Vogt realized that the post-Perrey period (1871–1920) and the BCSF period (1921–1977) also needed a complete revision (Vogt 1982). The revision would be based in part on a re-exploitation of IPGS archives. In 1982, a seismic service (*Antenne Sismique*) was created with the pre-existing Regional Geological Service of the BRGM, in the neighbourhoods of Strasbourg, directed by Jean Vogt. The BRGM archive boxes were sent to Strasbourg, after a safety microfilming was performed (the microfilms were later digitized for the Sirene database). In Strasbourg, Jean Vogt was confronted to many difficulties. A controversy arose between the BRGM and Universities, which complained having been spoiled from Rothé's files and catalogues and from the macroseismic enquiries. The BRGM underwent itself a profound crisis. The *Antenne Sismique* did not receive the necessary budget to complete all its missions, particularly the revision of the earthquakes of the past. Jean Vogt suffered from these difficult circumstances, and his relations with local BRGM and IPGS administrations were deteriorating (Vogt 2003a). This led him to a premature retirement in October 1984, at the age of 55, and to the closing down of the *Antenne Sismique* in Strasbourg.

6 Jean Vogt's Roaming 1985–2005

Vogt's professional retirement was all but a withdrawal from scientific activity and field investigation. Instead, once free of administrative slownesses and constraints, he became a protagonist and was at root of developing new ways and methods in the field of Historical seismology, in Europe and the rest of the world. He had planned to exploit the numerous documents he had gathered personally, i.e. during his free time, in the past 10 years. Unfortunately, the BRGM did not allow him to take back his documents that were stored with the rest of the Sirene stock. Jean Vogt sued the BRGM, lost the trial and, despite his frustration, from 1985 on he continued as a "free-lancer".

In 1986, the Working Group "Historical Earthquake Data", proposed by Rolf Gutdeutsch (University of Vienna), was established on the occasion of the ESC General Assembly in Kiel, Germany; Jean Vogt was among its pristine contributors. He actively joined the discussion during the first WG Workshop held in Vienna (June 1987), and from then on, he became one of the leading voices among the researchers on past earthquakes, both in practice and theory.

Jean Vogt was one of the researchers who collaborated with the European Commission project "Review of Historical Seismicity in Europe-RHISE" (1988–1992), specifically devoted to the seismicity of the past. He participated in meetings held in the partner countries (Portugal, Spain, Greece, Italy, United Kingdom, France, Belgium), supplied the project and the researchers involved with advices, suggestions, short papers with titles sparkling with humour ("L'imbroglio des catalogues de sismicité historique", Vogt 1994). He made some serendipitous discoveries, as in the case of the manuscript by von Degenfeld (Albini and Vogt 2008).

In accordance with his long experience, Vogt was also a specialist of macroseismic intensity scales (Vogt 2003a). The revision of the MSK macroseismic scale started in 1988 (ESC General Assembly, Sofia, Bulgaria) and he contributed in an important way to the redefinition of its criteria to become the new European Macroseismic Scale (EMS). He actively participated especially on the occasion of the first release, in 1992, of the EMS-92, as the leader of the discussion on the seismogeological and hydrogeological aspects, eventually collected in a joint paper (Vogt et al. 1994). After the publication of the final version, the EMS-98 (Grünthal 1998), Jean continued his speculations about geological effects and macroseismic intensity scale. The results he left in an almost complete form have been slightly edited and published in this volume (Vogt 2008b).

Alongside his collaborations in the framework of international projects, he maintained alive many individual scientific relationships. One of the most relevant was his long-standing fellowship with Nick Ambraseys (Ambraseys 2008), the most apparent result of which is a series of papers on the historical seismicity in some North-Africa countries, like Algeria and Tunisia (see Fréchet 2007). He received and made informal visits with most of the European researchers involved in the investigation of the earthquakes of the past centuries. He acted also as expert in historical seismology for international organizations, especially for International Atomic Energy Agency (IAEA) in the case of the investigation about the peninsula of Crimea, and took part in some IAEA sponsored meetings (e.g. at Damascus, Syria, in 1992). He also contributed to the EC project "Slow Active Faults in Europe" (SAFE) and maintained close contact with the IPGS seismo-tectonic group from 1999 on.

Along these 20 years, Jean Vogt went on spending most of his time in libraries and archives, every day improving his familiarity with the historical documentation, either collecting new primary sources or commenting on how they had been interpreted by historians and seismologists. He accumulated an unrepeatable comprehension of how the documentary deposits came to be formed, and had the key to enter their recesses and make them disclose their secrets. Based on a list supplied by Jean himself in 1995, Fig. 1 sketches, though in an approximate way only, the dense network of European libraries and archives he visited in 20 years, both on his own resources and in the framework of his collaboration with European projects (especially the EC RHISE project, mentioned above). In any case, he went visiting new repositories whenever he was in a place for the first time, in fact after having carefully planned to merge tourism and "work", especially in his out-of-Europe destinations (Fig. 2).

In the years between 2000 and 2004, though already with an unstable health (he used to say he was "tired"), he exploited most of the material on West Indies he had collected in the previous years. Several of his papers on this subject are still in press in 2008, including one in this volume (Vogt 2008a). From the late nineties he started avoiding the large meetings with hundreds or thousands of participants,

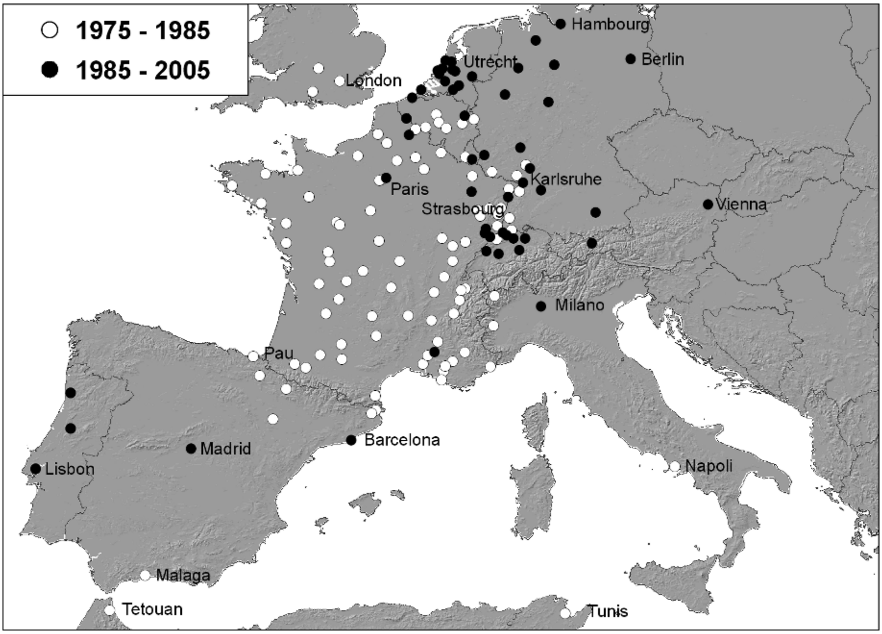
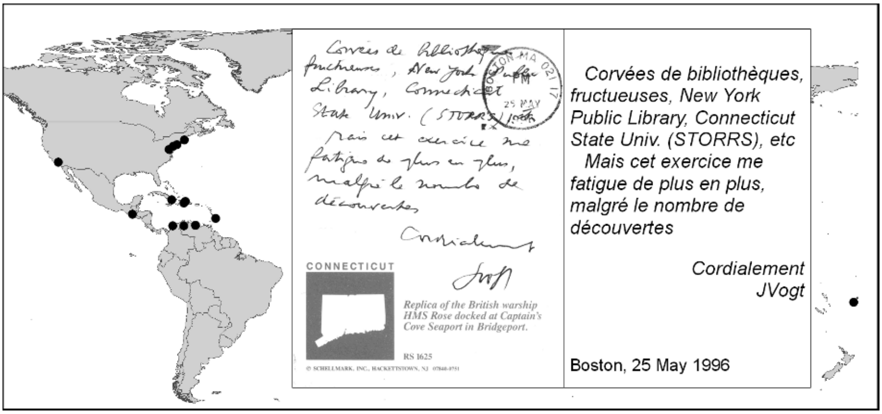


Fig. 1 European archives and libraries visited by Jean Vogt (1975–2005)

largely preferring the small, family-like reunions of few, well motivated researchers, on specific themes. He only made an exception for the Workshop in Erice, Italy, "Investigating the records of past earthquakes", in July 2002: this was perhaps the last international meeting he attended.



Corvées de bibliothèques fructueuses, New York Public Library, Connecticut State Univ. (STORRS) etc
Mais cet exercice me fatigue de plus en plus, malgré le nombre de découvertes

Cordialement
JVogt

BOSTON MA 021 17 PM 25 MAY 1996

CONNECTICUT

Replica of the British warship HMS Rose docked at Captain's Cove Seaport in Bridgeport.

RS 1625

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Corvées de bibliothèques, fructueuses, New York Public Library, Connecticut State Univ. (STORRS), etc
Mais cet exercice me fatigue de plus en plus, malgré le nombre de découvertes

Cordialement
JVogt

Boston, 25 May 1996

Fig. 2 Extra-European archives and libraries visited by Jean Vogt (about 1990–2000)

7 Jean Vogt's Legacy

7.1 Historical Seismology: Definition and Methodology

From the early 80s, Vogt published some short papers on methodology (Vogt 1981, 1987; Vogt et al. 1985), and because of his expertise, he was among the authors of the milestone paper "Notes on historical seismicity" (Ambraseys et al. 1983).

We owe him the current definition of "Historical Seismology" (Vogt (1991, 1993), but he used this wording in the 1988 draft of this paper submitted as a report to the EC Project RHISE) for the newly-born discipline dealing with earthquakes of the past by means of an interdisciplinary scientific approach, agreed and implemented by historians and seismologists, "together". That this scientific relationship had many problematic aspects, was definitely apparent to him, who wrote in his "Historical Seismology. Some notes on sources for seismologists" (Vogt 1993): "*While seismologists desperately need historians' help, they should correct some historians' excesses* [when they concern themselves with disastrous earthquakes only]. *On the other hand, seismologists are often frightened by seemingly irrational complex problems of tracing sources in a mosaic of depositories*".

Jean Vogt liked to quote his methodological papers both in public meetings and informal talks, and in his own wake, we are quoting them here and there to illustrate his perspective. In his search for sources, he regularly started from referring to what he called "Investigation tools", which, he said, helped to make his research "less frightful", and which consisted in an "arsenal of working tools at all scales, with useful overlappings" (Vogt 1993). He was thus recognizing the importance of library indexes and catalogues by subject, as well as of archival inventories, all those being the auxiliary tools well known to historians, and to him through the never abandoned parallel investigation of agrarian history. What Jean knew was that these tools were not known to and among seismologists, to whom this message was sent: "*After long preliminaries, how should proper research work be undertaken?* [. . .] *straightforward work is often impossible* [. . .] *Actually most of new knowledge comes from casual mentions, often limited to some words* [. . .]" (Vogt 1993).

This was Jean Vogt's approach, a combination of a deep knowledge of geopolitics and an enormous amount of serendipity. He was systematically turning piles of documents in libraries and archives, digging up plenty of records, and then minutely cross-checking his findings.

He was deeply concerned with all the aspects related to the interpretation of historical earthquake records in seismological terms. From his "two decades" of experience, "although as an outsider" as he defined himself, stems the nearly "epistemological" paper "The weight of pseudo-objectivity" (Vogt 1996). As usual, after proposing a series of case histories, he offers his solution: "*To avoid the pitfalls of* pseudo-objectivity, *a quickly growing danger thanks to hasty and irrational computer-work, a kind of* constructive subjectivity *is needed, in a seemingly paradoxical way, with an ability to master complex problems in a critical and interdisciplinary way, a modest approach towards more objectivity, not incompatible at all with the French expression of* libre arbitre" (Vogt 1996).

Jean Vogt's awareness of how critical is the interpretation of earthquake records to avoid the "shortcomings" in parametric earthquake catalogues (see also Ambraseys 2008) made him focus on the "earthquakes wrongly interpreted as such". He reckoned that the most widespread reasons were either the duplication of the date, an incorrect location of the effects, or a wrong interpretation of the description of another geological phenomenon (e.g. a landslide). A section devoted to these aspects is included in his introduction to the catalogue for France (Vogt 1979), but many and one examples can be found throughout his scientific production. His early understanding of how difficult was this problem to be properly solved was such that 15 years later he wrote: "*Discarding 'fake quakes', to which specialists often cling like children to their toys, is indeed an arduous task*" (Vogt 1996).

7.2 Papers

Vogt attended and contributed to a number of international meetings and workshops discussing the value of historical earthquake data in seismology, and left many traces of his views, sometimes outstanding but at no time trivial. To simply list all his public appearances at scientific conferences and workshops would not cast light on the importance and the impulse that his continuous presence gave to this field of research. Usually he submitted a short written contribution for the conference proceedings, so that by going through his huge written production, listed in Fréchet (2007), one may find out the different aspects of seismological research he dealt with and the *milieux* he addressed.

It is unfortunate that Jean Vogt did not find time to write some comprehensive work on all his results. He blamed himself for it, but at the same time his mind was more inclined to write detailed and incisive case studies. He published more than 850 articles and notes, in international journals as well as in poorly known local scientific or historical learned societies (Fréchet 2007). Among them, more than 200 were about earthquakes, more than 100 about geology or geomorphology, and more than 500 relate to history and rural world. Most were written in French, some in German, but several important papers were written in English.

7.3 Raw Material

Jean Vogt was a man of an impressive culture and a polyglot: he was fluent in French, German, English, Dutch, and Spanish, and he also read Italian, and of course Latin. He had the gift to master all the techniques of archive exploitation. He applied his skills in his three favourite domains of investigation: history, geology, and geophysics.

In Strasbourg, it was difficult not to meet him mornings in the reading rooms of the *Archives Départementales* or of the *Bibliothèque Nationale et Universitaire*.

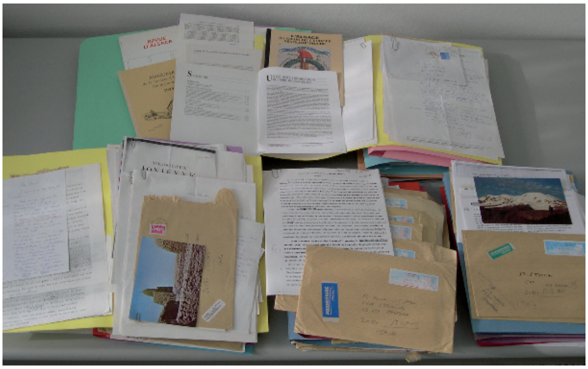

Fig. 3 Samples of the material supplied by Jean Vogt from his own archives

Vogt published several notes on archive science, but a large portion of his knowledge is unfortunately lost.

It does not come as a surprise that Jean Vogt gathered a considerable amount of documentation, he himself had organised by subject. His handwritten notes, articles, and xerocopies of original documents are stored in more than 380 archive units (boxes). About 200 units concerning agrarian history are deposited in the *Archives Départementales du Bas-Rhin* (ADB-R) in Strasbourg. The few "geological" units are deposited partly in the ADB-R and partly in the *Ecole des Mines* in Fontainebleau. The "seismological" units are deposited in the ADB-R (100 boxes) and in the archive depot of the *Ecole et Observatoire des Sciences de la Terre* (EOST) in Strasbourg (80 boxes).

For the not-yet-inventoried units in the ADB-R, with free access to the public, only a list of the unit titles is available. The seismological units in the EOST are undergoing a detailed cataloguing; they concern mainly earthquakes in France, Algeria, Tunisia, Balkans, Turkey, and the Caribbean, while the seismological units in the ADB-R concern Spain, Portugal, Morocco, Libya, Egypt, the Middle-East, Central and South America, the Caribbeans, and the Atlantic Ocean.

Jean Vogt's unique way of exchanging information, in an open and generous way, was by means of small handwritten notes of various shapes, cuttings from xerocopies (quite never an integer sheet of paper), transcriptions on all kinds of recycled paper. Figure 3 is just a sample of the variety and complexity of this material, which contained (i) pieces of information on earthquakes, (ii) hints for research in archives and libraries, (iii) papers, (iv) newspapers clippings (mostly from "Le Monde") on politics and other subjects, (v) and postcards from the countries he visited, with short and witty messages.

8 Conclusion

This paper is based on our personal memories, as well as on a few autobiographical notes written by Jean Vogt (e.g. Vogt J 1999, 2000, 2003a, b). In these notes, Vogt told us many anecdotes, often with humour, always applying his "no names" principle to the persons he criticized (Vogt 1996). He also developed his thoughts about his personal and professional life, highlighting his quest for interdisciplinarity.

Jean Vogt passed away on 5 June 2005 in Strasbourg, after several months of illness. Almost until the last day, he continued to visit the *Archives* and the *Bibliothèque* and to work on the manuscripts of several articles he was preparing. He leaves behind a brother, Henri, two daughters and several grand-children.

A citizen of the world, Jean Vogt was at the same time Alsatian: he had the gift of balancing himself between being a specialist of the very minute details of the history of small villages of Northern Alsace (Outre-Forêt), and a connoisseur of many different countries and cultures worldwide. Only those who had the chance to meet him could appreciate his great human qualities, a mixture of honesty, modesty, great intelligence, and wittiness.

Acknowledgments We are very grateful to Henri Vogt – Jean Vogt's brother, – Jean-Michel Boehler, and Pierre Louis Vincent for their help in the preparation of this biography. We would also like to thank Andrea Rovida for taking care of the figures.

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Comprendre et compléter un catalogue de séismes: le cas de Trinidad*

J. Vogt†

Foreword *From 1983 on, Jean Vogt published several notes on the historical seismicity of the Caribbean and adjacent countries of South America. He visited many archives and libraries in the region as well as in Europe and the United States, and collected a large number of new original sources. This paper analyzes several felt or damaging earthquakes in Trinidad and Tobago. Vogt presents new original archive findings that modify significantly the picture of the Trinidad seismicity as found in the catalogue of Robson (1964). An introduction and many details about this and the context of West Indies historical seismicity can be found in Vogt 2004 (A glimpse at...),* *which announces the present text.*

Jean Vogt prepared a draft of this paper in the months preceding his death in 2005. The manuscript was left in a near-final state. The file containing the manuscript contained several versions of the paper somewhat mixed together, with handwritten notes and corrections. It contained also copies of the original sources cited in the text. We edited the draft, trying to complete several references and notes. [Our corrections are written within brackets. The paragraph titles are ours.]

J. Fréchet

1 Introduction

N'importe quelle carte de sismicité montre que Trinidad est situé à un véritable carrefour sismo-tectonique.[1] Il se trouve que l'un des catalogues de la sismicité des

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Strasbourg, France

* English text can be found at: http://www.springer.com/earthsciences/geophysics/book/978-1-4020-8221-4

[1] Au sujet du contexte sismo-tectonique, voir par exemple, pour le Vénézuéla oriental, A. Cisternas et R. Gaulon, 1984, "Síntesis sismotectonica del nordeste de Venezuela", *Revista de Geofísica.* [Vol. 40, No 1, pp 3–10].
Pour la particulière densité des données instrumentales à l'Ouest immédiat de Trinidad voir par exemple, pour la période 1900–1973, J. Grases, 1977, "Introduccion al estudio sobre los sismos

J. Fréchet et al. (eds.), *Historical Seismology*,

Petites Antilles a naguère été élaboré à Trinidad, sans doute considéré comme un observatoire par excellence.[2] Cependant Trinidad et accessoirement Tobago sont caractérisés par une sismicité globalement modeste avec des événements notables à larges intervalles, quels que soient les épicentres, proches ou lointains. D'une manière significative, une comparaison est faite lors du tremblement de terre de 1825 avec le continent et les Petites Antilles: "We shall feel considerable anxiety until we hear from St. Vincent and the neighboring islands and opposite continent where these catastrophes are much more frequent and destructive than in Trinidad".[3]

Il a paru intéressant de considérer de plus près le catalogue en question, jusqu'en 1890, sans préjuger de travaux ultérieurs. À vrai dire, il ne présente qu'un intérêt limité pour les Petites Antilles dont il ne sera question qu'incidemment. C'est Trinidad qui retiendra notre attention d'autant plus que pour une importante tranche chronologique il est fait appel dans une large mesure aux sources locales (presse), sans préjuger, par ailleurs, d'emprunts à Mallet, au sujet desquels l'auteur s'explique d'ailleurs, et à Perrey dont l'apport n'est cependant exploité qu'en partie tandis que le catalogue de Poey n'est pas mis à contribution.[4] Ajoutons que les informations sont souvent simplifiées à l'extrême alors que les sources fournissent d'intéressantes précisions, par exemple au sujet des répliques. Les appréciations d'intensité sont parfois conventionnelles, comme le souligne d'ailleurs l'auteur.

Si aucune recherche spécifique personnelle n'a été entreprise, le hasard des lectures permet cependant d'apporter de nouveaux éléments, des précisions et des interrogations qui s'inscrivent dans un effort de révision poursuivi depuis plusieurs années aux Antilles.[5]

2 Période test: 1819–1890

Commençons par une rapide statistique des données de Robson, pour une tranche chronologique arbitraire, de 1819, année de la première mention d'un séisme au XIXe siècle, à 1890. D'une manière frappante, Trinidad apparaît seul à quarante reprises. Il n'est fait état d'un groupement Trinidad/Petites Antilles que six fois, tandis que celui de Trinidad, Petites Antilles et Guyane est consigné une dizaine de fois. Quant à la référence vénézuélienne, elle n'est présente qu'à deux reprises.

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destructores del Caribe", *Interciencia*. [Vol. 2, No 4, pp 222–230], sans préjuger d'une foule d'autres travaux.

[2] G.R. Robson, 1964, "An earthquake catalogue for the Eastern Caribbean, 1530–1960", *Bull. Seismol. Soc. Am.* [Vol. 54, No 2, pp 785–832].

[3] *Times* du 22/11/1825.

[4] A.M. Poey, 1858, "Catalogue chronologique des tremblements de terre ressentis dans les Indes occidentales de 1530 à 1857", *Annuaire de la Société Météorologique de France*. [Vol. 5, pp 75–127].

[5] En dernier lieu J. Vogt, 2004, "A glimpse at the historical seismology of the West Indies", *Annals of Geophysics*. [Vol. 47, No 2–3, pp 465–476].

Visiblement, c’est là surtout que le bât blesse. Sans nous limiter à cette tranche chronologique, Cumana fait figure de repère vénézuélien majeur, sans doute par “fixation urbaine”. Il reste qu’un tel tableau peut donner l’impression d’une sismicité trinidadienne en quelque sorte en vase clos.

À vrai dire, il suffit de parcourir le catalogue même de Robson dans son ensemble pour se rendre compte que plus d’un des événements régionaux recensés sans qu’il soit explicitement question de Trinidad, y a sans doute été ressenti. À ce propos il est permis de parler d’événements sans doute implicites. Tel serait le cas de deux événements notables de 1839. En effet, le premier, destructeur à la Martinique, le 11/1/1839, est signalé par Robson à la Barbade (dotée d’une intensité VII) et en Guyane. Une telle remarque peut aussi s’appliquer à la secousse du 2/8/1839 avec les mêmes repères.

Pour une tranche chronologique plus réduite encore, de 1819 à 1857, jetons un coup d’œil au catalogue de Poey, certes sommaire, mais qui a le mérite de multiplier les références. Si le nom même de Trinité/Trinidad peut s’appliquer à l’occasion à d’autres lieux, voici cependant des mentions de Trinidad seul, parfois de Tobago, en 1835, 1840, 1847, 1848, 1851, 1854, 1855.

Mais, en revenant à un cadre chronologique large, Poey alimente, en quelque sorte en compensation la liste des secousses “implicites”. Tel est le cas de l’événement du 24/4/1767, signalé tant aux Petites Antilles qu’en Guyane et du 22/12/1816, avec les mêmes repères. Nos propres recherches apportent d’ailleurs de tels éléments, par exemple les 11/1/1728 et 30/1/1728.[6]

3 Révision chronologique XVIIIe siècle

Suivons maintenant la chronologie en ne retenant toutefois que quelques événements notables ou d’un intérêt particulier, d’une manière quelque peu arbitraire, à la lumière de nos propres lectures.

Passons sur la plus grande partie des événements anciens consignés par Robson à quelque distance, en reprenant le plus souvent Mallet. Voici cependant une exception: c’est d’après un historien moderne qu’il est fait état d’une forte secousse, avec effets matériels, en 1765, à Saint-Joseph: “In St. Joseph, a strong earthquake damaged houses and a church”. Sources et contexte nous échappent. Si Robson fait état, comme il se doit une fois de plus d’après Mallet, de la destruction de Cumana le 21/10/1766, il ne souffle cependant mot de Trinidad, silence d’autant plus étonnant que Fiedler envisage un épicentre proche, dans les parages de Carupano. Le même séisme est consigné en Guyane.[7] Il se trouve par ailleurs qu’une esquisse d’isoséistes conduirait l’aire pléistoséiste jusque vers Trinidad.[8] Dans ce contexte

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[6] J. Vogt, “L’activité sismique antillaise en 1727 et 1728”, texte proposé à *Généalogie et histoire de la Caraïbe*. [Published as: J. Vogt, 2005, “Quelques précisions sur l’activité sismique antillaise de 1727–1728”, *Généalogie et Histoire de la Caraïbe*, No 183, pp 4594–4597].

[7] Supplément aux *Nouvelles extraordinaires* du 17/3/1767.

[8] V. Millán, 1978, “Un sismo que afecto la cuenca Amazonica”, *Interciencia*. [Vol. 3, No 4, p. 264].

vient d'être relevé un écho catastrophiste, visiblement de seconde main, relatif à l'île. Il est question d'une "secousse . . . si violente que la surface de cette île en avait été totalement changée, les plus grandes montagnes s'étant affaissées et se trouvant de niveau avec la plaine".[9] Encore que la source de cette information nous échappe, elle ne manque pas de susciter des interrogations en raison du contexte.

Robson garde le silence, jusqu'en 1790, année où il consigne trois secousses au seul Tobago, une fois de plus d'après Mallet. Empruntons à Poey une secousse survenue le 26/2/1785 tant à Trinidad qu'aux Petites Antilles.

À vrai dire échappe à Robson un événement essentiel, sans doute en 1794, année pour laquelle il n'est question que de la destruction de Cumana, cette fois-ci d'après le catalogue vénézuélien de Fiedler. Or, il semble que ce soit à cet événement que se rapporte la remarquable description par Moreau de Jonnès, témoin, qui deviendra un "classique" de la sismicité des Petites Antilles, de violentes secousses à Port-of-Spain. Ainsi lisons-nous: ". . . Soudain les cloches de la grosse tour de l'abbaye se mirent en branle et tintèrent comme pour un glas funèbre ou le tocsin. Une lampe . . . suspendue à une chaîne à la voûte . . . s'agita d'elle-même et oscilla comme une pendule . . . La terre trembla avec une si grande violence que nous faillîmes être renversés". Les décombres et la solidité des grilles du chœur empêchent les religieuses de s'échapper. Survient une nouvelle secousse: "un nouveau choc remua jusque dans leurs fondements les murs de la vieille église" et provoque la chute du cintre du transept, la déchirure de la voûte et la chute du dôme, avec quarante victimes. Notre témoin trouve refuge "sous les arches du bas-côté de l'église qui résistait encore aux secousses multipliées de la terre". Il ajoute que "à chaque nouvelle secousse, on entendait le fracas de l'écroulement des maisons . . . ". Les rues sont "obstruées par des amas de ruines". S'il est question d'une succession de secousses, deux d'entre elles méritent d'être mises en relief. En effet, c'est à deux reprises que se produit un mouvement de la mer au port: "deux fois la mer s'était retirée à perte de vue, laissant les navires à sec, puis elle était revenue en furie et avait rempli et coulé ceux de ces navires qui s'étaient couchés faute d'être soutenus".[10] Il est évident que s'impose une nouvelle discussion d'ensemble d'un événement majeur, discussion qui échappe présentement à notre propos.

Les larges intervalles d'activité sismique notable sont sans doute l'une des raisons de leurs effets psychologiques. Tel est le cas en 1795 à Port-of-Spain dont il n'est pas question chez Robson. Qu'il suffise de trois notations. D'une part, "à chaque nouvelle secousse on entendait le fracas de l'écroulement des maisons, avec des cris d'angoisse, d'agonie et des invocations à Dieu pour qu'il arrêtât cet affreux fléau". En second lieu, "d'autres, ne trouvant plus d'issue pour sortir de leur demeure et voyant les murs près de se renverser sur elles, se précipitaient du haut d'un balcon et venaient se briser sur les dalles de la place". Enfin "des terreurs paniques se répandirent dans cette multitude". En particulier, "on prétendit que les esclaves

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[9] Nouvelles Extraordinaires du 6/3/1767.

[10] M.A. Moreau de Jonnès, 1858, "Aventures de guerre au temps de la République et du Consulat", t.1, Paris, avec rééd. simplifiée en 1893.

de la geôle, libérés par la chute des murailles de leur prison, parcouraient la ville, égorgeant les habitants qui se sauvaient en emportant leur or et leurs bijoux . . . ". Peur fréquente ailleurs, justifiée ou non . . . Le séisme de 1888 suscite commentaires et initiatives moralisateurs: " . . . Notre premier acte fut de remercier Dieu de nous avoir préservés des plus grands malheurs. Il y eut le dimanche suivant des prières d'action de grâces dans toutes les églises, à la demande du gouverneur . . . Nous ignorons ce que Dieu nous prépare, mais nous savons qu'il reste le Père, même quand il châtie". Considérons à part un événement modeste, en 1843, sans date. Sans nous attarder aux réflexes d'un témoin, à chacune d'une succession de secousses, retenons "que ce fut la fréquence de ces tremblements de terre qui me décida à revenir en Europe".

4 Révision chronologique XIXe siècle

Passons à un événement de moindre importance qui n'apparaît pas chez Robson, à savoir le 13 ou 14/8/1811: " . . . a violent shock . . . accompanied by a subterranean noise . . . from three to five seconds . . . ". Mais ce n'est pour l'instant que pour mémoire qu'est consigné un événement signalé à Port-of-Spain en 1815, sans autre précision de date: " . . . the church and part of town were thrown down by an (earthquake)". L'allusion à des effets matériels n'exclut pas une confusion de dates, le recul aidant.[11]

Brûlons les étapes. C'est le 20/9/1825 que Trinidad est affecté à nouveau par un séisme notable auquel Robson attribue une intensité VIII. Si les effets aux Petites Antilles et en Guyane sont connus, le contexte vénézuélien lui échappe cependant. La rubrique de Robson résume une foule d'observations dont l'une ou l'autre retient particulièrement l'attention. Sont évoquées les lézardes qui affectent de nombreux édifices dont le temple et la résidence du gouverneur. Nombreuses sont les chutes de cheminées. En revanche, la nouvelle église catholique est indemne. Pour une fois nous parvient une information rurale, à Tacarigna, à la sucrerie Strealham Lodge Estate. Outre des maisons de la main-d'œuvre, "negro houses", la cheminée de la chaudière s'effondre. Est-il permis de songer à l'une de ces cheminées massives dont l'interprétation est délicate en termes d'intensité? Sont signalées des répliques.[12]

Robson passe rapidement sur la secousse du 3/12/1831 vers 19h 1/2, notable à la Grenade, en lui attribuant une intensité VII, en faisant état à Port-of-Spain de lézardes dans les murs d'édifices élevés. Un écho de seconde main sans doute, nous en donne une description relativement précise: " . . . nous avons essuyé un très fort tremblement de terre. Le souvenir nous en fait encore frémir. Il y a eu d'abord deux secousses bien distinctes ; la première a duré près de trois secondes ;

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[11] *Times* du 26/11/1811.

[12] W.H.B. Webster, 1834, "Narrative of a voyage to the southern Atlantic Ocean in the years 1828, 29, 30", t.1, Londres.
Voir *Times* du 22/11/1825 d'après *Trinidad Gazette* [21/09/1825].

une oscillation très sensible la suivit durant un intervalle de quatre à six secondes. Alors on entendit un bruit sourd semblable au roulement d'un tonnerre lointain, et une seconde secousse, beaucoup plus terrible que la première, se fit sentir dans la direction du sud-ouest. La terre parut se soulever comme les flots de la mer ; et les édifices les plus solides, ainsi que les appentis les plus frêles, cédaient également à la force de cette impulsion, et chancelaient sur leurs bases . . . Des glaces ont été brisées, quelques murailles lézardées et fendues. Les eaux du golfe étaient dans une agitation remarquable, et à bord des navires on crut avoir reçu un violent choc de quelque corps énorme. . . . A dix heures de la nuit et à deux heures du matin, la terre trembla de nouveau; mais ces secousses . . . n'étaient rien en comparaison des premières . . . ".[13]

Robson mentionne à Trinidad le séisme majeur antillais de 1843, en lui attribuant un degré III, d'autant plus étonnant qu'il fait état d'une intensité IV en Guyane. Avant et après l'événement notable du 19/1/1844, avec une intensité VII à la Grenade, V à Trinidad, d'après Robson, sont consignées trois autres secousses dont deux en Trinidad seule et une autre ressentie aussi à Sainte-Lucie. Pour cette époque, un témoin vient cependant à notre secours. Au terme d'un séjour de cinq ans il fait en effet le point en 1844: "La terre trembla treize fois", avec cette précision: "Durant les derniers six mois, depuis Janvier jusqu'en Juin, 1844, nous éprouvâmes sept secousses".[14] S'il s'agit sans doute de secousses mineures, il reste que le catalogue de Robson serait incomplet, une fois de plus. D'après le même témoin, un événement survenu en 1843, sans date, non identifié, présente un intérêt particulier dès lors qu'il permet de saisir une brève séquence, de nuit: " . . . l'île éprouva trois chocs en sept ou huit minutes", l'accent étant mis, semble-t-il, sur le second, avec ce propos: " . . . arrivé au milieu de chambre, la deuxième oscillation survint et fut si forte que j'en fus renversé". Une confusion avec le tremblement de terre consigné en 1844 n'est cependant pas exclue.

Si Robson énumère en 1851 quelques secousses des Petites Antilles, lui échappe cependant l'événement du 25/11/1851 à Trinidad et dont l'importance est soulignée par la presse: " . . . one of the most alarming (earthquake) felt lately in this island . . . ", avec réveil brutal.[15]

Le 10/7/1863, églises et maisons sont légèrement endommagées, avec, selon Robson, une intensité VI. Cependant un historien moderne écrit: " . . . Much damage was done to property, particularly to the roman Catholic and Anglican cathedrals".[16]

Si nous avons bien compris, c'est faute d'avoir consulté l'ensemble de l'œuvre de Perrey que des événements de quelque intérêt échapperaient à Robson. Tel serait le cas de la secousse du 22/11/1865, ressentie largement au Vénézuéla, en particulier

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[13] Nouvelles Annales des Voyages, t.2, 1832 [p. 140].

[14] H.E. Marquand, 1853, "Souvenirs des Indes occidentales [et impressions intimes]", Londres. [p. 236].

[15] *Antigua Herald* du 6/12/1851 d'après *Free Press*.

[16] G. Carmichael, 1961, "The history of the West Indian islands of Trinidad and Tobago [1498–1900]", Londres.

à Carupano, première d’une séquence qui se poursuivrait jusqu’au 2/12/1865, et de celle du 26/5/1866, largement ressentie elle aussi au Vénézuéla.

Comblons encore une menue lacune de Robson à savoir la légère secousse du 7/7/1868, vers 5h “. . . a smart shock . . . a few seconds only . . . accompanied by a rumbling noise . . . quite distinct from the rattling produced by the earthquake in the materials of a house, furniture, etc. . . . ”. Une fois de plus, voici une réplique, à 5h 25.[17]

Au-delà de la simple énumération de Robson, énumération d’interprétation parfois malaisée, l’une ou l’autre notation glanée par-ci, par-là, met fort à propos l’accent sur quelque événement, avec un certain recul. De la sorte, elles permettent de saisir des intervalles d’activité sismique de quelque intérêt quelle que soit, répétons-le, son origine. Tel est le cas de la secousse du 13/14/8/1811 qui échappe à la liste de Robson [*Times* du 16/11/1811]. Nous lisons “It was most severe than any felt in that island for many years preceding”, ce qui pourrait nous renvoyer à 1794. À propos du séisme destructeur du 20/9/1825, on souligne que rien de tel ne s’est produit de mémoire d’homme [*Barbadian* du 14/10/1825 d’après *Port-of-Spain Gazetee*]. Pareillement est mise en relief, à une autre échelle, la secousse du 10/1/1845 à Tobago, qui échappe à Robson, avec ce propos: “das stärkste (Erdbeben) welches wir hier erlebt haben . . . ”, sans doute en une dizaine d’années [Bericht von Montgomery auf Tabago von den Jahren 1845 und 1846. In “Nachrichten aus der Brüdergemeinde, 1848”].

Pour terminer ce survol, la grande affaire est l’événement majeur du 9/1/1888, destructeur à la Grenade, à Trinidad et au Vénézuéla proche. Pour Port-of-Spain, doté d’un degré VII, sont donnés quelques détails: caserne endommagée et évacuée, lézardes dans les maisons en pierre, chute de plâtre ailleurs. Voici encore des échos ruraux, par exemple lézardes à l’église de Diego Martin. Nous retrouvons les cheminées des plantations: si elles sont lézardées en grand nombre, elles résistent cependant. Robson fait état, au Vénézuéla, de Guiria (Golfe de Paria), d’après *Nature*: chute de maisons, crevasses, informations reprises par *Cosmos* qui fait, en outre, état d’une panique à Irapa. Une fois de plus se produisent des répliques: “Depuis, nous avons eu des secousses réitérées, jusqu’à deux dans un jour . . . ”[18].

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[17] Note on the earthquake of the 7th July, 1868, Proceedings of the Scientific Association [of Trinidad].

[18] L’Année Dominicaine, mai 1888.

Descriptive Catalogues of Historical Earthquakes in the Eastern Mediterranean and the Middle East; Revisited

N. N. Ambraseys

I met Jean Vogt in London about 35 years ago; there and then, it became clear that there was an affinity between us. He was an indefatigable protester of the system in which science works today, and the fact that he always called a spade a spade, often did not endear him to others. His profession was his hobby and he did not depend on others in his work.

Jean had an absurd sense of humour. He would encapsulate his impression about earthquake cataloguers concisely and succinctly. There were cataloguers, he said, who padded their work, others who "went through open doors" in their research, and those whose assessment of historical data was made ad absurdum.

Shortly after the excellent book by Alexandre was published in 1990 (Alexandre, 1990) which showed that 70% of the earthquakes between 394 and 1259 in Western European countries reported in national catalogues were either spurious, or doublets, Jean suggested that we do the same depoillement of the more important catalogues for Europe. However, our project didn't go very far. Far enough however to allow us to derive the "Alexandre coefficient" for three of the most authoritative European catalogues which had a coefficient greater than 30%.

What follows is a potpourri of observations and conclusions drawn from my own experience with the study of historical earthquakes in which Jean played an important role in formulating and that came into fruition in some of our papers.

Throughout the ages earthquakes have been one of the most destructive natural hazards, if not to human life itself, most certainly to the works of man. Earthquake hazards are not always perceived to their full extent. They have long been associated with crises in human affairs, the extent of the crisis being inversely proportional to the financial resources of the country. They are seen as having certain effects or consequences which are rarely specified in advance or fully understood. In a developing country of limited resources and with investments concentrated, the consequences of a large earthquake should be feared as much as the phenomenon itself.

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J. Fréchet et al. (eds.), *Historical Seismology*,

The literary and field studies of ancient and modern earthquakes show that people view differently the challenges and hazards of their natural environment. In historical times the damage and sudden crippling of the economy of a state, had lead to population movements, emigration, crises in political affairs, triggering invasions and wars as well as truce between belligerent states. Loss of life should have been considerable but difficult to estimate.

Also in modern times, particularly in developing countries, earthquakes have caused economic and political crises, increase in taxation and the undesirable, though necessary borrowing from other countries.

The average number of people killed annually is certainly less than the annual number of persons killed today by drugs and motor cars. At the present level of technology, earthquakes cannot be prevented. However, subject only to budgetary restraints their disastrous effects can be minimised.

Earthquakes are destructive because man has made them so by investing his wealth with a disregard for the hazards that Nature may have in store for him. This disregard stems from a variety of causes. The most important being the mere lack of awareness and technical knowledge to alleviate such hazards. Another cause is often the apathy of the populace which is probably due to ignorance. It was, and to some extent still is not uncommon for people to accept earthquakes and their effects as Acts of God about which very little can be done.

The difference in attitude to earthquake hazards found in both historical and modern times cannot be explained in terms of the magnitude or frequency of such disasters alone. It is the perception of the disaster that controls the attitude and stimulates awareness. For instance, very little improvement in building materials and in methods of construction results from an earthquake that destroyed or today destroys remote villages in a developing country. After a very short period of enthusiasm for restoring plan, the interest of the few concerned dies out. Apart from those inflicted, few in the country will be affected and soon the whole problem will be forgotten. In contrast, the damage or destruction of a capital city or of a major engineering structure on which depends the economy of the country will stimulate a completely different degree of awareness. Here, the disaster may or may not affect the economy of the country but the strain will be felt by all.

As we cannot know what will happen in the future, to estimate likely earthquake hazards we have to find out what happened in the past and extrapolate from there a little. Previous research has uncovered evidence of destructive earthquakes in areas where only small events have been experienced recently. This is not surprising: the timescale of geology is vastly different from that of human history, so some parts of the world may suffer violent earthquakes over a very short period of the geological time scale. It follows, therefore, that if we took account only of information about the last century, in which earthquakes have been recorded by instruments (and even then not uniformly throughout the globe), we would have no way of knowing whether an apparently seismically "quiet" area today is in fact at risk from a damaging earthquake.

For the Eastern Mediterranean and the Near East there is a large number of descriptive and parametric, but confusing catalogues of historical earthquakes. Obviously the value of parametric catalogues will be only as good as the descriptive catalogues.

The following descriptive earthquake catalogues are published, readily available and some of them are widely used.

- **Manetti**'s work is the earliest-known compendium of earthquakes and contains an annotated list of earthquakes in the Eastern Mediterranean and elsewhere up to 1456. Manetti does not always cite his sources and quite often the year of an earthquake is recorded only by reference to other events (Manetti ca. 1457).
- **Al-Suyuti**'s earthquake catalogue was compiled in the early part of the 16th century and extended by his continuators to the year 1588. It is a reliable source of information for the Muslim world, covering the region from Morocco to Transoxiana (Sa'adani ed. 1971).
- **Bonito**'s large world earthquake catalogue is an invaluable compendium of information about earthquakes that ends with 1690. Its 822 pages contain a wealth of information culled from a variety of sources, which Bonito quotes and occasionally annotates. His work provides an excellent starting point for the identification of earthquakes in Europe and in the New World (Bonito 1691).
- **Coronelli**'s work, although prepared as a global catalogue of earthquakes up to 1693, it deals mainly with events in the central and eastern Mediterranean. Annotations are kept very brief, making no reference to sources of information and occasionally neglecting to give the full date of an event (Coronelli 1686–1693).
- An anonymous compilation of earthquakes throughout the world was published in a series of issues of the **Dresdnische Gelehrte Anzeigen** in 1756, and is a useful source of information for earthquakes worldwide during the 16th and 17th centuries up to 1691 (Dresdnische Gelehrte Anzeigen 1756).
- **Hoff**'s general catalogue of earthquakes is a valuable work, covering events worldwide for the period up to the end of the 17th century. It is an accurate and methodical study, drawing on a variety of published sources, which are cited (Hoff 1840–41).
- The compilation of **Seyfart**'s work on earthquakes was prompted, like many similar works of the mid-18th century, by the large Lisbon earthquake of 1755. It contains interesting entries, mostly extracted from published material in Europe, such as flysheets and newsletters, as well as from the European press (Seyfart 1756).
- **Montbeillard**'s long chronological list is an annotated collection of information about earthquakes up to 1760. The author does not cite his sources but they seem to include, among others, earlier catalogues and information from the European press (Guéneau de Montbeillard 1761).
- **Hoff** compiled twelve annual earthquake catalogues for the years 1821–32. He extracted much of the information from press reports, travel diaries and from correspondence. His work is of interest for areas outside Europe (Hoff 1826–35, 1840–41).
- **Mallet**'s catalogue occupies nearly 600 pages and contains almost 7,000 events worldwide. Although based on several earlier catalogues, and especially on those of Hoff and Perrey, his catalogue for the period after the 17th century contains a considerable amount of information from relatively early press reports, some

of which are useful for investigating the seismicity of the Americas and the Far East (Mallet 1850–58).

- **Perrey**'s annual lists of earthquakes for the 28 years 1844–71 are invaluable. They occupy 28 papers and the total number of pages in these Mémoires is just over 2,500. Perrey collected much of the material by correspondence and also from the international press. His annual lists are a vast storehouse of facts; for the most part he was content to leave discussion of the results to others. There is seldom any attempt to determine the position of the epicentre, none to discover the relation between main shock and aftershocks or the relation between shocks felt at the same time at different places (Perrey 1844–1873).
- **Schmidt**'s catalogues for the Southern Balkans and Asia Minor is one of the most important sets of data for the region. It depends very little on previous lists or catalogues and from about 1800 onwards, is the result of his own labours. From after about 1858 to the end of 1878, his catalogue contains just under 4,000 entries, derived chiefly from correspondence with observers, travellers and consuls throughout the Eastern Mediterranean and from the Press in Athens, Istanbul, Izmir and other places in the area (Schmidt 1867, 1879).
- A long memoir containing lists of earthquakes for the twenty years, 1865–84, was published by **Fuchs**. These lists include nearly 10,000 entries altogether, containing a substantial amount of information for earthquakes worldwide. In common with some other catalogues, this work must be used with caution, for nowhere does Fuchs cite his sources, and it is accordingly difficult now to appreciate the value of the information which he retrieved (Fuchs 1886).
- **Mushketov and Orlov**'s earthquake catalogue for the Russian empire ends in 1888. It is based on previous catalogues but also on contemporary national and local Russian press reports and to a lesser extent on unpublished documents. Events are fully annotated and sources are given in full. This is a very useful source of information (Mushketov and Orlov 1893).
- **Milne**'s world catalogue of destructive earthquakes up to 1899 is based entirely on previous lists. It is devoid of information from original sources, except for the last decades of the period for which information comes from unpublished documents (Milne 1911).
- **Montessus de Ballore**'s world catalogue consists of 171,434 entries which cover the period up to 1906. Only a small fraction of this enormous volume of information, which covers mainly the second half of the last century, has been published, and it remains little known. However, the published information is not of very great value; the unpublished files, kept in the Département des Cartes et Plans, Dépôt de la Société de Géographie of the Bibliothèque Nationale in Paris, where they occupy 30 metres of bookshelf, did not prove, on examination, to be as useful as had been anticipated. Much of the information in these files was extracted from previous catalogues and press reports, with little original material derived from correspondence with observers (Montessus De Ballore 1906, 1924).
- **Sieberg**'s annotated world catalogue of earthquakes contains a considerable amount of information, including isoseismal maps for the larger historical earthquakes worldwide up to 1930. His work, he admits, is subjective, influenced by

his experience as a professional architectural engineer who, in the first quarter of the 20th century visited many sites of earthquakes. He is one of the first in Europe to test models of buildings on shake-tables. However, his catalogue contains many errors and duplications in entries and gives little indication of his sources of information. It is well illustrated with maps but nevertheless, this highly inaccurate work has for many years been regarded as a standard reference on the subject (Sieberg 1930, 1932).

- **Stepanian**'s annotated catalogues of earthquakes in Greater Armenia are a useful set of documents. They are based on a considerable number of primary published Armenian sources. These Armenian catalogues of Stepanian are little known; they are accurate and methodical, and contain about 800 events (Stepanian 1942, 1964).
- **Byus**' book of earthquakes in the Caucasus and adjacent regions is a systematic compilation of information from previous catalogues, in some cases critically selected, as well as from local Georgian, Armenian and Russian sources, including local newspapers and reports. This 600-page long work contains a wealth of information about events in the Middle East (Byus 1948).
- **Rethly**'s book of earthquakes in the Carpathian region and central Europe is a serious piece of work. It includes extracts from original sources and is fully referenced. This work is invaluable for the identification of events that affected southeast Europe (Rethly 1952).
- **Ambraseys'** three-volume Corpus of Documents of early earthquakes in the Near and Middle East, is a collection of little-known Greek, Arabic, and Syriac sources of information, compiled for UNESCO during the period 1961–1970 (Ambraseys 1970).
- The survey of the seismicity of the Balkan region carried out by UNESCO in the mid-1970s, contributed a summary of the material available at that time for the assessment of regional seismicity. Isoseismal maps for a few events before 1900 and a parametric catalogue were published, but they must now be used with caution (**Shebalin, Kárnik and Hadzievski** 1974).
- The catalogues of earthquakes in the Middle East and along the Dead Sea Rift by **Ben-Menahem** (1979, 1991) contain information extracted from earlier catalogues of varying quality and from secondary works. These lists, which include a parametric catalogue going back to 2050 BC, must be used with very great caution.
- The earthquake catalogue of the former USSR covers a large geographical area for the period before 1977. It is based chiefly on secondary sources but includes a detailed procedure for the systematic quantification of historical events (**Kondorskaya and Shebalin** 1977, 1982).
- The catalogue of **Poirier and Taher** (1980), covers the seismicity of the Middle East, listing nearly 200 events up to 1800. It summarises information taken from a thorough survey of Arabic source material, presented in Taher's doctoral thesis, Sorbonne (1979). References are properly identified and cited. Though the catalogue contains various errors and duplications, this is a considerable improvement on earlier works. A more extended summary of this primary data,

although regrettably without any reference to modern studies, is contained in Taher (1996).

- The books by **Ambraseys and Melville** (1982, 2005) and **Ambraseys, Melville and Adams** (1994, 2005) present a thorough re-evaluation of the long-term seismicity of Iran, Saudi Arabia and the Red Sea, based as far as possible on primary Persian, Arabic and occidental sources. These works present in some detail the methodology proposed to assess historical seismicity by combining instrumental data and macroseismic information.
- The book by **Guidoboni** (1989) is an attempt, to compile a descriptive catalogue of information of earthquakes in Italy and in the eastern Mediterranean as a whole and covers the period 8th century BC to the 10th century AD. Events are annotated and texts originating from sources in Greek and Latin are given in their original script with a translation in Italian. Generally no attempt is made to "de-weed" or discuss the historical information it presents.
- The part of the Catalogue (and Map) of the "Global Seismic Hazard Assessment Programme" that refers to the eastern Mediterranean region is the result of a compilation of a kaleidoscope heterogeneous data taken from various catalogues. And it must be used with great caution (Giardini and Basham 1993; Giardini 1999).
- The book by **Ambraseys and Finkel** (1995) covers Turkey and parts of the Middle East for the period from 1500 to 1800. Its value is chiefly the presentation of unpublished Turkish and occidental sources of information about earthquakes for this period.
- The catalogues of **Papazachos and Papazachou** (1989, 1997, 2003) cover the historical seismicity of Greece and adjacent regions. These are annotated compilations essentially based on previous catalogues without scrutiny, adding little or no new information.
- The book by **Guidoboni, Comastri and Traina** (1994) deals with earthquakes in the Mediterranean area up to the 10th century AD. Events are annotated and texts originating from sources written in Hieroglyphic, Greek, Hebrew, Latin, Syriac, Coptic, Armenian, Aethiopic and Arabic, are given in their original script with a translation into English, obviously for the very many readers who are not familiar with these dead languages. The book is decorated with many maps, figures and photographs.
- The work by **Spyropoulos** (1997) is an exhaustive annotated corpus of extracts from original but chiefly secondary sources relating to historical earthquakes in Greece.
- **Sbeinati, Darawcheh and Mouty** (2005) present an analysis of large and moderate earthquakes in Syria from 1365 BC to 1900 AD.
- The book by **Guidoboni and Comastri** (2005) is an ambitious work. It consists of a compilation of information about earthquakes in the Eastern Mediterranean region and in the Middle East over the period 1000–1499. This impressive catalogue, 1037-page long, is written in the same style as the earlier book by Guidoboni, Comastri and Traina (1994) and lists 383 events of which 154 belong to Italy and 229 to the rest of the Eastern Mediterranean.

The existence of all these readily available descriptive catalogues does not, of course, mean that no further research remains to be done, and no new sources remain to be discovered. A catalogue at best can sum up the state of knowledge at the time it was written, and provides a basis for new work with a view to promoting knowledge of studies on local seismic activity and to evaluating its contribution to the previous state of knowledge.

But new original information can only be found in less readily available places. Taking Greece for example, much of the data for the period 1846–1879 exist in detailed reports written by the local authorities to the Ministry of Ekklesiastic (Religious Affairs) and Public Education in Athens.

Early descriptive catalogues are few and necessarily summary, and cannot go into all the details that exist in manuscripts, tracts and pamphlets which are numerous and difficult to locate.

There is relatively little that can be found in unpublished manuscripts, much of which is in the short notices, almost telegraphic or in general references of 14th–16th century earthquakes illustrated with imaginary wood-cuts or drawings of the event. One of the few interesting manuscript notes of that period is that of Leonardo da Vinci, who describes the effects of the earthquake of 1481 at sea near Cyprus (Fig. 1). The year he gives is clearly written as ‘89, probably a slip of the pen for ‘81. From the style of his account it seems that Leonardo was not an eyewitness of the earthquake but it is known that in late 1480 or early 1481 he was in Cyprus. There is also an interesting news-sheet of 1545 that gives first hand information for an earthquake in central Greece about which little is known from other sources.

There is a lot of information that can be found in tracts and pamphlets written at second or third hand of this and of later periods, but tracts would focus comprehensibly on the local information available for a particular event than would be appropriate in a more general work. Accounts, at second hand, were published for calamities, among which earthquakes, for Cyprus and Palestine as well as in Dutch pamphlets (Fig. 2) bring to light events little known or unknown from other sources. Turkish court documents referring to repairs of public buildings after earthquakes (Fig. 3) show quite often that damage was far less serious than that presented by church writers and the occidental press report.

The effects in Istanbul of the earthquake of 10 September 1509 in the Sea of Marmara have been grossly exaggerated in secondary sources to the extent that the earthquake became known as *küçük kiyamet* (little apocalypse). A woodcut made in 1529 a print of which shows the Fatih mosque with truncated minarets, attributed

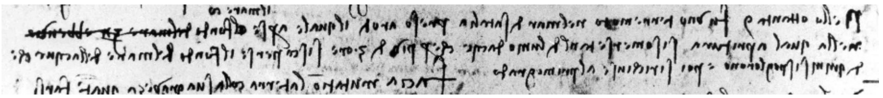
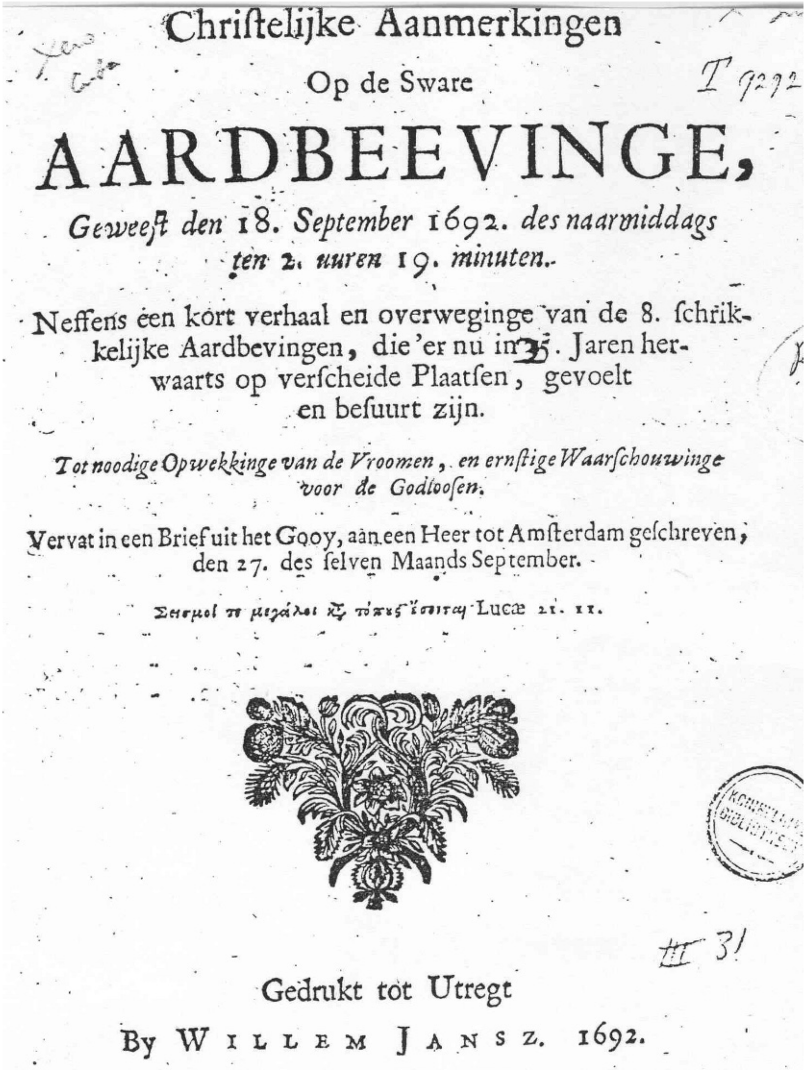


Fig. 1 Excerpt from Leonardo’s manuscript known as Codex Leicester (formerly, Leicester 699, Holkham Hall; formerly called the Codex Hammer, when it was owned by Armand Hammer), now Collection of Bill and Melinda Gates, Seattle, Washington. The text deals with the 1481 earthquake in Cyprus



Chriſtelijke Aanmerkingen
Op de Sware
AARDBEEVINGE,
Geweeſt den 18. September 1692. des naarmiddags ten 2. uuren 19. minuten.

Neffens een kort verhaal en overweginge van de 8. ſchrikkelijke Aardbevingen, die 'er nu in 35. Jaren herwaarts op verſcheide Plaatſen, gevoelt en beſuurt zijn.

Tot noodige Opwekkinge van de Vroomen, en ernſtige Waarſchouwinge voor de Godlooſen.

Vervat in een Brief uit het Gooy, aan een Heer tot Amſterdam geſchreven, den 27. des ſelven Maands September.

Σεισμοί τε μεγάλοι κατὰ τόπους ἔσονται Lucæ 21. 11.

Gedrukt tot Utregt
By WILLEM JANSZ. 1692.

Fig. 2 One of the Dutch pamphlets of the period 1690–1710 that referred frequently to earthquakes worldwide (J. Vogt)

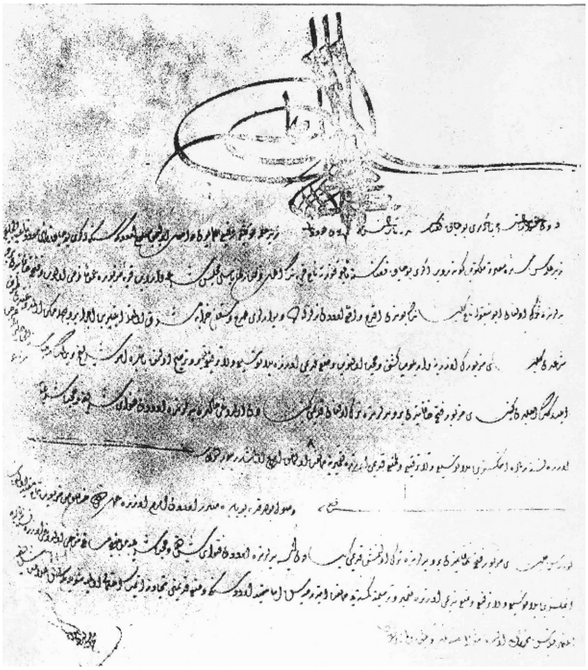


Fig. 3 Facsimile of an Ottoman Imperial order, bearing the cipher (tugra) of Mustafa-II, which allowed the execution of repairs to the church of St Nicholas in Quzna (Kozani) in northern Greece, issued after the earthquake of 26 September 1695

to the 1509 earthquake (Fig. 4). That the minarets would have remained unrepaired for 20 years seems rather strange and an inspection of another print of this woodcut, kept at the British Library, shows some damage in that area and a portion of the minaret and dome may have been lost. Later prints from a better pressing from the same block at the British Library show no flaw and the tallish minarets built outside the body of the mosque, so that the only indication of their collapse is the

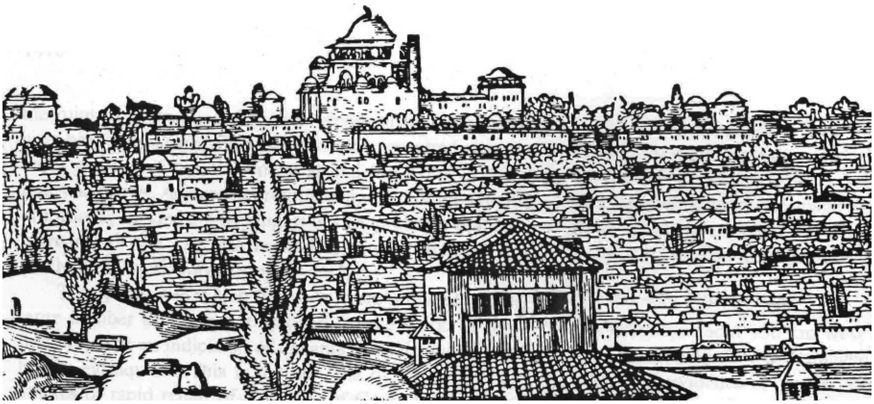


Fig. 4 A woodcut by Coecke, made in about 1529, showing the Fatih mosque in Istanbul with its truncated minaret

misinterpretation of Sanudo's statement that "[. . .] il *marati* del Segnor vechio va in rovina et la mazor parte de le mochee [. . .]" (Sanudo 1496–1533). In fact *marati* should be *imarets*, the ancillary buildings of the mosque and not minarets.

Many earthquakes are illustrated with contemporary wood-cuts and prints, almost all of them accompanied by caption written with some poetic licence.

The earthquake of 14 January 1546 in Palestine is considered by late sources to be one of the most important earthquakes to have occurred in the district of Jerusalem. It caused some small damage in the region but contemporary pamphlets and wood-cuts prove that the reported damage was grossly exaggerated. Oldrich, a Czech pilgrim, who was in Jerusalem very early in the summer of 1546 notices that only the top part of the church of the Holy Sepulchre collapsed because it was heavy, revetted with sheets of lead. A view of the Holy Sepulchre and its square, was drawn by Oldrich's companion, Dominik de la Greche, and appended to his book (Fig. 5). The detailed panoramic view of Jerusalem, also drawn by de la Greche, shows no other tall structures missing or the collapse of the dilapidated city walls.

Even in more recent times damage and loss of life reported in private correspondence, for instance after the destructive earthquake of 1894 from the region between Adapazari and Lake Iznik in Turkey, is not mentioned in the Turkish press,

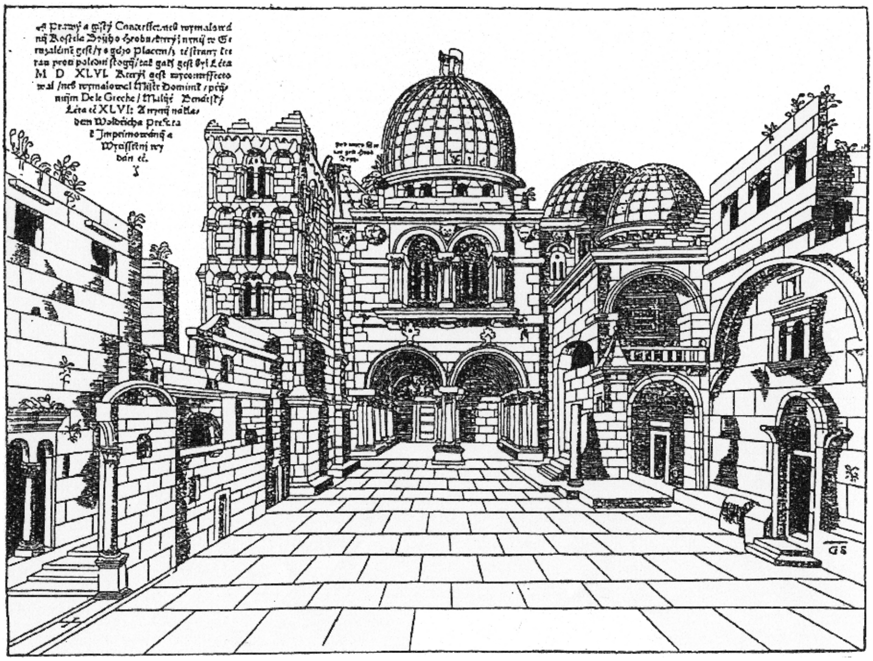


Fig. 5 Church of Resurrection. View of the Church of the Holy Sepulchre and its square seen from the south side, drawn by Dominik de la Greche a few months after the earthquake of 1546. Notice the missing top part of the bell tower

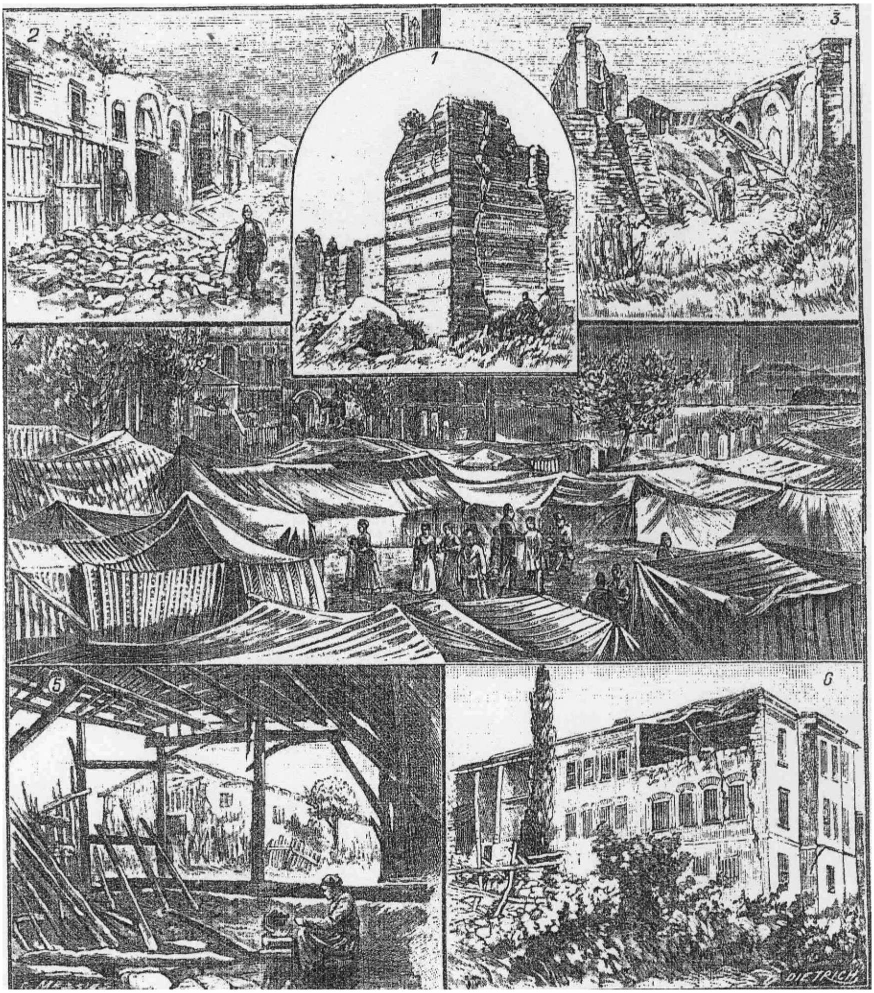


Fig. 6 Scenes of the effects of the earthquake of 10 July 1894, Gulf of Izmit, shown in "La Nature" (1894, no. 1114)

who concentrated chiefly on the effects of the earthquake in the capital (Fig. 6). This supports the opinion expressed by foreign eyewitnesses at the time that news in the press about the disasters in Turkey were systematically censored.

There is also a substantial number of "original" descriptions of destructive earthquakes, reported not only in contemporary 16th–17th century fly-sheets but also in early documents, which the information on examination proved to be spurious. This shows that the fact that the information is coeval or even eyewitnessed is not a guarantee that it is not spurious or the result of political or religious figment of imagination.

Fig. 7 The effects of the earthquake of 2 September 1754, Istanbul, depicted, with some poetic licence, by the European press, from a woodcut print made in 1755 and published in Basel

An illustration in a contemporary flysheet shows imaginary damage in Istanbul in an earthquake in 1754 (Fig. 7). This is a typical theme of the contemporary European press which was wont to publish as "news" concerning the Ottomans at times when relations were unstable, or on the occasion of an Ottoman military victory, in order to encourage confidence that they would be overcome by the West.

Also, out of context interpretation of events written in different languages together with the confusion of place names, contribute to an increase in the number of spurious events. A sample of mislocated places is: Alexandretta (Turkey) confused with Alexandria (Egypt), Argos (Peloponnese) with Argostoli (Kefalinia), Bilad al Yunan (Greece) with Bilad al Waynan (Yemen), Chalki (n. Rhodes) with Chalkis (Negreponte or Eğribos), Carinthia (Kärnten in Austria) with Corinthia (in Greece), Edessa (Urfa in Turkey) with Edessa (Vodena in Greece), Kastamonu with Kostambul and Istanbul in Turkey, Karahisar-i Sahib (Afyonkarahisar) with Karahisar-i Şarki (Sebinkarahisar in Turkey), Kayseri (in Turkey) with Caesarea (Palestine), Philippople (Plovdiv in Bulgaria) with Filippi (Greece), Sparta (Greece) with Isparta (Turkey), Syros and Syra (Greece) with Syria or Styria (Steiermark in Austria), Tire (Turkey) with Thera (Greece), Tuscia (Italy) with Turcia (Turkey), Veroia (Greece) with Veroi (Stara Zagora, Bulgaria), Zituni (Lamia in Greece) confused with Zeytun (Elbistan in Turkey).

This brings me to the problem of the survival of historical data. Here I am quoting part of the discussion on the subject I had recently with Roger Bilham. One feels uneasy with electronic repositories of historical material and supplements of words, probably because words have survived longer than the digital revolution of the past two decades. As pointed out by Roger Bilham, our work for northern India exhumed more than a millennium of paper materials, whereas our discs crashed three times during the project. The promise of an electronic repository is that, rather like nuclear waste, it has to be guarded by someone for the next millennia. The written word in the past five millennia, despite being in many languages is always to some degree readable. In contrast I can't read archival tapes from 1990.

Are we unnecessarily paranoid about society's ability to guarantee survival of electronic archives?

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Part II

Reappraisal of Historical Earthquake Information

A Glimpse into the Seismicity of the Ionian Islands Between 1658 and 1664

P. Albini and J. Vogt

Abstract Mostly based on traditional catalogues, without further research, several modern parametric catalogues are nevertheless straightforward, without question marks, and easily misleading (chronology, epicentre, epicentral intensity, not to speak of magnitude). The example of an Ionian time-window (1658–1664), with several major events, shows that the historical seismicity of the Ionian Islands, often thought to be well-known, actually needs a more or less drastic revision. A wealth of sources was collected, mostly from the Archives of the Republic of Venice, then ruling the main three islands of the Ionian Archipelago; it was ascertained that there are no important chronological gaps in the surviving documentation.

Similarly outstanding, and in fact at the basis of a more balanced and precise view of one of the events in this time-window, are the souvenirs of Christoff von Degenfeld, a German nobleman at the service of the Republic of Venice. His manuscript, discovered at the library of Karlsruhe (Germany) in 1992, has been consulted again in the original, on the occasion of the preparation of this paper.

Some question marks remain on the distributions of macroseismic effects of the earthquakes within this time-window, and this is due to the lack of information concerning the mainland. For this reason this study does not propose epicentres and, of course, magnitudes. An unusually long documentary appendix is provided, with the hope that it might contribute in discouraging authors of parametric earthquake catalogues from hasty exploitation and interpretation of often unreliable current catalogues.

Foreword The idea of writing this paper goes back to 1992 (Vogt and Albini, 1996) and an advanced draft was ready since 1997; an unfortunate series of events hampered its publication. This revised and updated version maintains some of the parts originally written by Jean Vogt, who discovered the von Degenfeld's manuscript, one out of his many serendipitous and little known findings.

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J. Fréchet et al. (eds.), *Historical Seismology*,

1 Introduction

The past seismicity of the Ionian Islands has attracted seismologists' attention since many years; some papers were published (e.g. Makropoulos and Kouskouna, 1994; Albini et al., 1994) and, apart from the parametric catalogues, the modern studies on the seismicity of Greece commonly deserve a particular attention to this area (e.g. Spiropoulos, 1997). Notwithstanding this favorable situation, gaps and doubts still concern both the date and the distribution of effects of several damaging earthquakes occurred before the 20th century. This paper will try and use the relatively small time-span between 1658 and 1664 as a case history to state the need for further studies on the seismicity of the Ionian Islands.

After an overview of the geopolitical scenario of the Ionian Islands under the domination of the Republic of Venice, the documents, including information on earthquakes and who wrote on them, are presented, to help determine if and how much they are reliable and complete with respect to the investigated time-window.

These investigations concerned both the discovery of some new sources and the thorough and systematic research carried out in the already known sets of documentary sources. The results are presented according to three main aspects: (i) interpretation of the earthquake records by putting them in a coherent time-space context; (ii) correction of errors in the dates of the earthquakes; (iii) description of the effects caused by the damaging earthquakes in this time-window.

The conclusion the authors would especially stress is that there are still many undetected documents to be found in European archives and libraries or misinterpreted ones, to cast light on. It is not time yet to disregard the investigation of historical documents and the intepretation of the earthquake records they contain: the current knowledge of the seismicity of the Ionian Islands and other areas could be significantly improved by the memory of the past earthquakes, waiting to be rediscovered.

2 The Ionian Islands and Their Background in Mid 17th Century

In mid seventeenth century, the rule of the Republic of Venice towards East extended to some coastal areas of Dalmatia and Albania, and to the three Ionian Islands of Kerkyra (*Corfu* in the Italian documents), Kefallinia (*Cefalonia* or *Ceffalonia*) and Zakynthos (*Zante*) (Fig. 1). To gain possession of the island of Lefkas (*Santa Maura*), at that time under Ottoman rule, the Venetians had to wait until 1684. In the 17th century, the Republic of Venice and the Ottoman Empire (Fig. 1) entered into a continuous conflict, which became intense during the long-lasting war (1645–1669) for the island of Crete (*Candia*).

In the time-window this paper considers, the Republic of Venice is suffering from a financial, administrative and military crisis and is paying for the heavy toll taken by a war that ended in the loss of the Venetian hegemony on Crete. The strategical position of the Ionian Islands with respect to the actual war theater made them a

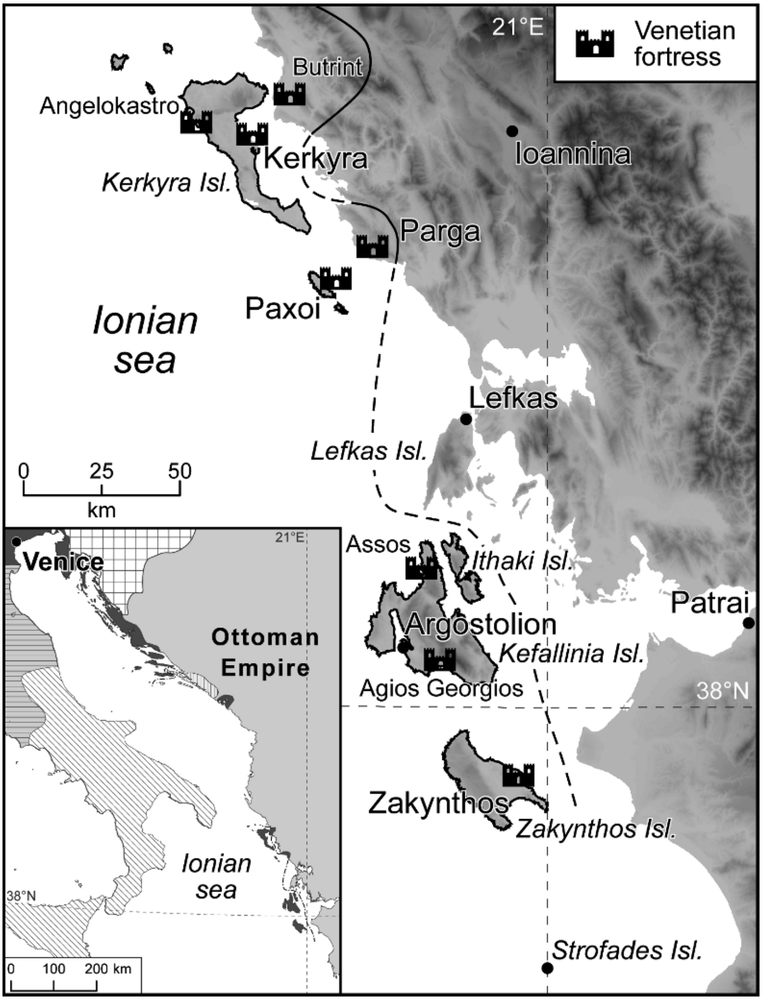

Fig. 1 The Ionian Islands and their geopolitical situation in mid-seventeenth century. The islands enclosed in a thick line belonged at that time to the Republic of Venice

natural choice as the logistic outpost. In particular, the island of Kerkyra was in charge of equipping the galleys, recruiting soldiers and soundly contributing to their provisions. All this seriously reflected on the state of the island. Though less involved in the war for Crete than Kerkyra, Kefallinia suffered from this situation. Specifically, Kefallinia's importance consisted also in the forest of black pine trees then covering Mount Enos, a fundamental resource for the good quality timbers the naval arsenal of the Republic needed to build and repair the fleet.

The island of Zakynthos, scarcely inhabited apart from the homonymous town and harbour, was in fact the southernmost and closest to the Western Peloponnese, where the Venetian strongholds of Methoni (*Modone*) and Koroni (*Corone*), the so called "eyes of Venice" were located.

The events of the everyday life in the Ionian Islands during the war for Crete are minutely detailed in the documents written by the Venetian officers and by other protagonists, who took time and care to leave a written memory of their observations.

3 The Observers and Their Documents

3.1 Venetian Officers

From 1658 to 1664, the officers selected and sent by the Republic of Venice to their *Levante* (Eastern) territory were posted in the three islands as follows:

- *Kerkyra* – Since when the island became a Venetian possession (1386), a governor with the title of *Bailo* was appointed by the Senate; he resided in the homonymous town, had both administrative and judicial authority, and was assisted by two Counsellors. The Venetian and Greek nobility annually elected a Council of 150 members. In the 16th century, the increasing strategic importance of the island made necessary to appoint also a *Provveditore e Capitano*, in charge of the civil and military administration, and especially of the two fortresses (Old and New) in the town of Kerkyra. He had to take care as well of the fortress in Angelokastro (about 30 km north-west of the town of Kerkyra), of the fortress in the island of Paxoi, south of the island of Kerkyra, and of the fortress of Parga on the opposite coast of Epirus (Fig. 1).
  From the 16th century, Kerkyra was also the seat of the highest-in-rank Venetian officer in the area, the *Provveditore Generale alle (Tre) Isole del Levante*. He had to superintend the whole Eastern area under Venetian influence, and among his duties there was to pay regular visits to the other two Ionian Islands.
- *Kefallinia* – The *Provveditore Ordinario* was living in the fortified site of Agios Georgios (ASVe 1660b and 1660d), situated on an inland hill about ten kilometres south of Argostolion (Fig. 1). Within and nearby the Castle, there were some 60–100 inhabited houses. Argostolion was at that time the most developed harbour of the island, but it was to become the capital of the island in 1757 only (Pignatorre, 1887). Business made the *Provveditore* spend some time at harbour in Argostolion, taking care of special charges, such as controlling the shipping of *uve passe* (raisin) (ASVe, 1660b). Another *Provveditore* was appointed to the fortress of Assos, about 40 km north-east of Argostolion.
- *Zakynthos* – The *Provveditore Ordinario* was living in the homonymous town. Few other important settlements existed in the island at the turn of mid 17th century. Finding information from the rest of the island in the available documents is a matter of luck, well into mid 18th century. The main urban

feature was the Fortress, built in the 16th century, when the Venetians took hold of the place.

To get a comprehensive scenario of the life in the Ionian Islands in the period of interest, the investigation was oriented towards some specific documentary series, all belonging to the documentation pertaining to the Senate of the Republic of Venice:

a. *Dispacci, Rettori*, gathering the dispatches written to the Senate in Venice by the *Provveditori* of Kerkyra, Kefallinia and Zakynthos;
b. *Provveditori da Terra e da Mar*, collecting the dispatches written to the Senate in Venice by the *Provveditore Generale alle Isole del Levante*, residing in the town of Kerkyra.

The two series complement each other, the first being made up by the documents produced by the *Provveditori* appointed in each Ionian Island, and the second series proposing a general view of this eastern portion of the Venetian territory, described both through the personal experience of the *Provveditore Generale alle Isole del Levante* and the locally produced documentation.

A systematic investigation was carried out, to check upon the documentary *versus* the seismological coverage for the years 1658–1664. The number of documents has been plotted *versus* 6-month periods between July 1658 and June 1664 for both documentary series (Fig. 2a,b). The comparison is permitted by the coincidence of the places of origin of the documents.

In Fig. 2a are shown the documents originated from the *Provveditori* in Kerkyra, Kefallinia and Zakynthos. In Fig. 2b, the dispatches written by the *Provveditore Generale alle Tre Isole del Levante* are shown according to their places of origin, which are in fact the same three islands from where the documents in Fig.2a originated.

The gaps that could affect our knowledge of the investigated time-window can be seen in Fig.2a: (i) from January 1661 to December 1662 for the island of Kefallinia, period for which two dispatches only are available; (ii) from January to June 1662 for the three islands. The documents made available by the *Provveditore Generale alle Isole del Levante* (Fig.2b) partially fill in these gaps.

If one looks for the actual reasons of these gaps, one can start listing the common loss of documents that marks the 17th century correspondence between the peripheral and central authorities, and consequently their archives. The Ionian Islands local archives suffered from subsequent losses and might only in a few (lucky) cases supplement with items not found at the State Archive of Venice. The systematic reading and investigation of the documentation for this period make possible to guess that a further, specific reason to account for these gaps could be the usual delay in the arrival of the newly appointed *Provveditore* from Venice (see below the case of the *Provveditore* of Zakynthos, in the section devoted to the 1662 earthquake).

For the sake of completeness, information was also searched for in files and registers of *Decreti* (Resolutions) by the Senate. Unluckily, these documents (ASVe,

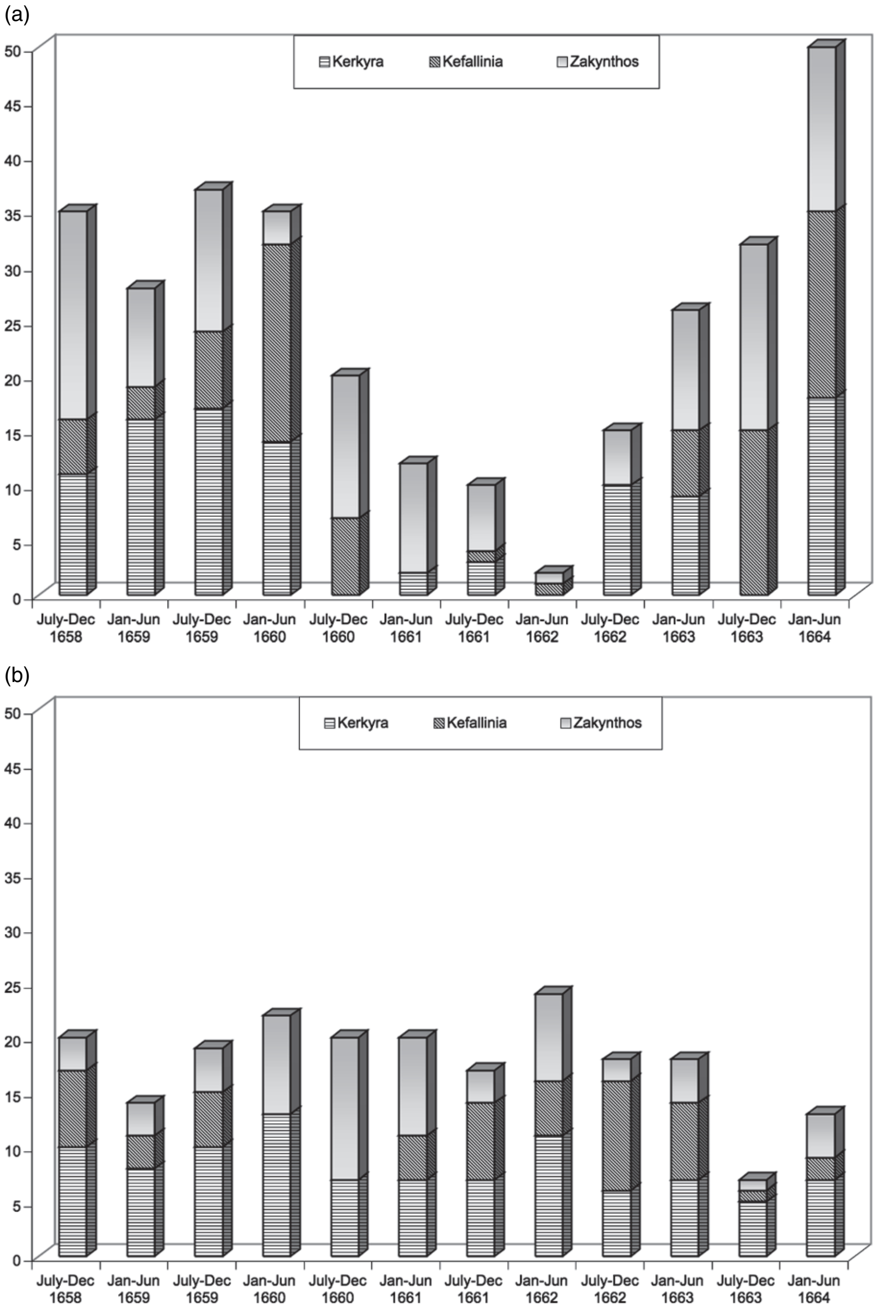

Fig. 2 (a) Number of dispatches available in “*Senato, Dispacci, Rettori: Cefalonia, Zante, Corfu*” versus 6-month periods between July 1658 and June 1664. (b) Number of dispatches available in “*Senato, Provveditori da Terra e da Mar, Provveditore Generale alle Tre Isole*”, versus six-month periods between July 1658 and June 1664

1661d; ASVe, 1663a; ASVe, 1664c) do not supply fresh information on earthquake effects, though they help in restraining the dates of the earthquake occurrence.

A good documentary coverage is consequently assessed for the investigated period, both considering the number of events and the quality of the descriptions. What is the content of the retrieved documents is detailed in the following (Section 4).

3.2 Christoff Freyherr von Degenfeld

In the framework of the EC project "Review of Historical Seismicity in Europe" (1988–1992), many manuscript holdings of libraries were explored, mostly in Belgium, France, The Netherlands, Germany and Switzerland, and focusing on the 18th century (Stucchi, 1993). Many discoveries were made for earlier times also, as it is the case of a manuscript covering the time span 1661–1669, here described.

3.2.1 The Author

Christoff was one of the six sons of Christof Martin I (1599–1654) Freyherr von Degenfeld, a small place near the German town of Schwäbisch-Gmünd about 50 km east of Stuttgart (Seehofer, 1978; Eickhoff, 1988; Bächle, 2005). Maintaining the family's military tradition, Christoff (1641–1685) entered at the service of the Republic of Venice in the final stage of the war for the control of Crete (1645–1669). After his brother Adolf *Condotto* (commander, said of a mercenary soldier) was deadly wounded (1667) at the end of the 22 years siege of the town of *Candia*, the capital of the island (today Irakleion), he took over the command of his battery (Degenfeld, 1670 *ca*).

Evidence of the time when Christoff and his brothers were known to the officers in the Eastern possessions of the Republic of Venice was left for us by Girolamo Contarini, *Provveditore Generale in Dalmatia e Albania*, living in Split (today in Croatia, *Spalato* in Italian documents). On 29 November 1663, Contarini informs the Senate of the Republic of Venice that three members of the von Degenfeld family, "*Il signor Adolfo Barone di Degenfeldt Condotto al servizio di Vostra Serenità* [. . .], *con li signori Cristoforo e Massimiliano suoi Fratelli venturieri*", were given a safe-conduct, while travelling within the Venetian sphere of influence along the Eastern Adriatic coast (ASVe, 1663c).

3.2.2 The Manuscript

Kept first in the archives of the Kraichgau Chivalry, this item is stored today in the manuscript department of the Badische Landesbibliothek, Karlsruhe (Germany). Binded in a wood and cuir cover, this imposing (32 × 20.5 cm) manuscript starts on top of fol. 1 with the following sentence: "*Beschreibung der reyse so ich Christoff Freyherr Von Degenfeldt, Im Jahr Christi 1661 Von Dürnau aus angefangen, Undt im Jahr 1670 vollendet habe, auch was auf solchen Vorgangen, Undt sonsten Marckwürdiges zu sehen gewesen*" [Description of the journey that in the year 1661

I Christoff Freyherr von Degenfeldt started from Dürnau, and finished in the year 1670, of what happened during such procedures and what else of remarkable I have seen] (Degenfeld, 1670 *ca*).

The author did not divide the manuscript into sections, but chose instead a continuous writing. When one gets rid of the difficulties in reading its writing and language, this manuscript appears quite clearly as the result of the juxtaposition of two quite different items:

1) a diary, or better a travelogue, from fol. 1 to fol. 710, adorned and enriched by about 150 drawings of the visited places. This is the incipit: "*Im Jahr 1661 nach Christi Unsers Erlöser geburth den 12 Martij Stil: Vet: bin ich Von Dürnau in Schwaben, als eines meines herren Vatteren seeligen hinderlassenen guth, frühe morgens nach dem ich Von denen damahlen anwesenden geschwistrigen abschiedt genohmen, abgereyset, Undt um 9 Uhren zu Altenstatt einem Almischen Flecken so nur zwey meyl Von Dürnau, angelangt umb mich von daraus auf die Post gegen Venedig zu begeben, und bin auch noch selbigen Tag über Ulm bis nach Dillerdissen*" [In the year 1661 A.D. on 12 March Old Style I departed from Dürnau in Schwaben, one of the manors left by my father, early in the morning after I took leave from the siblings at that time present, I arrived at Altenstatt which lies two miles away from Dürnau at 9 o'clock, to make my way from here to the post towards Venice, and I travelled also on the same day via Ulm to Dillerdissen] (Degenfeld and von, 1670 *ca*). For more than 700 pages, Christoff describes his journeys from Germany to Istria, the Eastern Adriatic coast, the Italian peninsula, back to the southernmost part of the Eastern Adriatic coast, the Ionian Sea, and Crete, eventually (March 1661–January 1667);
2) for the remaining two hundred written folios, the text changes into a daily war report of the 1667–1669 Venetian military campaign in Crete, in the war against the Turks for the possession of the island. There are no more drawings, the writing becomes smaller and denser (especially with fol. 770), and abruptly ends on fol. 888 with the notation "3 July 1669". The opening of this part contains details on army batteries and battalion, and on the military operations. Apart from the total absence of illustrations, the style does not change much from the previous part.

As for the information about the earthquakes, it has to be unwaveringly looked for, as it is hidden among the lot of, sometimes second and third hand, news on the places he went visiting during his quite amazing and *ante litteram* Grand Tour. Scattered in the manuscript, there are short, and sometimes inexact, references to earthquakes. For instance, Degenfeld mentions the one that, in his opinion, determined the actual shape of the island of Thira/Santorini around 1500 B.C. (fol. 683).

But what makes this manuscript of utter importance to the time-span and area investigated in this paper, is that Christoff is an eyewitness of an earthquake sequence occurred in Zakynthos in March 1662. The pages preceding his testimony contain plenty of information on his way to Zakynthos, where he got on 24 February 1662, around noon (fol. 26). After describing the island and its main town, and the high-society style of life he is enjoying (fol. 29), he devotes one and a half page to the effects of this earthquake sequence, beginning with: “It is a pity that such a beautiful island is so subjected to earthquakes, which I fully experienced myself in a most dreadful way” (fol. 30). Albini et al. (1995) published an English translation of this part and shortly commented it. In this paper, its content is discussed in Section 4, and the whole account left by von Degenfeld is proposed in the original 17th century German language, together with a revised English translation in the *Documentary Appendix*.

On board the English vessel *Phoenix*, Christoff lands in Kefallinia on 2 June 1662. He introduces the island, mentioning the small town of Argostolion, located not far from the harbour, and subject to earthquakes in the same way as Zakynthos. He mentions also the Fortress (of Agios Georgios, see Section 3.1 and Fig. 1) where the Venetian *Provveditore* is living (fol. 34). Contrary to the precision in describing the 1662 earthquake effects in Zakynthos, in this case Christoff explicitely writes that he learnt from hearsay that in 1661 an earthquake damaged Kefallinia (fol. 34). This information is discussed below in Section 4.3. For the sake of completeness, at the same point (foll. 34–35) Christoff mentions the dreadful experience of a violent storm in Kefallinia on 12 June 1662. It caused him and a not otherwise known person named “Anglant” to save themselves from a flash flood by leaping out through a window. In the middle of this “disaster”, “also an earthquake occurred”. Christoff’s statement did not find any confirmation in any other sources, and will not be further discussed.

4 The Earthquakes and Their Effects

The parametric catalogues listing earthquakes in this area and in the selected time-window are Shebalin et al. (1974) and Papazachos and Papazachou (1989, 1997 and 2003). Their sources of information are some modern studies, but mostly some seismological compilations of the second half of the 19th century. All these sources are referenced in the sub-sections devoted to each earthquake and in the figures illustrating the relationships among them (Figs. 3, 5, 8).

What is known after the investigation of 1658–1664 time-window for each earthquake is presented by means of: (i) a scheme of the relationships among the sources (Figs. 3, 5, 8), (ii) a table with a summary of the documents that are the closest in time to the earthquake (Tables 1–4), (iii) a map showing the places affected (Figs. 4, 6, 7, 9), and (iv) further details on the context of both the research and the records used.

Geographical names deserved a particular care in that they needed to be homogeneous and according to the modern standards. The adopted modern names and their georeferentiation are taken from GEOnet Names Server (GNS) (NGA, 2007). Whenever a corresponding name in Italian is used in the documents supplied in the *Documentary Appendix*, it has been given at its first appearance in the text of this paper, immediately after the modern one, and between parentheses. Modern names only are used in tables, figures and text, while of course the original ones have been preserved in transcribing the documents.

The dates are given in the "New Style" (not yet in use in the Greek area at that time) only, or both in the "New Style" and in the "Old Style", abbreviated in "S.V." (*Stile Vecchio*), to maintain the original Italian wording.

A *Documentary Appendix* supplies the reader with full references and text of the documents in their original language; documents from the State Archive of Venice are in Italian only, Degenfeld's text (1670 *ca*) is both in German and in English translation.

4.1 Tuesday (3 S.V.) 13 August 1658, St. Dominic's Day Eve, Kefallinia

The entry by Shebalin et al. (1974) is supported by Montandon (1953), relying upon a footnote that Perrey added to Barbiani and Barbiani (1864) (Fig. 3). Papazachos and Papazachou (1989 and 1997) quote mainly from Partsch (1890) and Tsitselis (1960); Papazachos and Papazachou (2003) add the modern compilation by Spiropoulos (1997).

There are two sources of information, directly or indirectly known to the compilers of the parametric catalogues (Fig. 3), and worth to be mentioned: Ricciolio (1669) and Pignatorre (1887), though none of them gives the complete date of the earthquake. Used by Perrey, Ricciolio (1669) most probably took his information from *Theatrum Europaeum* (1667) (not shown in Fig. 3). What the *Theatrum Europaeum* reports is that in the year 1658 in the island of Kefallinia, located between Epirus and Peloponnese, two villages ruined because of a strong earthquake. Pignatorre (1887) in his history of Kefallinia refers to a dispatch dated 30 August 1658, written by Marin Marcello, *Provveditore Generale alle Isole del Levante*. This dispatch does not exist among those stored at the State Archives of Venice; they are numbered, no gaps exist in the period 4 August-29 September and the only two dealing with the earthquake are dated 18 August (ASVe, 1658b) and 29 September (ASVe, 1658e). Probably Pignatorre cut and pasted pieces of some dispatches written by Marin Marcello (Fig. 3), then stored at the archives of the town of Kerkyra. In all, these sources supply only a partial and incomplete description of the 1658 earthquake.

In contrast to this scarcity, it is now possible to present a thorough description of the effects of the 13 August 1658 earthquake (Table 1 and Fig. 4), thanks to the coeval records supplied by the Venetian officers in their documents (Fig. 3, oval framed documents). The Venetian *Provveditore* in Kefallinia, Alvise Gritti, begins his dispatch of 5 August (S.V.) comparing the violence of this earthquake with the one experienced by the inhabitants of Kefallinia in 1636 (ASVe, 1658a). The first shock occurred at sunset on 3 August (S.V.), eve of St. Dominic's Day, celebrated on 4 August. Damage is reported in Argostolion, Lixourion (*Lixuri*) and in the district of Palichi (*Palachi*), where houses and churches collapsed or were damaged beyond

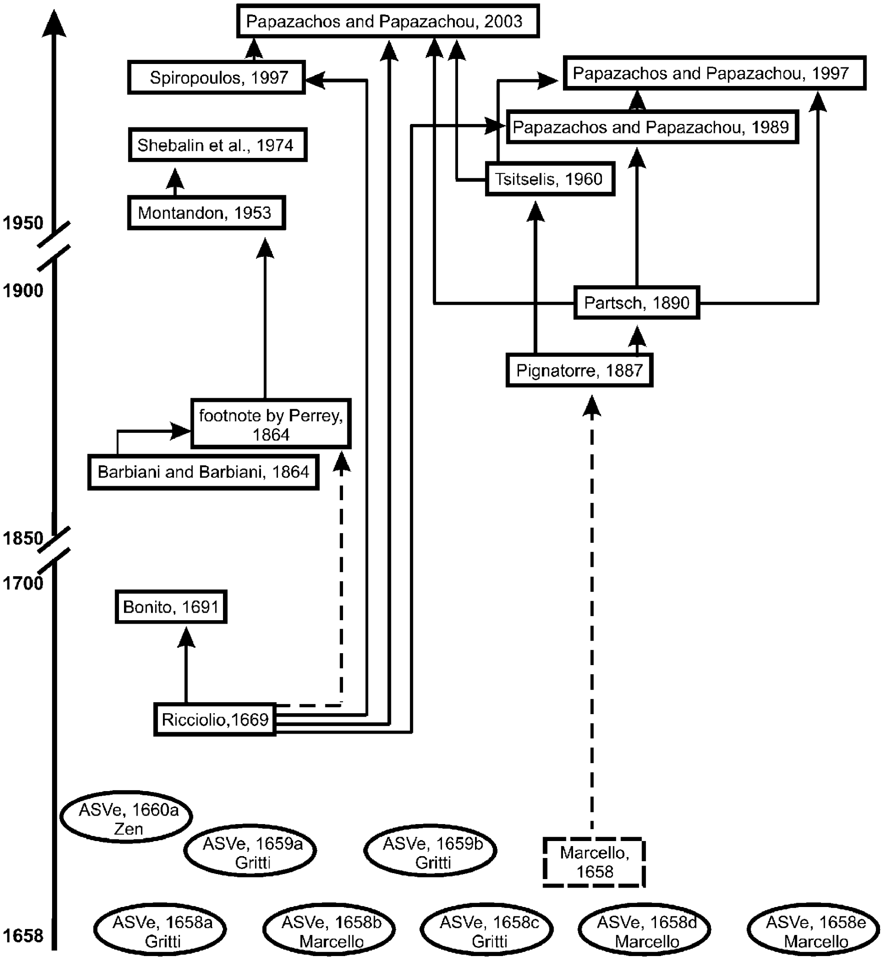

Fig. 3 Scheme of relationships among the parametric earthquake catalogues and their sources for the 1658 earthquake. "Marcello, 1658" in a dotted frame refers to the documents by the governor Marin Marcello as reported by Pignatorre (1887). Framed by an oval are the newly retrieved coeval documents

repair (Fig. 4). Deads and casualties were many, but "*Buono incontro fu che seguì in tempo che tutti ancora erano in piedi, e ritirati in campagna, che han potuto fuggire questo horribilissimo influsso*" (It was a nice coincidence that it occurred at a time of the day when everybody was still awake, and mostly stayed in the countryside, so that they could escape this horrible event).

Marin Marcello, at that time *Provveditore Generale alle Isole del Levante*, sends a dispatch from Zakynthos, where he had arrived soon after leaving Kefallinia (ASVe, 1658b). Two weeks later (ASVe, 1658c), when shocks were continuing and people were still living outside, Alvise Gritti informs the Senate that up to 300

Table 1 13 August 1658, Kefallinia

Date and place of the document	5 S.V./15 August Kefallinia	18 August Zakynthos	28 August Kefallinia	[September] Assos	29 September Assos
type of document and author	*Dispatch, Alvise Gritti, Provveditore in Kefallinia*	*Dispatch n. 25, Marin Marcello, Provv. Gen. (Tre) Isole del Levante*	*Dispatch, Alvise Gritti, Provveditore in Kefallinia*	*“Nota dei legnami” Piero Zen, Provveditore in Assos*	*Dispatch n. 33, Marin Marcello, Provv. Gen. (Tre) Isole del Levante*
general information on the earthquake	It occurred on 13 August (3 S.V.)	It occurred on Tuesday 14 *[but the 14th was a Wednesday]*.	People still live in the countryside.		
			300 people died and many injured people		
	Just before sunset. Many aftershocks.	Just before sunset. Many aftershocks.			
Affected places					
Argostolion	In Argostolion and territory, some houses and churches collapsed, some other were damaged.	Some houses collapsed. People went to live in the countryside.			
Lixourion	Many collapsed buildings in Lixourion and surroundings.	About 400 houses collapsed in Palichi, Lixourion and their surroundings.	Most buildings collapsed and there are troubles in storing the harvests of “uvepasse” (raisins) and “moscato” (muscat).		
	Unknown amount of dead and injured.	*[only 20 people died]* 300 people died			

Table 1 (continued)

Date and place of the document	5 S.V./15 August Kefallinia	18 August Zakynthos	28 August Kefallinia	[September] Assos	29 September Assos
Palichi	Many collapsed buildings in Palichi.	About 400 houses collapsed in Palichi, Lixourion and their surroundings.	Most of the buildings collapsed and there are troubles in storing the harvests of "uvepasse" (raisins) and "moscato" (muscat).		
	Unknown amount of dead and injured.	*[only 20 people died]* 300 people died.			
Assos		Damage to the fortress.		Timbers needed to restore the 64 public and private houses ruined inside the fortress.	Many damaged houses.
		60 houses inside it are in ruins.			Timbers are needed.

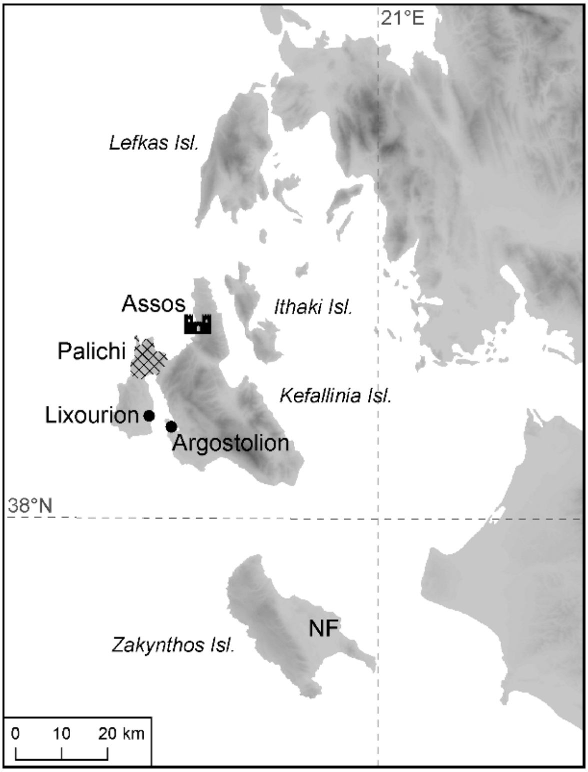

Fig. 4 Map showing the places and area (*Palichi*) damaged by the 1658 earthquake. Not Felt (*NF*) means that coeval and local sources do not mention effects in Zakynthos

hundred people died or were injured in the districts of Palichi and Lixourion, which were spared by the 1636 earthquake.

In one of his first dispatches, some sixteen months later (ASVe, 1659b), the new *Provveditore* in Kefallinia, Francesco Valier, reports to the Senate that some public buildings in Argostolion are still in bad conditions "because of the past earthquakes".

In the period when the earthquake occurred, harsh disorders among factions were upsetting Lixourion; both the local and the general governors report that such disorders were momentarily calmed down by the violence of the earthquake (ASVe, 1658a, b). The earthquake is recalled also in a document, written approximately one year after the earthquake, concerning the trial against one of the ringleaders (ASVe, 1659a). In late September 1658, Piero Zen, *Provveditore* of the fortress in Assos (*Asso*), reports the damage to the fortress and the buildings inside it (ASVe, 1658d), on the occasion of a visit of the *Provveditore Generale* (ASVe, 1658e); such damage was repaired within approximately two years (ASVe, 1660a).

The coeval documents do not mention effects in Zakynthos (ASVe, 1658–1659) nor in Kerkyra (ASVe, 1657–1661).

4.2 21 and 25 May 1660, Kefallinia

The 1660 earthquake (Fig. 5) is listed by Shebalin et al. (1974), according to Montandon (1953). Papazachos and Papazachou (1989 and 1997) do not quote this event, while Papazachos and Papazachou (2003) mention it shortly and do not assess any parameter. Montandon relies upon Barbiani and Barbiani (1864). As in the case of the 1658 earthquake, in a footnote to Barbianis' text, Perrey refers to Bonito (1691). The latter quotes Ricciolio (1669), who turns out to be the only coeval narrative source so far known to account for the 1660 event in Kefallinia. Ricciolio writes "*Iterum Cephaleniae Terremotus multas aedes subvertit*" (Once again in Kefallinia an earthquake caused the collapse of many houses). He does not refer to any specific

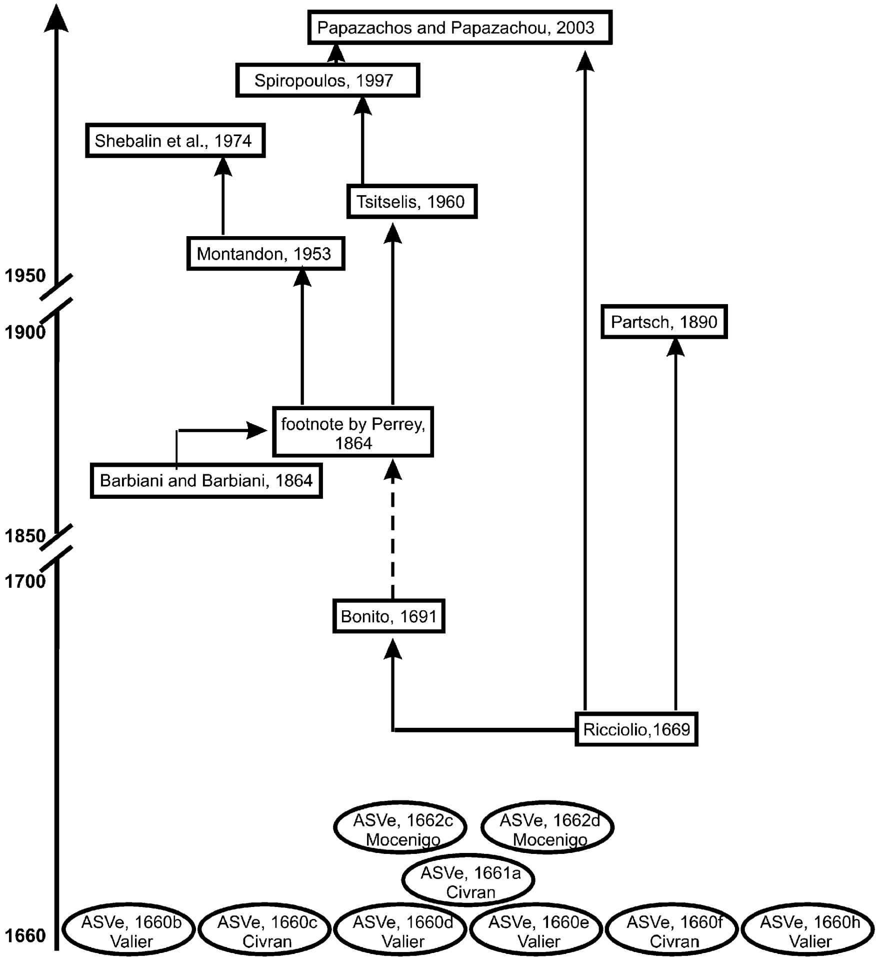

Fig. 5 Scheme of relationships among the parametric earthquake catalogues and their sources for the 1660 earthquake. Framed by an oval are the newly retrieved coeval documents

source, but as for the 1658 event it is possible to guess that he took the information from the *Theatrum Europaeum* (1667).

As in the case of the 1658 earthquake, are the Venetian governors who supply us with new and valuable information on this sequence of earthquakes (Fig. 5, oval framed documents, and Table 2).

Francesco Valier, *Provveditore* in Kefallinia, writes three dispatches between 21 May and 25 May. The 21 May dispatch was not found in the same file where the 24 and 25 May dispatches are stored today (ASVe, 1660b, d), though it is referred to by Valier himself in his dispatch of 25 May (15 May S.V.) (ASVe, 1660d) and by Alvise Civran, *Provveditore Generale alle Isole del Levante*, in his 25 May dispatch (ASVe, 1660c). The surviving documents inform us that the first earthquake occurred on 21 May, around midnight ("between 3 and 4 hours of the night", according to the Italian style of time counting) and lasted one *Ave Maria*. Francesco Valier is in Argostolion and writes that "I barely had the time to jump out of the bed in my night-shirt and run outside, and still being on the stairs a part of a wall fell near me, but for God's grace I did not injure myself" (ASVe, 1660b). Some cracks opened in the walls of the Fortress of Agios Georgios, and a great number of houses and whole villages were seriously damaged; many of the buildings still standing were in such a bad shape, that Valier says that they could not resist a second shock. There were some deads and many injured people. The second shock occurred on 25 May, at about 1 a.m. ("around 5 hours of the night"); it lasted one *Credo* and was soon followed by another shock lasting one *Ave Maria*. Valier adds also (ASVe, 1660d) that most people were safe because they were staying outside since the previous event, afraid of the continuous trembling of the earth.

As for the affected places (Fig. 6), the buildings inside the Fortress of Agios Georgios suffered serious damage; there was no shelter for soldiers, and according to Valier the damage amounted to hundred of thousands of *ducati*, in the currency of the Republic of Venice. The most damaged settlements were Lixourion and Argostolion; the dispatch written from Zakynthos on 25 May by Alvise Civran (ASVe, 1660c) also mentions a place called *Livathò*, today Livadhion; he will have the opportunity to visit Kefallinia in August only, as he recalls in a later dispatch (ASVe, 1661a).

The earthquakes caused many difficulties to the inhabitants of the damaged area, the richest of the island: windmills and bakeries could not work, an early ripen *uve passe* harvest was in danger, because roofs that were used to dry the fruits were out of order (ASVe, 1660e). Horses and collecting pioneers could not be accomplished (ASVe, 1660f) and the Community of Kefallinia had instead to levy a new tax on grapes and wine selling (ASVe, 1660g, h). Shocks were still continuing at the beginning of July (ASVe, 1660f).

The coeval documents do not mention effects in Zakynthos (ASVe, 1660–1662) nor in Kerkyra (ASVe, 1657–1661).

Two years later, in May 1662, Francesco Mocenigo, *Provveditore Generale*, visited Kefallinia. On that occasion he was forwarded a plea by Prior Giacomo Achielli, responsible for the Church and Monastery of San Nicolò and Santa Maria della Vittoria, run according to the Latin rite and directly depending on Venice (ASVe,

Table 2 21 and 25 May 1660, Kefallinia

Date and place of the document	1660 24 May Kefallinia	1660 25 May Zakynthos	1660 25 May Kefallinia	1660 29 May Kefallinia
type of document and author	*Dispatch, Francesco Valier, Provveditore in Kefallinia*	*Dispatch n. 27, Alvise Civran, Provv. Gen. Isole Levante* It contains the information by F. Valier in his 21 May, missing dispatch.	*Dispatch, Francesco Valier, Provveditore in Kefallinia*	*Dispatch, Francesco Valier, Provveditore in Kefallinia*
general information on the earthquake	It occurred on 21 May, around midnight. It lasted one Ave Maria.		It occurred on 25 May, around 1 a.m. It lasted one Credo, and was followed by another that lasted one Ave Maria.	Shocks are continuing.
Affected places				
	Many houses were heavily damaged, and every building suffered by the violent shock.	Many houses fell down and many people were injured.	Destruction and ruins in the town.	People are still leaving outside.
Argostolion			If not warned by the first shock, many more people would have died.	The Provveditore fears that some illness will rise and spread.
	The Provveditore himself was nearly hurt by a collapsing wall.	A supply of "Pan biscotto" is sent to Kefallinia, because all wind-mills and bakeries are out of order.		Tax collection will have to be postponed.

Table 2 (continued)

Date and place of the document	1660 24 May Kefallinia	1660 25 May Zakynthos	1660 25 May Kefallinia	1660 29 May Kefallinia
Unidentified hamlets	Heavily damaged.			
Agios Georgios	The Fortress suffered damage in the walls. Some private buildings inside it collapsed.	Damage to the Fortress.	Damage increased to the walls and to the buildings. Storehouses, quarters, public buildings were so damaged they had to be pulled down. Huts for the soldiers were built with timbers from fallen buildings.	
Lixourion		Damage.	Destruction and ruins in the town.	
Livadhion		Damage.		

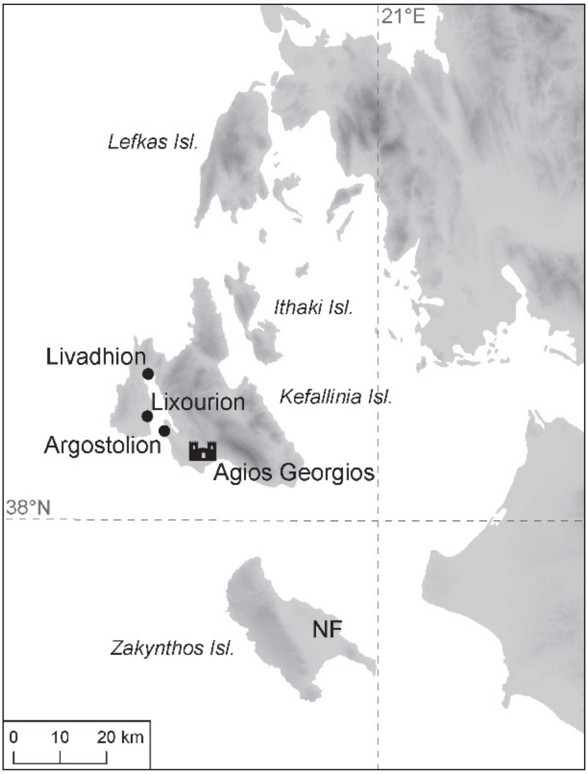

Fig. 6 Map showing the places damaged by the 1660 earthquake. Not Felt (*NF*) means that coeval and local sources do not mention effects in Zakynthos

1662c). The documents report that the state of disrepair of the monastery is due to the earthquakes, though no dates are given. Mocenigo endorses such request in a later dispatch (ASVe, 1662d), stressing that no other place on the island is available for Latin religious offices.

These documents are discussed here because we refer them to the 1658 and 1660 earthquakes. There are no hints that such damage was caused by the March 1662 earthquake (see below), while (i) it is highly probable that a plea had been sent previously (and not filed in this series); (ii) such a lack of financial (and religious) sensitivity from Venice was a habitual behaviour during the war against the Turks for Crete.

4.3 1661

Some records have been found about earthquake effects in the year 1661 at Zakynthos, the Strofades Islands (south of Zakynthos, west of Peloponnese), and Kefallinia (Fig. 7). Except for the record on Zakynthos, the other two do not carry the day and month of occurrence. The information is supplied for the sake of completeness, though at this stage it is not detailed enough to refer all the records, and especially the one about Kefallinia, to one and the same earthquake.

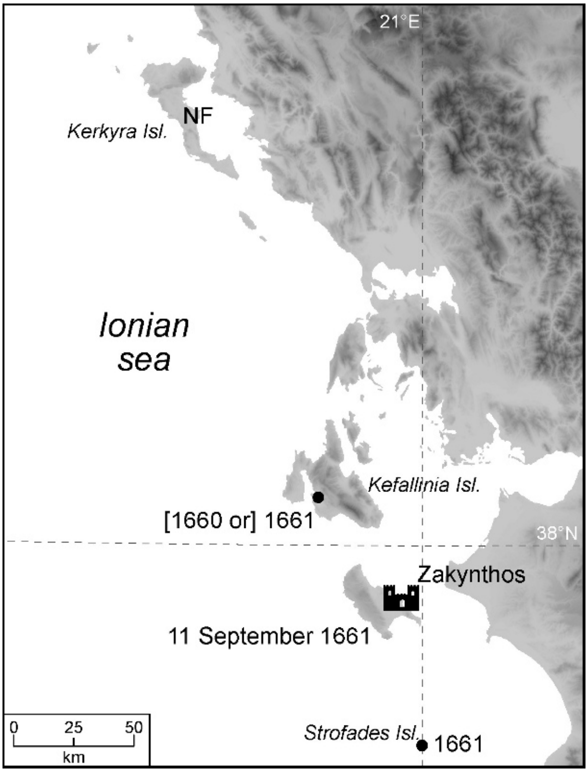

Fig. 7 Places mentioned by the sources as affected by an earthquake in the year 1661. Not Felt (*NF*) means that coeval and local sources do not mention effects in Kerkyra

- Sunday, (1 S.V.) 11 September 1661, Zakynthos
  In his 6 September 1661 (S.V.) dispatch, the *Provveditore* in Zakynthos Francesco Ruzini says that "some cracks [opened] in the walls of this fortress, caused by earthquakes, which began last Sunday [1 September S.V.] in the evening and are still continuing." (ASVe, 1661b). The *Priore del Lazaretto* and the *Ammiraglio dell'Arsenale* report in two documents – today missing – the damage suffered by each of the two public buildings (Table 3). Alvise Civran, *Provveditore Generale*, arriving in Zakynthos from Kefallinia, is given full report and he assures the Senate he will take care of the repairs (ASVe, 1661c). In a Deliberation addressed to the *Provveditore* in Zakynthos, the Senate recognises the importance of such repairs, at the same time stressing that a moderate financial support is all that can be guaranteed (ASVe, 1661d). Heavy rains increase the damage to the Fortress (ASVe, 1661e) and in February 1662 (that is before the March sequence discussed further) Francesco Mocenigo, new *Provveditore Generale*, informs that the Fortress and *Lazaretto* are still in bad conditions (ASVe, 1662a). The coeval documents do not mention effects in Kefallinia nor in Kerkyra (ASVe, 1660–1662).

Table 3 Sunday (1 S.V.) 11 September 1661, Zakynthos

Date and place of the document	1661 [ante 16] September Zakynthos	1661 [ante 16] September Zakynthos	1661 16 September Zakynthos	1661 10 October Zakynthos	1661 26 November Venice
type of document and author	*Letter, "Priore del Lazaretto"*	*Letter, "Ammiraglio dell'Arsenale"*	*Dispatch, Francesco Ruzini, Provveditore in Zakynthos*	*Dispatch n. 87, Alvise Civran, Provv. Gen. Isole del Levante*	*Senate, Deliberation*
	Referred to in 16 September dispatch, Provveditore Generale, but **missing**	Referred to in 16 September dispatch, Provveditore Generale, but **missing**			
Zakynthos			It occurred on Sunday 11 September, in the evening.	Damage to Fortress walls and *Lazaretto*, as referred by F. Ruzini	Damage to Fortress walls and *Lazaretto* have to be repaired, but with a moderate expense
			Damage to: – the Fortress walls; – the *Lazaretto* (document by the Priore); – the *Arsenale* (document by the Ammiraglio).		

- No month no day, 1661, Strofades Islands
  Issel and Agamennone (1893) report that an earthquake was felt in the Strofades Islands (south of Zakynthos) in 1661. They claim to have received the information from A. Gaeta Foscardi, librarian in Zakynthos. Foscardi, in his turn, received it from a monk Cirillo, abbot of the monastery in Strofades, who probably took it from a chronicle then existing in the monastery. This information could possibly be related to the earthquake that affected Zakynthos.
- No month no day, 1661, Kefallinia
  Getting to Kefallinia, von Degenfeld (1670 *ca*) says: "Last year 1661, one [earthquake] has been so violent, that nearly all houses throughout the island collapsed, even those built of square stones linked together by iron links. The stones were separated from each other, the iron being without any strength. This earthquake also split a high and strong rock from top to base" (fol. 34).

The coeval Venetian documents from Kefallinia (ASVe, 1660–1662) do not support von Degenfeld's statement. In this case he is not an eyewitness, as for the 1662 earthquake in Zakynthos (see Sections 3.2 and 4.4), and he could be simply combining and wrongly dating what he had been told of the damage caused in Kefallinia by both the 1658 and the 1660 earthquakes.

4.4 12–19 March 1662, Zakynthos (Formerly dated 1664)

The event known to have hit Zakynthos in 1664 is the only one within this time-window that Barbiani and Barbiani (1864) report on the basis of what they thought were coeval documents. Both Shebalin et al. (1974) and Papazachos and Papazachou (1989) indirectly derive their information from the same documents through Barbiani and Barbiani (Fig. 8). Papazachos and Papazachou (1997 and 2003) use both 19th century compilations and recent studies, as shown in Fig. 8.

It is interesting to see how the 1664 came to be accepted as the date (no month, no day) of this earthquake. What Barbiani and Barbiani (1864) supply is the full text of two documents transcribed from a register that they say it was then kept at the archives of the Council of Zakynthos:

- a Resolution of the "Council of 150" (local assembly of the citizens of Zakynthos), dated 24 March 1664;
- a Deliberation of the Senate of the Republic of Venice, dated 3 May 1664.

Both documents concern the amount of 1,500 *ducati*, the local Council established to be collected in order to repair the fortress damaged by the past earthquakes. But they were just the last of a series of documents concerning this earthquake written in the two years since it had happened, as it will be discussed in the following.

All those who relied on Barbiani and Barbiani (1864) consequently assumed that the year of these two documents (1664) was the one in which the earthquake occurred. The correctness of this assumption can now be re-discussed, thanks to the new evidence emerged from the whole series of documents available at the State

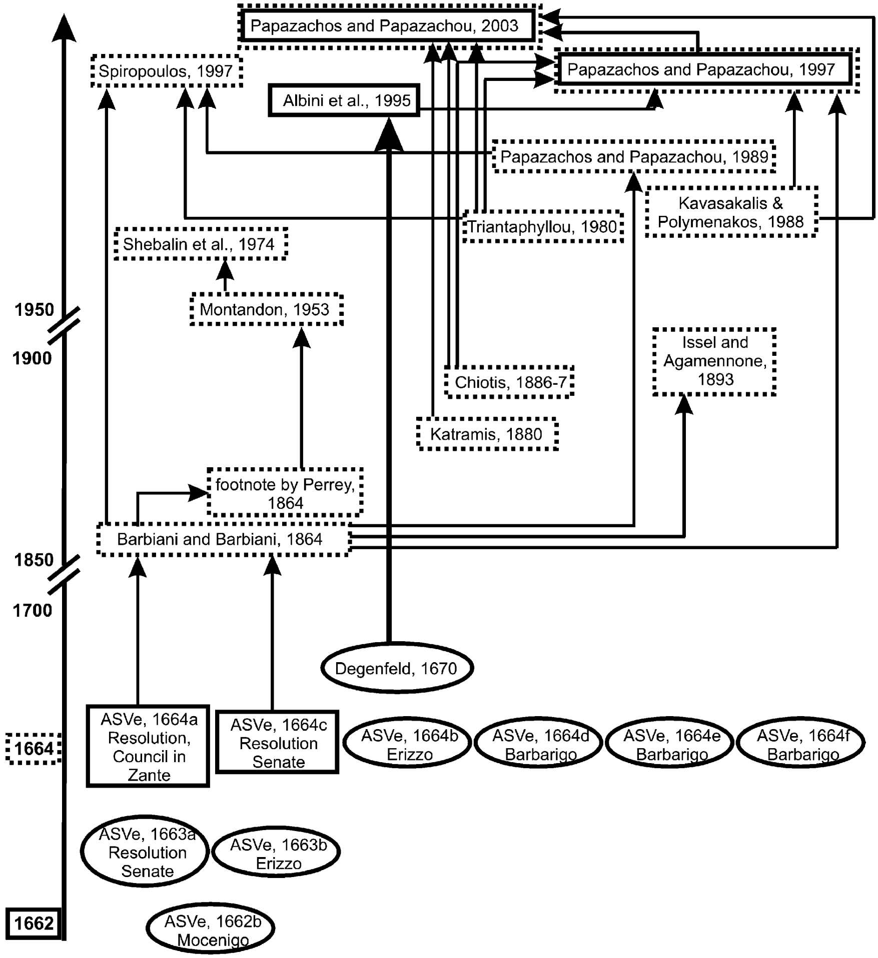

Fig. 8 Scheme of relationships among the parametric earthquake catalogues and their sources for the 1662 earthquake. The *dotted line* shows which references wrongly date the earthquake at 1664. ASVe, 1664a and 1664c are the documents previously used to date the earthquake at 1664. Framed by an oval are the newly retrieved coeval documents

Archive of Venice, including the same two mentioned by Barbiani and Barbiani (1864). The documentation has been read again and put in a wider chronological and administrative context, and to it it has been added the original testimony by von Degenfeld (1670 *ca*) (Table 4).

In this case there are two reliable eyewitnesses who left us their descriptions of the earthquakes: one is Francesco Mocenigo, *Provveditore Generale alle Isole del Levante*, who was visiting Zakynthos from mid February to mid April 1662 (ASVe, 1662b); the other is the author of the manuscript presented in an earlier Section 3.2 of this paper, Christoff von Degenfeld (1670 *ca*), the German

Table 4 12–19 March 1662, Zakynthos

Date and place of the document	1662 16 March Zakynthos	1662 March	1663 18 September Venice	1663 10 October Zakynthos	1664 3 April Zakynthos	1664 3 April Zakynthos	1664 3 May Venice	1664 16 August Zakynthos
type of document and author	*Dispatch n. 14, F. Mocenigo, Provv. Gen. Isole del Levante*	*von Degenfeld, 1670*	*Senate, Deliberation, Venice*	*Dispatch n. 33, Giacomo Erizzo, Provveditore in Zakynthos*	*Resolution, Council of 150, Zakynthos*	*Dispatch n. 44 Giacomo Erizzo, Provveditore in Zakynthos*	*Senate, Deliberation, Venice*	*Dispatch n. 10, Piero Barbarigo, Provveditore in Zakynthos*
1662 12 to 13 March	During the night 12 to 13, many shocks. The Fortress walls were damaged and six barracks collapsed.							
1662 16 March		Shortly before 10 in the evening a small shock had occurred. Around 10 in the evening, it lasted three quarters of an hour [*sic*].	The storehouses and the army buildings have to be restored. The Fortress has to be repaired using the sum of 260 *ducati*, already	The public buildings are in ruins. The damage to fortress walls due to earthquakes is recalled.	The sum of 1500 *ducati* is destined to repair to the Fortress.	A “universal tax” is established to collect 1500 *ducati* to repair the fortress.	The new tax is approved.	The Avogadore rejects the resolution of the Council of *Zakynthos* about the new tax. The repair works must be stopped.

Table 4 (continued)

Date and place of the document	1662 16 March Zakynthos	1662 March	1663 18 September Venice	1663 10 October Zakynthos	1664 3 April Zakynthos	1664 3 April Zakynthos	1664 3 May Venice	1664 16 August Zakynthos
			assigned and mentioned in November 1661 deliberation [ASVe, 1661d] Financial support from the local community is strongly recommended.					
		A large part of the fortress, some 70 houses and 16 Greek churches fell down.		260 *ducati* are not enough to repair the damage..				
1662 18 March		At lunch hour glasses fell from the cupboard.[3pt]						
1662 19 March		Fruit fell from the trees. People were tumbling like drunken.						

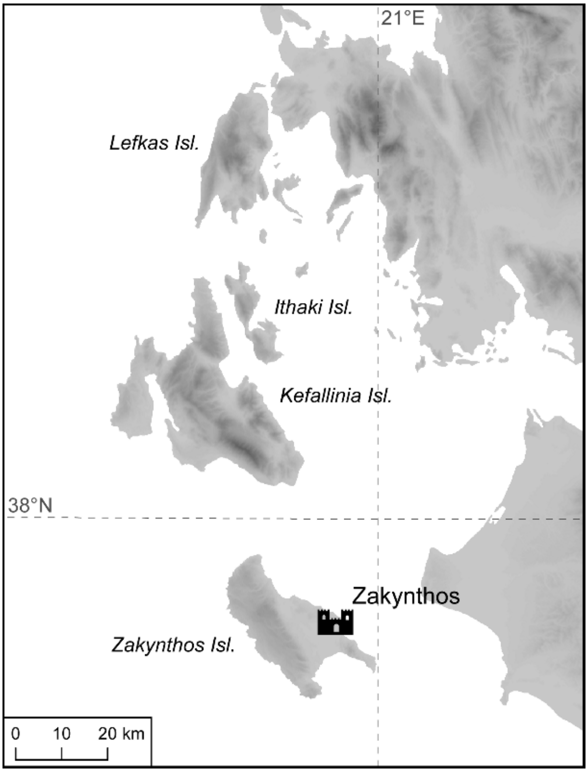

Fig. 9 Map showing the only place damaged by the 1662 earthquake

"*condotto/condottiero*" (commander), who had arrived in Zakynthos on 24 February 1662.

Together, they tell us that in the year 1662, the town of Zakynthos (Fig. 9) was shaken by a sequence of earthquakes, which started during the night 12–13 March and lasted for some days. The damage to the Fortress walls insisted on the same parts already affected by the 1661 earthquake; some churches and buildings suffered as well.

No information is available from any other places in the island neither from the other islands or the mainland. Mocenigo and von Degenfeld describe for the first shock the same effects, the first dating it the night 12–13 and the latter the evening of 16 March (Table 4). There is no way to solve, at this stage, this slight contradiction.

The testimony by von Degenfeld is really outstanding: for the details on the main shock and the aftershocks, but mainly for filling in the most consistent documentary gap in the *Provveditore* of Zakynthos dispatches for the years 1658–1664 (see Fig. 2a). The reason for this dark area is the death of the *Provveditore* in charge, who was momentarily substituted by his son, while the new one appointed by the Senate travelled from Venice to Zakynthos. These administrative details are supplied at length by the *Provveditore Generale*, who decides instead to maintain a sort of a grinning silence on the sequence of earthquakes and their effects. He simply reports with a short, annoyed sentence the 12–13 March shock (ASVe, 1662b) in the very last paragraph of a ten-page dispatch (a particularly long one). He avoids mentioning earthquakes in the next five dispatches and then leave Zakynthos towards Kefallinia. The coeval documents do not mention effects in Kefallinia (ASVe, 1661–1665) nor in Kerkyra (ASVe, 1662–1665).

The Republic of Venice had serious financial problems due to the long-lasting war operations in Crete. This is one of the reasons for the lack of funds to repair the fortress and the public buildings damaged in Zakynthos by the September 1661 and March 1662 earthquakes, as it emerges from the following documents (Table 4).

In the 10 October 1663 dispatch, the *Provveditore* in Zakynthos Erizzo (ASVe, 1663b) describes the miserable conditions of the public buildings and makes clear that the sum of 260 *ducati* is not even enough to start the needed repairs. In the meanwhile, on 18 September 1663, a Deliberation of the Senate (ASVe, 1663a) was pushing the *Provveditore* of Zakynthos to take care of the restoration of the "public storehouses, where the munitions and other war devices are collected" and let the Senate know about the expenses. The Fortress also has to be restored, using the sum already assigned. The Deliberation ends with the suggestion that the inhabitants of Zakynthos contribute in such effort, so to lessen the financial charge for the Republic of Venice. The 1663 Deliberation makes due reference to the 23 November 1661 one (ASVe, 1661d), also mentioned by the *Provveditore Generale* Mocenigo in a February 1662 dispatch (ASVe, 1662a).

It is only from the 3 April 1664 dispatch by the same Erizzo (ASVe, 1664b) that we learn the local Council has decreed to collect the sum of 1,500 *ducati* to be devoted to the restoration of the fortress (ASVe, 1664a). The latter is the same document reported by Barbiani and Barbiani (1864), who did not notice that it was dated 24 March according to the Old Style calendar (3 April in New Style). With a new Deliberation, on 3 May 1664 (ASVe, 1664c) the Senate approves the tax levied by the Council of Zakynthos. But the efforts of the inhabitants were not sufficient, and the fortress of Zakynthos remained unrepaired (ASVe, 1664d, e): on 16 August (ASVe, 1664f) the recently appointed *Provveditore* Piero Barbarigo reports that, notwithstanding the Senate approval, the High Advocate had declared not valid the tax established by the Council of Zakynthos. As a consequence, the funds could not be used to repair the fortress and the works had to be stopped once more.

5 Conclusion

Originated by the retrieval of a hitherto unknown source on earthquakes in the Ionian Islands (Degenfeld, 1670 *ca*), this paper shows that the study of a time-window of the seismicity of an area may result in a more balanced interpretation of the available data, if compared with the narrow, and sometimes diverting, perspective offered by the study of a single earthquake. For the 7-year time span here considered, the newly available primary sources allowed us to fill in some of the gaps that were revealed by the investigation of the documents written by the Venetian governors, so that this study provides a sufficiently reliable knowledge of the seismic activity in the Ionian Islands for the period 1658–1664, as it is briefly summarised in the following.

After having put the earthquake records in a comprehensive time-space context, it has been possible (i) to define the correct day and month when the 1658 and 1660 earthquakes happened, and (ii) to move the “1664” event back to 1662, and definitely excluding that the coeval records could report and refer to two different earthquakes. The correct date is an important parameter also in the case of earthquakes imperfectly known to the parametric earthquake catalogues; from now on the chances of retrieving information from the mainland and from the far field area increase, as well as decreases the risk of overestimating the earthquake size through a wrong combination of effects, in fact related to different earthquakes.

The information concerning the 1661 seismic activity in the area, especially in Zakynthos, was unknown to parametric earthquake catalogues. This is a piece of information that contributes in completing the list of the earthquakes known to have affected this area in the past. This systematic research supplemented us also with the reliable information that no earthquakes at all affected the island of Kerkyra in this period.

A strong limit still influencing the studies on the earthquakes in the Ionian Islands lies in the fact that the observers focus their reports mostly on the islands; there still remains a disturbing silence from the mainland, silence that has to be interpreted in terms both of the few easily available (and useful) sources and of the uneven interest shown by Venetian observers toward their neighbours.

For these reasons, at this stage, authors prefer to refrain from proposing macroseismic intensities and epicentral parameters. The quite complete absence of information on far field effects means for us that data are not enough to be processed, to obtain and yield reliable magnitude values. To conclude with a suggestion, it seems to us that one of the more promising ways the collected data could be used is to compare them with the data on the 20th century earthquakes.

Acknowledgments If Jean Vogt were still with us, he would have surely agreed with me in acknowledging the many people who contributed to this paper.

Jean Vogt’s brother, Henri (Université Louis Pasteur, 3 rue de l’Argonne, 67083 Strasbourg Cedex, France), is gratefully acknowledged for making the consultation and reading of the von Degenfeld’s manuscript possible: this task would not have been accomplished without his help and patience.

Special thanks go to Massimiliano Stucchi, Vicki Kouskouna and Jean Bonnin, for their keen reviews and suggestions; to Christa Hammerl, who helped out with the difficulties in translation from 17th century German; to Michela Dal Borgo, *Archivio di Stato di Venezia*, for suggestions in handling and reading the documents; to Paola Migliavacca, Andrea Rovida and Ruben Tatevossian, for figures and text editing.

Documentary Appendix

Abbreviations

ASVe	Archivio di Stato di Venezia
DRt	Senato, Dispacci, Rettori
DPGIL	Senato, Provveditori Generali da Terra e da Mar, Provveditore Generale alle Tre Isole del Levante
DelRt	Senato, Deliberazioni, Rettori

Tuesday (3 S.V.) 13 August 1658, St. Dominic's Day Eve, Kefallinia

- **ASVe, DRt, Cefalonia, b. 12, 3 March 1657–17 September 1660**
- **ASVe, DPGIL, b. 1167, 9 March 1658–18 February 1659**

ASVe, 1658a, DRt, Cefalonia, b. 12

Serenissimo Prencipe

Ha voluto il Signor Dio rinovare nella memoria di questi sudditi il flagello dell' horribile terremoto provato in questa isola l'anno 1636.

Hieri, che fu li tre del corrente S.V. vigilia del glorioso Patriarca S. Domenico verso l'imbrunir della sera ha provato quest'Isola una così horribil scossa, che nella terra di Argostoli, ove mi attrovavo di ritorno dalla visita dell'Ecc.mo Provveditor Generale, molte case sono cadute a' terra, altre ricevettero notabil crollo, come pure le chiese, che in un spatio di breve tempo, che durò, pareva fosse vicina la desolazione di quest'isola.

Maggiore danno però s'è provato ancora in altre parti della medesima, et in particolare nella pertinenza di Palachi, e terra di Lixuri, che più nobile, e ricca del rimanente dell'isola, e più frequente d'habitationi s'è resa un solo grandissimo cumulo di ruvine. Molte ville resteranno inhabitabili e deserte afato, ne tanto posso dire a Vostra Serenità quanto grande è stato il danno nella terra di Lixuri, et nella cinconferenza dil Palachi.

Molti sono per questo gravissimo accidente rimasi prima sepolti che morti, et il numero non posso per hora ben disignarlo all'E.VV. non servendomi ancora il tempo d'haverne l'intiera notitia, ma bene vi supplirò con più distinta narratione.

Buono incontro fù, che seguì in tempo che tutti ancora erano in piedi, e ritirati in campagna, che han potuto fuggire questo terribilissimo influsso.

Continua la terra tutta via à scuotersi giorno e notte con indicibile horrore, cadauno vivendo et alloggiando in campagna, o nelle pubbliche strade.

Da questo così horribile terremoto l'animo fierissimo degli habitanti di Lixuri, che ardevano in risse implacabili e per le quali molti e considerabili homicidij sono seguiti, con rottura di pace e mancanza di fede; da sé stessi, quando non hanno valso tutti i mezzi, si sono finalmente uniti e abbracciati in sembianza di pace sincera. Ho voluto nella terra di Lixuri presentarmi in persona, e tanto da me vederò con l'occhio proprio rappresenterò brevemente a V. Serenità per non perder l'occasione di porgerne la dovuta notizia, rimettendomi a quel di più sarà rappresentato con altre mie. Gratie, etc.

Ceffa, li 5 agosto 1658 Stile Vecchio
Alvise Gritti Provveditor Ordinario

ASVe, 1658b, DPGIL, b. 1167
n. 25
Serenissimo Prencipe
A qual segno sijno arrivati gl'odij interni, et in quale rillassatezza di vivere homicidiale non meno che d'aperta disubbidienza verso i publici decreti siano caduti i Popoli di Ceffalonia, resta il tutto dal fatto stesso comprobato, et da precedenti mie portato à pubblica notitia e m'assicuro informate pienamente le EE.VV. dalle relazioni dell'Ilustrissimo Signor Provveditor Gritti [. . .] Dopo la mia partenza come apparente fu il loro accommodamento così con dupplicata rissolutione divennero al manneggio dell'armi trà d'essi, sprezzando tutti quegli invitti, e mezzi procurati e pratticati da Publici Rappresentanti, à segno tale che diversi sono rimasti innocentemente interfetti per isfoggo della loro rabbia interna, la quale da queste mortalità non diminuita ma d'avvantaggio accesa, tra di loro, resisi hormai incorriggibili alla giustitia del mondo, con sprezzo delle leggi e commandi della Serenità Vostra, han irritato a tal segno quella del Cielo, che non potendo più tollerare l'ingiustizia de gl'homicidij, soppressione dell'innocenza, il dispreggio al Prencipe suo naturale, ha rillasciato sopra di loro un improvviso castigo che come effetto dell'Ira giusta di Dio contro d'essi, ha posto gli uni e gl'altri e l'Isola tutta in un sommo terrore e spavento.

Essendo il martedì sera fu li 14 del Corrente sul tramontar del sole arrivato un terremoto così vehemente e spaventevole che ha ravvivato la memoria d'un simile in queste parti dell'anno 1636. L'impeto, e furia di questo per volere di chi tutto può sfoggò sopra la terra stessa di Lixuri e pertinenze di Palachy, essendo all'improviso cadute quasi tutte le case diciamo da quattrocento e più gli habitanti la maggior parte fuggiti si sono salvati, soli 20 rimasti sepolti nelle rovine. La terra mostra grandi aperture, et i rimbombi sotterranei pare minaccino maggiore castigo. Tutte quelle habitationi, che non han potuto cadere affatto alle prime scosse, sono cadute alla replica di esse che per il tempo che mi sono trattenuto han sempre continuato giorno e notte, con forza e spavento maggiore in quelle parti che in altra. Rimane al presente quella terra già ricettaccolo di gente sanguinaria, e fazionaria, dishabitata, e distrutta, sentendosi di continuo ancora il crollar della terra, con quel terrore, che può considerare la grandezza dell'EE.VV. apportano casi cosi grandi, e castighi cosi innaspettati. Il danno et la mortalità grande, è seguita veramente nelle Ville, Casali, et attinenze di Lixuri e Palacchij essendo molte case cadute, et altre trecento persone d'ogni sesso morte; In Argostolli ove io pure m'attrovavo cadutene alcune con spavento tale di Popoli, che abbandonate le habitacioni si sono portati a stanciare, e dormire alla Campagna; le ruine di così funesto successo sono pur arrivate alla Fortezza di Asso, tenendo avviso da quel Signor Proveditore Zen che sessanta case sijno à basso, con danno e terrore di tutti quei poveri habitanti et io quanto prima potrò mi porterò sopra loco per rivedere il vero stato delle cose, e di quella Fortezza particolarmente dopo un tanto avvenimento.

Quelli di Lixuri, e luoghi circonvicini à così evidente flagello del Cielo spaventati tra loro stessi, han immediatamente deposte l'armi et abbracciatisi con lacrime à gl'occhi, deponendo affatto quegli odij, che tra loro regnavano et che han attirato sopra d'essi si grande castigo, di cui si confessano prima d'hora meritevoli; Ma si come per l'adietro con la riunione de gl'animi han fatto simili protestationi, così potria seguire che mitigate le memorie, et i sentimenti del presente travaglio, si suscitassero tra d'essi nuove maggiori persecutioni interne, rittornando à quelle licentiose forme di vivere che come naturali hormai poco o nulla s'aggiustano al timore di N. Signor Dio al rispetto et obbedienza de commandi della Serenità Vostra per il che al mio partire ho ordinato la continuacione del processo formato di mio ordine contro Caporioni e mal viventi dell'Isola per divvertire per tal Via al possibile il discapito notabile à pubblici datij, grande il pregiudicio à tutti gli interessi della Serenità Vostra, et in fine i danni et soppressioni ingiuste à Popoli dell'Isola e sudditi dell'EEVV. Gratie
Zante li 18 agosto 1658 S.N.
Di Vostra Serenità
Marin Marcello Provveditore Generale delle Isole

ASVe, 1658c, DRt, Cefalonia, b. 12
Serenissimo Prencipe
Doppo il primo horribile terremoto seguito in questa Isola li 3 del corrente continua tutta via la terra à scuotersi giorno, e notte con gran terrore di questi habitanti; le case de quali parte desolate affatto come nella pertinenza di Palachi, et altre havendo ricevuto notabil danno sono da loro abbandonate alloggiando la notte, et il giorno con le loro famiglie alla campagna, fino, che piaccia al Signor Dio, assicurar l'animo loro dell'imminente pericolo, o di darle modo di riparar le proprie rovine.
Tutta la parte de Palachi, e Lixuri, ch'era la più nobile, e la più bella d'ogn'altra restò desolata à segno, che si può dire non vi sia pietra sopra pietra, né certo la barbaria d'un crudele nemico haverebbe potuto tanto danno apportare.
Con la caduta delle case tutto quello, ch'era dentro nelle medesime si può dire resti affatto distrutto, et al presente che sono sopra il raccolto dell'Uvepasse, e moscati non hanno luogo ne modo ne meno d'unirlo ò raccoglierlo, come gli anni passati.
Il numero de morti e feriti nella parte de Palachi arriva fino a trecento persone per diligente nota da me havuta.
Nel resto poi dell'Isola è stato inferiore assai il danno, molte case cadute, et altre rese inhabitabili, pocchi quelli però che sono morti da tale incontro; questo grandissimo horribile flagello piacendo al Signor Dio d'indirizzarlo più contro gli habitanti del Palachi che in ogn'altra parte; all'[sic]contrario dell'anno 1636, nel quale tutto il resto di quest'isola restò dal terremoto quasi che desolata et illesi, soli quei de Lixuri, e della circonferenza de Palachi.
Giusto giudicio del Signor Dio per correggerli al presente de loro misfatti e per castigarli de continuati homicidij, che andavano ogni giorno seguendo per l'interne loro discussioni; sopra le quali menne io andavo formando processo, con proclama de principali caporioni, et auttori de tutti i mali, ha voluto la giustizia del Signor Dio precorrer quella di V. Serenità con un severissimo flagello, ammoniti et atterriti

dal quale hanno finalmente deposte l'armi et unitesi fra se stessi nelle più sincere apparenti dimostrationi di pace e di quiete. Gratie
Ceffa, li 18 agosto 1658 Stile Vecchio
Alvise Gritti Provveditor Ordinario

ASVe, 1658d, DPGIL, b. 1167
Document annexed to the 29 September dispatch by Marin Marcello (ASVe, 1658e), no date
Notta di legnami trasmissi dall'Ill.mo signor Provveditor d'Asso ricercati per il bisogno di case sessanta quattro e pubbliche e private, rovinate dal terramoto rese in habbitabili giusta la fede del Ingenier Gentilini.

ASVe, 1658e, DPGIL, b. 1167
n. 33
Serenissimo Principe
[. . .] La Fortezza d'Asso dal presente mio viaggio rimane diligentemente da me osservata de suoi più imminenti bisogni originati particolarmente dalle rovine di molte case dirrocate, et altri pregiudicij occorsi alla medesima per causa de terremoti, che tuttavia istantanei si fan sentire alla parte di Lixuri principalmente; con oggetto dunque di riparare à più pressanti danni di essa, ho fatto caricare sopra le galere quelle quantità de legnami, chiodarie et altro che la prudenza publica resterà servita d'osservare dall'ingionta Nota, mà dalla trasmessami dall'Illustrissimo Provveditor Zen che pur unisco alle presenti, riuscendo la provvisione debole al bisogno non posso che approvare la risolutione fatta dal medesimo signore [. . .]
Asso li 29 settembre 1658 S.N.
Di Vostra Serenità
Marin Marcello Provveditore Generale delle Isole

ASVe, 1659a, DRt, Cefalonia, b. 12
Replicata
Serenissimo Principe
Dà secoli in quà non ha provato questa Isola devota alla Serenità Vostra huomo più inhumano, e scelerato quanto la persona di Zuanne Castelani [. . .] Questo huomo torbido e tirano nutrito nella perversità del mal opperare diede il primo mottivo alle gravissime discordie nella terra di Lixuri principiate l'ultimo marzo 1658 per le quali divisa non solo la Terra, ma tutta la Pertinenza in due fattioni con fatti d'armi continui à guisa di guerra [. . .] seguirono più de cinquanta homicidij, oltre numerabili feriti, essendo tanto sconvolti gli animi di quelli habitanti che la Giustizia non sapeva più che deliberare per qualche compenso come io più volte mi portai sopra il fatto con ogeto d'impiegare le provvisioni opportune, che finalmente represse le loro crudeltà da horibile terremoto li 3 agosto susseguente rimasero rafrenati per decretto del Signor Dio [. . .]
Ceffa 27 Giugno 1659 S.V.
Alvise Gritti Provveditor Ordinario

ASVe, 1659b, DRt, Cefalonia, b. 12,: Cefalonia, 9 dicembre 1659 Stile Vecchio, Francesco Valier
Serenissimo Prencipe

Stimando più che necessario e conveniente il fare, che la Serenità Vostra et l'EEVV restino di tempo in tempo raguagliate et che con distinto restretto vedano l'entrata et uscita di quest'Isola, hò ordinato à questi ministri di Camera il cavarne di mese in mese il conto, tutto che da miei Precessori non si sij stillato [. . .]
Stimo però il meglio siano venduti detti stabili conforme la loro conditione, e stato risservando solamente quelli devono servire per il servizio pubblico, et degl'altri, cavarne quella maggior somma si può, essendone buona parte mall'acconci da terramoti, et volendoli rissarcire la spesa sarebbe di consideratione. Di tutto ne' starò attendendo gl'espressi ordini dell'EE.VV. Queste barache, habbitationi ordinarie de pubblici Rappresentanti, sono state da me ritrovate affatto disfatte; onde supplicatone l'eccellentissimo Signor [Provveditore] Generale Marcello me ne permise la restauratione, come si va facendo con ogni possibile risparmio, che nell'istesso stato pure ho ritrovato tutti li Quartieri, Corpi di Guardia, restelli monettioni e magazeni affatto diroccati sì per li terremotti; come anco per la pocca cura et carità [. . .]
Ceffa, 9 Decembre 1659 S.V.
Francesco Valieri Provveditor Ordinario

ASVe, 1660a,DRt, Cefalonia, b. 12
Ceffa - Ristretto del Scosso et speso del mese di agosto 1660
* Corso de spese fatte dall'Illustrissimo Piero Zen fu Provveditore di Asso l'anno 1658, nel restaurar questa fortezza stante il terremoto che seguì li 3 agosto 1658 et cio de ordine dell'Ecc.mo S. Provveditor Marcello
ducati 1849: 9

21 and 25 May 1660, Kefallinia

- **ASVe, DRt, Cefalonia, b. 12, 3 March 1657-17 September 1660**
- **ASVe, DPGIL, b. 1169, 15 March 1660-22 January 1662**

***Missing dispatch**, Cefalonia, 21 May 1660, Francesco Valier (see ASVe, 1660c and 1660d)*

ASVe, 1660b, DRt, Cefalonia, b. 12
Serenissimo Prencipe
Impetuosissimo e spaventevole terremoto si è fatto sentire in quest'isola li 22 del corrente S.N. tra le tré, e quatro della notte, che durò un avemaria incirca e guardi Iddio, che fosse continuato altro tanto non ci restava né casa, né tetto e pochissimi si salvavano.
Io ero in Argostoli, come pure mi ritrovo sono hormai giorni vinti per la espeditione delle Navi Inglesi, che levano l'Uvepasse per ovviar à contrabandi et fraudi, che potessero essere pratticati a pregiudicio di V. Serenità, et acciò con cellerità si esseguisca il loro carico, dove con fattica mi fugi dal letto in camicia, con piedi à terra, e mi portai nella strada, che nel scender le scalle mi cadé una muraglia appresso quale per gratia di Dio Benedetto non mi offese; hora mi ritrovo alla campagna havendo continuato tutta la notte li terremoti come pur alquanto non lasciano tutta via di travagliarci con continui squassi. Il danno de maggiore fin hora provocatosi

havendo distrutte quantità grande di Case et le Ville intiere, ma quello che più importa è che ogni Casa si è rissentita in modo, che guardi ne succedesse un altro simile tutte si atterebbero [*sic*], piaccia a Dio liberarci da sì horrendo spettacolo, molti feriti ed alcuni morti. In Fortezza per quello mi dicono li Protti in diversi lochi la muraglia si è aperta, molte case atterrate affatto, alla mia Baracha quale havevo fatto accomodar da novo sono caduti li medesimi muri, tutti restato solo il legname. Onde con buona gratia di Vostra Serenità procurarò di far restaurar il tutto, muraglia della Fortezza et altre publiche fabriche acciò maggiormente non pattiscano, che perciò saria necessaria la subbita mession del legname degià deliberato dall'EE.VV. per questo effetto come mi vien accenato in Ducali di 14 marzo prossimo passato essendo pure necessarie le chiodarie d'ogni sorte con la ferramenta per l'Altellaria, che à questo proposito devo dir all'EE.VV. come ho retrovato qui Maestri, quali sarano sufficienti per accomodar li letti, e rode della detta, senza che VV.EE. invijno altro cararo come le scrissi et come pure mi avisano dovermi far capitare; onde si potrà fermare la mession; servendomi di questi. Gratie
Ceffa a 24 maggio 1660 S. N.
Francesco Valier Provveditore

ASVe, 1660c, DPGIL, b. 1169
n. 27
Serenissimo Prencipe
[. . .] Con lettera di 21 [*the 21 May dispatch is missing; see ASVe, 1660d also*] m'avvisa l'Illustrissimo Provveditor di Ceffalonia, haver li terremotti atterrate l 'habbitationi della fortezza, del Borgo, d'Argostoli, Lixuri e Livathò, con danni considerabili dell'Issola tutta, delli Parapetti di detta fortezza, e delle fabriche publiche, con mortalità di molta gente, e con horrore spaventevole di quelli habbitanti, che si sono sparsi per la campagna; havendo nel disfacimento de molini, e forni convenuto soccorrer li medesimi di qualche quantità di biscotti, col pagamento però in Camera del precio loro ordinario. Ne faccio avanciar alcuna summa à quella parte sopra l'instance del Suddetto Signor; e sarei anco passato in persona per ripparar à quanto potesse occorrere quando non havessi l'ubbligatione, d'attender qui gli Ausiliarij. Questi accidenti così travagliosi, acrescono il dubio, che frastornata resti l'unione de Guastatori e Cavalli, à che havevo io ubligata l'Issola medesima, in ordine alle commissioni del'Ecc.mo Capitano Generale. [. . .]
Zante 25 maggio 1660 S. N.
Alvise Civran Provveditore Generale delle Isole

ASVe, 1660d, DRt, Cefalonia, b. 12
Repplicata
Serenissimo Prencipe
Il spavento et il pericolo nel quale si è ritrovata quest'Isola la notte decorsa alle 5 hore incirca della notte è innarabile, et indicibile, terremotto così fiero e sì potente si è fatto sentire per il spacio di più di un credo, quale replicato per un'altra Ave Maria poco doppo ha caggionato la destruzione e desfacimento tottale di tutto Lixuri tutto Argostoli, e della maggior parte de Villaggi non essendo restato pure un sasso

sopra l'altro con morte di più persone et molte ferite, che se alli undeci come di già con altra mia [*the 21 May dispatch is missing; see ASVe, 1660c also*] ho dato parte alla Serenità Vostra non si fosse la gente portata fuori delle case a dormire avvisati dal primo, pochissimi si sarebbero salvati. Io ero in Argostoli avendo fornito d'espedire le Navi, che perciò glielo posso attestare de visu; capitato poi questa mattina a buon'hora in Fortezza ritrovo tutte le case conquassate, le muraglie della detta per la maggior parte, aperte et dirocate, un balouardo disfatto affatto che è il più essenziale, tutti li Caselli disfatti, et quelli, che sono restati in piedi non posso, che immediatamente farli finir di distruggere essendo per cader affatto li Quartieri Magazeni, et case pubbliche di V. Serenità affatto per terra, si che per ricoverare questi soldati e pubbliche Monettioni, converà per hora far barache del legname vecchio restato sino a tanto che l'EE. VV. mi faranno capitare bon numero di collami e chiodarie, che co' quei procurarò far tagliare i travi in Montagna, acciò l'EE. VV. sentino minor incomodo. Di grazia le supplico con ogni riverenza non mi lasciare senza questa necessarissima provvigione poiché mi crederei affatto disperato nelli travagli e rancori, che mi ritrovo. Compatiscano supplico le EE. VV. l'incommodo, che le porto poiché se vedessero queste miserie con l'occhio proprio lacrimerebbero di sicuro, essendo il danno universale di centinaia di migliara di ducati. Gratie
Ceffa li 15 maggio 1660 S. V.
Francesco Valier Provveditore

ASVe, 1660e, DRt, Cefalonia, b. 12
Serenissimo Prencipe
Non cessano li terramoti di travagliarci di continuo giorno et notte con squassi considerabili et si dubbita, che possino prosseguire per molto tempo rispetto alla secità grande della terra et al callore insoportabile dell'Aria, essendosi matturati li grani vinti e più giorni fuori di staggione, come pure fra quindici giorni né sarano dell'Uve passe matture, quello, che à ricordo di questi popoli mai più è succeduto; piaccia a Dio che ci liberi da qualche influsso maligno di mallatie, poiche oltra il callore grande che si prova li pattimenti et le vigilie che si fanno per il timore essendo ogn'uno fuori della propria casa in campagna con solo riparo di lenzuoli, e tapedi, non v'essendo modo d'alloggiare in altra forma, prima per la sicurezza et poi per esser cadute da fondamenti tutte le case, ce lo pressagisse, piaccia a Dio benedetto assisterci con la sua santa gratia.
Io non manco di soccorrer questi Popoli et consolarli distribuendoli biscotto col pagamento però in Camera, et senza alcun incomodo di Vostra Serenità rispetto che li Molini et forni sono tutti atterrati. Ho supplicato anco l'Eccelentissimo Signor Generale per la messione di qualche summa non me ne ritrovando che solo quatordici quindici mila; onde stimarei necessario, che la Serenità Vostra mi trasmettesse in questo Porto qualche summa, scansandosi la spesa della condotta da loco a loco [. . .]
Replicarò riverentemente per la missione di legnami, e ferramenta in buona quantità, poiché avanzandone sarà levato da questi popoli suddetti con l'esborso del denaro effettivo havendomi anco portato l'instanze.

Mi spiace nell'anima, che si ritardarano in qualche parte le scossioni delli pubblichi Dacij, et che quello delle biave fatto in cantiere da me più volte essendo uno de maggiori non mi si concorso si che converrà come già scrissi alla Serenità Vostra portarmi in persona alla decimatione essendo uno de più rilevanti.
Prego Iddio benedetto che mi conservi sano; io certo non risparmiarò fattica, né incomodo per avantaggiare l'interessi dell'EE.VV.quali mi sono a cuore al maggior segno. Gratie
Ceffa a Ventinovesimo Maggio 1660 S. N.
Francesco Valier Provveditore

ASVe, 1660f, DPGIL, b. 1169
n. 33
Serenissimo Prencipe
[. . .] A Ceffalonia non saprei à che si fusse riddotta l'unione né di Guastatori, né di Cavalli; rappresentandomi l'impossibilità quel Signor Provveditore nelle afflitioni de continuati terremoti che tutta via vanno dirocando Case, e inferrendo danni gravissimi a quell'Isola.
[. . .] non lasciando di dire, che aggravandosi l'Issole tutte dell'impositioni multeplici sofferite la corente guera, supplicano il respiro nell'avenire, rappresentandomi li Sindici e Capi non saper come più adempire ad altre scielte di huomini, né ad altre contributioni che venissero suggerite. Gratie
Zante 18 giugno 1660 S. N.
Alvise Civran Provveditore Generale delle Isole

ASVe, 1660g, DRt, Cefalonia, b. 12
Document annexed to the 19 July dispatch by Francesco Valier (ASVe, 1660h)
Copia tratta dal Libro del Consiglio della Nobile Comunità di Ceffa
1660 Addì primo Luglio [. . .]
Quando l'irra di dio volendo l'ispaventevol flagelo del taramoto con dano e spavento indicibile non solo ha aterato le case tutte et rese inhabitabili con danni e [. . .] ma tota via continuando cosi frequenti e vigorosi temendo della perdicione totale tutti somersi a sostenere et recuperare le proprie creature che leva il modo di ogni uno per pensare ad'altro che alle [. . .] miserie et alla vita propria de figli.

ASVe, 1660h, DRt, Cefalonia, b. 12
Replicata
Serenissimo Prencipe
Tutto che i fieri colpi di contraria fortuna habbino abbatuto in modo quest'aflita Isola di Vostra Serenità con terribili terramoti, quali pure non desistono giorno, et notte di farsi sentire. In ogni modo desiderando di far conoscer all'EE. VV. quanto desideri il publico avantaggio. Hò fatto chiamare questi Signori Sindici, et rappresentatogli l'urgente bisogno, che tiene il Prencipe nella presente campagna, di denaro. Ho fatto si che ponghino parte in questo conseglio di metter gravezza sopra ogni migliaro d'Uvapassa, come pure d'ogni botta di Moscato, et Vino, che si estraderano da quest'Isola, di quarto uno di reale, da pagarsi dalli venditori, et questo in segno della divotione che proffessano alla Serenità Vostra; quale fu presa, come dall'ingionta

copia l'EE.VV. potrano vedere. Supplichole pertanto aggradire questo mio segno di riverenza, quale mai si smorzarà nell'avantaggio di pubblici interessi; spiacendomi solo che gli accidenti sopracenati habbino levato à me, et à questi fidelissimi suoi sudditi di dimostrare, e il desiderio, che io tengo nei pubblici avantaggij, et della divotione indefessa di questi benemeriti. Gratie
Ceffa li 19 luglio 1660 S. N.
Francesco Valier Provveditore

ASVe, 1661a, DPGIL, b. 1169
n. 65
Serenissimo Prencipe
Trattenutomi qualche tempo à Ceffalonia per sedar i disordeni, e i rancori di quei habbitanti [. . .]
Portatomi nel passato mese d'Agosto [*1660*] in quella fortezza per prescriver il modo, di ripparare alle rovine che erano causate da' terremotti, osservai non picciol disordine nella Publica Scrittura, per occasione della quale, fatta dà mé la terminatione che stabiliva non meno il giro regolato d'essa, che la conservatione più cauta del publico danaro [. . .]
Corfù 23 maggio 1661 S. N.
Alvise Civran Provveditore Generale delle Isole

ASVe, 1662c, DPGIL, b. 1170
n. 20
Serenissimo Principe
[. . .] Il Priore fra Giacomo Achielli curato e Vicario della Chiesa e Monasterio di S. Nicolò e di Santa Maria della Vittoria Iuspatronato della S.V. m'ha presentato l'ingionta lettera [*see below*]; io col solito di mia riverenza l'accompagno all'EE. VV. perche non avendo sopra d'essa voluto deliberare cos'alcuna siano contribuiti dalla loro prudenza i proprij riflessi al contenuto della medesima, e mi siano prescritti quegli ordini che per conservatione della Chiesa stessa, non meno che del rito Latino saranno considerati convenienti. Gratie
Argostoli di Cefalonia li 10 maggio 1662 S. N.
Francesco Mocenigo Provveditore Generale all'Isole
Document annexed, no date
Ill. mo et Ecc.mo Signor Provveditore Generale Inquisitor delle 3 Isole di Levante
Abenche la grandezza dell'Eccellenza Vostra habbi col proprio occhio osservato l'innumerabili Danni, et ruine seguite per cause de gli ultimi terremoti particolarmente in questa Terra d'Argostoli con la derrocatione da' fondamenti della chiesa e monasterio di S. Nicolò e di S. Maria della Vittoria Jus Patronato di Vostra Serenità pochi mesi prima restaurata, et fabricata da fondamenti mediante le pietosi limosine fatte, dalla Gloriosa memoria dell'Ill.mo et Ecc.mo Signor Lazaro Mocenigo Procurator Reverendissimo Capitano General; et altre fattiche et assistenze di me fra Giacomo Achielli Curato et Vicario di essa ad ogni modo perche non si manchi dalla parte dell'incombenza mia. Hò voluto anco con la presente portare all'humanità sue la Notitia, et reiterare le supplicationi mie, afine resti servita di applicare quelle provvigioni, che stimerà proprie in coadiuvatione nel poter riddure,

se non al pristino stato, almeno in qualche forma, una di dette Chiese, per administrar Dio, e distribuire i santissimi sacramenti, a divoti del Rito Latino, essendo statto à questo effetto dal Pubblico heretto detto Monasterio et assignato agli Curati quel poco d'entrade, che rende il loro quotidiano sostentamento. Di questa opera gratta a Dio, et alla pia mente di V. Serenità et che renderà maggiormente Gloriosi gli auspicij et merito grande di V.E. viene dall'humiliatione mia supplicata. Gratie

ASVe, 1662d, DPGIL, b. 1170
n. 32
Serenissimo Prencipe
[. . .] Il Priore fra Giacomo Achielli nella sua supplicatione che accompagnai alla S.V. con mie de n. 20 altro non chiede, che qualche pietosa carità per ristorare in parte la Chiesa, e Monasterio di San Nicolò e Santa Maria della Vittoria pubblico Iuspatronato per potersi continuare il culto divino in essa a gloria del Signor Dio, et à consolatione di quelli del rito Latino, che non hanno altro ricorso vicino per udire li santi ufficij; io con ogni verità posso attestare alla S.V. haver veduto quel pio luoco dirocato in molte parti da terremoti, con dubbio della totale dessolacione, quando dalla religiosa mano delle EE. VV. non venghi reparato con qualche sovegno, ch'è quanto d'informatione riverendissima circa ciò posso apportare [. . .]. Gratie.
Cefalonia li 16 settermbre 1662 S. N.
Francesco Mocenigo Provveditore Generale all'Isole

Sunday (1 S.V.) 11 September 1661, Zakynthos

- **ASVe, DRt, Zante, b. 23, 30 March 1660–16 January 1665**
- **ASVe, DPGIL, b. 1169, 15 March 1660–22 January 1662**
- **ASVe, DPGIL, b. 1170, 14 October 1661–24 September 1663**
- **ASVe, DelRt, f. 54, September 1661–February 1662**

ASVe, 1661b, DRt, Zante, b. 23
Serenissimo Prencipe
Capitata gieri l'altro la Nave S. Simeon Capitano Zuanne Guechier mi pervenero l'ingionti trè Pachetti publici dell'Ecc.mo Capitano General e dell'Ill.mo Provveditor d'Armata Battaglia che incamino alla Serenità Vostra con la presente Nave, come feci l'altro giorno di due dispacij dell'Eccellenza sudetta Capitano General, con gl'avisi de fortunatissimi sucessi delle Armi publiche, con un Vassello Francese S. Zorzi Picolo Capitano Antonio Surva, de quali nè portai immediatamente le notitie, con espresso caichio all'Ecc.mo Signor General Ciurano [*sic*] à Ceffalonia, cosi per capo di publico servitio come per sodisfatione de miei doveri.
Alla cui Eccellenza diedi riverite parti di alcune apperture, causate da Tarramoti, attorno le muraglie di questa Fortezza, che principiorono la sera di Domenica [*11 September, S.N.*] prima dell'inserta alla Vostra, e tutta via vano continuando, con la trasmissione di due scritture portatemi dal Prior del Lazaretto, e dall'Ammiraglio, per li danni seguiti nella casa publica, che si chiama Arsenale, et in detto Lazaretto; per che col solito del suo Zelo nè prenda le proprie prudentissime delliberationi.

Questa mattina fecero levata le Galere Ausiliarie per la prossecutione del loro viaggio, verso li quali hò contribuito tutti gli usi di buoni trattamenti, e soliti saluti, per incontrare nella loro intiera consolatione, cosi stimato di publico vantaggio. Gratie.
Data li 6 settembre 1661 S.V., Zante
Francesco Ruzini Provveditore

ASVe, 1661c, DPGIL, b. 1169
n. 87
Serenissimo Prencipe
[. . .] Dai teremotti che seguirono i giorni passati si sono rissentite le muraglie di questa fortezza, e del Lazaretto come m'ha rappresentato quest'Ill.mo Provveditore. Sarò perciò a ricconoscer il stato loro per rifferirlo in lettere à parte alla Serenità Vostra, né mancherò in tanto d'andar ripparando à quello ricercasse il bisogno. Gratie.
Zante 10 ottobre 1661 S. N.
Alvise Civran Provveditore Generale alle Isole

ASVe, 1661d, DelRt, f. 54
1661 26 Novembre in Pregadi
Al Provveditore Generale Inquisitor delle Isole
[. . .] Vi raccommandiamo con tal ordine di far rissarcire qualche danno fatto al Zante nella Fortezza, e nel Lazaretto da terremoti, e si come la necessità è grande cosi siamo sicuri darete gli ordini subito; vedrete che si ripari con spesa moderata e come ricerchi il bisogno. [. . .]

ASVe, 1661e, DPGIL, b. 1169
n. 91
Serenissimo Prencipe
Rissentitesti le mura di questa fortezza per li terremotti già dà mé riverentemente rappresentati alla Serenità Vostra, s'andavano anco ripparando possibilmente coll'errettione de Caselli massime, che dà tali accidenti erano dirroccati affatto: mà sopragiunte le pioggie, e fattesi così continuate, e copiose, che indebolite le parti ove erano apperte le mura stesse, hanno fatto cader à terra dalla parte di Ponente vinti passa in circa d'incamisatura d'esse mure resesi deboli per esser state costrutte da molto tempo sopra il grebano, con materiali non tanto buoni. Vi resta non dimeno il grebano medesimo in modo che contrasta l'accesso, e il scallo, né mancai ad ogni maniera di far vedere dai periti il bisogno, di quanto valesse ripparar alla rovina: ma contraponendovisi di presente la scarsezza delle materie, e l'impedimento delle dette pioggie che continuano vi si rende impossibile il lavoro neccessario. Stimai però ad ogni buon fine far costruir due Caselli, per mantenervi anco le sentinelle che vaglino, ad invigillare per maggior sicurezza del posto stesso. [. . .]
Zante primo decembre 1661 S. N.
Alvise Civran Provveditore Generale alle Isole

ASVe, 1662a, DPGIL, b. 1170
n. 12
Serenissimo Prencipe

Le mie lettere humilissime a V. Serenità del n. 11 per causa della strettezza del tempo, che capitai in questa città, non accompagnarono la scrittura che mi doveva consegnare il S. Marchese Villanova General dell'Armi per il stato in cui si ritrova la fortezza d'Asso [. . .]
Con tale occasione ho diligentemente riveduta la fortezza, et altri luochi pubblici, et osservato che à causa de terramoti per il giro de più de 20 passa la mura è caduta dalla parte di Tramontana e benche l'Illmo provveditor Ruzini, hora deffonto, l'ha fatta aggiustare con sole pietre senza calcina, che più non permetteva la stagione, ad'ogni modo necessariamente dev'essere restaurata in forma durabile come richiede il dovere d'una fortezza, alla quale non devono mancare i requisiti di perfettione, e pure i lochi delle munitioni e del magazeno di biscotto meritano sollecita restauratione essendo comossi e atterati con parte dei coperti.
Le Ducali della Serenità Vostra di 26 novembre prossimo passato [*ASVe, 1661d*] fanno conoscere precisa l'intentione pubblica perche siano rissarciti li danni nella fortezza e quello pure che ha patito il Lazareto, ond'io colla ubbidienza dovuta distribuirò gli ordeni proprij acciò à tempo opportuno con la mira al maggior risparmio siano aggiustate le preacenate necessità della Fortezza, senza permettere che a niente di superfluo s'estendano le oppere che saranno impiegate nei soli inevitabili bisogni, com'anco si deve dei magazeni detteriorati per renderli habili alla custodia de Pubblici Capitali; mentre per quello riguarda la restauratione del Lazareto s'aspetta intieramente ad Antonio Gioachini, che con tal obbligo è stato eletto Priore con Terminatione dell'Ill.mo Signor Provveditor del Zante, e dalla Serenità Vostra confermato con ducali di 10 dicembre decorso, ottenuto tal carico col solo dispendio di reali 250 [sic] che può impiegar per la spesa, e pure conseguisce d'entrata annualmente cento reali, oltre le cose incerte che rillevano a suo proffitto considerabilmente, et il pubblico resta leso. L'Arsenale parimente destinato per l'istesso effetto hà patito l'infortunio del terramoto, con non picciol pregiudizio, quale anco meritando d'esser quanto prima restaurato nelle parti rovinose, rimane alla sapientia pubblica la più celere rimessa de legnami descritti nella polizza alegata che quanto al dispendio per le opere e fatture farò che sia assai più ristretta di quello appare nella polizza stessa.
[. . .]
Zante 22 febbraio 1661 [*more veneto*] S. N.
Di Vostra Serenità
Francesco Mocenigo Provveditore Generale alle Isole

12 to 19 March 1662, Zakynthos (formerly dated 1664)

- **ASVe, DPGIL, b. 1170, 14 October 1661–24 September 1663**
- **ASVe, DRt, Zante, b. 23, 30 March 1660–16 January 1665**
- **ASVe, DelRt, reg. 38, 1663**
- **ASVe, DelRt, reg. 39, 1664**

ASVe, 1662b, DPGIL, b. 1170
n.14
Serenissimo Prencipe

[. . .] La notte di 12 venendo li 13 del corrente seguì più di un terramoto di qualche vehemenza, à segno che dal moto, in questa Fortezza sono caduti a terra sei caselli, et alquanti passa della mura nella parte apunto di Tramontana, dove nell'adietro la mura rissentì quel danno che fù accenato a Vostra Serenità, onde disponerò anco per questo gli ordini per la restauratione. Invierò alla Serenità Vostra il dispaccio havuto di Candia acciò quanto più presto col recapito pervenga sotto l'occhio publico. Gratie
Zante 16 Marzo 1662 S. N.
Di Vostra Serenità
Francesco Mocenigo Provveditore Generale all'Isole

Degenfeld, 1670 *ca*.
(*fol. 30*) [. . .] Es ist wohl zu bejammern das eine solche schöne Insul dem erdböben so sehr underworfen, welche ich zur gnüge mit grosem entsetzen erfahren müssen, den dieser frühling wenige Zeit Vorgangen das nicht welche gegeben; den 16. Martij abents umb 10 Uhr fieng eines ahn so 3 Viertelstundt anhielt, undt nicht anderst wahr als schon alles zu trümmeren gehen wolte, wir dan auch ein guth theyl der Vöstung, auch bey 70 häusern undt 16 griechische Kirchen, als welcher Religion diese einwohner bey 60.000 seelen starck, zu gethan seint, eingefallen, auch in meiner Cammer eine seiten wandt, also dass wen ich nicht so balt dass reyß/(*fol. 31*) aus genohmen, todt oder Zuschanden geschlagen were worden, es lag auch ein Venetianischer Obrister frantzösicher nation, mit dem nahmen Pan in gemelter meiner Cammer am Podagra, demselben fiel ein stück mauer auf ein Bein undt schlug ihm dasselbe entzwey, sonsten ist keinem menschen was geschehen. Das glück wahr das kurtz vorhero sich ein klein erdböben höhren lassen, dadurch die leüthe munder worden, undt also Zeit haten sich aus den häuseren auf die ofene undt freye Plätze zu reteriren, sonsten waren Viel todt geblieben, den sie haben im gebrauch so balt sie ein erdböben Vernehmen, dass sie sich Von den Häusern weg machen, damit solche ihnen nicht auf die Köpfe fallen, die weibsleüthe welche sehr eingezogen leben, absonderlich die erlich sein wollen, begeben sich Zu solchen Zeiten auf die tächer, welche als altanen gebauet, undt Von der erden nur zwey Stock hoch aufs höchste [*sic*] seint, wegen der erdböben, geben vor das wen ein haus einfält, so blieben sie auf dem Haus, und daselbe nicht auf sie; es sollen sich auf solche Weiß viel saluiret haben, auch pflegen die einwohner wen sie von einem erdböben übereylet werden, undt sich nicht getrauen einen freyen ofenen Platz zu ereichen, wegen den einfallenden häusern, under den hausthüren zu laufen, welche sie zu diesem endt Vöster mit starcken steinen gebaut, sagent wen das gantze haus ein fiele so bliebe doch das thor stehen, undt geschahe auch dissmal ein solch exempel, in denen sich auf solche weis ein türckisches mägdlein saluiret, welches haus über sie weg gefallen. Von diesen iezo erzehlten erdböben an, innerhalb 5 tagen undt fünf nächte haben sich über 400 höhren lassen, welche Von undterschiedlichen gezehlet wurden, denn da kaum eines aufgehöret hatte, fieng wieder ein neu[l]es ahn.
Den 18. Martij als ich Zu mitag bey dem Prov. Gnal speysete, hat sich ein so starckes ereignet, dass alle trinckgeschirr vom Credentz/(*fol.32*)/tisch fielen, und wir uns aus dem staub machen Mussten. Den 19. Martij gieng ich nebst anderen Officiren im

gartten vom Franciscaner Closter so mein logament wahr spatziren, da fieng wieder ein so starckes ahn, dass das ops Von den bäumen fiel, da es doch gantz windstill wahr, undt wir taumelten, als wen wir uns voll getruncken hetten, konten auch nicht stehen, sondern mussten uns niedersetzen.

das aller merckwürdigste ist das die schife so bey 15 Welsche meyl Von der Insul auf der see wahren in Bonaza oder Windstill, die höchste gefahr davon ausgestanden, denn solche so starck nach den schifleuthe aussage, beweget seint worden, als wen alles zu grundt hette gehen wollen. Jedoch ist zu mercken dass nicht alle Jahr dergeleichen giebet, sondern Zu weylen im gantzen Jahr nicht eines.

[English translation:

"It is a pity that such a beautiful island is so subjected to earthquakes, which I fully experienced myself in a most dreadful way. During the present spring only short time-spans were without some of them. On the 16th March, around 10 in the evening one lasted three quarters of an hour. It seemed that all would be turned into ruins. Indeed a large part of the fortress, some 70 houses and 16 Greek churches, most of the 60.000 inhabitants belong to this religion, fell down. In my room a side-wall fell and I would have been dead or hurt if I had not fled in time. Also a Venetian colonel of French origin was lying in my room suffering of podagra and his leg was hit by a piece of wall, so that it broke. Nobody else was harmed. Luckily, shortly before a small shock had occurred, warning people and giving them time to go out of the houses to open places. Otherwise many would have been killed. Actually they are accustomed to flee from their houses as soon as they hear an earthquake, thus escaping the collapse of the houses on their heads. At such times (when an earthquake occurs), the women, living in a very secluded way, especially the straightforward ones, proceed to the roofs, which are built like a balcony, to the utmost two stories high because of earthquakes. Their argument is that when a house collapses they stay atop of it, avoiding its fall on themselves. It seems that many of them saved their life doing so. If an earthquake comes so suddenly that the inhabitants do not dare to reach an open space, fearing collapsing houses, they proceed to doorways, solidly built for this reason of strong stones, saying that if the whole house collapses the doorway would nevertheless stand on. Such a case for example occurred also this time, a Turkish girl being saved while the house fell on her. From this earthquake on, more than 400 shocks were heard, counted by different people, during five days and five nights. Indeed when one scarcely ended, another one began.

On 18th March, while I had lunch with the Provveditor General such a violent shock occurred that the crockery for drinking fell from the board of the credence and we had to flee. On 19th March, while I walked with other officers in the garden of the Franciscan monastery where I lodged, another occurred, so violent that fruit fell from the trees, although it was calm. We tumbled like drunk, could not stand and had to sit down.

The strangest thing is that ships some 15 "Welsche" miles off the island, during "Bonaza" [lack of wind, from the Italian "bonaccia"] or calm, experienced highest danger, being, from the seamen's report, moved so violently that it seemed that anything would be destroyed. It should however be noted that such earthquakes are not occurring every year, actually sometimes no one does during a whole year.]

ASVe, 1663a, DelRt, reg. 38, c. 263r
Mille seicento sessantre, 18 settembre in Pregadi
Al Provveditor del Zante
[. . .] Partito il Provveditore Generale siamo certi che dal vostro zelo s'impiegarà ogni studio per assistere à tutte le parti con particolare merito. Per quello riguarda il risarcimento de pubblici magazzeni dove si conservano le monitioni et apprestamenti da guerra doverete per hora far accomodare nella miglior forma i coperti onde non vadano à male li pubblici capitali, e ci avvisarete per la spesa che potrà concorrervi per la perfettione dell'opera. La fortezza pure tenendo somma neccessità d'esser rissarcita doverete opportunamente impiegar li doicento e sessanta Reali destinativi à questo fine, ed essendo la muraglia smossa à causa de terremoti, potete con propria desterità procurar che cotesti habitanti alcuna cosa contribuiscono per minorarci i dispendij. [. . .]

ASVe, 1663b, DRt, Zante, b. 23
n. 33
Serenissimo Prencipe
Con la mossa dell'Illustrissimo Eccellentissimo Signor Provveditore Generale Mocenigo da quest'Isole per il suo ripatriare [. . .]
Conosco in oltre esser dovuta la partecipatione del stato, et essere di questa Fortezza non solo mà anco de pubblici magazini ne quali si conservano le monitioni et aprestamenti di guerra, com'anco quelli de Biscotti, et in particolar dell'Arsenale affatto dirocato, et imposibile al servirsene; li magazeni poi predetti in stato che il publico poco o nulla di comodo o sicurezza ne può sperare quando con celere provvigione non si ripari a danni.
Non dissimile è il stato di questa Fortezza nella quale verso la parte di Ponente ritrovasi vinti quattro passa di brechia fatta da terremoti nella muraglia smossa anco et rovinata in diversi altri luochi, da non tralasciare senza l'apportarvi il necessario compenso. L'Artiglieria per la mancanza, ò mala qualità de letti per il più marzi né da valersene, che per poco; riesce inutile ad ogn'evento di bisogno, et le polveri esistono nelle monitioni per l'inabilità de luochi sogetta a grandissimi patimenti, sono divenuta in stato di niuna speranza di servitù bona.
Biscotti publici di quali se ne dispensa anco alla militia estraordinaria s'attrova in questo pressidio, et si soccorre la Fortezza di Ceffalonia non ve ne sono se non miara trenta.
Tutto ciò ho stimato mio debito portar reverentissimo a notitia di Vostra Serenità, affine dalla pubblica sapienza resti proveduto a così necessarij, et importanti bisogni; essendo quanto rappresentai, Verità patente et di comune, et publica osservatione, onde in quel si sij tempo non sij attribuita a questa Caricha minima trascuratezza nel ben servire la Patria, se bene m'assicuro che tutto ciò sia stato da detto Eccellentissimo Signor Generale Mocenigo rappresentato alla publica notitia in tempo di sua sopr'intendenza à mottivo de miei pressanti ricorsi; tutta volta non vedend'io altro provedimento sino a questo segno che soli reali doicento sessanta destinatimi

per la restauratione delle mura di questa Fortezza, picciol sovegno a tanto bisogno, che per la tenuità ne meno mi son posto all'impresa di farne principio, per che si perderebbe la spesa senza seguire altro buon effetto; oltre che la staggione per sé stessa sin hora secchissima, quando anco si havesse havuto danaro sufficiente haverebbe levato il modo di farvi alcun lavoro; per il che restando a mé di presente il peso, et incombenza del rimedio, con la partecipatione, adempisco i tratti di mia dovuta obbligatione et humilissimo a Vostra Serenità m'inchino. Gratie.
Zante, li 30 settembre 1663 S. V.
Di Vostra Serenità
Giacomo Erizzo Provveditore

ASVe, 1664a, DRt, Zante, b. 23
Copia
Laus Deo 1664 alli 24 marzo [*S. V.*]
Congregato questo Consiglio di 150 nella stanza solita d'esso a son di Campana [. . .]
La Publica Providenza [. . .] con duplicate Ducali dell'Eccellentissimo Senato [DelRt, 1661d; DelRt, 1663a] ha deliberato appoggiar al zelho et diligenza di questo illustrissimo signor Provveditor il ressarcimento delle mura di questa fortezza in quella parte che da formidabili terramoti sono statte smosse et dirocate per la refabbricatione de quali dovendosi applicar dispendio considerabile ad universal sicurezza di tutti in questi perigliosissimi tempi, volendo però noi Francesco Roma Nicolo Comisso et Marco Zallari [. . .] et sindici dar segno della fede et devotione universale di tutti questi fidelissimi habbitanti [. . .] siamo devenuti alla propositione della presente Parte consistente nella sominiстrazione per alleggerimento della preffata spesa nell'impiego et refabricatione sudetta di ducati Mille cinquecento correnti di questa città affine con magior facilità et quanto più prima resti perfezionato l'affare da esser ricavati essi ducati 1500 ut supra da tutti li habbitanti la città e Fortezza [. . .]
Demetrio Barbiani della Cancelleria della Città del Zante

ASVe, 1664b, DRt, Zante, b. 23
n. 44
Serenissimo Prencipe
[. . .] Per la restauratione poi delle mura di questa Fortezza dirocate già da Terramoti passati intesi quanto sia la brama della Serenità Vostra mottivatami in due mano di Ducali [*ASVe, 1661d; ASVe, 1663a*] et io che conobbi non men neccessario il ridurre nel primiero stato le muraglie per la sicurezza del luocco, et decoro Pubblico, mà il provedimento del dinaro devessi consumare estraendoli da ogn'altro luocco che dal Pubblico errario, per le stretezze in cui s'atrova ho praticato tutti quelli atti d'insinuatione e desterità per ridurre gl'animi di questi Cittadini à risolvere in ciò quel tanto che per natural obligo sono chiamati ad assicurarsi la propria libertà, le vite et facoltà, e doppo moltissime essortationi fattegli, ridottisi a Consiglio havuto in consideratione quel tanto è stato dalla debolezza mia con vivissimi sentimenti rappresentato fu dalli signori Sindici della Comunità proposta la Parte che qui ingionta in copia vedrà la Serenità vostra et presa con pienezza di voti per ricavare con

tassa universale da farsi nella Città Ducati mille cinquecento, il ché chiamando per molti riguardi l'approbatione della suprema Pubblica mano quella ne attende con primo passaggio, et può assicurarsi la Serenità Vostra che non ho punto mancato à tutto quello ho stimato convenevole per incontrar li pubblici cenni. Gratie
Zante, li 24 marzo 1664 S. V.
Giacomo Erizzo Provveditore

ASVe, 1664c, DelRt, reg. 39, c. 61r
Mille seicento sessantaquattro, 3 maggio
Al Provveditor del Zante
Hanno consolato i nostri animi le vostre lettere ultimamente ricevute di 24 [*ASVe, 1664b*] e 31 marzo [. . .]
Colla lode, che conviene al zelo di cotesta fedelissima Communità approviamo l'applicatione, che hà fatto delli mille cinquecento Reali al ristoro della Fortezza. Vedrete però, che s'esseguiscono celermente, e in maniera valida, per stile, e con quell'impiego ben regolato e cauto d'esso denaro, che è proprio della vostra buona direttione, e che certamente incontrerà la soddisfattione dei sudditi et il publico servitio. [. . .]

ASVe, 1664d, DRt, Zante, b. 23
n. 2
Serenissimo Prencipe
Intrapresa da mé questa Carrica, come diedi riverente parte alla Serenità Vostra con Lettera del n° 1, m'applicai all'osservatione diligente di questa Fortezza che ritrovo con infinito mio scontento danneggiata da terremoti à segno, che s'è fatto in diversi luochi d'essa libero addito d'entrare, et uscire à chi si sia, senza contrasto, massime alla Castrina di S. NIcolò, dalla parte di ponente, ove vi sono rovinate le mura per il giro di passa vinti cinque in circa. In altri luochi pure creppate le medesime con separatione considerabile, vi lasciano pericoli evidentissimi, con spiacere di questi habitanti, in congiontura, così molesta dà Guerra, che chiama le gelosie maggiori e le circonspitioni le più accurate.
Questa Comunità fedelissima hà però nel suo Consiglio sino li 24 Marzo decorso, mandata parte che siano applicati ducatti milli cinque cento correnti da Zante e per detto in riparo delle stesse rovine; mà dovendosi questi riscuotere da' Popoli in forma di tansa non s'è per anco non solo unita alcuna summa di detto danaro, mà né meno stabilito verun ordine per l'istessa riscuossione; à che io però m'andrò applicando con tutto il spirito e fervore.
[. . .] I Ponti, le Porte, e i Restelli tutti ricchiedono il ristauro non potendosi serrare, n'aprire, et i Caselli delle sentinelle diroccati per li terremoti, et alcuni d'essi riffatti de tavole, li ritrovo infraciditi à segno che restano i poveri soldati esposti all'ingiurie de' venti e della pioggia, impossibile riuscendo loro d'adempire à numerosi intieri di servitio, et della vigillanza.
Li magazeni, ove sono ripposte le monitioni da guerra ressentono molti pregiudicij, havendo la pioggia fatto marcire i colmi et i suolari, con deterioramento, e diminutione delle monitioni stesse.
[. . .] Li corpi di guardia, et i Quartieri sono in stato pessimo, e deplorabile non n'essendo pagioli, ne riccovero a poveri soldati, che convengono dormire sopra

la terra nuda, con pregiudicio notabile della loro salute, resta perciò supplicata la Serenità Vostra di comandare che sia mandata qualche quantità di legnami d'ogni sorta, e di chioderie, per ripparare à bisogni medesimi.

Ho pur veduto quest'Arsenale, colla Casa d'habitatione solita dell'Ammiraglio in stato rovinoso, che necessario si rende il suo riparo. Vi si trovano nell'Arsenale medesimo diversi legnami, e chiodi trasmessi da costà, sino quando si trovava alla carica di Generale dell'Isole l'Eccellentissimo signor Francesco Mocenigo, né io farò metter mano ad alcuna cosa, se non mi pervengano prima le commissioni supreme dell'EE.VV.

[. . .] Di tutto ciò ho voluto render raguagliate distintamente l'EE.VV. in sodisfattione delli miei doveri humilissimi sottoponendo il tutto all'infalibil intendimento della Serenità Vostra. Gratie.

Zante, 15 giugno 1664 S. V.

Piero Barbarigo Provveditore

ASVe, 1664e, DRt, Zante, b. 23

n. 4

Serenissimo Prencipe

[. . .] Certo che il mio bassissimo intendimento non mi lascia capire, come tutte queste pubbliche fabriche si siano ridotte in stato così deplorabile, essendo state da gran tempo sotto l'occhio de tanti sapientissimi Pubblici Rapresentanti. L'affare della tansa, intorno a quanto essibi questo Spettabil Consiglio à riparo delle rovine della Fortezza si va incaminando; onde se sortirà di essigerla, come spero, farò dar princio al ristauro col fondo medesimo delle Ducali della Serenità Vostra di 3 maggio passato [. . .] Gratie

Zante, 29 giugno 1664 S. V.

Piero Barbarigo Provveditore

ASVe, 1664f, DRt, Zante, b. 23

n. 10

Serenissimo Prencipe

Nel mentre s'andava principiando, di mio ordine dalli signori Sindici di questa fedelissima Comunità il à gl'habitanti della Città per l'essatione delli mille cinque cento ducatti offeriti spontaneamente alla Serenità Vostra per parte presa da questo Consiglio li 24 marzo passato à restauro delle mura della fortezza estremamente derroccate da' terremoti, mi furono presentate lettere dell'Ecc.mo sig. Avogador Balbi di 7 Giugno decorso per parte delli Tenenti delle Contrade, per nome loro, e degl'altri tenenti di questo Popolo, colle quali mi viene commesso di far cittar non solo i sindici suddetti per li quattro mesi susseguenti, per vedersi intrometter la parte soprascritta del Consiglio, mà anco à dover io sospender il tutto dopo la presentazione delle dette lettere.

In riverenza dovuta al detto Eccellentissimo Avogadore, non potei che render sospeso il tanso medesimo, che s'andava esseguendo con diligenza, e celerità, prescritta dalla Serenità Vostra in Ducali di 3 Maggio, dirette all'Illustrissimo mio Precessore [. . .] onde ho stimato mio debbito, di rappresentarlo prontamente all'EE. VV., acciò comprender possa l'infalibil loro virtù, non potersi per tal causa dar principio al riparo

delle mura medesime, in staggione, che riesce molto propria, la quale avanzandosi così senza l'opera stessa, non potrà ch'acrescervi di altre tanta passa per le pioggie, che neccessariamente vi conseguiranno, e per la rigidezza de' tempi, non senza pericolo [. . .]; né io resto di non portar il tutto sotto l'occhio della Serenità Vostra, affine si compiaccia far che con mano celere siano diffinite le dette Controversie, onde non resti per tal causa interrotto un'opra così profficua, e necessaria. Gratie.
Zante, 6 agosto 1664 S. V.
Piero Barbarigo Provveditore

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ASVe, (1658b, d, e.) Senato, Dispacci, PTM, Provveditore Generale alle Isole del Levante, b. 1167 (marzo 1658–febbraio 1659): (b) Dispaccio n. 25, Provv. Gen. Marin Marcello, Zante, 18 agosto; (d) Inserta al dispaccio n. 33, Provv. in Asso, [settembre] 1658; (e) Dispaccio n. 33, Provv. Gen. Marin Marcello, Asso, 29 settembre

ASVe, (1659a, b.) Senato, Dispacci, Rettori, Cefalonia, b. 12 (marzo 1657–settembre 1660): (a) Dispaccio, Provv. Alvise Gritti, 27 giugno S.V.; (b) Dispaccio, Provv. Francesco Valier, 9 dicembre S.V.

ASVe, (1660a, b, d, e, g, h.) Senato, Dispacci, Rettori, Cefalonia, b. 12 (marzo 1657–settembre 1660): (a) Ristretto del scosso e speso, Pietro Zen Provv. in Asso (Cefalonia), agosto; (b) Dispaccio, Provv. Francesco Valier, 24 maggio; (d) Dispaccio, Provv. Francesco Valier, 15 maggio S.V.); (e) Dispaccio, Provv. Francesco Valier, 29 maggio; (g) Copia di delibera Consiglio Comunità di Cefalonia,1 luglio, inserta al dispaccio del 19 luglio; (h) Dispaccio, Provv. Francesco Valier, 19 luglio

ASVe, (1660c, f.) Senato, Dispacci, PTM, Provveditore Generale alle Isole del Levante, b. 1169 (marzo 1660–gennaio 1662): (c) Dispaccio n. 27, Provv. Gen. Alvise Civran, Zante, 25 maggio; (f) Dispaccio n. 33, Provv. Gen. Alvise Civran, Zante, 18 giugno

ASVe, (1660–1662). Senato, Dispacci, PTM, Provveditore Generale alle Isole del Levante, b. 1169 (marzo 1660–gennaio 1662)

ASVe, (1661–1665). Senato, Dispacci, Rettori, Cefalonia, b. 13 (16 agosto 1661–22 febbraio 1665)

ASVe, (1661a, c, e.) Senato, Dispacci, PTM, Provveditore Generale alle Isole del Levante, b. 1169 (marzo 1660–gennaio 1662): (a) Dispaccio n. 65, Provv. Gen. Alvise Civran, Corfù, 23 maggio; (c) Dispaccio n. 87, Provv. Gen. Alvise Civran, Zante, 10 ottobre; (e) Dispaccio n. 91, Provv. Gen. Alvise Civran, Zante, 1 dicembre

ASVe, (1661b.) Senato, Dispacci, Rettori, Zante, b. 23 (marzo 1660–gennaio 1665): Dispaccio, Provv. Francesco Ruzini, Zante, 6 settembre S.V.

ASVe, (1661d.) Senato, Decreti, Rettori, f. 54 (settembre 1661–febbraio 1662): Decreto, 26 novembre

ASVe, (1662–1665). Senato, Dispacci, Rettori, Corfù, b. 30 (27 settembre 1662 SV–26 febbraio 1664 *more veneto*)

ASVe, (1662a, b, c, d.) Senato, Dispacci, PTM, Provveditore Generale alle Isole del Levante, b. 1170 (ottobre 1661–settembre 1663): (a) Dispaccio n. 12, Provv. Gen. Francesco Mocenigo, Zante, 22 febbraio 1662 (1661 more veneto); (b) Dispaccio n. 14, Provv. Gen. Francesco Mocenigo, Zante 16 marzo; (c) Dispaccio n. 20, Provv. Gen. Francesco Mocenigo, Argostoli di Cefalonia, 10 maggio; (d) Dispaccio n. 32, Provv. Gen. Francesco Mocenigo, Cefalonia, 16 settembre

ASVe, (1663a.) Senato, Decreti, Rettori, reg. 38 (1663): Decreto, 18 settembre, c. 263r

ASVe, (1663b.) Senato, Dispacci, Rettori, Zante, b. 23 (marzo 1660–gennaio 1665): Dispaccio n. 33, Provv. Giacomo Erizzo, 30 settembre S.V.

ASVe, (1663c.) Senato, Dispacci, PTM, Provveditore Generale in Dalmazia e Albania, f. 491. Lettera, Provv. Gen. Gerolamo Contarini, Spalato, 29 novembre

ASVe, (1664a, b, d, e, f.) Senato, Dispacci, Rettori, Zante, b. 23 (marzo 1660–gennaio 1665): (a) Copia di delibera Consiglio Comunità di Zante, 24 marzo S.V., inserta al Dispaccio n. 44, 24 marzo S.V.; (b) Dispaccio n. 44, Provv. Giacomo Erizzo, Zante, 24 marzo S.V.; (d) Dispaccio n. 2, Provv. Piero Barbarigo, Zante, 15 giugno S.V.; (e) Dispaccio n. 4, Provv. Piero Barbarigo, Zante, 29 giugno S.V.; (f) Dispaccio n. 10, Provv. Piero Barbarigo, Zante, 6 agosto S.V.

ASVe, (1664c.) Senato, Decreti, Rettori, reg. 39 (1664): Decreto, 3 maggio, c. 61r

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Investigation of pre-1700 Earthquakes Between the Adda and the Middle Adige River Basins (Southern Alps)

M. Stucchi, F. Galadini, A. Rovida, A. Moroni, P. Albini, C. Mirto and P. Migliavacca

Abstract While the seismicity of the Southern Alps is high in the Eastern sector, corresponding to the Veneto and Friuli regions, it decreases towards West up to the Adda River. In the sector between the Lessini Mts. and Eastern Friuli the damaging earthquakes are clustered in a well defined seismic belt, where seismogenic sources responsible for earthquakes with Mw 6 have been defined in recent works. In contrast, the knowledge of the Southalpine sector West of this area is sparser; the area experienced some earthquakes with Mw $>$ 5.5 and varied events with $4.8 \leq \mathrm{Mw} \leq 5.5$ the distribution of which is, apparently, random.

For the area roughly defined by the basins of the Adda River to the West and the middle Adige River to the East, this paper reappraises the background knowledge of the earthquakes occurred before 1700. The investigation and the results are presented according to two successive periods, up to 1995 and from 1995 on. In the research performed up to 1995, the most important achievements concerned two different aspects: (i) the assessement of several "fake quakes", some of which were the object of paradigmatic case-histories; (ii) the resizing and relocation of several, presumed damaging earthquakes. Though this round of investigation changed significantly the picture of the seismicity with respect to the Seventies, the research continued. For the period from 1995 on, the discussion focuses on the reliability of the available information; material that received little or no consideration before, new historical findings and comments to the seismological interpretation as in the most recent literature are also presented. This part includes also the discussion of archaeoseismological evidence of damage related to past earthquakes.

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1 Introduction

The seismicity of the Southern Alps is rather high, in terms of both frequency of occurrence and energy released per event, in the Eastern sector, corresponding to the Veneto and Friuli regions; then, it decreases towards West up to the Adda River. Further west, the Southern Alps are almost aseismic. In the sector between the Lessini Mts. and Eastern Friuli, the damaging earthquakes are clustered in a well defined seismic belt, where seismogenic sources responsible for earthquakes with Mw $\geq$ 6 have been defined in recent works (Galadini et al., 2005; Burrato et al., in press). In contrast, the knowledge of the Southalpine sector West of this area is sparser (Fig. 1). The area experienced some earthquakes with Mw $>$ 5.5 and varied events with 4.8 $\leq$ Mw $\leq$ 5.5 whose distribution is, apparently, random.

This paper first reviews the main results of the investigation performed until 1995 in a domain roughly comprised between the basins of the Adda River to the West and the middle Adige River to the East (Section 2). The review includes material which received little or no consideration before. Then the paper reviews the most recent investigation and the present knowledge of the seismicity in the same domain (Section 3). In particular, it discusses the reliability of the available information of the events before 1700, including new historical findings, comments to the available interpretation and archaeological indication of past earthquake damage.

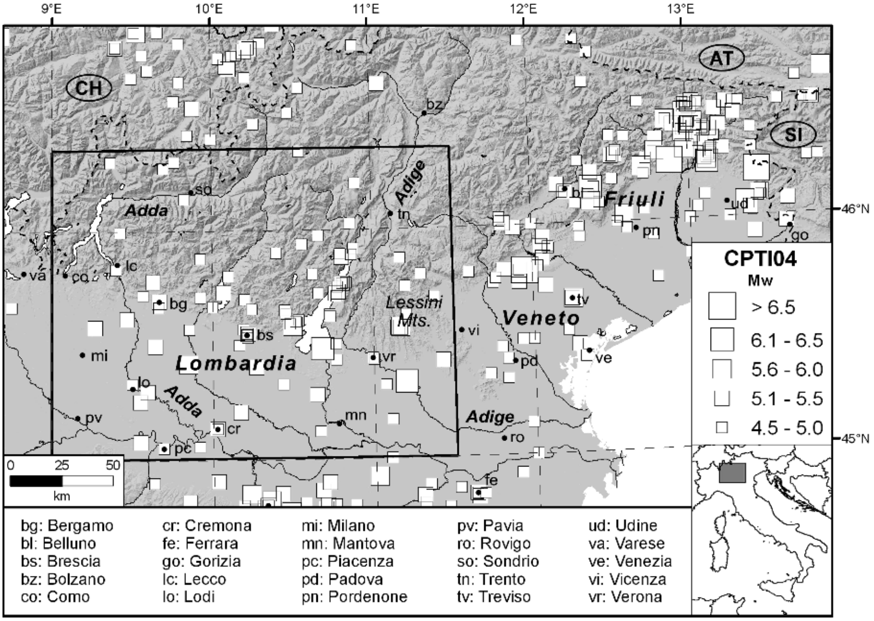

Fig. 1 Seismicity (Mw $\geq$ 4.5) of the Southern Alps from the catalogue CPTI04 (CPTI Working Group, 2004) in the time-window 1000–2002. The box shows the study area

Macroseismic intensities come from the original, quoted studies and are given in the Mercalli-Cancani-Sieberg scale (MCS). Magnitudes come from current parametric catalogues: Postpischl (1985a), uses Mm; CPTI04 uses Mw.

2 Historical Investigation up to 1995

2.1 Background

As most of Northern Italy, from the 11th to the 13th century the area was fragmented into a number of small lordships and counties under either imperial or ecclesiastic rule, some of them evolving in independent Communes. The governmental institutions and their territorial extensions underwent many changes along the two centuries from mid 13th to mid 15th century, and as a consequence of these contrasts and disputes, two main regional states affirmed their respective area of influence: with the Adda and Oglio Rivers as a border (Fig. 2), they were (i) the Republic of Venice to the east, (ii) and to the west the Duchy of Milano, or the possession of the powerful families of Visconti and then Sforza (14th-mid 16th century), under Spanish rule from 1535 on. The area of Valtellina, northern Lombardy, belonged to the Duchy of Milano for about two centuries; in 1512 it passed under the rule of the Helvetic Confederation. The valleys around Trento and Bolzano, an area known also as the historical Tyrol, were quite uninterruptedly ruled by the Bishop Princes of German origin.

As a consequence of these geopolitical and linguistic differences, the main authors of Italian earthquake compilations, such as Mercalli (1883), Baratta (1901), etc. made use of primary information which incorporated just a few sources from Valtellina and the areas of Trento and Bolzano (the last ones were annexed to Italy in 1918).

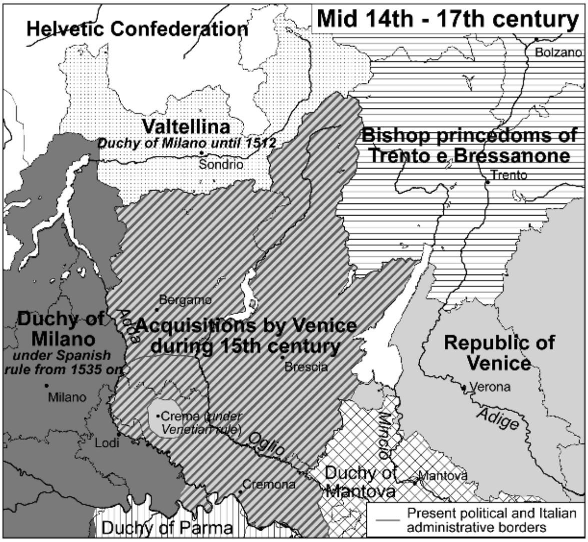

Fig. 2 Political frontiers and modifications between mid 14th and 17th century

2.2 The Main Phases of Investigation

As for most of the Italian territory, in the late 1970s the image of the seismicity of this area derived essentially from the parametric earthquake catalogues by Giorgetti and Iaccarino (1971), Carrozzo et al. (1973) and ENEL (1978). All of them mostly relied on the information gathered by Baratta (1901). Main sources for Baratta (1901), time-window 1000–1700, were the work of the historians like Corio (1503) for the whole Lombardy, Calvi (1676) for Bergamo, Dalla Corte (1592–1594) for Verona. Unfortunately, these authors are not completely reliable, as sometimes they distort the information, making the effects larger than they actually were. In 1985 the "Catalogue of the Italian earthquakes from 1000 to 1980" by Postpischl (1985a) was published. Postpischl led a working group which merged together the most recent national and regional parametric earthquake catalogues and the results of the first, modern historical earthquake investigation, published as the "Atlas of isoseismal maps of Italian earthquakes" (Postpischl, 1985b).

Figure 3 presents the seismicity of the investigated area as proposed by Postpischl (1985a). It shows 25 heavy damaging events (Io $\geq$ 8 MCS, roughly corresponding to Mw ≥ 5.6, Mm ≥ 5.2), most of which are located near the main cities of Milano, Bergamo, Brescia and Verona. They include:

a) an event (1513, Io 9) located in Switzerland exactly on the Insubrian Line;
b) some events located around Pavia and Milano;
c) a cluster of events located around Bergamo;

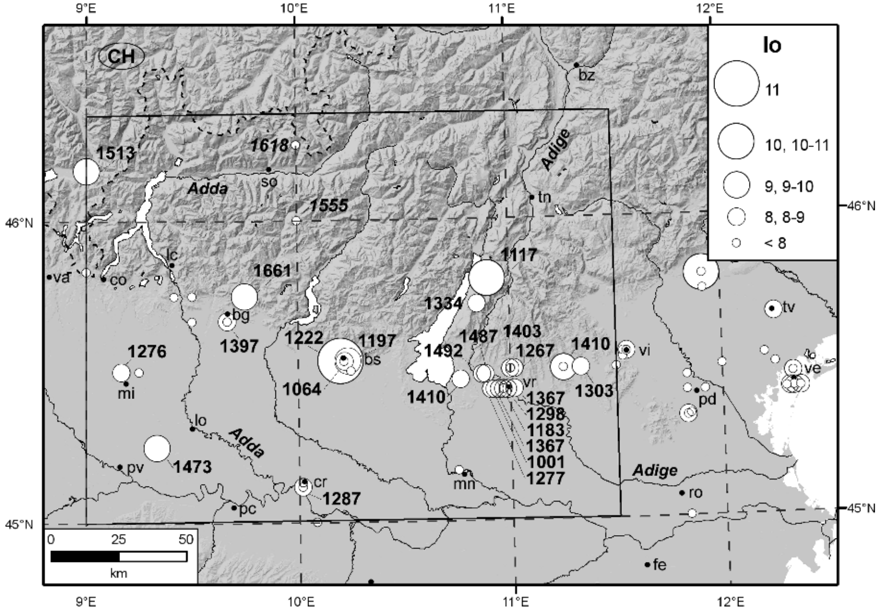

Fig. 3 Seismicity from Postpischl (1985a) in the time-window 1000–1700

d) a cluster of events located around Brescia, including the event of 1222, Io 11 MCS, Mm 6.8, which appears as the most energetic one of the area;
e) a number of events located west and east of Verona, at the border of the Lessini Mountains;
f) the event of 1117, Io 10–11 MCS, Mm 6.5, located near the Northern part of the Lake Garda.

In 1983–1984 the seismicity of the Southern part of the area was the object of a massive investigation in the framework studies for the sites of the projected nuclear power plants in Northern Italy (ENEL, 1985).

The seismicity of Valtellina and the of the strongest events of the surrounding regions in the 13th–20th centuries was studied by CNR in 1987–1988 (Stucchi and Albini, 1988; see also Albini et al. 1988; Albini et al. 1994a). CNR then updated the knowledge on the seismicity of Lombardy (Stucchi et al., 1993) and Trentino-Alto Adige (Albini et al., 1994b). In the framework of these investigations seismological compilations hitherto not considered were searched, such as Lavizzari (1716) and Candreia (1905) for Valtellina and the Graubuenden, Tovazzi (1803) and Schorn (1902) for the provinces of Trento and Bolzano and for Tyrol. A study by Albini et al. (1996) was performed to assess the informative potential of Schorn (1902) with respect to the seismicity of the historical Tyrol.

2.3 Relocating and Resizing Earthquakes

Some events were given more reliable location and size. As for the location, the earthquake of 1276 was known in Postpischl (1985a) as located near Milano, Io 8 MCS, Mm 5.2. ENEL (1985) studied this event together with two others: (i) one reported near Asti, Piedmont, without damage by a reliable source (Ventura, 14th cent.); (ii) the other one reported by Dalla Corte (1592–1594) as happened on 1277, July 28, with damage to the buildings, although this information could not be supported by other sources. The final result was that the three events are just one earthquake, to be located somewhere south-east of Milano, with Io as great as 6 MCS (ENEL, 1985).

The event of 1267 was found to have little to do with Verona and relocated in Austria (ENEL, 1985), where the national catalogue already listed it. In a similar way another, although smaller event in the Postpischl catalogue, the one of 1295 near Bergamo (Io 7 MCS), was found to represent nothing else than the effects of a strong earthquake occurred in the region of Chur, Switzerland (Albini et al., 1994a). The "Bergamo", 1295 event had actually been built up from a limited dataset based on Italian sources only, derived from Baratta (1901). It must be said that this was not the only case in the area: in a similar way a later event of 1670 near Verona was built on the far field effects of a strong earthquake in Tyrol (Guidoboni and Stucchi, 1993). Similarly, the Postpischl catalogue (1985a) located two small earthquakes (Io 4 MCS in both cases) at Menaggio (1943) and

Rovereto (1955), which actually originated from the far field effects of events occurred in Germany and France, respectively (Camassi et al., 1994). Although the epicentral intensity was low, Margottini and Screpanti (1991) attributed the magnitude of the "true" earthquakes, respectively Ms 5.87 and Ms 5.26, to the two presumed "Italian" earthquakes (Camassi et al., 1994). Most of these problems are now solved; unfortunately it must be admitted that the CPTI04 catalogue (CPTI Working Group, 2004) still shows the 1991, Graubuenden earthquake as located in the area of Lecco, due to the fact that – also in this case – only Italian data were used.

As for the size, the Io of many events, if not most of them, were found to be overestimated by at least one degree MCS. This was due, in most cases, to the conservative approach used by the compilers of the previous catalogues, all involved in safety planning issues.

The event of 1304, 23 October, listed by Postpischl (1985a) as happened in 1303 because of a misinterpretation of Baratta (1901), located near Vicenza, Io 8 MCS, Mm 5.2, was given Io 7 MCS by ENEL (1985). The earthquakes of 1287 (Cremona), 1334 (Monte Baldo), 1410 (Verona), saw their Io drop from about 8 to less than 6 (ENEL, 1985).

A very interesting case is the event of 7 May 1473, located by Postpischl (1985a) and previous compilers between Pavia and Lodi, Io 9, Mm 5.2. Further studies (ENEL, 1985; Gazzini et al., 1991) excluded the possibility that it caused serious damage, especially in Milano, on the basis of the diary by Cicco Simonetta (15th cent.), secretary of the Duke of Milano; its maximum intensity was re-evaluated as 5 MCS. This event is interesting because the documents of the Archive of the Sforza family (1454–1535), although they do not mention damage, report a considerable interest by the Duke in the event to such an extent that, on May 12th, 5 days after the event, he wrote to his ambassadors in varied Italian cities, such as Bologna, Roma and Napoli, asking whether the earthquake had been felt there:

> *"A dì septe del presente mese circa le tredece hore fo qui nel dominio notro in diversi lochi uno terremoto el quale durò pocho et non fece nocumento alcuno a li edificii. Desideramo intendere si lo è intervenuto altrove, però volimo tu ne scrive et daghe aviso si dicto terremoto è stato sentito lì et ne le terre circumstante et quanto durò et si lo ha nociuto a le case et particularmente de tutto quello che è possuto intervenie per tale casone". (ASMi, 1473a)*
>
> [On the 7th of this month, at about thirteen hours, there was an earthquake in our domain, in different places, which lasted shortly and did not cause any damage to buildings. We would like to know whether this event happened in others places, so we would like that you write about it and give information whether this earthquake was felt there and in the nearby areas, how long it lasted and whether it damaged houses and all the things that could have happend for this reason].

He got negative answers from Roma and Napoli (ASMi, 1473b; 1473c), while the Ambassador in Bologna wrote:

> *"Rispondo che l'è più d'un mese che per alcuni se disse esserci stato alcun movimento sul fare del dì, ma fu sì breve et sì leve ch'el parse essere in noticia de pochi et come di cosa quasi non ben certa non se ne fece caso" (ASMi, 1473d)*

> [My answer is that one month ago someone said there was some shaking at the beginning of the day, but it was so short and so light that few people accounted for it and, like an uncertain event, it was not recorded].

In addition, the investigation by Gazzini et al. (1991) clearly shows how the impact of the event was then increased by the later compilers of local histories (Fig. 4). Although it cannot be demonstrated in a paradigmatic way, this trend seems to be similar for other events, too. For instance, the work of Corio (1503) represents the basis for all later historical compilations for the Milano area. The later users of his work extended to other localities the information he referred to Milano or Lombardy. This is the case, for instance, of the already mentioned earthquake of 1287, which

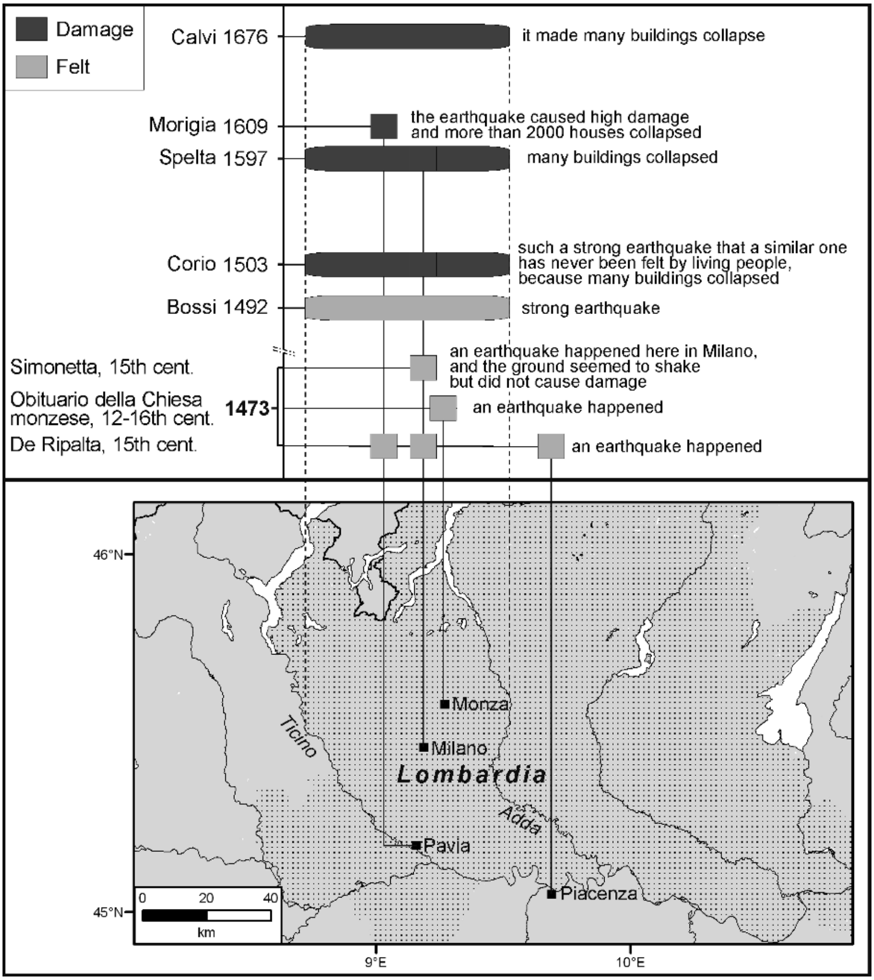

Fig. 4 The effects and the damage area of the earthquake of May 7, 1473 were increased from the coeval sources by the later compilers of local histories

Corio reported as very strong in Milano, and then it grew to a damaging earthquake in Cremona (Cavitelli, 1588) and from that in Postpischl (1985a) as Io 8 MCS, Mm 5.2.

For Verona, on the opposite, Dalla Corte (1592–1594) added damage to the events reported by coeval sources as not damaging ones. This is the case for the events of 1334 (Io 8/9 MCS, Mm 5.5 in Postpischl, 1985a) and of 1410, (Io 9 MCS, Mm 5.7 in Postpischl, 1985a), reported without mention of damage by chronicles of Verona (Parisius de Cereta, 1117–1278 for the first one; Zagata, 15th cent., for the second one); they became destructive events with collapse of buildings in Dalla Corte (1592–1594) and, from there, in Postpischl (1985a) through Baratta (1901). Both earthquakes were studied by ENEL (1985); for the event of 1410 they reduced Io to 8, while in the case of 1334, despite the fact that Parisius de Cereta (1117–1278) and Zagata (15th cent.) do not mention damage, ENEL (1985) assessed I 7/8 MCS at Verona, and Io accordingly.

2.4 Assessing Fake Quakes

As a typical result of this investigation phase through all Europe, several false earthquakes were detected also in this area, mostly related to the medieval time-window. The hunt of the so-called “fake quakes” was very popular in that stage of historical seismology, because rigorous methodologies and professional historical expertise allowed to understand how, in many cases, previous compilers performed wrong interpretations, duplicated events and built up imaginary events from landslides, storms, etc. A pioneer work by Jean Vogt is found in his “Les tremblement de terre en France” (1979), which contains a section devoted to “Problèmes de méthode” where he clearly shows the need for a careful reading of the primary sources to avoid mistakes and creation of “faux séismes”. Methodological aspects and paradigmatic Italian case histories can be found in Guidoboni (1985), where the quoted case of 1276–77 event is also discussed, Guidoboni and Ferrari (1989), Bellettati et al. (1993), Albini and Vogt (1992), Castelli (1993), etc. Through an analysis of the published sources for the Middle Ages, in his book “Les séismes en Europe occidentale de 394 à 1259” Alexandre (1990) identified 276 “false” European earthquakes, resulting from careless interpretation of chronological and/or location wordings. Alexandre’s demolition of the myth of the earthquake of the year 1000 (Alexandre, 1991) is a milestone on the topic of fake or exaggerated earthquakes in Europe.

In the investigated area, the events of 1001 (Io 8–9 MCS, Mm 5.5 in Postpischl, 1985a) and 1298 (Io 8 MCS, Mm 5.2), located near Verona, were proved as fake by ENEL (1985). The supporting information derived from Dalla Corte (1592–1594), who extended to his city the effects of known earthquakes: the myth of the earthquakes around the year 1000 and the 1298 event in Central Italy. Similar are the two following cases: (i) the event of 1277, which was found by Guidoboni (1985) and ENEL (1985) to be a duplication of the already discussed 1276 event, and: (ii) a supposed foreshock of the 10 June 1410 event (Io 8–9 MCS, Mm 5.5), equally assessed by ENEL (1985) as a duplication of the Verona earthquake mentioned above. The earthquake of 1197 (Io 9 MCS, Mm 5.7 in Postpischl, 1985a) was accounted for by Rosaccio (1593) and by the two 17th century authors Benincasa (1653) and De Gregorio (1645). These, not coeval, sources are quoted by Bonito (1691), and also Baratta (1901) relied upon Bonito's sources for this event. After investigating a set of coeval sources without finding any other record, ENEL (1985) concluded that the event had to be considered very doubtful, and in any case its effects should not have exceeded Io 6–7 MCS.

The 1513 event in the area of Biasca/Bellinzona (Switzerland, Ticino) represents a paradigmatic case of a landslide erroneously interpreted as an earthquake. The event was located by Postpischl (1985a) at Bellinzona, Io 9 MCS, dated 10 February 1513 on the basis of Mercalli (1883) who associated it with the records of an earthquake which occurred on the same date in Alessandria. The Swiss catalogue (Mayer-Rosa, 1988) located the event near Biasca, Io 8 MCS, dated 1512, following Volger (1857), who gathered information from German sources, although he also mentioned sources that dated the event 1513, too. The event is clearly described as a landslide since the source closest to it: Paolo Giovio (1550–1552), who was used also by Bonito (1691). Scheuchzer (1716) put this event in a section entitled *"On landslides"*; Bertrand (1757) considered it unlikely to be an earthquake, as well as von Hoff (1840) and Perrey (1848). Coeval sources, such as Muralto (1492–1520), Cavitelli (1588) and, mostly, a manuscript note by the notary Nicolino Rusca of Bellinzona (Rusca, 1515) reported a complex event: the landslide – still clearly visible today and known as "Buzza di Biasca" – dammed the Blenio River that formed a lake near Malvaglia. In 1515 a breach took place in the dam and the waters flooded the valley down to Bellinzona and Lago Maggiore. The date of the landslide is accurately determined as 30 September 1513 by the already quoted note by Nicolino Rusca excluding any association with earthquakes of February 1513. Nicolino Rusca reported: *"1513, die veneris, ultimo septembris, ... fuit maxime ruyna lapidum"*. In addition, a systematic research in a number of coeval published chronicles of the main towns in the area (for Sondrio: Merlo, 16th cent.; for Milano: Morigia, 1592; for Como: Muralto, 1492–1520; for Bergamo: Foresti, 1520; for Cremona: Cavitelli, 1588) did not provide any earthquake record in September 1513, while one of them (Muralto, 1492–1520) mentions the landslide: *"Mons qui est ultra Belinzonam Bregni Vallis scissus est"*.

Finally minor, although interesting cases, are the events of 1555 (Val Seriana, Io 6 MCS) and 1618 (Piuro, Io 5 MCS). Both have been proved to be landslides (Albini et al., 1988); the last one captured the European interest, because the town of Piuro was buried under the landslide. The false "Piuro" event was later located by the early parametric catalogues about 30 km east of Piuro, near Chiuro, because of a misinterpretation of the place-name.

2.5 Conclusion

Altogether, out of the 25 earthquakes with Io $\geq$ 8 MCS in Postpischl (1985a) 9 were proved as fake or very doubtful and only 8 survived with moderate to high damaging capacity (Io $>$ 7 MCS). The largest event became the one of 1117; a few earthquakes underwent further Io reduction in later studies. Table 1 summarises

Table 1 Left: summary of the main earthquake parameters as obtained from Postpischl (1985a). Right: the results of the historical investigations up to 1995

Postpischl, 1985a									After			
Year	Mo	Da	Ho	AE	Io	Lat	Lon	Mm	Study	Year	Io	Comment
1001				VERONA	8–9	45,433	10,967	5,50	ENEL, 1985			fake
1064	04	11		TRAVAGLIATO	8	45,533	10,200	5,20	ENEL, 1985	1065	7–8	
1117	01	03	21	VERONESE	10–11	45,800	10,900	6,50	ENEL, 1985		9–10	relocated
1183	01			VERONA	8–9	45,433	10,967	5,50	ENEL, 1985			very doubt.
1197				BRESCIANO	9	45,533	10,233	5,70	ENEL, 1985			very doubt.
1222	12	25	11	BRESCIANO	11	45,533	10,200	6,80	ENEL, 1985		8–9	
1267	08			VERONA	8	45,500	11,000	5,20	ENEL, 1985			relocated
1276	07	28		MILANO OVEST	8	45,500	9,167	5,20	ENEL, 1985		6–7	relocated
1277	07	20		VERONA	8	45,433	10,967	5,20	ENEL, 1985			fake
1287	04	11		CREMONA	8	45,117	10,017	5,20	ENEL, 1985		5	
1298	12			VERONA	8	45,433	10,967	5,20	ENEL, 1985			fake
1303	10	23		MONTEBELLO	8	45,500	11,333	5,20	ENEL, 1985		7	relocated
1304				VICENZA	8	45,550	11,550	5,20	ENEL, 1985			fake
1334	12	04	23	M.BALDO	8–9	45,717	10,850	5,50	ENEL, 1985		7–8	
1367	09	21		VERONA	8	45,433	10,967	5,20	Stucchi et al., 1993	1365	5–6	
1367	09	21		VERONA	8	45,433	10,967	5,20	ENEL, 1985			fake
1397	12	26	02	BERGAMO	8	45,667	9,667	5,20	Stucchi et al., 1993	1396	7	
1403	01	17		VERONA	8	45,500	11,000	5,20	ENEL, 1985		7–8	
1410	06	10	20	CASTELNUOVO	8–9	45,467	10,767	5,50	ENEL, 1985			very doubt.
1410	06	10	21	VERONA	9	45,500	11,250	5,70	ENEL, 1985		8	
1473	05	07		MILANESE	9	45,250	9,333	5,70	ENEL, 1985		5	no damage
1487	01	11	22	PESCANTINA	8	45,483	10,883	5,20	ENEL, 1985		7	
1492				PESCANTINA	8	45,483	10,867	5,20	ENEL, 1985	1491	7–8	relocated
1513	02	10		BELLINZONA	9	46,167	9,000	5,70	ENEL, 1985			fake
1661	03	12		BERGAMASCO	9	45,750	9,750	5,70	Stucchi and Albini, 1988		7–8	

the main parameters of these events before and after the investigation, as they are provided by the quoted authors: Mm was calculated by Postpischl (1985a) from Io.

3 The Present Knowldege

3.1 Introduction

The material produced by (ENEL, 1985) became later the starting point for the work by Boschi et al. (1995), who published the first version of CFTI, the "Catalogue of Strong Earthquakes in Italy", followed by the second version published in 1997 (Boschi et al., 1997). In the same year the results of the first phase of investigation, discussed in the previous chapter, were used for the compilation of the NT4.1 parametric catalogue (Camassi and Stucchi, 1997), and the macroseismic database DOM4.1 (Monachesi and Stucchi, 1997).

After 1997 the investigation continued, mainly under the initiative of Boschi et al. (2000), with reference to the main events of 1117 and 1222. The first event also captured the attention of investigators such as Galadini et al. (2001), Galli (2005), Guidoboni and Comastri (2005) and Guidoboni et al. (2005). The results of the investigaton from 1995 on were progressively used for the compilation of the CPTI99 (CPTI Working Group, 1999) and CPTI04 (CPTI Working Group, 2004) catalogues (Fig. 5), the supporting material of which was later compiled in the macrosesimic database DBMI04 (Stucchi et al., 2007). In the following, the present knowledge of the main events will be reviewed following a geographical criterion.

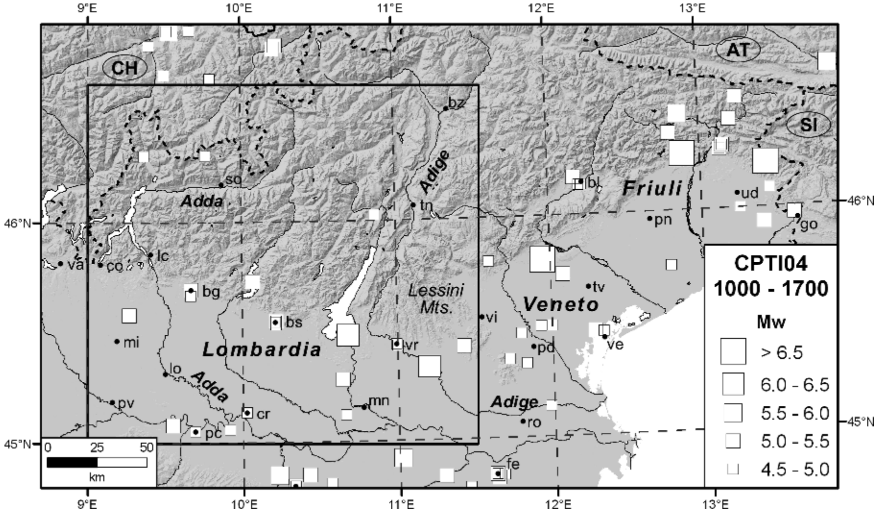

Fig. 5 Seismicity (Mw $\geq$ 4.5) of the Southern Alps from the catalogue CPTI04 (CPTI Working Group, 2004) in the time-window (1000–1700)

3.2 The Valtellina Area

In this area no relevant seismicity appears before the 20th century. Two of the already quoted false events, 1513 and 1618, were located along the tectonic lineament called Insubrian Line; before being proved false, they provided evidence for a possible recent activity of the Line itself.

The seismic histories of Sondrio and Bormio provide data only after the beginning of 20th century (Fig. 6). On the other hand, historical compilations are available from the 14th century (e.g. Beltramolo da Silva, 14th cent.; Merlo, 16th cent.), although earthquake records are not found. As an example, no records of the 1295, Chur earthquake are found in the "Cronica Valtellinese" by Beltramolo da Silva (14th cent.), which covers the time-window 1233–1335. This earthquake could have produced damage in Valtellina, which is closer to the epicentral area with respect to Bergamo, from where damage is reported by Calvi (1676):

> *"1295 settembre 17.* [...] *Lo sentì la patria nostra, che dall'insolito tremare della terra atterrita, et sgomenta l'ultimo precipitio, et rovina attendeva. Terminò in breve corso di poche hore con diversi crolli, havendo nelle case infiniti danni partorito"*
>
> [1295 September 17. [...] [the earthquakes] was felt in our homeland, which by the unusual trembling of the earth was frightened, and daunted, and was waiting for the ruin to come. In a few hours the earthquake ended and caused collapses and great damage to the buildings]

Although one cannot exclude that some local events are missing, in the case they really happened they should not have reached a large magnitude.

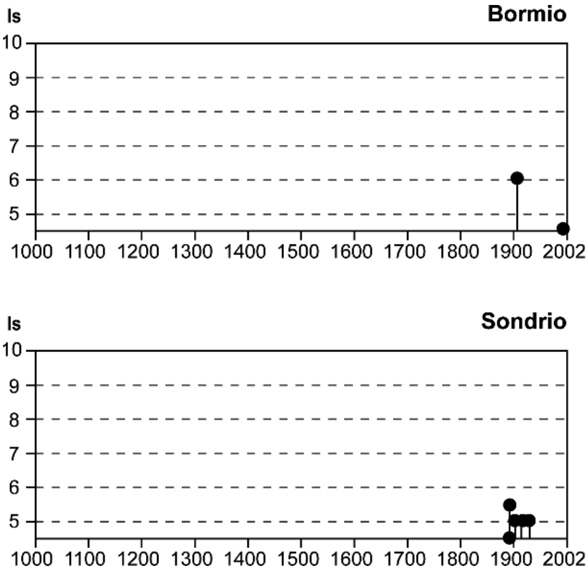

Fig. 6 Seismic histories of Sondrio and Bormio, with data from the 20th century on (data from DBMI04, Stucchi et al., 2007)

3.3 The Prealpine Margin

Apart from the aforementioned 1117 and 1222 earthquakes, which will be discussed below, a little more than 20 events are reported by CPTI04 in the investigated area and time-window. The relevant background consists of information from one or two localities only; therefore, the parameters of these earthquakes are not very reliable. The temporal and spatial distribution shows that the information mainly comes from three localities: Bergamo, Brescia and Verona (Fig. 7). These cities seem to represent the centre of the information in different periods: Brescia, during the 11th–12th centuries and in the time-window 1470–1600; Verona, 1340–1470; Bergamo, 1570–1670. Moreover, the seismic histories of the cities indicate that in most cases the events are reported from only one of the mentioned localities (Fig. 8).

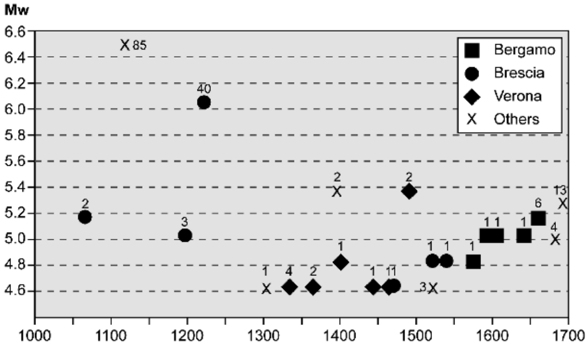

Fig. 7 Time vs energy distribution of the earthquakes in the alpine margin, according to CPTI04. Symbols show the main origin of the information for each earthquake; the number of macroseismic observations of each earthquake is also shown

3.3.1 The Bergamo Area

3.3.1.1 1396, Monza (?)

This earthquake was reported by Postpischl (1985a) with the date of 26 December 1397; it was located in the Bergamo area, Io 8 MCS, Mm 5.2. ENEL (1985) investigated another earthquake that appeared in the catalogue by Postpischl (1985a) with the date of 26 November 1369, located in Milano, Io 7 MCS, Mm 4.7 and found that it was nothing else than a duplication of the 1397 event. The earthquake was then studied by Stucchi and Albini (1988) and Stucchi et al. (1993), mainly using earthquake records from local historical compilations written between the 16th and 17th centuries (Table 2). From these studies an event emerges which caused damage to Bergamo (Calvi, 1676), and was felt over a large area, including Alessandria (Schiavina, 1616; Ghilini, 1666), Lodi (Agnelli, 1895), Verona (Zagata, 15th cent.), Rovigo (Nicolio, 1582), Trento (Tovazzi, 1803) and Como (Tatti, 1683). The analysis of the records allowed Stucchi and Albini (1988) to assess that most of them, with the possible exclusion of Tovazzi (1803), come from a single source (Corio, 1503), sometimes not explicitely quoted. Corio reports:

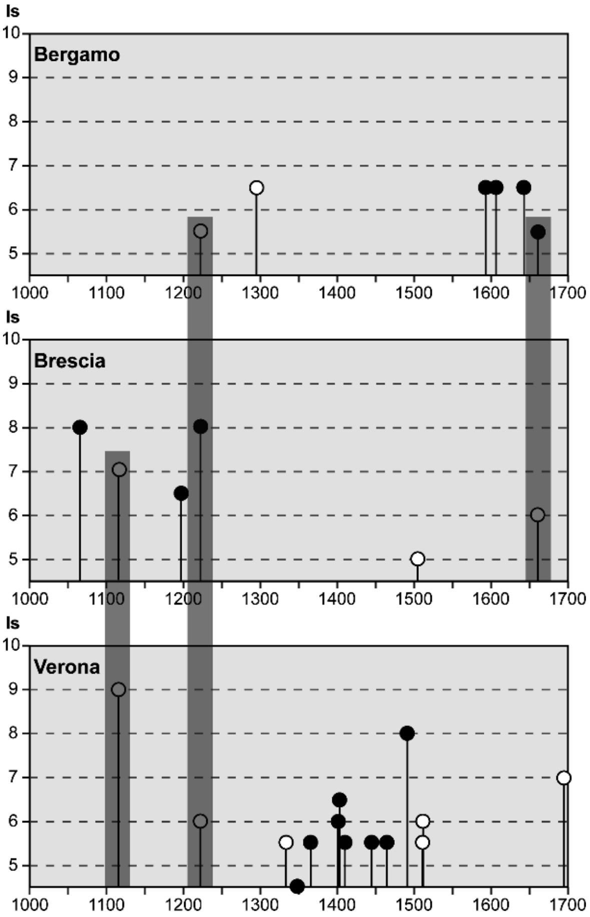

Fig. 8 Seismic histories of Bergamo, Brescia and Verona. Black dots indicate effects of earthquakes located near the locality. Grey bands show the earthquakes 1117, 1222 and 1661 which are reported from more than one locality

> *"E l'anno nonagesimo septimo sopra mille trecento, nel giorno dedicato a San Stephano circa l'ora di terza quasi per tutta la Lombardia intervenne uno inaudito terremoto mediante il quale ruinorono molti edifici"*
>
> [1397, on St. Stephen's day, at about the terce, in all Lombardy there was an exceptional earthquake that caused the collapse of many buildings.]

This record is very precise as for the date while it is not for the location of the event. The date, the day of Saint Stephen of 1397, is indicated according to the so-called "Nativity style", the year beginning on December 25; therefore it has to be corrected to 1396. The earthquake is reported as felt all over Lombardy, without detail. As explained in the previous chapter, also in this case the information of Corio was then extended by late compilers to their home localities.

Stucchi and Albini (1988) and Stucchi et al. (1993) investigated also civil documentary sources (Atti Cancellereschi Viscontei, 1359–1447; 1338–1447), ecclesiastic

Table 2 Summary of the information available about the 1396 earthquake from historical compilations

Source	Effects	When	Where
Agnelli, 1895	Strong earthquake; many buildings collapsed	The day of St. Stephen, 1397	Lombardia
Tovazzi, 1803	An earthquake happened	26 December 1397	Trento
Tatti, 1683	Strong earthquake; many buildings collapsed	26 December, the day of St. Stephen, 1397	Lombardia
Calvi, 1676	Strong earthquake; many buildings collapsed	26 December 1397	Bergamo and Lombardia
Ghilini, 1666	Strong earthquake; many buildings collapsed	26 December, the day of St. Stephen, 1397	Alessandria and Lombardia
Schiavina, 1616	Strong earthquake; many buildings collapsed	The day of St. Stephen (1397)	Alessandria and Lombardia
Nicolio, 1582	Strong earthquake; many buildings collapsed	The day of St. Stephen (1397)	Rovigo and Lombardia
Corio, 1503	Strong earthquake; many buildings collapsed	The day of St. Stephen 1397 (the year is expressed according to the Nativity calendar style, corresponding to 1396)	Lombardia
Zagata, 15th cent	Strong earthquakes	26 December 1397	Verona
Mezzotti chronicle	Some houses collapsed	26 November 1396	Monza

ones (Annali della Fabbrica del Duomo di Milano, 1387–1411) and coeval chronicles, such as Annales Mediolanenses, 1230–1402; Castelli, 1387–1407, without success. Only the chronicle (1337–1517) of the Mezzotti family of Monza, published in 1840 (Mezzotti, 1840), quoted by Mercalli (1883) with reference to the presumed "26 November, 1369" event, reports:

> *"ai 26 di novembre del 1396 si sentì grave scossa di terremoto e rovinarono alcune case"*
>
> [on the 26 November 1396 a strong shock was felt and some houses were damaged]

Stucchi and Albini (1988) did not rely on this date and proposed to accept the date of 26 December 1396 according to Corio (1503). Later, Stucchi et al. (1993) assessed I 7–8 MCS at Monza (Fig. 9). Boschi et al. (1997 and 2000) assigned I 7–8 MCS at Monza on the basis of the Mezzotti chronicle. Guidoboni and Comastri (2005) reappraised the analysis and, though confirming the above mentioned intensity at Monza, concluded that the lack of information from coeval sources in Lombardia and Veneto suggests that the epicentral location should be considered with caution.

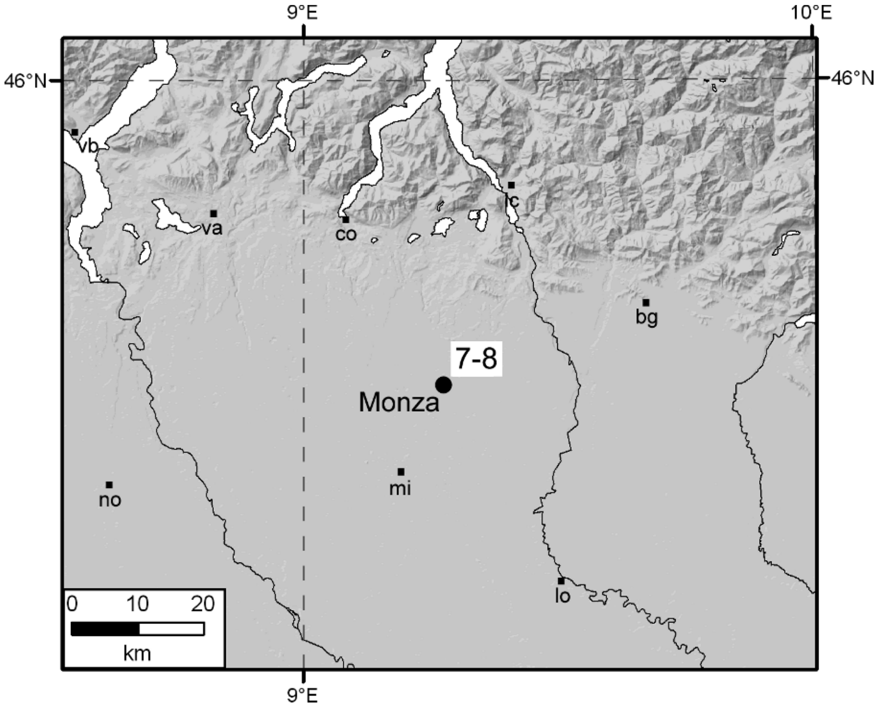

Fig. 9 Location of Monza and intensity for the 1396 earthquake (from Stucchi et al., 1993)

3.3.1.2 1576, 1593, 1606

These events are known by preliminary investigations mostly based on the retrieval of the sources provided by Baratta (1901) and, mainly, on Calvi (1676) who reports the same record for the three events:

> *"[. . .] scossa che fece più camini andar per terra"*
>
> ["an earthquake occurred, which made some chimneys collapse"; on the occasion of the 1576 event, Calvi said that glasses broke]

No substantial progress has been achieved so far. SGA (2002) found the information of an earthquake felt in Milano in the same year (1576), from a late compiler (Gargantini, 1874) who does not quote his sources. The earthquakes of 1593 and 1606 were investigated by Stucchi et al. (1993). According to a poorly reliable seismological compilation (Bettoni, 1908) which does not provide sources, the event of 1593 was presumably felt in Brescia, too; for the event of 1606 no additional information was found.

3.3.1.3 13 June 1642

This earthquake appears in CPTI04 catalogue with Io 6–7 MCS, located near Bergamo on the basis of a preliminary study (Archivio Macrosismico GNDT, 1995), which assessed I 6–7 at Bergamo only. This event was later investigated by Moroni (2001); here we present an updated interpretation.

At Bergamo, according to Calvi (1676), the earthquake produced damage to the houses and the collapse of many chimneys:

> *"Verso le tre hore di notte fiero terremoto scosse la nostra patria [Bergamo] apportando alle case molti danni particolarmente ne camini, che quasi tutti cadero"*
>
> [At three hours of the night a strong earthquake shook our homeland [Bergamo] and caused many damage to the houses, particulary to the chimneys, the most part of which collapsed.]

The source for Mantova (Gionta, 1741) reports:

> *"La notte delli 13 giugno in sabato, udironsi tre scosse di Tremuoto, che recarono grande spavento, ma poco danno fecero alle fabbriche"*
>
> [On the night of 13 June, Saturday, three earthquakes were felt, which caused great fear, but little damage to the buildings].

The source for Lecco (Cronichetta, 1718, quoted by Mercalli, 1888) reports:

> "Anno 1646 – *La notte avanti la Festa di S. Antonio di Padova* [che cade il 13 giugno] *li 12 Giugno venne un grande e spaventoso terremoto, che per lo spatio d'un miserere circa diede tre continuati crolli. Il primo fece ben bene tremare questo Convento di Pescarenico, il secondo fu molto più impetuoso e formidabile, in modo che, se fosse durato più d'un miserere, siccome durò meno fu tenuto fermo il total diroccamento del Convento. Si svegliarono tutti li Religiosi, e tutti gridavano Giesù e Misericordia. Il terzo crollo fù simile al primo gratie a Dio, non vi fù danno notabile, come si può vedere dalla memoria dell'Archivio. Plico 4" (Cronichetta della fondazione del Convento de' Ceppuccini di Lecco, par. 4, p. 14)*
>
> [Year 1646. The night before St. Anthony's day (13th of June). On the 12th a great and frightening earthquake happened, which for the duration of a miserere shook three times. The first one shook this monastery in Pescarenico, the second one was stronger in such a way that would have it lasted more than a miserere, but as it was shorter the complete ruin of the monastery did not happen. All the monks woke up invoking Jesus and Mercy. The third shock was similar to the first one. Thanks God, there was no remarkable damage, as we can see in the document of the archive. File 4, Foundation of the *Convento de' Cappuccini di Lecco*, Chronicle, sect. 4, p. 14].

We share Mercalli's opinion (1888) who considered the year "1646" the result of an inaccurate transcription of "1642", done by the author of the "Cronichetta" (1718) while copying a document possibly then stored in the Lecco archive.

The earthquake was felt in Milano, where it caused panic, and possibly at the nearby place of Gessate, where Cremosano (1642–1691) was staying with his family at the time the earthquake occurred:

> *"1642, 13 giugno. Alle ore 2 1/2 di notte si fece sentire in Milano e quasi per tutta l'Italia un terremoto qual mise grande spavento, ed io mi trovava al mio luogo di Gessate con tutta la mia famiglia."*
>
> [1642, 13 June. At two and a half hours of the night an earthquake was felt in Milano and almost all Italy, causing great panic, and I was staying at my place in Gessate with all my family.]

Cremosano proceeds saying that the bell tower of the Church of St. Stephen "in Broglio" collapsed on 22 June, describing it as an event independent of the earthquake. This contrasts with Formentini (19th century), a source today lost and known through the quotation by Mercalli (1883), that says that the collapse occurred on 13 June and because of the earthquake.

For Parma we have contradictory information. The Zunti chronicle (1589–1645) reports:

> *"1642 [...] et il 13 giugno tirò forte il terremoto che gettò a terra molte mazze da camino"*
>
> [1642 [...] and on the 13th of June the earthquake was so strong that knocked down many chimneys]

Another source (Pugolotti, 16th–17th cent.) does not mention any damage:

> *"Alli 13 di Giugno 1642 suddetto giorno di Venerdì circa tre hore di notte venendo al sabato, si è sentito in generale il terremoto, con gran strepito, qual [...] non si è mai sentito così terribile, e spaventoso."*
>
> [On Friday the 13th of June, 1642, at about three in the night, an earthquake was felt, with such a great noise, that it has never before been felt so terrible and frightening].

The latter record is here considered as the most reliable one, also because the time coincides with the reports by Calvi (1676) and Cremosano (1642–1691). The earthquake was strongly felt also at Lodi (Agnelli, 1895) and lightly at Alessandria (Ghilini, 1666). Aftershocks are mentioned as felt at Alessandria (Ghilini, 1666), Lodi (Agnelli, 1895) and Mantova (Gionta, 1741).

In conclusion, we have a sufficiently clear picture of an earthquake of moderate size, with damage in Bergamo and possibly light damage in Mantova; for the remaining places the sources report effects "close to" collapse and a great fear (Fig. 10). The list of intensity datapoints is:

Bergamo	6–7 MCS
Mantova	6
Lecco	5–6
Gessate	5 (possibly)
Lodi	5
Milano	5
Parma	5
Alessandria	3

3.3.1.4 January–March 1661

An earthquake dated 12 March 1661 was reported by Postpischl (1985a) as a heavily damaging one (Io 9 MCS) located in the area to the east of Bergamo. Seismologists have been interested to this earthquake since it occurred few days before the strong and well documented event of 22 March 1661, which struck the Romagna region, about 300 km from the Bergamo area. The earlier studies by Stucchi and Albini (1988) and Stucchi et al. (1990) already showed that a number of coeval sources describe several earthquake effects in the period 17 January – 20 March in varied localities of Lombardy.

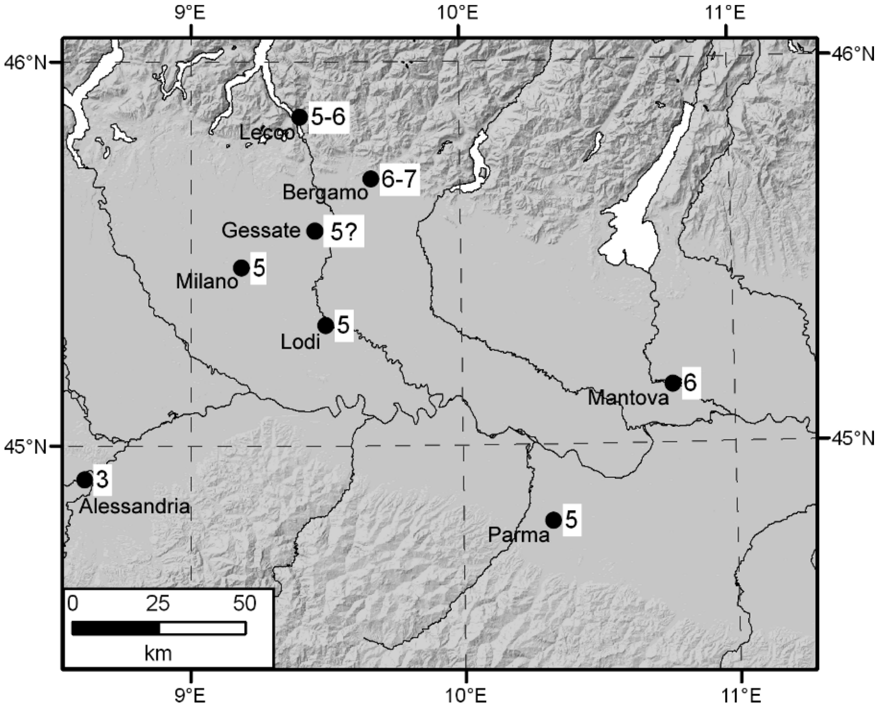

Fig. 10 Intensity distribution for the June 13, 1642 earthquake (this study)

Earthquake records mainly cluster around few dates (Fig. 11). One is the 18 January, the main effects being:

i) strongly felt in Bergamo, as reported by Marchese Clemente (1660–1689)

> *"1661. 18 Genaro. In cerca all'hore cinque di notte venne un terremoto alquanto gagliardo che mosse tutte le case et fece in alquanti luoghi danno notabile"*
> [1661. 18 January. At about the five hours of the night a vigorous earthquake happened, shaking all the buildings and causing visible damage at some places]

and in Crema, as reported by by Canobio (1849), non coeval source, but possibly relying upon sources today lost:

> *"(1661) quando finalmente la notte del 18 gennaio s'udì, tra le cinque e le sei ore, di repente un terremoto spaventoso, che atterrì tutta la città"*
> [(1661) when finally in the night of 18 January, between the fifth and the sixth hour, a threatening earthquake suddenly occurred, and caused fear in all the town]

ii) felt in Milano by Cremosano (1642–1691)

> *"1661, 18 gennaio. All'ora 5 1/2 in circa gran terremoto"*
> [1661, 18 January. At about the 5 and 1/2 hour a strong earthquake].

The strongest event took place on 11 March; a Friday according to Calvi (1676), who reports damage at two monasteries, in Albino and Montecchio:

> *"1661. Giorno di venerdì [. . .] in cui la Patria nostra fu da fierissimo terremoto crollata, che cagionò nel territorio moltissimi danni; caduta del refettorio de' Padri di Montecchio*

Day and month	Time	Source	Excerpt	Place
17 Jan	h. 6	De Mezavachis 1692	[An earthquake was felt]	"Insubria" (Lombardia)
18 Jan	h. 5	Clemente 1660-1689	A vigorous earthquake happened, causing damage at some places	Bergamo
	h. 5-6	Canobio 1849	A terrifying earthquake happened	Crema
	h. 5.30	Cremosano 1642-1691	A great earthquake occurred	Milano
January		*Bianchi* 1629-1743	*[Seven to eight earthquakes were felt]*	*Brescia*
11 March, Friday	--	Calvi 1676	An earthquake cause much damage, the ruin of the refectory of the Montecchio monastery and severe damage to the monastery at Albino	Bergamasco: - Montecchio - Albino
	h. 19	Cremosano 1642-1691	Another earthquake was felt	Milano
18 March	midday	Canobio 1849	A very light and quite imperceptible earthquake occurred	Crema
20 March	mid morning	Calvi 1676	A very light earthquake was felt	Castro
	h. 20		Landslide of a portion of a mountain on the coast of Lake Iseo	Lake Iseo: Castro Lovere Pisogne
March		*Bianchi* 1629-1743	*[Seven to eight earthquakes were felt. One caused the collapse of chimneys vaults and buildings]*	*Brescia and territory*
			Landslide	*Lake Iseo*

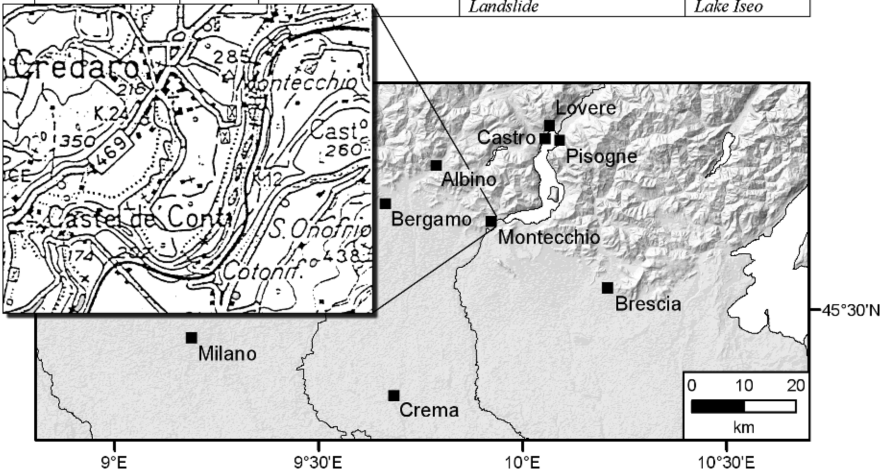

Fig. 11 Earthquake records of January–March 1661 as reported by coeval sources, and related localities

> *con morte d'alcuni, conquassamento del Convento de Cappuccini di Albino, aperture voraginose della terra, staccamento de Monti dal luogo loro con altre rovine. Fu il terremoto sentito non solo hoggi, ma anco in altri giorni antecedenti e susseguenti, ma l'hodierno riuscì più degli altri spaventoso"*
>
> [1661. On a Friday [. . .] our Homeland was shaken by a strong earthquake that caused much damage in our territory; the refectory of the Friars of Montecchio fell with deaths of some of them; the Capuchin monastery in Albino shook, fissures opened in the ground, mountains moved away from their places, and other ruins. The earthquake was felt not only today, but also in the previous and following days, but the one of today was more frightening than the others.]

It is difficult to assess whether, with the wording *"la nostra Patria"*, Calvi does refer to the city of Bergamo – the place he mostly deals with in his book – or the whole area, which would include both Albino and Montecchio. While Albino is easily located, the name of the other place, Montecchio, is a rather common one and can be referred to many localities in the area. Stucchi et al. (1990) identified the monastery as the one of Santa Maria delle Grazie of Montecchio near Credaro, not far from the Lake Iseo. Founded in 1470, the monastery was transformed into a private property in mid 18th century. Documents on the Montecchio monastery are stored in the State Archive of Milano; they concern the management (ASMi, 1491–1579; 1504–1755), the exemption from taxes (ASMi, 1507–1682) and the affairs related to the building and the annexed church (ASMi, 1563–1724); documents regarding the Albino monastery are stored in the "Capuchins Friars" Provincial Archive (APCL, 17th cent.). All these documents do not provide any record on the earthquake.

Another trace of this earthquake comes from Milano; Cremosano (1642–1691) mentions:

> *"1661, 11 detto [marzo]. All'ora 19 altro terremoto"*
>
> [1661, 11 ditto [March]. On the 19th hour another earthquake].

On March 18, around midday, a nearly imperceptible earthquake is reported by Canobio (1849) in Crema. On March 20 a complex sequence of events is reported by Calvi (1676) in Castro, near the Iseo Lake – in a separate section with respect to the event of March 11: a light earthquake in the morning, an eclipse and, at about h.21, a landslide which fell into the lake causing casualties and damage on the banks:

> *"20 marzo. 1661. Fù questi un giorno per molti capi alla terra di Castre memorando; picciol terremoto à mezza mattina scosse la terra. S'ecclissò alle 18. Hore il Sole, così durando per quasi quattro, e sù le venti una, cadè da un monte mezzo miglio discosto nel vicino lago, tanto vasto pezzo di rupe sassosa, che causò più gran rumore di qual si voglia fiero tuono, ò terribil terremoto. Si posero i popoli di Castre in fuga, quelli di Lovere, Pisogni, & altre terre alla gran furia del lago atterriti rimasero, & il rumor dell'aqua, fù per deciotto miglia sentito. Si sconvolsero de pescatori le barche, & molti, ne rimasero affogati sembrando volesse il mondo tutto subissare"*
>
> [20 March. 1661. This was a day for many reasons memorable for the place of Castre; at mid morning a very light earthquake shook the earth. The sun eclipsed at 18 hours, and it lasted for four, and around twenty and one hours, from a mountain half a mile far from the coast such a large portion that it caused a greater noise than the fiercest thunder, or a terrible earthquake. Fled the people from Castre, those from Lovere, Pisogni and other places were

> frightened by the fury of the lake, and the noise of the water was heard as far as eighteen miles. The fishermen fell from their boats, and many were drowned, and the world seemed to sink]

The diaries of the Bianchi family (1629–1743) give a cumulative description covering January to March, including earthquakes, also felt in the city of Brescia to which the diaries mostly refer, and the above mentioned lanslide, without supplying a precise date.

> *"In quest'anno in Gennaro, Febraro e Marzo si sentono sette o otto terremoti di più si vede uno eclissi del sole e nell'istesso tempo un terremoto per il crollo del quale cadono in Città e per il territorio camini, volte e fabriche con morte anche di qualcheduno. Un pezzo di monte cade nel lago d'Iseo e l'onda si porta verso la riva opposta cioè verso sera che rese a quelle terre molto terrore se bene cessa in tempo di due ore tal commotione"*

> [On January, February and March of this year seven or eight earthquakes are felt, and further there is a solar eclipse and at the same time an earthquake the shaking of which makes chimneys vaults and buildings collapse in this City and the surroundings and the death of some people. A portion of a mountain falls in Lake Iseo and the wave goes to the opposite coast that is to the west and this caused a great fear in those places though the commotion ends in two hours].

Boschi et al. (1995; 2000), using the same sources, associate all the effects referred to March 1661 to a single event with date 12 March 1661. This includes the damage at Brescia, the presumed shaking in Bergamo, the light shaking in Crema and the landslide near Castro. The resulting intensities are I 7–8 MCS at Montecchio (which they locate north of Lake Iseo), I 7 MCS at Albino, I 6 MCS at Brescia, I 5–6 MCS at Bergamo, I 3 MCS at Crema.

In our opinion this is a sequence of moderate events, rather difficult to be sorted out. The overall picture looks dominated by the damage to single buildings in Albino and Montecchio – at which we do not assess I MCS following the standards adopted for the compilation of DBMI04 (Stucchi et al., 2007) – and by the landslide; from this picture there is no clear evidence supporting a widely damaging event. Our resulting intensity distributions are:

17 or 18 January 1661

Bergamo	5 MCS
Crema	5
Milano	F

11 March 1661

Albino	D
Montecchio	D
Bergamo	5 (possibly)
Milano	F

3.3.2 Around Brescia: 1064–1065

Postpischl (1985a) reported two earthquakes dated 11 April 1064 in the Brescia area; the first one without time, Io 8 MCS, Mm 5.2 and epicentral location at

Travagliato; the second one at 11 a.m., Io 7 MCS, Mm 4.7 and epicentral location at Castenedolo. The study by ENEL (1985) using coeval sources such as Arnolfo da Milano (11th cent.) and Malvezzi (14th cent.), reports two earthquakes with date 17 March 1065 and I 7–8 MCS at Brescia. Guidoboni and Comastri (2005), using the same sources report only one earthquake with date 27 March 1065, in the morning, and intensity distribution with 8 MCS at Brescia and F (felt) at Milano.

3.3.3 The Area of Verona

As from the previous chapter, the today knowledge of this area no longer shows many damaging earthquakes as it appeared from Postpischl (1985a). Here follow the few surviving ones.

3.3.3.1 1183

This earthquake was reported by Postpischl (1985a) with the date January 1183, Io 8–9 MCS and epicentral location at Verona. The study by ENEL (1985) considered the available information as debatable and hypothesised a rather low level of shaking, assessing Io 4–5 MCS. Alexandre (1990) considered this event as false. Boschi et al. (1995), using Parisius de Cereta (1117–1278) date the earthquake to 1183 and attribute to it the collapse occurred in January 1184. They assign I 4–5 MCS to Verona. This picture was the reason for not inserting the event in the catalogue CPTI04 (CPTI Working Group, 2004). Stucchi et al. (1993) investigated a chronological issue already remarked by Baratta (1901) and considered reliable his oldest source (Parisius de Cereta, 1117–1278) which dates the earthquake 1183 January but places it in a conflicting historical frame. The source relates that in July 1183 there was a meeting in Verona between Pope Lucius III and Emperor Frederick I:

> *"MCLXXXIII. Dominus Lucius papa, et dominus Fredericus Imperator ultimo die iulii fuerunt Veronam. Et hilariter recepti, et honorifice pertractati" (Parisius de Cereta, 1117–1278)*
>
> [1183. Pope Lucius and Emperor Frederick were in Verona the last day of July. And they were received with great happiness and treated with great honours.]

Information about the earthquake is given after this event:

> *"Millesimo supradicto intrante mense ianaurio. Maxima pars alae Arenae cecidit terremotu magno per prius facto, videlicet ala exterior".*
>
> [In the mentioned year, at the beginning of the month of January the largest part of one side of the Arena, in the outer wall, collapsed because of an earthquake that happened some time before.]

The contradictory chronology could be explained by the use of different calendars; in Verona the Nativity style was in use and the January "coming" month could be related to 1184. As a matter of fact Lucius III and Frederick I met in 1184, not in 1183; therefore, the information about damage at the Verona Arena should be dated January 1185. In this case, following Stucchi et al. (1993), it has to be taken into account that Alexandre (1990) reported a (true) "*terraemotus modicus*" in Italy which would have happened in 1185. Recently Guidoboni and Comastri (2005), reappraising the same information used by Boschi et al. (1995 and 2000), assign I 6–7 MCS at Verona, and propose for the earthquake the date December 1183.

3.3.3.2 1491, Verona–Padova (?)

This earthquake is reported in Postpischl (1985a) with date August 1492, located in the Verona area with Io 8 MCS. Boschi et al. (1995; 2000) date the earthquake on 1491 and identify two damaged localities (Fig. 12), Verona (I 8 MCS) and Padova (I 7 MCS). However, no contemporaneous sources have been found for Verona. Moreover for Padova, according to documents in the State Archive of Padova (quoted in Boschi et al., 1995; 2000), a heavy snowfall increased the damage to the roofs. Guidoboni and Comastri (2005) reappraised the sources related to Verona and concluded that *"there seems to be no justification for the attribution to Verona of an intensity of grade 8 MCS given in Boschi et al. (1995; 1997; 2000)"*. Therefore, the authors cancel Verona from the list of the damaged localities (Fig. 12). Moreover, the intensity at Padova, reduced at I 6–7 MCS, is considered doubtful due to the quoted climatic effects. In the whole, the earthquake occurrence itself seems questionable. If the earthquake really occurred, it should not be related to the Verona area.

3.4 The Earthquake of 1222

This earthquake has been the object of several studies (Magri and Molin, 1986; ENEL, 1985; ENEL, 1986b; Guidoboni, 1986; Boschi et al., 1997; 2000) which, through time, have decreased the size it had in the previous catalogues. The most recent review on this event has been published in Guidoboni and Comastri (2005). Available information from primary sources defines a significant damage to Brescia. According to the mentioned authors, however, the city was not completely destroyed as, with great emphasis, is reported in the primary sources. Intensity at Brescia has been estimated I 8 MCS. A higher damage (I 9 MCS) probably affected some villages of the Brescia diocese, corresponding to the present province of Brescia, particularly in the Southern area; however, this damage cannot be exactly located. Damage is also attributed to the villages of Lazise (in the Lake Garda area, I 7–8 MCS), Marano di Valpolicella (in the Verona area, I 7–8 MCS), Modena (I 7 MCS) and, probably, Milano (6 MCS). The earthquake was felt in varied towns and villages of Northern Italy (Fig. 13); however, Guidoboni and Comastri (2005) reduce the number of macroseismic observations from the 39 published in Boschi et al. (2000) to only 20.

The current epicentral location is problematic, due to the uncertainty in the intensity assignment at the known places and the impossibility to identify the localities of the Brescia diocese which suffered damage. For this reason, the algorithms defining the epicentral location, such as "Boxer" (Gasperini et al., 1999) are strongly conditioned by the known localities east of Brescia; therefore, the epicentral location some tens of kilometres east of Brescia is probably not precise. These aspects also condition the determination of the magnitude which the CPTI04 catalogue assesses as 6.05 ± 0.13 Mw.

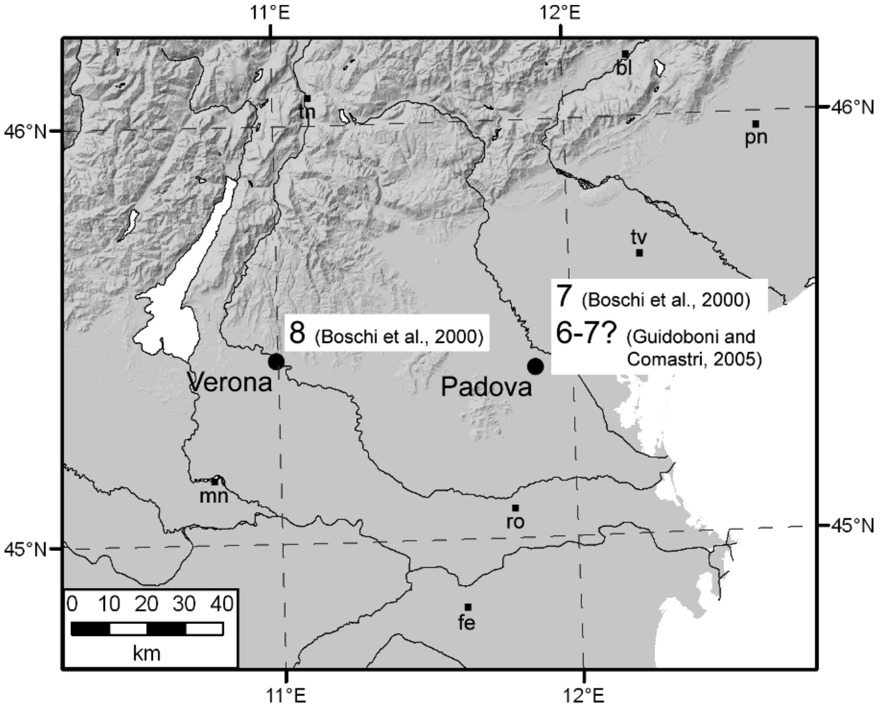

Fig. 12 Intensity distribution for the August 1491 earthquake according to Boschi et al. (2000) and Guidoboni and Comastri (2005)

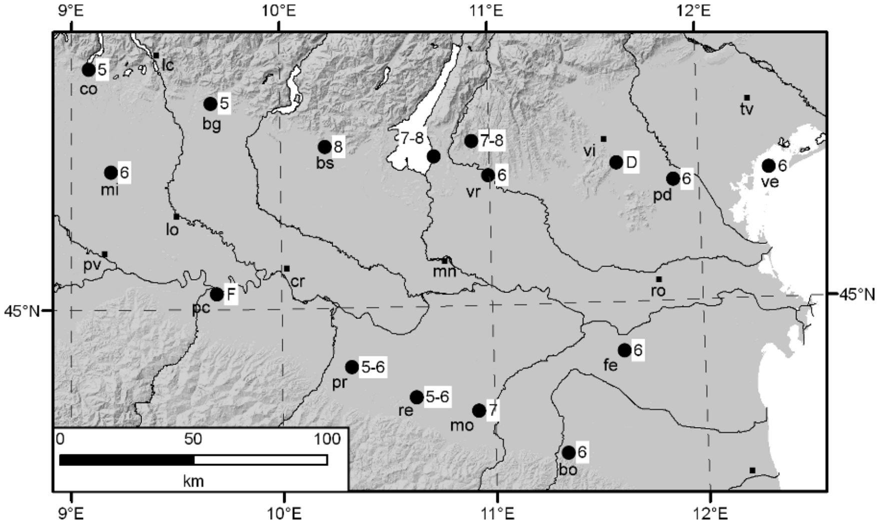

Fig. 13 Intensity distribution of the 1222 earthquake (from Guidoboni and Comastri, 2005)

3.5 The Event of 1117

This earthquake is by far the largest one occurred in the investigated area. It has been the object of various studies which, during the years, modified the interpretation.

The earthquake was studied as early as 1980s by Magri and Molin (1986), Guidoboni (1984), Guidoboni and Boschi (1989), ENEL (1986a). The reader may refer to the papers by Galadini et al. (2001a), Galli (2005), Guidoboni and Comastri (2005), Guidoboni et al. (2005), in order to have a complete picture of the literature on this complex event. All these papers interpret the event as a complex, not easily explained seismic sequence; one of the main unresolved points is that the area from which damage is reported is much larger than allowed, even by a less probable 7.5 Mw event. It must also be said that many earthquake records come from single, monumental buildings, and that the typologies of the non-monumental building stock is poorly known.

The main problem hampering the solution of the case is that most accounts do not clearly differ in time; therefore, the solutions are generally based on how to split the available intensity distribution in some more or less reasonable intensity distribution, to be consistent with one or more events. The most recent work by Guidoboni et al. (2005) splits the event into three earthquakes, to have occurred respectively in Southern Germany, Northern Italy and North-Western Tuscany, with damage at Pisa. This interpretation is mainly based on the fact the sources report two shocks, with a difference in time of about 12 h for 8 localities: Disibodenberg, Freising, Augsburg, Zwiefalten, Melk, Salzburg, Saint Blaisien, Peterhausen, located in today Switzerland, Austria and Germany (Fig. 14). The remaining localities are then grouped according to the two timings and the intensity datapoints split into three groups: one in Germany, one in the traditional area around Verona and one near Pisa. Moreover, in the quoted paper and the companion volume by Guidoboni and Comastri (2005) – both items refer to one another – some 40 intensity datapoints are missing with respect to the recent interpretation by Boschi et al. (2000). As a matter of fact, the attribution of the records to the two origin times ends up in intensity distributions which show strange pattern, and give rise to parameters of the two events which have to considered with caution.

Although the interpretation of the primary sources remains controversial, disregarding here the presumed events near Pisa and in Southern Germany, all interpretations admit that this earthquake was responsible for significant damage in a large sector of Northern Italy, reaching a very high level of damage in the area of Verona. In addition:

i) the sources report significant geological effects (large landslides) due to the shaking in the Adige valley between Verona and Trento (Galadini et al., 2001; Guidoboni et al., 2005);
ii) archaeoseismological information permitted to infer high damage also at Trento (Galadini et al., 2001) and Cremona (Galli, 2005), to which the intensity 8 MCS has been attributed on historical basis by Guidoboni et al. (2005);
iii) high damage is reported also for Padova (I 8 MCS by Guidoboni et al. 2005).

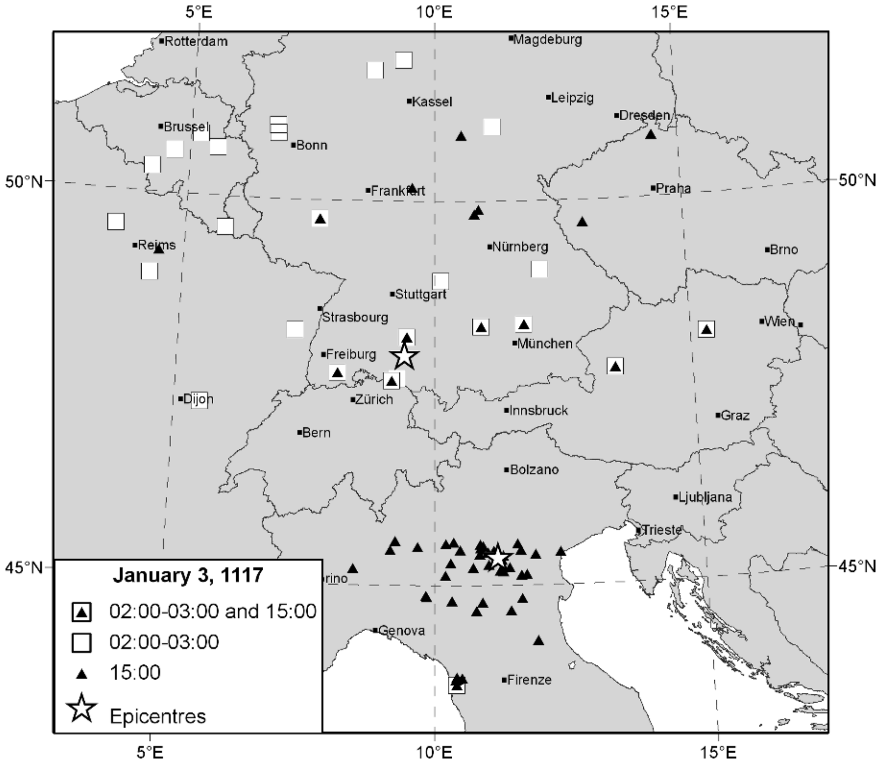

Fig. 14 Distribution of the localities that felt one or two earthquakes in 1117, according to Guidoboni et al. (2005)

This pattern confirms a very large area of damage in Northern Italy, being Cremona and Padova separated by more than 120 km and Cremona and Trento by more than 100 km. This large damaged area makes still difficult the determination of the epicentral location and magnitude.

3.6 Adige Valley

3.6.1 1046, "Valle Tridentina"

This event, the effects of which are referred to a not clearly identified "Valle Tridentina", is known to the seismologic literature since the study by Leydecker and Brüning (1989). It has been subsequently reappraised by Alexandre (1990), considered as doubtful by Albini et al. (1994b), not reported by Boschi et al. (1995; 1997; 2000). For these reason it was not included in the catalogues NT4.1 (Camassi and Stucchi, 1997), CPTI99 and CPTI04 (CPTI Working Group, 1999; 2004). Recently, the earthquake has been reappraised by Guidoboni and Comastri (2005). Damage area is supposed to cover the area between Salorno and Ceraino, an Adige valley

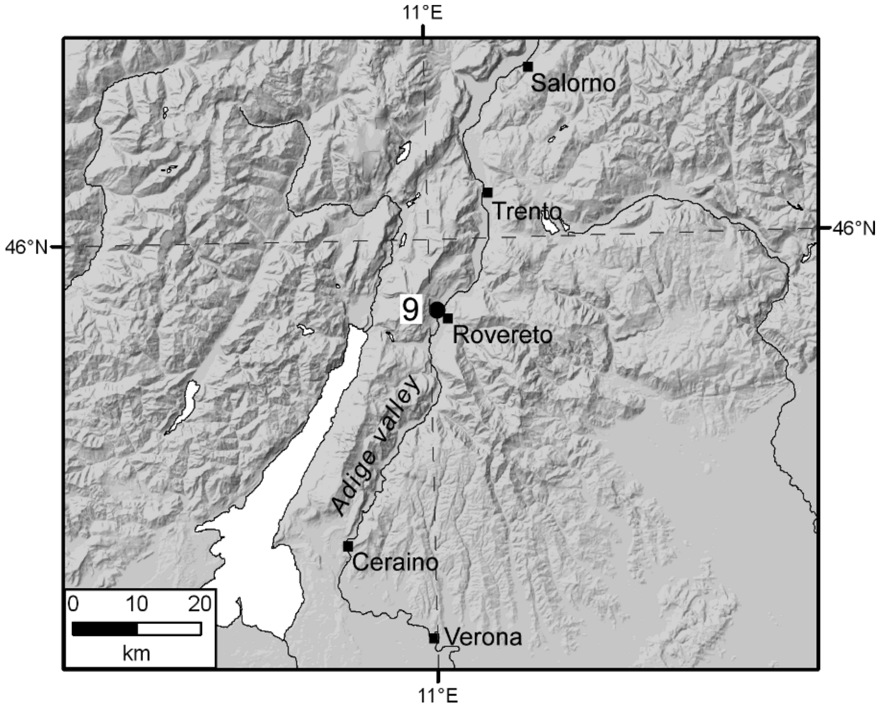

Fig. 15 Location of the main effects of the 1046 earthquake according to Guidoboni and Comastri (2005)

segment about 80 km long (Fig. 15); the main effects (I 9 MCS) are referred to a point in the middle of the Adige valley, corresponding to the area of Rovereto.

3.6.2 Adige Valley: Archaeoseismological Evidence

Archaeoseismological data suggest that a destructive event occurred during the Antiquity in the Adige Valley. In 1997, archaeological excavations in the village of Egna-Neumarkt uncovered remains (edifice along the road Claudia Augusta Padana) showing evidence of a destructive event. The destruction occurred in the half of the 3rd century AD (Galadini and Galli, 1999; Di Stefano, 2002). Moreover, an evident displacement of the foundations was observed (about 0.6 m of vertical motion; about 0.3 m of dextral strike-slip motion). The walls were displaced by at least four shear planes striking NNE-SSW, i.e. parallel to the main faults having the "Giudicarie trend" in this sector of the Adige Valley. Moreover, the paleoseismological investigation, made by means of excavations down to 7 m depth, indicated that another displacement event had struck the site after 2581–2197 BC (calibrated radiocarbon age, 1 sigma). In the whole, the gathered data suggested a seismic origin for the destruction. Indeed, the stratigraphy derived from four boreholes and the geomorphological investigation permitted to exclude alternative causes such as differential settlement, instability of the Adige river flank or liquefaction. The main limit of the hypothesis of surface faulting affecting the ancient building was represented by the impossibility to detect the prolongation of the shear planes towards both north and south.

Indeed, the archaeological site was completely surrounded by the modern buildings within the Egna village. The analysis of the aerial photographs preceding the modern development of the village did not permit to identify geomorphological traces of recent displacements (e.g. fault scarps). This was probably due to the significant alluvial deposition subsequent to the displacement of Roman age, responsible for sealing the displacement (Galadini and Galli, 1999). Considering the difficulty of the tectonic analysis, the archaeoseismological case of Egna was approached from a “territorial” point of view, i.e. through the review of the archaeological information derived from the literature on other archaeological excavations of the Trentino-Südtirol region. The information gathered in Galadini and Galli (1999) defined a period of significant changes to edifices and villages (destruction, abandonment, restoration or rebuilding) during the 3rd century. For example, the excavation at the Teatro Sociale in Trento uncovered numerous structures dated at the 3rd century AD, sealing older remains (Zamboni, 1989, pers. comm.). This period of important change is traditionally attributed to the instability related to the Alaman invasions of northern Italy, since 258 AD (Christlein, 1979; Buchi, 2000; Ciurletti, 2002). Data published more recently and related to the northernmost sectors of the investigated area (Tesido, close to Monguelfo-Welsberg and San Candido-Innichen; Di Stefano and Pezzo, 2002; Dal Ri et al., 2002, respectively) define changes to the pre-existing edifices in the second half of the 3rd century AD. Therefore, this important period of interventions to the Roman buildings seems to be related to a very large territory. This area may be larger than that potentially affected by coseismic damage due to an event approximately located in the Egna area, also in case of a large magnitude event. In conclusion, on one side the archaeological information suggests the occurrence of a destructive seismic event at the border between the Trento and Bolzano provinces, in the half of the 3rd century AD, on the other side the full comprehension of this event is hindered by the local instabilities related to invasions.

3.6.3 Bolzano: Archaeoseismological Evidence

Archaeological excavations in the cloister of the Capuchin Convent in Bolzano uncovered remains of a tower bearing traces of collapse and damage. This edifice was defined as the “little tower” of the Wendelstein Castle (property of the Earls of Tyrol) by Bombonato et al. (2000). The building of this tower, based on the comparison with the style of other towers of the zone, has been attributed to the first half of the 13th century. Two angular walls, pertaining to an edifice having a quadrangular geometry in plan view, each side being 5.5 m long, were uncovered. The walls were made by stones with irregular forms and size, linked by mortar. The walls were about 0.9 m thick. The collapsed materials (including remains of the upper floors) filled the building. A thick collapse layer buried the entire area of the archaeological site and some large stones were also located some metres far from the building. The collapse layer contained remains of the windows of the "little tower" (Bombonato et al., 2000). Finally the two walls still *in situ* showed a corner expulsion (Galadini and Stucchi, 2007). The archaeological information permitted to relate the destructive event to the 13th–14th century. The collected data (particularly the corner expulsion and the "launch" of stones far from the original edifice) can be considered consistent with the effects of a strong seismic shaking. Bombonato et al. (2000) attributed the destruction to the 1348 earthquake, that caused severe damage in Friuli, Kärnten and Western Slovenia (Hammerl, 1994) whose epicentre is presently located in Friuli (CPTI Working Group, 2004).

The effects in Bolzano have been significant. The *Bozner Chronik* (14th cent.) report the destruction of ten houses and a tower. In such case the consistency of the historical and archaeoseismological information is evident. However, the 1348 high damage in Bolzano, located about 150 km east of the epicentral area, is surprising. This may result from possible site effects in the area: indeed, a small damage (I 6–7 MCS), not comparable with the destruction depicted by historical and archaeoseismological data for the 1348 event), affected Bolzano also in 1976 as an effect of a Mw 6.5 earthquake originated in the same region of the 1348 event. Alternatively, the 1348 damage in Bolzano may result from a local still undefined event. In such a case this event might corroborate the hypothesis of a significant, seismogenic potential of the upper Adige valley region, already suggested by the Egna archaeoseismological case, consistent with the NNE-SSW alignment of the seismicity from the southern sector of Lake Garda to the Adige Valley.

3.7 Giudicarie Valley

Similarily to the Insubrian Line, this area represented a concern for many geologists of the 60's and 70's who hoped, in some way, that seismicity located in the area might prove that the lineament was active. Actually, an instrumental recording campaign promoted by the former Istituto per la Geofisica della Litosfera of CNR, Milano, in 1971 gave practically no results and very little seismicity appeared from the Postpischl (1985a) catalogue. Then, during the phase of the hunt for the fake quakes, a couple of moderate events, 1683 Mw 5.0 and 1851, Mw 4.96, located in the area or just near by, were unearthed by Albini et al. (1994b), following hints by Tovazzi (1803) and Schorn (1902).

4 Conclusion

Most of the events up to 1700 in the investigated area are still known through sparse traces; their epicentral location and magnitude show therefore large uncertainties. The earthquakes of 1117 and 1222 represent an exception with respect to data availability; however, the aspects discussed above do not help to constrain the parameters of these events, too. Unfortunately, there is little hope to improve the available traces with new historical findings.

The completeness assessment, performed by the MPS Working Gruoup (2004) in the frame of the evaluation of seismic hazard of Italy, concluded that in the study area, with the exclusion of Valtellina and Alto Adige areas, Mw ≥ 5.5 could be considered as complete after 1700 according to the statistical procedure (Albarello et al., 2001) and after 1500 according to the historical procedure (Stucchi et al., 2004). Actually, as a matter of fact the analysis of the seismic histories of the main localities (Fig. 16) do not show large, overall chronological gaps. It seems then

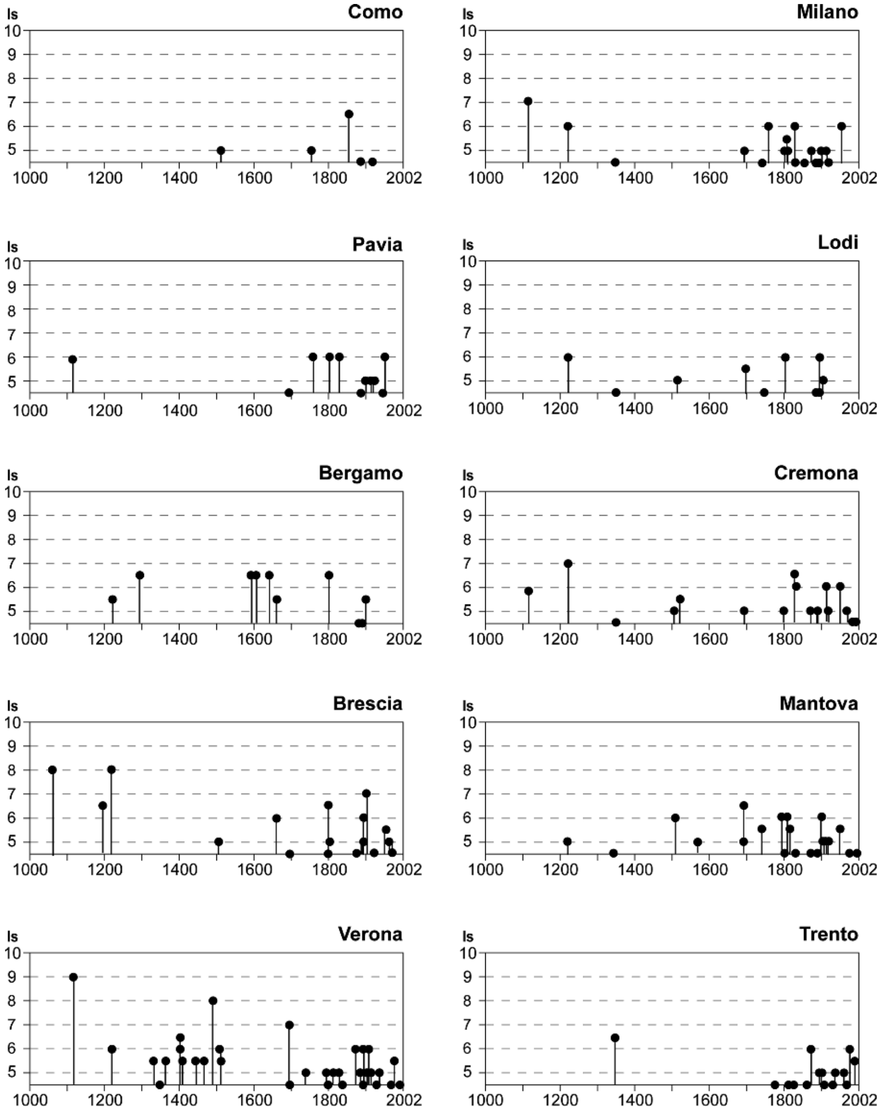

Fig. 16 Seismic histories of the main localities in the study area (from DBMI04, Stucchi et al., 2007)

reasonable to infer that no large earthquakes (Mw $\geq$ 5.5), in addition to those of 1117, 1222 and, possibly, 1396, should be missing in the study area after the 1117 event.

In conclusion, the historical data do not significantly help to constrain the assessment of the seismogenic potential of the area, which remains one of the most unknown, although potentially dangerous, seismic areas of the Italian region.

Acknowledgments This paper summarises the investigation performed by a number of investigators, who allowed improving the understanding of the seismicity of the area. We are indebted with Jean Vogt for sending material form countless European libraries and for encouraging our work. We are also grateful to P. Galli, who participated to the archaeoseismological surveys in the Bolzano and Trento provinces, and to the reviewers who helped improving the quality of the original ms.

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Past and Future of Historical Seismicity Studies in France

J. Fréchet

Abstract The Lisbon earthquake of 1755 heralded a host of historical seismicity catalogues. The XIX century gave rise to two famous French catalogue producers, A. Perrey and F. de Montessus de Ballore both compiling earthquakes worldwide. But the systematic investigation of French macroseismicity would not begin before 1908 and the creation of the seismological service of the *Bureau Central Météorologique* (BCM) in Paris. The seismological service was transferred to Strasbourg in 1921, with the creation of the *Bureau Central Sismologique Français* (BCSF). The BSCF performed macroseismic enquiries for every contemporaneous felt earthquake. Edmond Rothé and his son Jean Pierre Rothé succeeded one another as directors of the BCSF until 1975; their seismic catalogue mainly relied on the works of Perrey and Montessus. In 1975, the *Bureau de Recherches Géologiques et Minières* (BRGM) engaged in a major revision of French historical seismicity with the *Projet Sismotectonique*, directed by Jean Vogt until 1984.

We present recent individual initiatives related to historical seismicity, including those of Jean Vogt, along with some results of our own research on the seismicity of the French Alps. We discuss these results and the evidence about improving the knowledge of French seismicity to which they attest. We then outline the new potential offered through digital libraries and archives. Our conclusions will underline the necessity of developing an academic programme devoted to French historical seismicity and seismic hazard.

Keywords Historical seismicity · earthquakes catalogues · France · Alps

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1 Introduction

The study of historical seismicity in France was developed step by step over the last 250 years. It began just after the 1755 Lisbon earthquake, when several worldwide catalogues were published, in Germany first and in France soon after. Later in the XIX century, five major projects were developed, each initiative building on those preceding. The earliest began in 1841 with the first of the well known regional and annual catalogues of Alexis Perrey until 1872, and it was continued by the global catalogue of Fernand de Montessus de Ballore completed by 1907. Between 1908 and 1920, the *Bureau Central de Météorologie* in Paris (BCM) established a systematic investigation of French contemporary earthquakes. The seismological service was transferred in 1921 to the *Institut de Physique du Globe de Strasbourg* (IPGS), where Edmond Rothé and his son Jean-Pierre Rothé continued to conduct macroseismic enquiries of contemporary events. They compiled the so-called "Rothé catalogue" of French historical seismicity, based largely on Perrey's and Montessus de Ballore's work. The most recent period, from 1975 on, began with the *Projet de la Carte Sismotectonique de la France* in relation to the French nuclear power plants programme. Eventually, this project gave birth to an associated database, Sirene, partly published now on the Internet under the name SisFrance (SisFrance 2008).

Considering the huge amount of data collected in the framework of the *Projet Sismotectonique*, one might doubt the potential for further fruitful research in French historical seismicity. However, since his retirement in 1984, Jean Vogt pursued intensive archive research in France and elsewhere culminating in a considerable number of discoveries: new earthquakes, identification of "false" earthquakes, revision of macroseismic analysis of some major earthquakes, etc. His new results were published in more than 200 notes and articles.

In this paper, we will recall the history of catalogues describing historical earthquakes in France. We will introduce some new results in the French Alps and describe the new techniques that could be valuable in investigating the historical seismicity.

2 A Brief History of Catalogues

Along history, countless earthquakes catalogues were already compiled and published worldwide. Some were nothing else than compilations of previous catalogues, while other, more valuable, searched books and periodicals for new information, or even found original sources in manuscripts or local newspapers. Catalogues may be classified on the one hand as global and regional, on the other as annual usually compiled in quasi real time from primary sources. Analyses and discussions of some major catalogues for Western Europe may be consulted (see Alexandre 1990; Vogt 1993; Vogt 2003). For France, over a hundred local and regional catalogues are listed in (Lambert and Levret-Albaret 1996), and a comparable number for Germany in (Grünthal 2004). For Italy, a history of catalogues has been established by

(Camassi 2004), in the case of Switzerland more than sixty catalogues are listed in the Macroseismic Earthquake Catalogue of Switzerland (MECOS 1999).

2.1 Alexis Perrey and Predecessors

Well before Alexis Perrey began his masterful catalogues in the 1840s, many earthquakes catalogues were already available. It is generally conceded that scientific seismology begins with the 1755 Lisbon earthquake (e.g. Quenet 2005). So the first modern catalogue is considered to have been compiled in 1756 by the German writer Johan Friederich Seyfart (1727–1786) (Seyfart 1756). His catalogue described earthquakes worldwide, from an uncertain date[1] in ancient times up to 1756. It included a useful geographical index and mentions of a few sources. Shortly later, Count Philibert Guéneau de Montbeillard (1720–1785), a French naturalist and a friend of Buffon, published another catalogue of global earthquakes, and included volcanic eruptions along with other meteorological phenomena (Guéneau 1761). His catalogue included descriptions of effects for the earthquakes listed, but without citing the sources of data. This compilation served as a starting point for many of his followers. Soon after, Father Louis Cotte (1740–1815), considered as the founder of meteorology, prepared annual catalogues for the years 1764–1809 (Cotte 1776, 1807, 1809, 1810). These catalogues were simple lists of earthquakes and other meteorological phenomena, providing almost no other information than the dates of events. His work was continued by François Arago (1786–1853), the French astronomer, who published annual catalogues between 1818 and 1830 (Arago 1818–1830). Each catalogue began with a supplement for the previous year.

At about the same time the German geologist Karl Ernst Adolf von Hoff (1771–1837) was working in Gotha on his memoir on “Natural changes of the earth surface” (Hoff 1822, 1824, 1834). For this work, he compiled a global earthquakes and volcanic eruptions catalogue spanning from 3460 BC to 1832 AD, published posthumously (Hoff 1840, 1841). He also compiled annual catalogues, for the years 1821–1830 (Hoff 1826–1834), but these annual catalogues were reprinted in (Hoff 1841) with some additions. Von Hoff introduced a major improvement to seismic catalogues not only including accurate descriptions of earthquake effects, but also providing detailed references to sources. Another German geologist, Christian Keferstein (1784–1866), also compiled a global catalogue, for the years 17 AD to 1825 AD (Keferstein 1827), but generally with far less details than von Hoff’s one and without references.

Alexis Perrey (1807–1882) had pursued his career as professor of mathematics and astronomy in Dijon since 1837 (Rothé and Godron 1924). It is not known how he became interested in earthquakes. His first mention of his work on historical

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[1] “*Das erste Erdbeben,* (...)*, ist ohne Zweifel dasjenige, das Gott am dritten Schöpfungs-Tage durch die Gewalt des Feuers in dem Erd-Bal erregete*” [The first earthquake (...) is undoubtedly the one triggered by God on the third day of the creation, through the power of the fire inside the globe]

earthquakes dates back to 21 June 1841, when he sent a preliminary compilation of global earthquakes to the French *Académie des Sciences* (Perrey 1841). If we risk hypothesizing any specific event that could have drawn Perrey's attention to earthquakes, two dates are the most probable candidates: the Maurienne (French Alps) seismic swarm that began on 19 December 1838 and lasted for over five years, or the catastrophic event on 11 January 1839 in the Martinique (Lesser Antilles). Between 1843 and 1860, Perrey published twenty-six catalogues of historical earthquakes for the major seismic regions of the world (see e.g. (Rothé and Godron 1924) for a complete bibliographic list). His catalogues introduced a new standard of precision by including original sources, accurate references, detailed descriptions of damage, details on the timing of main shocks and aftershocks, etc. Nevertheless, present-day historical seismology cannot just satisfy itself with the catalogues, and necessarily has to resort to the original sources.

Between 1844 and 1874, Perrey also published twenty-nine invaluable annual catalogues spanning from 1843 to 1871. His last catalogue, for the year 1872, was submitted to the *Académie royale des sciences* of Belgium, but unfortunately not accepted (Anonymous 1875) and the manuscript remains to be found. As others, Perrey added to each annual catalogue supplements for the previous years, as well as some *errata*. This makes it a little tricky if one wishes to find all references to a given earthquake. Most Perrey catalogues were published by the Science Academies of Brussels and Dijon; a list, almost complete, can be found in (Rothé and Godron 1924) or (Lambert and Levret-Albaret 1996).

For his compilations, Perrey consulted books and periodicals from libraries in Dijon. He went through several collections of newspapers beginning with the *Gazette de France*. He also collected over the years a huge personal library of books, periodicals, and documents, and corresponded with contacts worldwide. Perrey sold his library and archives around 1870 to the Alpine Club of Naples (Rothé and Godron 1924). De Rossi already used it in the 1880s. The collection was donated in the 1900s to the library of the *Società Napoletana di Storia Patria* in Naples where it is still located today. This library's collection is certainly worth the visit, and particularly for the related correspondence covering the years 1842–1868 (Fréchet 2001). The contents of Perrey's library was published under the title, *Bibliographie séismique*, in three volumes containing more than 4,000 references (Perrey 1855–1865); the final volume available in manuscript also belongs to this Naples collection. Some manuscripts of Perrey are also archived in the manuscript department of the *Bibliothèque Nationale et Universitaire* in Strasbourg, probably donated by his grandson Henri Godron (Rothé and Godron 1924). Perrey's catalogues remained the principal source of knowledge about historical earthquakes in France and elsewhere for at least a century.

2.2 Montessus de Ballore

Von Hoff and Perrey had many followers who compiled regional, global, or annual catalogues, e.g. Robert Mallet, Carl Fuchs, John Milne, to cite but a few. But the most famous was certainly Count Fernand de Montessus de Ballore (1851–1923) (Hammond 1912; Renier 1923). In the years 1880–1907, Montessus de Ballore compiled a new world catalogue, based on the catalogues of his predecessors and on his own findings, mainly from the current press. His catalogue was not published, but it was the basis for his milestone books on seismology, and for his many articles.

Shortly before Montessus left France for Santiago to become director of the new Chilean Seismological Service in 1907, he donated the file containing his seismic catalogue to the *Société Géographique* in Paris. The file was composed of folders occupying a length of nearly 26 m in the library shelves. The library of the *Société Géographique*, after a first move, ended up in 1942 being concealed in the vaults of the *Bibliothèque Nationale* in Paris, beyond reach of the German occupant (Fierro 1983). It remained the property of the *Société Géographique* and is still located there. The catalogue languished forgotten until Jean-Pierre Rothé, the director of the *Institut de Physique du Globe* in Strasbourg, tried to locate it on the occasion of the 50th anniversary of Montessus' death in Chile, in 1973. Unfortunately the very librarian who had taken part in the 1942 move, by the 1970s graduated to head librarian, was not able to find the file, and after a 4-year long correspondence with Rothé the Geographical Society maintained that the file was definitely not in its library. Failure to inspect the basement shelves with sufficient thoroughness prolonged the delay until September 1980, when the file was found by the new librarian. Jean Vogt was the first to examine the catalogue; he asserted that the catalogue was mostly a compilation of previous catalogues, particularly those of Perrey, except for the recent years from 1885 to 1905 approximately, when Montessus brought his own original information. The file is stored as 79 "parcels" – *colis* – (Montessus 1905); an inventory has been made by (Fierro 1984). The complete file was microfilmed recently. The catalogue for the period December 1902–February 1907 was published in the periodical *Ciel et Terre* (Montessus de Ballore 1904–1907).

Though Montessus' catalogues do not provide us with a wealth of new sources, his files represent the last global catalogue of historical earthquakes, including more than 170,000 events. His objective was to produce seismic maps of the world. In 1892, he compiled the first seismic map of France which, we believe, did not differ dramatically from modern maps (Montessus de Ballore 1892). The remarkable achievement of Montessus lies in the advanced geological conclusions he was able to draw from these maps and from his profound knowledge of earthquakes, in the first place being the link between earthquakes and Mesozoic geosynclines. He published his results in numerous articles and several well-known books notably that of 1906 (Montessus 1906).

2.3 The Bureau Central Météorologique (BCM) and the Bureau Central Sismologique Français (BCSF)

In 1908, the *Service Sismologique* of the *Bureau Central de Météorologie* (BCM) was created under the direction of Alfred Angot (1848–1924). It initiated a systematic investigation of contemporary French earthquakes by means of seismic stations, macroseismic enquiries and questionnaires, and collection of all available documents, whether letters or newspaper articles, from 1909 to 1920 (Vogt 2003; Fréchet 2007b). After the damaging earthquake in Provence 1909, more than 4200 questionnaires of the 4500 sent were received and processed (Angot 1910). We do not know whether these questionnaires survived. Some later questionnaires are now in the IPGS archives, particularly for the 1911 Swabian Jura earthquake of which we discovered recently with Jean Vogt the complete survey folder.

In 1921, the *Service Sismologique* was transferred to the newly created *Institut de Physique du Globe de Strasbourg* (IPGS), and was given the name *Bureau Central Sismologique Français* (BCSF). Under the direction of Edmond Rothé (from 1921 to 1942) and of his son Jean-Pierre Rothé (from 1943 to 1977), the so-called Rothé catalogue of French historical seismicity was developed, based largely on Perrey's and Montessus de Ballore's work, for older earthquakes, and on the continuation of macroseismic surveys for contemporary events.

Edmond Rothé also collected many archive documents with the collaboration of French libraries and archive depositories (principally *Archives départementales*). He sought the collaboration of local learned figures and societies, focussing his requests on the period 1872–1919, i.e. the post-Perrey and pre-BCSF period (Rothé 1927). Guillaume Bigourdan had made a similar request 20 years earlier (Bigourdan 1908), but we have not yet found trace of his catalogue. On the whole between 1921 and 1975, little progress was made in the study of historical earthquakes. Edmond Rothé and Jean-Pierre Rothé relied mainly on previous catalogues. Edmond Rothé published in 1926 a small catalogue that is actually the first catalogue of French historical earthquakes (Rothé 1926). Jean-Pierre Rothé published three regional catalogues, for the Western Alps, the Rhine Graben, and Algeria.

Contemporaneous earthquakes were studied by means of macroseismic questionnaires and instrumental studies. Edmond Rothé and his collaborators published annual catalogues of earthquakes in France and its colonies between 1919 and 1930 in the *Annuaire de l'Institut de Physique du Globe*; Jean-Pierre Rothé, Joseph Lacoste, and other collaborators continued the catalogues for the years 1931–1939 in the same *Annuaire* (which changed name to *Annales de l'Institut de Physique du Globe* in 1936). From 1940 on, until the year 1970 J.-P. Rothé published three decennial catalogues, in the same *Annales*, in collaboration with N. Dechevoy. His last catalogue, for the years 1971–1977, appeared in 1983 in the IPGS series *Observations Sismologiques*. After 1977, the macroseismic enquiries were in charge of BRGM, until 1986. Since 1987, they are again carried out by BCSF.

2.4 The Seismo-Tectonic Project (Projet Sismotectonique)

In 1975, the concern about safety of the nuclear industry gave birth to the French Seismo-Tectonic Mapping Project (*Projet de la Carte Sismotectonique de la France*) led by Jean Vogt until 1984. The *Projet Sismotectonique* was a common initiative of

BRGM,[2] CEA,[3] and EDF.[4] Very quickly Jean Vogt realized that French historical seismicity needed a profound revision through a *retour aux sources*. Within a few years, above all between 1976 and 1977, he and a small number of collaborators performed an intensive gleaning of original and new sources. Systematic scrutiny of hundreds of periodicals and newspapers, visits to countless archive depositories and libraries throughout France led to a completely renewed knowledge of French historical seismicity (Vogt 1979; Vogt 2003; Fréchet and Albini 2008). This work soon gave birth to a computer database (Sirene), partly available since 2002 on the Internet under the name of SisFrance (SisFrance 2008). After Vogt's retirement in 1984, emphasis was focussed on the improvement of the computer database and its parameterization, to the detriment of seeking new sources (Vogt 2003).

3 Improving the Knowledge of French Historical Seismicity

3.1 Recent Developments

For twenty years after his retirement in 1984, Jean Vogt continued his permanent gleaning and deciphering of new sources, above all in the Upper Rhine region (Fréchet and Albini 2008). His method was based on several techniques, including systematic perusal of periodicals and newspapers, search of administrative-, notarial-, and family-archives, or investigation of neighbouring countries' libraries and archives. He accumulated countless notes, copies, citations, and references in his personal seismic files stored in more than 50 archive boxes containing data on earthquakes in France and surrounding regions. He published his findings in numerous notes, through international journals, or local learned society bulletins, e.g. no less than 62 notes on the Upper Rhine region from 1985 to 2005 (Fréchet 2007a). His achievement shows that a large amount of information on French historical earthquakes lies concealed in libraries and archival depositories. Most of his findings remain untapped, stored in the *Archives Départementales* and EOST depots in Strasbourg (Fréchet and Albini 2008).

Another recent initiative was the imposing work of Grégory Quenet in collaboration with the BRGM and CEA *Projet*. In his book on earthquakes in the XVII and XVIII centuries, Quenet presents an extensive study of the 1708 Manosque (Provence, France) earthquake (Quenet 2005). He was able to gather an impressive number of new sources. His genealogical analysis of available sources (Fig. 4 in his book) is a convincing demonstration of what exhaustiveness of sources means, making the Manosque earthquake probably the best studied in France. Several other scattered works were published, that are related to French historical earthquakes, but they usually missed open access to the Sirene database (e.g. Camelbeeck et al. 2000; Lacassin et al. 2001; Meghraoui et al. 2001).

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[2] *Bureau de Recherches Géologiques et Minières*

[3] *Commissariat à l'Energie Atomique*

[4] *Electricité de France*

3.2 Historical Seismicity of the French Alps

In the 1990s, noticing that the Sirene database was not publicly available, we started a study on the historical seismicity of the French Alps, particularly in the Grenoble region. Special emphasis was placed on the study of small earthquakes, which had not always been given sufficient attention in previous studies, despite Jean Vogt's efforts in this regard. This led to the discovery of a large number of new primary and secondary sources. The analysis of small earthquakes proved very useful in order to assess epicentres with high precision. Evidence of an alignment of epicentres could be obtained, that had not previously been visible (Thouvenot et al. 2003).

The list of earthquake dates found in the SisFrance database is usually rather exhaustive, and we could scan local newspaper or literature to find new sources improving the knowledge of events in this list. Nevertheless, both missing events and false events still persist, and it is necessary to continue checking all known catalogues as described above to complete it. As an example, we investigated a hitherto unknown earthquake that occurred near Grenoble on 18 February 1909 at 10:13 a.m. Not less than eight descriptions were found in four regional newspapers (Appendix 1). This earthquake was felt in the four villages, Vizille, Notre-Dame-de-Commiers, Saint-Georges-de-Commiers, and La-Motte-d'Aveillans; its maximum intensity can be evaluated as IV MSK.

The region of Grenoble is located in the *département* of Isère (France is divided into 96 *départements*); we located no less than 36 local newspapers published in the Isère between 1697 and 1945, and six historical scientific periodicals published in Grenoble that contained data on earthquakes. Only a small percentage of these had been exploited previously. Further north, in Savoy (France), historical sources are located both in France and in Italy. Indeed Savoy has had a complex history, growing from County to Duchy, and from Duchy to Kingdom, with its capital moving in the mid XV century from Chambéry (Savoy, France) to Torino (Piedmont, Italy). The region was incorporated into France in 1860 and was divided from then on into two *départements* with capitals in Chambéry and Annecy. In the Haute-Savoie *département*, 23 historical newspapers are available. For the Chamonix 1905 earthquake (Intensity VIII MSK), we found 14 new newspaper articles in the epicentral region (Appendix 2). Collecting a list of newspapers titles, with publishing dates, locations, and call numbers, is not an easy task. Often, library or archive depositories do not maintain such lists, although this is gradually improving with the progress of digital cataloguing.

4 Discussion

Often, seismic catalogues concentrate only on the largest damaging earthquakes in a region, neglecting valuable information on foreshocks and aftershocks and on smaller events. However, based on studies of present-day earthquakes with temporary seismological networks, it is obvious that macroseismic epicentres can be assessed with higher precision if one concentrates on the macroseismic study of aftershocks rather than that of the main shock. The inhabitants that live very close to the hypocenter often feel aftershocks of very low magnitudes, smaller than 1 (Thouvenot and Bouchon 2008). Researching such local testimonies for historical earthquakes may lead to greater accuracy on the position of the main shock. Small earthquakes are also very useful to define seismic zones, or even to identify active faults. Many catalogues do not assign an epicentre to small events felt in only one or two places. However, in most cases, the description is sufficiently accurate to ascertain that it corresponds to a local earthquake; it is then usually possible to assign the epicentre to the place where it was felt without incurring the error of assigning an epicentre in the middle of the poorly defined isoseismals of a larger event.

It is thus necessary to try and be as exhaustive as possible when investigating historical earthquakes. For each event, it is necessary to make exhaustive use of all existing catalogues in order to identify the least trace of earthquake, aftershock, and background seismicity. Once an event date and location is known approximately, it is usually straightforward to search for original descriptions in newspapers, periodicals, etc., for the last three centuries at least. For events in earlier periods, the collaboration of historians is advisable (Alexandre 1990), and finding new sources may be very infrequent.

The feasibility of exhaustive analysis of a given earthquake has been much improved since the digital revolution and the Internet. Old books and periodicals are scanned and made available online by libraries worldwide in continuously growing number. Archive depositories prepare digital catalogues of their collections. Gallica, the French *Bibliothèque Nationale* digital library (http://gallica.bnf.fr), provides us with a wealth of scanned books and periodicals, annually increased by 100,000 new documents. To cite just a few, the *Journal des Savants*, the *Histoire de l'Académie Royale des Sciences*, or the *Philosophical Transactions of the Royal Society of London* are available. It gives online access to the catalogues of Arago (in *Annales de Chimie et de Physique*), von Hoff (in *Annalen der Physik und Chemie*), and Perrey (in *Annales de la Société d'Emulation du Département des Vosges*). Regional learned society periodicals, and newspapers (mainly from the XIX century), are being scanned. The European Library (http://www.theeuropeanlibrary.org), presently under development, will give access to digital (text) documents from a large number of European libraries.

Scientific disciplines rely on specialized documents that are not often available through general digital libraries. This implies the necessity of specialized digitization programmes, such as Numdam (http://www.numdam.org) for mathematics, or ADS (http://cdsads.u-strasbg.fr) for astronomy. Geosciences unfortunately do not yet benefit from such a digital library. Scanned or digital documents related to historical seismicity do exist, but they are dispersed among many institutions. In the course of our research on seismological history we were led to scan a number of useful documents, including catalogues, creating access for some of them on an Internet page, GeoArchive (http://eost.u-strasbg.fr/jv/geoarchive). A number of Perrey's regional catalogues are available on GeoArchive, as are all his annual catalogues. It has already been observed that annual catalogues include supplements and errata that make their use a little tedious. For this reason, we have created modified catalogues containing the original annual catalogues appended with all published supplements and errata, making it easier to access all mentions of a given earthquake.

5 Conclusion

Since 1975, unlike neighbouring countries, French Universities and public research organisms like the *Centre National de la Recherche Scientifique* (CNRS) have not developed any major project related to historical seismicity and seismic hazard. Although the BCSF performs quality macroseismic enquiries of contemporary events with magnitude larger than 3.5, that it publishes in its *Observations Sismologiques* volumes, it does not investigate historical earthquakes. The SisFrance database remains the unique French historical seismicity database. SisFrance developed within a non-academic environment: from its source in 1975 until 2002, it was not open to academic research. It is owned today by BRGM, IRSN[5] (a former Institute of the CEA, independent since 2002), and EDF. Since 2002, a subset of the database is available on the Internet (SisFrance 2008), but with strong copyright constraints. This policy seems questionable, since the database includes the catalogue of Jean-Pierre Rothé, a direct product of Rothé's work as a University Professor in Strasbourg. Nevertheless, SisFrance provides us today with an invaluable catalogue and a vast reference list of French historical earthquakes.

Other isolated research initiatives in French historical seismicity were performed recently by individuals, private associations (AFPS, APS, etc.), or occasionally by university research groups. It is clear that the French seismicity would deserve a much larger effort from the academic research community, and should not be forced to rely entirely on the database of nuclear-industry-supported organizations. There is a need for a future large research programme, as was the industry-oriented Seismo-Tectonic Project of the 1970s. Such an interdisciplinary programme should address many issues from historical seismicity to seismic hazard. For this project, several sets of data are available, particularly in Strasbourg, including the BCSF macroseismic enquiries, Rothé's archives, historical seismograms and seismic bulletins. Hopefully, this project would also take advantage of the huge collection of unexploited original documents gathered in the last twenty years worldwide by Jean Vogt (Fréchet and Albini 2008).

Appendix 1

Vizille earthquake, 18 February 1909: newspapers articles.

L***a République de l'Isère***, 19/02/1909, n°2907
St-Georges-de-Commiers, 18 février. Une assez violente secousse de tremblement de terre, précédée d'un bruit sourd et rapide, s'est produite ce matin, vers dix heures

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[5] *Institut de Radioprotection et de Sûreté Nucléaire*

et demie. Elle a causé l'arrêt de plusieurs pendules. Au moment où le phénomène se produisait, des chevaux se sont arrêtés net, refusant d'avancer. Le mécanicien du train arrivant de La Mure a ressenti la secousse sur sa machine en marche. Il n'y a pas eu de dégâts, mais l'émoi a été vif parmi la population.

Croix de l'Isère, 19/02/1909, n°3562, p.3
"VIZILLE
Secousse de tremblement de terre. - Jeudi matin, à 10 heures 13 minutes une forte secousse de tremblement de terre a été ressentie partiellement dans notre ville. A certains endroits elle n'a pas été ressentie, dans d'autres on a seulement entendu un sourd grondement. Ainsi à l'usine Mouly et Schulz l'effet a été très bizarre. Dans la salle du dévidage qui se trouve au rez-de-chaussée, l'ourdissage, et dans deux salles de tissage de plus de 300 mètres de longueur qui se trouvent également au rez-de-chaussée, les ouvrières ont été mises en émoi. Elles ont poussé des cris en entendant le ronflement souterrain et en se sentant bercer. Dans une autre salle sur terre également où il ne se fait pas de bruit, on ne s'en est pas aperçu. Dans l'ancienne fabrique de cinq étages superposés le fait est passé inaperçu."

Croix de l'Isère, 20/02/1909, n°3563, p.3
"LA MOTTE D'AVEILLANS
Tremblement de terre. - Une secousse sismique qui a duré environ deux secondes a été ressentie jeudi matin à La Motte-d'Aveillans et dans plusieurs localités de la région.
[...]
NOTRE-DAME-DE-COMMIERS
Tremblement de terre. - On nous écrit: Une légère secousse de tremblement de terre s'est produite ici jeudi vers les 10 heures du matin. On a entendu venant des profondeurs du sol comme un gros roulement de tonnerre sourd et prolongé qui a ébranlé les maisons."

La Dépêche Dauphinoise, 19/02/1909, n°2090
"SECOUSSES SISMIQUES
A La Motte-d'Aveillans
Une secousse de tremblement de terre, d'une durée de deux secondes, s'est fait sentir à la Motte-d'Aveillans, hier, à 10 h. 10′ 23″ du matin.
A Vizille
Vizille, 18 février.
Ce matin, à 10 h. 13′, une forte secousse de tremblement de terre, accompagée de sourds grondements, a été ressentie dans notre ville.
A l'usine Mouly et Schultz, une véritable panique, vite apaisée, d'ailleurs, s'est produite dans les salles de dévidage, d'ourdissage et de tissage, longues de plus de trois mètres, et qui se trouvent au rez-de-chaussée.
Tout s'est heureusement borné là."

Le Petit dauphinois républicain, 19/02/1909, n°10462, p.2
“La Terre tremble à St-Georges-de-Commiers
Les pendules s’arrêtent. - Vif émoi parmi la population.
St-Georges de Commiers, 18 février.
Une assez violente secousse de tremblement de terre, précédée d’un bruit sourd et rapide, s’est produite ce matin, vers dix heures et demie. Elle a causé l’arrêt de plusieurs pendules. Au moment où le phénomène se produsait, des chevaux se sont arrêtés net, refusant d’avancer. Le mécanicien du train arrivant de La Mure a ressenti la secousse sur sa machine en marche.
Il n’y a pas eu de dégâts, mais l’émoi a été vif parmi la population.”

Le Petit dauphinois républicain, 20/02/1909, n°10463, p.3
“VIZILLE. - Le tremblement de terre. -
Voici de nouveaux détails sur le tremblement de terre dont nous avons parlé hier et qui s’est produit jeudi à 10 h. 13 minutes du matin. La secousse a duré environ 2 secondes. Ses effets ont été partiels. Fortement ressentie à certains endroits, elle n’a pas été perçue à d’autres.
Dans une importante usine où fonctionnent plus de 300 métiers, les ouvrières ont entendu le grondement souterrain et se sont senties bercées. Dans une vaste de salle de dévidage, les ouvrières ont poussé des cris et ont été effrayées par le grondement et une vacillation bien prononcée; il en a été de même en ville où beaucoup de personnes ont été effrayées; dans certains magasins, des objets sont tombés des rayons.”

La République de l’Isère, 19/2/1909, n°2907
Same as *Le Petit dauphinois républicain*, 19/02/1909

La République de l’Isère, 20/2/1909, n°2908
Same as *Le Petit dauphinois républicain*, 20/02/1909

Appendix 2

Chamonix earthquake, 14 April 1905: newspapers references.

Allobroge, 06/05/1905, n°18, p.3
Les Alpes, 30/04/1905, n°35
Avenir savoyard, 06/05/1905, p.2
Cultivateur savoyard, 04/05/1905, n°18, p.3
La Dépêche Dauphinoise. 30/04/1905, n°705, p.1
La Dépêche Dauphinoise. 01/05/1905, n°706, p.1
Echo du Faucigny, 06/05/1905, n°18, pp.2–3
Indépendant savoyard, 06/05/1905, n°18, pp.2–3
Indicateur de la Savoie, 13/05/1905, n°1346, p.2
Industriel savoisien, 06/05/1905, n°2683, p.6

Le Journal de Bourgoin, 04/05/1905, n°18, p.1
Mont-Blanc républicain, 07/05/1905, n°19, p.2–3
Mont-Blanc républicain, 14/05/1905, n°20, p.3
Croix de Haute-Savoie, 07/05/1905

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Review of Historical Earthquakes in the Lower Middle Ages: Earthquakes of the XIV and XV Centuries in Catalonia (NE Spain)

C. Olivera, E. Redondo, J. Lambert, A. Riera-Melis and A. Roca

Abstract In 1985 the Geological Survey of Catalonia started a project to compile a comprehensive catalogue of seismic activity in Catalonia in order to provide a correct evaluation of seismic hazard. The project concludes with the publication, in 2006, of a book that gathers the results of the interdisciplinary work carried out on the most important historical earthquakes in Catalonia, which took place in the XIV and XV centuries.

One of the most prominent features of this monograph is that it provides a compilation of all the documentation concerning the earthquakes of the late medieval period. For the first time it has been possible to undertake a joint analysis of all the documentation of the earthquakes of the late medieval period in Catalonia and to evaluate these events using homogeneous criteria.

In this paper some methodological aspects of this research are discussed and the main results are given.

A catalogue of the earthquakes of the XIV and XV centuries has been compiled. From this catalogue it can be deduced that the earthquake with the greatest intensity, IX, occurred on 2 February 1428 (M_w about 6.5). The second largest earthquake occurred on 3 March 1373, with an epicentral intensity of VIII–IX (M_w about 6.2).

1 Introduction

A number of large earthquakes occurred in Catalonia (NE of the Iberian Peninsula) during the XIV and XV centuries, some of them producing important damages.

The existence of contemporary sources of the late medieval period in Catalonia allows us to study these earthquakes in more detail. The good state of preservation of old documents and the wealth of description of the events have enabled us to make a reliable reconstruction of these events.

Despite some sporadic attempts to compile reports of earthquakes in the XVII century, it was not until the XIX century that cataloguing of earthquakes were

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initiated. Nevertheless, the work of Fontserè and Iglesiés (1971) constitutes the first reliable compilation of seismic activity in Catalonia. Their painstaking task provides the basis for any study of historical seismicity in Catalonia.

Using the studies of Fontserè and Iglésies some authors focused their attention on specific earthquakes. This is the case of Cadiot (1979) and Banda and Correig (1984) concerning the earthquake of 2 February 1428.

In 1985 the Geological Survey of Catalonia contacted the Department of Medieval History at the University of Barcelona to compile a comprehensive catalogue of seismic activity in Catalonia in order to provide a correct evaluation of seismic hazard. The possibility of finding errors in the existing seismic catalogues prompted us to make a collection of contemporary accounts in order to obtain new data or complete our information on the effects of the earthquakes of the XIV and XV centuries. A critical and in-depth analysis of the contemporary sources of the most significant earthquakes was undertaken.

As parts of France had also been affected by the earthquakes, collaboration was also established with the *Bureau de Recherches Géologiques et Minières (BRGM)* in order to carry out a joint analysis and evaluation of all the data. In recent years a macroseismic databank – SISFRANCE (www.sisfrance.net) – has been set up in France in an attempt to better understand historical seismicity.

This interdisciplinary collaboration has yielded partial results since 1987 that have been presented in several national and international journals and books. This research formed part of the projects funded by the European Economic Community (RHISE: Review of Historical Seismicity in Europe (1989–1993) and BEECD: Basic European Earthquake Catalogue and a Database (1995–1998)), according to which collaborations are established with research workers in different countries in Europe.

The findings of these studies were regarded as incomplete given that the interpretation of each earthquake had been made without considering the other earthquakes of the period. Thus, a monograph (Olivera et al. 2006) compiling all the available information and presenting a joint evaluation of all events in XIV and XV centuries has been published. Thus, a revised catalogue for this period is now available.

Chronologically, the first important event ($I_0 =$ VIII–IX) is that of 1373, occurred in the Central Pyrenees (Fig. 1). Next, a long sequence of earthquakes with epicentral intensities up to VIII occurred in the north eastern region in 1427 following a NW – SE oriented band that corresponds to a known fault system. The 2nd of February, 1428, an earthquake of epicentral intensity IX, the largest event ever known in the region in historical times, occurred in the Eastern Pyrenees; a few documents mention that in July–August 1428 some aftershocks still took place but their vague descriptions do not allow to individualize or to quantify none of these aftershocks. Twenty years later, a smaller earthquake ($I_0 =$ VII–VIII) occurred in 1448 at a distance of about 34 km away (N-NE) from the town of Barcelona.

In this paper we present the main results obtained and discuss some methodological aspects, in particular the approaches followed to solve some of the problems encountered.

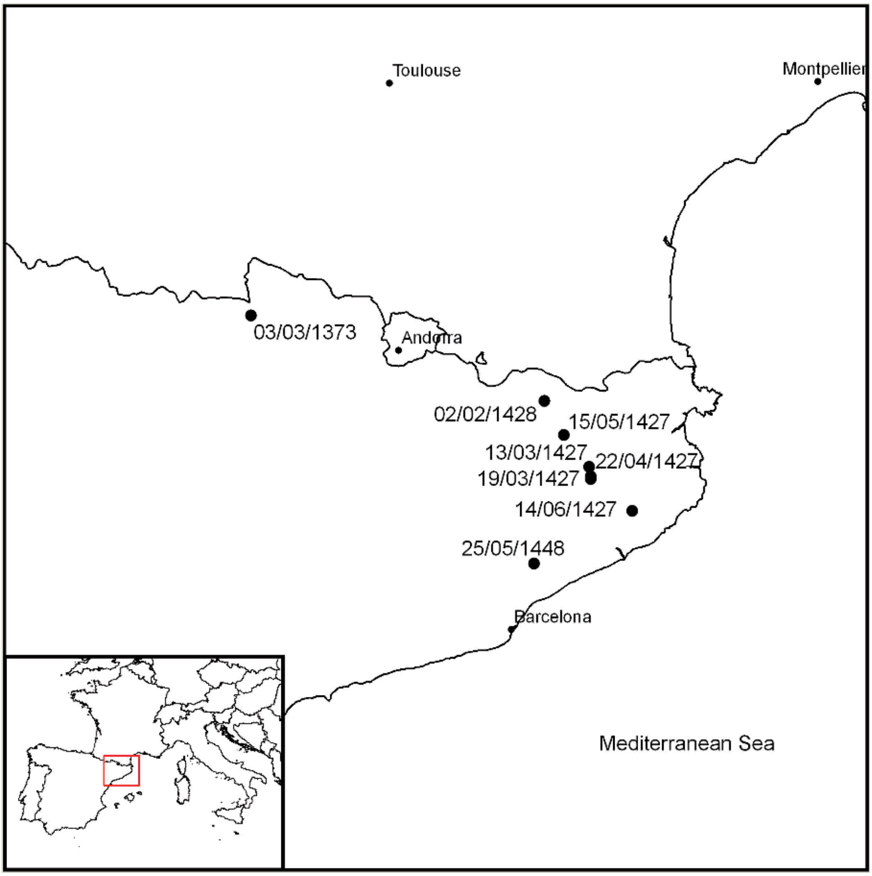

Fig. 1 Macroseismic epicentres for the earthquakes of the XIV and XV centuries, with Io > VI

2 From Historical Sources to Earthquakes Parameters

Our research into contemporary sources has yielded a large volume of documents some of which are new and contain accurate descriptions. A rigorous analysis of the historical sources and context has enabled us to interpret older documents in a different perspective with respect to earlier studies.

In order to obtain the most reliable evaluation of the earthquakes, only primary sources – those contemporary to the events – have been used. Occasionally, secondary sources – non contemporary to the events but clearly derived from former primary sources – were considered in accordance with the context and type of source.

The Geological Survey of Catalonia has established an archive collection, which includes microfilms and photocopies of the documentation consulted. The information obtained is stored in a database that allows us to make consultations combining different criteria, and facilitates the incorporation of new reports. This also constitutes an excellent point of departure for subsequent studies.

For the first time it has been possible to undertake a joint analysis of all the documentation of the earthquakes of the late medieval period in Catalonia and to evaluate these events using a homogeneous criterion. Our evaluation of the earthquakes is a marked improvement on earlier studies in two respects: number and quality of the descriptions, and homogeneity.

The cataloguing of historical earthquakes is of paramount importance especially in areas where the rate of deformation is low as is the case of Catalonia. European Macroseismic Scale 98 (EMS-98) (Grünthal 1998) has been used to assign intensity at the different sites in order that historical earthquakes can be characterized with parameters that are comparable to those of current earthquakes.

For a given earthquake a value of site intensity and an index of quality are assigned for each locality based on historian's criteria, type of documentary sources and information that contain, including those referring the conditions of the buildings before the earthquakes (Olivera et al. 2006). Moreover, the earthquake macroseismic parameters (epicentre location and epicentre intensity Io) are associated with an index of quality based on the criteria established by Lambert et al. (1996) depending on the quality, density and geographical distribution of the intensity data points. For the epicentre location: A – few km; B – around 10 km; C – between 10 and 20 km; D – between 20 and 50 km. And for the epicentral intensity: A – certain, dense distribution, with precise maximum locality intensities; B – fairly certain, less dense distribution, with precise maximum locality intensities; C – uncertain, sparse distribution, with imprecise locality intensity values; D – fairly certain, derived from an attenuation-law base calculation (Sponheuer); E – arbitrary, due to the sparseness of locality intensities.

This paper focuses on the assessment of macroseismic parameters – epicentre and epicentral intensity – to a set of medieval earthquakes through an intensive and exhaustive review and analysis of historical documentary sources. However, in order to have a preliminary estimate of seismic parameters other than location and epicentral intensity, e.g. depth and magnitude, existing empirical relation can be used.

In order to estimate focal depth, Sponheuer (1960) type intensity decay curves have been adjusted to the observed intensity data points.

In order to estimate magnitude, the following approaches have been chosen among many other available, to be applied:

(a) Empirical relations Imax – magnitude.

A classical proposal is that from Gutenberg and Richter (1954), given by $M = 2Io/3 + 1$. For earthquakes in stable continental regions, Johnston (1996b) proposed the following correspondence between Imax and moment magnitude Mw:

Imax	Mw
IX	6.4 ± 0.53
VIII	5.8 ± 0.52
VII	5.3 ± 0.52
VI	4.7 ± 0.52

(b) Empirical relations giving magnitude from Io and focal depth (h).

One of the most used relations is that from Kárník (1969): $\mathrm{Ms} = 0.55\mathrm{Io} + \log h + 0.35$ (Ms is surface wave magnitude). A more recent relation from Gutdeutsch et al. (2002) obtained from earthquakes in Central and Southern Europe gives: $\mathrm{Ms} = 0.654\mathrm{Io} + 1.868 \log h - 1.682$, with a standard deviation of ±0.284.

(c) Empirical relations to obtain magnitude estimates from the radius of or area delimited by isoseismal lines.

Levret et al. (1994), based on 140 events in France, proposed the following relation: $M = 0.44I + 1.48 \log R + 0.48$, with a standard deviation $\sigma = \pm 0.4$, where M is what the authors called macroseismic magnitude and I is the intensity of the isoseismal at the mean focal distance R. One the one hand this relation has the advantage of having included some events in or near our study area but, on the other hand it may have some problems for intensities larger than VII as it was obtained mainly with earthquakes of intensity III–VII; for larger intensities the use of this equation is an extrapolation and the macroseismic magnitudes deduced from this relation tends to be lower than instrumental magnitude.

Johnston (1996a; 1996b) obtained a relation between Mo and the area of the isoseismal I, A_I. The expression we have used for the isoseismal I = VIII is:

$\mathrm{Log\ Mo} = 24.05 + 0.440 \log A_{VIII} + 0.00586\,(A_{VIII})^{1/2}$. Once the value of Mo is obtained from the previous equation, Mw is estimated using Hanks and Kanamori (1979) relation: $\mathrm{Mw} = 2/3 \log \mathrm{Mo} - 10.7$.

3 The 1373 Earthquakes: Felt Far Away from Epicentre but Few Intensity Data Points Available

The study on the 1373 seismic series by Olivera et al. (1994) furnished new and valuable data for the evaluation of seismic hazard. Historical contemporary sources were thoroughly analyzed and then transcription errors in former catalogues were detected. As a result of that research, the epicentral zone of this series, which in many catalogues had been erroneously situated in Olot (southern slope of the Eastern Pyrenees) was corrected, and was located 200 km to the west in the earldom of Ribagorça (southern slope of the Central Pyrenees). Moreover, two earthquakes catalogued with intensities IX and VIII were considered to be false, and the largest event, that of March 3, was identified and its epicentral intensity assessed as VIII–IX (MSK).

The joint interpretation of all the large middle ages earthquakes in Catalonia such as those in 1427, 1428 and 1448 (Olivera et al. 2006) provided new information that enabled us to re-evaluate the main earthquake of 3 March 1373. Site intensity values in the earlier study have been re-evaluated and some new intensity data points have been added. Moreover, quality index for every intensity value has also been assigned. Olivera et al. (1994) did not determine epicentral location but only indicated a roughly-defined epicentral are. This new analysis allowed the epicentre to be located on the North boundary of the earldom of Ribagorça. Although the earthquake was felt up to 360 km away from the epicentral area, the number and geographical distribution of localities where the intensity is known are quite small as shown in Fig. 2.

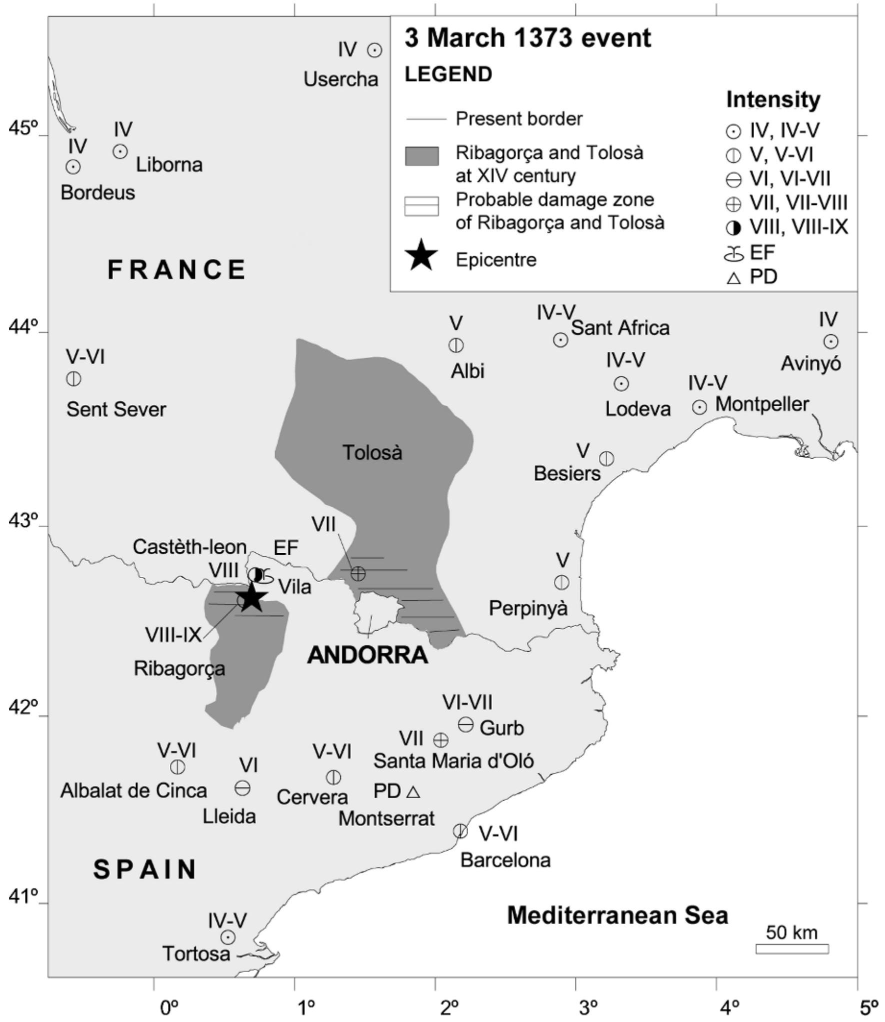

Fig. 2 Intensity map (EMS-98) for the earthquake of 3 March 1373 and macroseismic epicentre. PD = probable damage and EF = effects on springs

4 The 1427 Series: How Events in Sequences are Difficult to Separate and How the Far Sources can Help

The sequence of earthquakes in 1427 is less well known, probably because it has been overshadowed by the earthquake on 2 February 1428, which was more destructive.

Given that all the available documentation had not been used in earlier studies, the evaluation of the earthquakes presented here is more complete and more reliable since it provides epicentre and epicentral intensity, with a quality index for each earthquake of the sequence (Table 1). Detailed information on intensity data points can be found in Olivera et al. (2006).

As it can be seen in Table 1 in a relativity short time period an important number of events occurred. In earthquake sequences as this one it is always difficult to separate the effects of the individual events and so to estimate intensities. Even in present times when earthquake sequences take place – as it is the case of the Umbria-Marche, Italy, 1999 series – to assign intensity associated to individual events is some times an impossible task.

In our study a special care has been taken to separate the available documentary sources according to the date they were written. The analysis is carried out in a sequential way carefully analysing each individual document. Documents that describe effects related probably to more than one event are only considered at the end of the process.

Sometimes sources from the near field (that is documents written from near the epicentral area, the area of damages) do not have precise date. On the contrary, sources in the far field, as it is the case, in the 1427 sequence, of the chronicles from Barcelona and Pamiers (France) located 75 and 135 km, respectively, from the damaged areas, contain very accurate timing. Moreover, these chronicles precisely describe the degree of perception, comparing each event of this series. This information in the far field has been of crucial importance for us to be able to separate the effects of individual events and to have their correct chronology (Olivera et al. 1999; 2006).

The critical analysis of sources is always needed. In this sequence, for instance, the earthquake of March 15th was previously considered to be one of the largest of the series. This former interpretation was based only on contemporary sources describing that the Monastery in Amer was destroyed by the earthquake. Analysing with more detail these documents one can realize that this destruction was due to a fourth of the battlement of belfry of the monastery that felt upon the vault of the church and the vault collapsed completely, all over the main altar and the choir pews. This damage to the Amer monastery became the focus of considerable attention because of its symbolic significance and so, this earthquake was considered to be of intensity at least VIII–IX (Olivera et al. 1994). After a critical analysis of the sources related the damage in Amer together with other sources referred to former and latter earthquakes and the above mentioned chronicles distant from the epicentral area, it can be concluded that this event was not so large ($I_0 = \text{VI}$).

Table 1 Catalogue for the seismic sequence of 1427. The table gives date and time of the earthquake, macroseismic epicentre (Region: name of the epicentral area, Lat N = latitude north, Lon E = Longitude east), Q_e = quality of epicentre, I_o = epicentral intensity (EMS-98), Q_i = quality of I_o. Quality indexes are explained in the text (Section 2)

Date	Time	Epicentre			Q_e	I_o	Q_i
		Region	Lat N	Lon E			
1427.02.F		Amer	42° 02′	2° 35′	C	< IV	C
1427.03.02	21 h	Amer	42° 02′	2° 35′	C	V	C
1427.03.03	1–2 h	Amer	42° 02′	2° 35′	C	V	C
1427.03.13	11 h	Amer	42° 02′	2° 35′	C	VI–VII	C
1427.03.14	12 h	Amer	42° 02′	2° 35′	C	VI	C
1427.03.15	23 h	Amer	42° 02′	2° 35′	B	VI	C
1427.03.19	21 h	Amer- Osor	41° 59′	2° 35′	B	VIII	C
1427.03.21	12 h	Amer- Osor	41° 59′	2° 35′	C	IV–V	C
1427.03.22	13 h	Amer- Osor	41° 59′	2° 35′	C	IV–V	C
1427.04.13	1–24 h	Lloret Salvatge	41° 59′	2° 35′	C	< IV	C
1427.04.22	22 h	Lloret Salvatge	41° 59′	2° 35′	B	VI–VII	C
1427.04.23	11 h	Lloret Salvatge	41° 59′	2° 35′	B	IV	C
1427.05.15	15–16 h	Vall d'en Bas - Olot	42° 10′	2° 26′	B	VIII	C
05.15–06.04	1–24 h	Vall d'en Bas - Olot	42° 10′	2° 26′	C	< IV	C
1427.06.08		Caldes de Malavella	41° 51′	2° 49′	C	V	C
1427.06.12	1–24 h	Caldes de Malavella	41° 51′	2° 49′	C	< VI	C
1427.06.14	8 h	Caldes de Malavella	41° 51′	2° 49′	C	VII	C
06.15–08.31		Caldes de Malavella	41° 51′	2° 49′	C	< V	C
1427.12.25		?	?	?		?	

5 The February 2nd, 1428 Earthquake: After Correcting by the Results of the 1427 Sequence, Still the Largest Earthquake Known in the Eastern Pyrenees

The earthquake of 2 February 1428 wrought heavy destruction in Catalonia and France (Fig. 3). Taking into account the households for 1378 (Redondo 2002) considering that inhabitants = households ×4 and the available descriptions, the number of deaths caused by the earthquake has been estimated around 1000.

This earthquake occurred at the end of the 1427 sequence commented in the previous section and so the damage accounts for this event can be contaminated by accumulated effects of the complete sequence.

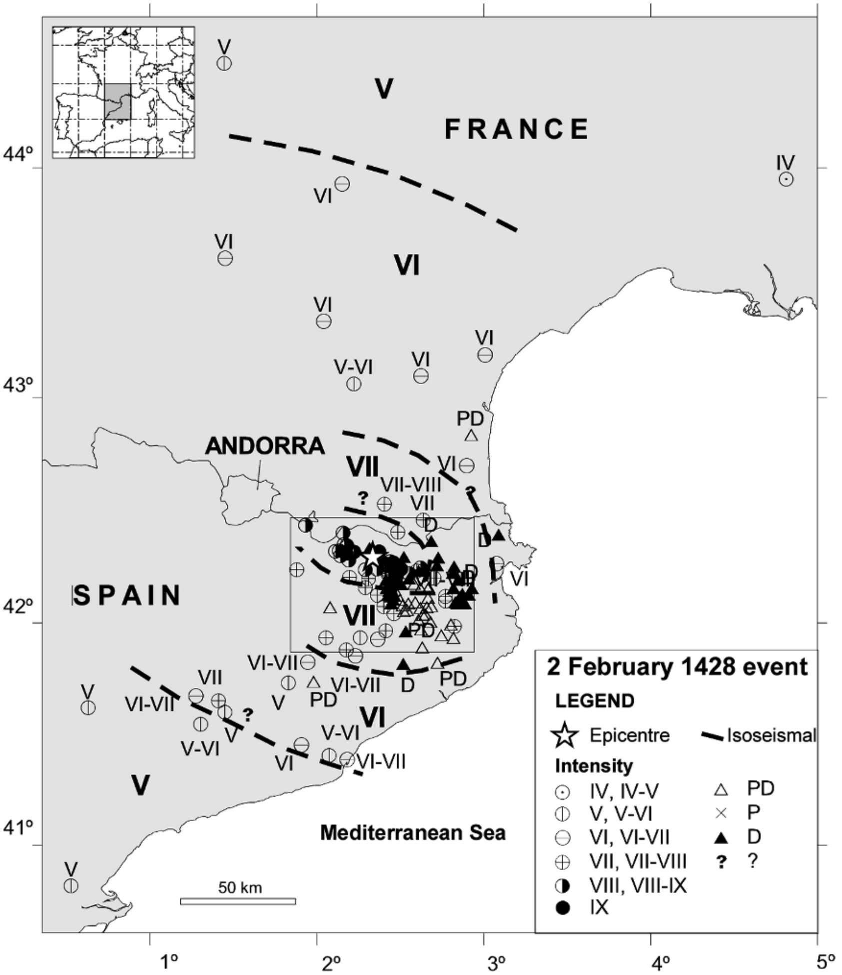

Fig. 3 Intensity map (EMS-98), macroseismic epicentre and isoseismal lines for the earthquake of 2 February 1428. P = perception, PD = probable damage, D = damage

A rigorous review of an important set of the contemporary accounts of the earthquake of 1428 has been carried out. It is the first time that an interpretation of this earthquake has been made, bearing in mind the reappraisal of the seismic sequence of 1427 and that of the earthquake of 1448.

The destructive effects caused in some localities by the previous 1427 earthquakes were considered. Given that the epicentral zones of the earthquake of 1427 and that of 1428 do not coincide, it is possible to evaluate the epicentral intensities independently. By contrast, for certain localities devastated in March 1427 (Vall d'Amer and Vall d'en Bas) and those affected by the earthquake on 15 May 1427 (Vall d'en Bas, Olot . . .) the descriptions record the accumulated effects of both 1427 and 1428 earthquakes. Some of these localities have not assigned intensity values because of the impossibility of discriminating between the effects of the different earthquakes. Only destruction or probable damage is indicated in such cases.

Data from some French localities were incorporated (Fig. 3). A review and analysis of the records from the French archives (Lambert 1993) led to the exclusion of some towns, as Bordeaux, Libourne and Montpellier, among others, which had been included in earlier studies. This is an important finding when evaluating the extension of the area of perception; with the available documentation it seems that the earthquake was not felt at distances larger than 300 km. from the epicentre. Cadiot (1979), had proposed an epicentral intensity of X–XI, basing himself on a larger area of perception.

According to the new results of our study, the epicentre of the 2 February 1428 earthquake is located near the village of Camprodon, about 15 km to the West from the location from Banda and Correig (1984). We assign an epicentral intensity of IX (EMS-98) instead of IX–X (MSK) as given by Banda and Correig (1984) or even X–XI given by Cadiot (1979). Provided that this earthquake is the largest one known in historical times in the study region, the above conclusions are of special relevance for the seismic hazard assessment.

6 The 1448 Event: Earthquake and Meteorological Effects Mixed

The proximity of the earthquake of February 2nd, 1428 to that of the event of 1448 (only 20 years earlier) probably coloured the accounts that are available for this last earthquake.

This study is significant with respect to earlier ones (Salicrú 1995) as it is the first work to assess the effects of this earthquake in terms of point intensity. As explained in the previous sections, in this study damages produced by former earthquakes (1373, 1427, 1428) have been considered when assessing the intensity at specific sites. Looking at some of the documentary sources mention to hydro-meteorological episodes was found. Then, a more intensive search for sources related to extreme meteorological episodes was carried out by establishing an interdisciplinary collaboration between historians, climatologists and seismologists (Olivera et al. 2004). It was clear that at specific sites some damages attributed to the earthquake had already

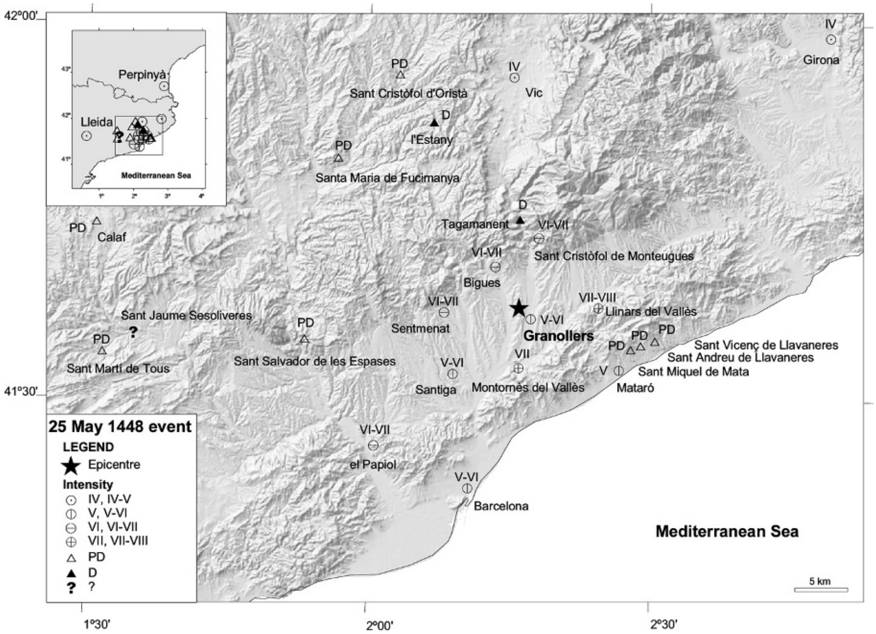

Fig. 4 Intensity values (EMS-98) assigned to localities affected by the earthquake of May 25th, 1448 and macroseismic epicentre. PD = probable damage, D = damage

been reported as previous hydro-meteorological effects. A joint analysis of documentary sources referred to the earthquake and to the previous hydro-meteorological episodes yield to a more reliable site intensity values (Fig. 4).

Many localities do not have assigned a point intensity value because of the lack of reliable information, and because of the possible cumulative effects of the 1428 earthquake. The earthquake claimed 7 lives in 4 separate localities, which increases the uncertainty when evaluating the macroseismic parameters.

Although the epicentral intensity of this earthquake is only VII–VIII, its proximity to the city of Barcelona (about 30 km) makes the study of this event relevant for the risk assessment of this densely populated coastal area.

7 Main Results and Discussion

The review of the earthquakes of the period under study allowed us to make a classification of the events into 48 earthquakes, 46 false events and 4 doubtful ones. The date of some earthquakes and localities affected by these events underwent some modifications with respect to earlier studies. From these, 8 events have epicentral intensity $I_o >$ VI (EMS-98). The values of their parameters are given in Table 2.

The quality index assigned to the different epicentre locations range from B (about 10 km accuracy) to D (20–50 km). The quality index assigned to Io is C for all

Table 2 Late medieval earthquakes with $I_o > VI$ (EMS-98) obtained as a result of the review. Lat N = latitude north, Lon E = Longitude east, Q_e = quality of epicentre, I_o = epicentral intensity, Q_i = quality of I_o. Quality indexes are explained in the text (Section 2)

Date	Time	Lat N	Lon E	Q_e	I_o	Q_i
1373.03.03	1–2	42° 38′	0° 41′	D	VIII–IX	C
1427.03.13	11	42° 02′	2° 35′	C	VI–VII	C
1427.03.19	21	41° 59′	2° 35′	B	VIII	C
1427.04.22	22	41° 59′	2° 35′	B	VI–VII	C
1427.05.15	15–16	42° 10′	2° 26′	B	VIII	C
1427.06.14	12	41° 51′	2° 49′	C	VII	C
1428.02.02	8–9	42° 18′	2° 20′	B	IX	C
1448.05.25	1	41° 38′	2° 17′	C	VII–VIII	C

events. This assignment could be questionable but the authors think that there are not consistent arguments to assign different quality indexes to the different earthquakes considered as we are dealing with Middle Ages events for which the documentary sources are quite different from those for Modern period. The information on damages is, in general, not detailed enough and, moreover, is almost only referred to singular buildings, namely castles, palaces, churches and monasteries, i.e. properties of the king or the church. Detailed damages on dwellings are rarely reported. Under these circumstances it is not possible to assign intensity properly using statistical criteria according to the definitions of the Intensity scale. For this reason we keep Qi = C for all events.

In order to complement the obtained macroseismic parameters (epicentre and Io) which are the main goal of this study, hypocentral depth and magnitude have been estimated for some of the events in Table 2, using the approaches described in Section 2. Focal depth has been estimated from intensity decay curves using Sponheuer model (see Section 2).

Figure 5 show the intensity data points for the March 3rd, 1373 earthquake. The best fit to Sponheuer curve is obtained for $\alpha \leq 0.001$ and $h = 16$ Km. Due to the scarcity of data, in particular for the epicentral region, these values have low reliability. On November 11th, 1923 an earthquake of intensity VIII (MSK) occurred on the same area as that of 1373. For the 1923 event a large amount of intensity data points are available and the best fit to Sponheuer curve were obtained for $\alpha \leq 0.001$ and $h = 5$ Km (Susagna et al. 1994). Comparison of the data from these two earthquakes supports the hypothesis that the hypocentre of the 1373 event is deeper than that of 1923.

Figure 6 shows the intensity decay curve for the February 2nd, 1428 earthquake. As it can be seen comparing Figs. 5 and 6 the number of intensity data points for 1428 earthquake is much larger. The best fit to Sponheuer curve is obtained for $\alpha \leq 0.001$ and $h = 9$ Km. The lower value of α obtained is in agreement with most of the attenuation studies carried out in the Pyrenean region (Banda and Correig 1984; Levret et al. 1994; Susagna et al. 1994; Secanell et al. 2004).

Some magnitude estimates have been obtained for the earthquakes listed in Table 2 using, depending on the available data, the various empirical relations

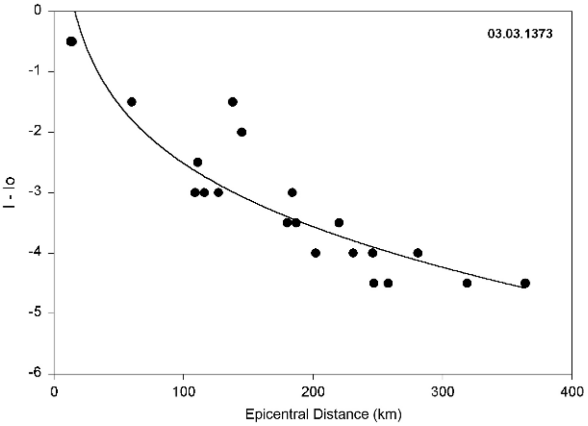

Fig. 5 Intensity decay data points for the earthquake of 3 March 1373. The *solid line* represents the fit to the Sponheuer attenuation law

presented in Section 2. These estimates are presented in Table 3. For a same earthquake the values of magnitude obtained by different methods show a quite large dispersion; this is due to several factors:

- the different magnitude scales used (Ms, Mw, Macroseismic magnitude, . . .),
- the uncertainties associated to each empirical relation for the various magnitude intervals and for the various regions considered,
- and last but not least, the number of intensity data points available for each earthquake and the quality on their intensity assessment.

As the documentary review has been finalized and the full set of intensity data points are available (Olivera et al. 2006), a more detailed study will be undertaken to obtain a specific relation between isoseismal areas and Mo for the study region.

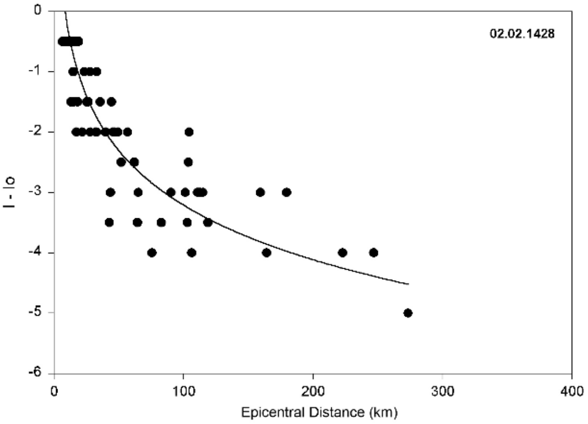

Fig. 6 Intensity decay data points for the earthquake of 2 February 1428. The *solid line* represents the fit to the Sponheuer attenuation law

Table 3 Late medieval earthquakes with $I_o > VI$ (EMS-98) referred in Table 2. I_o = epicentral intensity; Magnitude deduced from I_o: (1) Gutenberg and Richter (1954), (2) Johnston (1996b); R_{VIII} radius of isoseismal VIII; Magnitude from isoseismal area: (3) Macroseismic magnitude using Levret et al. (1994), (4) Mo = seismic moment in N.m. deduced from Johnston (1996b), (5) Mw = moment magnitude using Hanks and Kanamori (1979) from the previous values of Mo (Column 4); h = depth in km; Ms proposed by: (6) Kárník (1964), (7) Gutdeutch (2002). See Section 2 for details

Date	I_o	(1)	(2)	R_{VIII}	(3)	(4)	(5)	h	(6)	(7)
1373.03.03	VIII–IX	6.3–7.0	5.8–6.4	–	–	–	–	16	6.2	6.1
1427.03.13	VI–VII	5.0–5.7	4.7–5.3	–	–	–	–	–	–	–
1427.03.19	VIII	6.3	5.8	5	5.0	8.43×10^{17}	5.9	6	5.5	5.0
1427.04.22	VI–VII	5.0–5.7	4.7–5.3	–	–	–	–	–	–	–
1427.05.15	VIII	6.3	5.8	4	4.9	6.31×10^{17}	5.8	–	–	–
1427.06.14	VII	5.7	5.3	–	–	–	–	–	–	–
1428.02.02	IX	7.0	6.4	25	6.1	5.95×10^{18}	6.5	9	6.3	6.0
1448.05.25	VII–VIII	6.0	5.3–5.8	–	–	–	–	–	–	–

8 Conclusions

The results of this study have been reached through a rigorous review of primary documentary sources and to a critical analysis of such sources in its historical context taking extreme care of the chronological aspects given that sequences of earthquakes occurred in the studied period.

Uncertainties associated to the epicentral coordinates and intensities for the Middle Ages earthquakes studied here are, as usual in macroseismic studies, difficult to assess and this may seem to be a handicap claimed by some seismologists. However, the rich descriptions encountered in this study, the large amount of documentation used and the rigorous methodology followed by the interdisciplinary team working in this topic for years of extensive and intensive research, guarantee the reliability of the results achieved.

The revision carried out yields to a new catalogue for the study period that includes 8 events with epicentral intensity larger than VI (EMS-98). Table 2 show the macroseismic parameters of these events. The most important earthquakes of the period studied are those of 1428 and 1373, with epicentral intensity IX and VIII–IX, respectively.

The two most destructive earthquakes of the sequence of 1427 are those of 19 March and 15 May; both have the same value of epicentral intensity VIII. It should be pointed out that the accumulation of effects of all the earthquakes that occurred would be equivalent to the area of maximum destruction intensity IX.

It can be stated that, in the area under study, there is very little likelihood of other late medieval earthquakes with $I_o > \text{VII}$ not being included in this review.

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Strong Earthquakes in North-Western Africa in the Second Half of the 17th Century, AD: A Critical Reappraisal of the Historical Evidence

R. Camassi, C. H. Caracciolo and V. Castelli

Abstract The recent seismological literature recorded three strong earthquakes in Algeria, Libya and Tunisia between 1656 and 1694 AD. The historical evidence for these derives from European sources only (gazettes, journalistic pamphlets, missionary literature). Considering the kind of sources involved, their likely biases and the geographical distances that divided their places of production from the places that they spoke about, it is possible that some of these accounts could be less than reliable, and therefore have little use as materials from which to assess earthquake parameters. To answer these doubts, we have retrieved, cross-checked and critically analysed the original historical sources quoted in previous compilations and studies.

1 Introduction

The recent achievements of earthquake research in Maghreb countries are attested by the reports of many scientific studies and the release of Maghreb-including hazard maps on the part of GSHAP (Giardini, 1999). This shows that there is a growing interest in hazard evaluation in these regions. Much of the available data deal with the instrumental period of seismological recording only, although the historical seismicity of the Maghreb region has also been the object of painstaking studies. These started with the groundbreaking research by the founding fathers of modern historical seismology (Ambraseys, 1984; Ambraseys and Vogt, 1988; Ambraseys et al., 1994; Vogt, 2004), in whose footsteps did follow Benouar (1994; 2004), Mokrane et al. (1994), Benouar and Laradi (1996), Hamdache (1998), Hamdache et al. (1998), Oussadou (2002), Harbi et al. (2003; 2005), Suleiman et al. (2004) (Fig. 1).

The study of historical earthquakes is a constantly ongoing process, however, because of the complexities of historical research and the interactions between historians and seismologists. According to the trends of local historical research and the completeness of the records available, any regional historical earthquake catalogue

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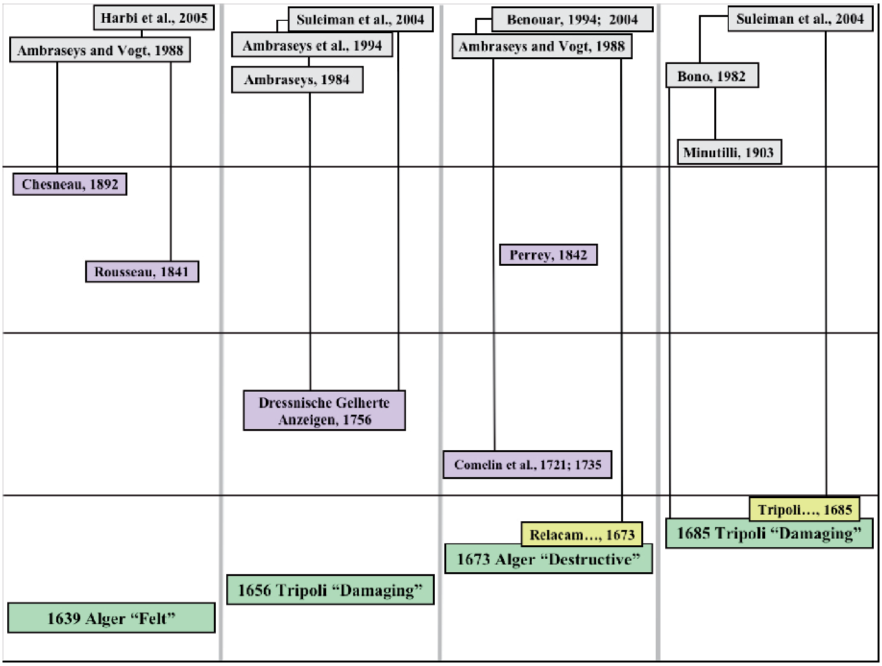


Fig. 1 Simplified filiation scheme of sources and studies available for the main north-west Africa earthquakes

is likely to be more complete within some time windows than within others. This is well illustrated by the earthquake catalogue for Libya from classical antiquity to the present by Suleiman et al. (2004), which lists several earthquakes in the 19th and 20th centuries, but almost none for the 704 AD to 1803 time window. Similarly, the Harbi et al. (2005) catalogue for North Algeria, from 1359 AD to 1895, lists 14 earthquakes through the whole of the 14th–17th century, 21 in the 18th century and 90 in the 19th century.

The present study focuses on a very short time window in the seismicity of north-west Africa: the second half of the 17th century AD; very few earthquakes are listed within this time window by the current catalogues and the only evidence available on them is of European origin. Our aim is to retrieve, cross-check and critically analyse the original historical sources quoted by previous compilations and studies in connection with these earthquakes. Through this approach, we hope to contribute to a better understanding of the historical seismicity of the Mediterranean basin.

2 The Earthquakes Studied and Their Historical Evidence

Table 1 lists the earthquakes that we have set out to investigate, indicating their dates of occurrence and their presumed epicentre locations, and the general descriptions and evidence quoted by the seismological studies that made first mention of them.

Table 1 The earthquakes under consideration

Date	Epicentral area	General description and quoted historical evidence	First mentioned in seismological literature
1656	Tripoli (Libya)	"Exceptionally strong earthquake in Tripoli in Libya destroyed almost half its houses and caused the loss of five pirate vessels in the harbour." (Source quoted: Dresdnische, 1756)	Ambraseys (1984)
1673 March 10	Algiers	"A destructive earthquake in Algiers and its surroundings, comparable, it is said, to the earthquake of 1716. Strong aftershocks, 71 in all, lasted for about 40 days" (Source quoted: Anonymous, 1673; Comelin and Bernard, 1735)	Ambraseys and Vogt (1988)
1685 May 25	Tripoli (Libya)	"The earthquake made more than 200 buildings collapse" (Source quoted: Anonymous, 1685)	Suleiman et al. (2004)

Harbi et al. (2005) stated that most of the eight 17th century earthquakes included in their catalogue were either poorly known or doubtful, except that of 1673 in Algiers, which was assessed as Io 8 MM (the parametric Ibero-Maghrebi catalogue by Mezcua and Martines Solares, 1983 gives similar parameters, locating the earthquake in Algiers with Io VIII). Regrettably, Harbi et al. (2005) did not expand upon their statement with a discussion of the local 17th century historical evidence, which would have been of enormous help for an outside historian to assess the reliability of non-local historical evidence against that which is local. However, this critical judgement by an authoritative local study must be kept in mind as one appraises the historical evidence that has been responsible for the identification of the earthquakes listed in Table 1.

2.1 The 1656 Tripoli Earthquake

The first mention of the 1656 Tripoli earthquake in the seismological literature was by Ambraseys (1984), followed by Ambraseys et al. (1994) and Suleiman et al. (2004). The original historical source for Ambraseys (1984) was an 18th century German earthquake listing (Dresdniche Gelehrte Anzeigen, 1756), according to which this earthquake affected "Tripoli in der Barbaren", now the capital of Libya. This source is not necessarily unreliable just because it was published a century after the earthquake it describes; however, as pointed out by Ambraseys (1984) himself, there is no general consensus concerning the real location of this 1656 earthquake.

Indeed, the earliest seismological compilations that mentioned it (Hoff, 1840; Perrey, 1850) proposed that it should be re-located as having been in the Tripoli on the Lebanese coast.

2.2 The March 10, 1673, Algiers Earthquake

As evidence of the March 10, 1673, earthquake in Algiers, Ambraseys and Vogt (1988) quote an 18th century French missionary report concerning a redemption expedition undertaken by three Trinitarian Fathers to Algiers and Tunis in 1720 (the Trinitarian and Mercedarians were "ransoming orders", whose mission was buying back Christian slaves). This work was originally published in 1721 (Comelin et al., 1721; the study quotes a later edition, Comelin et al., 1735), and is therefore almost 50 years later than the earthquake about which it provides evidence. Indeed, the evidence in question is also rather roundabout, forming a part of a description of a strong earthquake that affected Algiers in 1716 (the consequences of which were still clearly visible in 1720). Thus Comelin et al. (1735) related how in the aftermath of the 1716 earthquake, a member of the Turkish community of Algiers was sentenced to death for having remarked, seditiously, that "40 years before" (i.e. *circa* 1676) there had been another earthquake that had been followed by a series of aftershocks as long as the current one, and that these had only stopped after the murder of the Dey (Regent) of Algiers. As can be seen, this source only indicates the occurrence of an earthquake around 1676. Ambraseys and Vogt (1988) pinpoint its date to 1673 by taking into account evidence of a contemporary journalistic pamphlet, which they were not able to retrieve, but the existence of which they were indirectly aware of from its description (possibly extracted from a Portuguese library catalogue) as a "Relacon em espanol dadata de 30 de maio de 1673, feita por un religioso... estragos que os tremores de terra ali fizeram" [Report written in Spanish on May 30, 1673, by a cleric... on the damage caused by an earthquake].

2.3 The May 25, 1685, Tripoli Earthquake

Suleiman et al. (2004) mention, although as a possibility only, an "unknown" destructive earthquake that occurred in Tripoli (Libya) on May 25, 1685. Their source was a contemporary journalistic pamphlet printed in Bologna (Italy). This purporting to be based on a letter sent to a merchant living in the town of Ancona, on the western coast of the Adriatic Sea (Tripoli, 1685b), the reference to which they obtained from Minutilli (1903). Suleiman et al. (2004) also state that this account "sounds emphatic, and verging on exaggeration", but they defer to the opinion expressed by Bono (1982), according to whom this account "though unsupported by other sources [and] extremely unlikely in parts, cannot be said to be completely inauthentic".

3 Seventeenth Century Journalistic Sources as Providers of Information on Earthquakes of North-West Africa

The two aims of the present study are: (a) to retrieve and critically analyse the original sources responsible for the inclusion of studied earthquakes in the north African seismic record; and (b) to collect additional information on the same earthquakes from contemporary sources. As the large majority of the sources concerned are of a journalistic nature, it is opportune to provide here some information concerning the 17th century European journalistic network, a body of serial historical sources of outstanding importance for information relating to the Mediterranean basin (Camassi and Castelli, 2004).

In the 17th century, news circulated in three basic ways: as "*Avvisi*", gazettes and pamphlets. The *Avvisi* (literally translated as "Announcements") were short manuscript summaries of recent occurrences in one or several towns, and were issued regularly to subscribers. Gazettes were rather like *Avvisi* in layout (correspondence from several sites), range of topics (wide) and style (terse), but unlike *Avvisi* they were meant for a more general market. Pamphlets (also known as tracts, broadsheets, canards, and *Relazioni*) were cheap printed accounts of single occurrences that were often of a sensational nature, also meant for a more general market. The modern equivalents of these three forms of news circulation would be press-agency releases, general newspapers and the tabloid newspapers, respectively.

North African news generally reached the Italian journalistic market via the Thyrrenian seaports, such as Genoa and Leghorn, both of which produced their own *Avvisi* and also despatched them to Florence, Genoa, Rome and elsewhere. Venice, the other great Italian newsgathering centre, is less important than the Thyrrenian seaports for the present study as it was mostly focused on the Balkan and Eastern Mediterranean areas.

Generally speaking, *Avvisi* and gazette writers tried to be fairly accurate, and would explicitly disclaim any seemingly relevant items of news if it turned out to be untrue. The same could not always be said of the cheaper pamphlets, among which fabrications abounded. For the term fabrication, the concept is of a story that although presented as "new" news, was actually duplicated from earlier pamphlets and therefore not new, or potentially not even true at all, although their actual contents could originally have been both new and true (Caracciolo, 2001). These were thus prepared by taking a story that had been reported by a different pamphlet, giving it a new date, freshening it up a little by changing a few names, transposing a few adjectives, and adding a paragraph or two. The result was a story ready to be sold as "new". The easiest stories to multiplicate in this way were those set in exotic places, which had the double advantage of lowering the chances of their ever being easily checked or refuted, while counting on the age-old human tendency to equate "abroad" with "outlandish". The countries on the southern and eastern Mediterranean shores were particularly associated in the collective imagination of 17th century Italy as the abode of the pirates that periodically raided the Italian coasts (Davis, 2004). These thus represented far-off places of wonder and fear, with odd customs that were known through the tales of ransomed prisoners. It can therefore maybe be expected that several “multiplicated” pamphlets take the misfortunes of Christian slaves in north-Africa as their subject: e.g., there was the death of the Italian Friar Francesco Zirano, who was actually executed in Algiers in 1603 (Devilla, 1924), but which was then re-told a further three times, in 1639, 1718 and 1740. There was also the killing of a Sicilian youth in Tunis that was told twice, in 1660 and 1716 (Caracciolo, 2001).

Although a favoured subject for pamphlets, earthquakes did not appear to have been as favoured a subject for multiplication. An ongoing census of earthquake pamphlets shows that most of them deal with events that have been amply attested to by independent sources. The one specific mention of a fictional Italian earthquake so far identified occurred in the *title* of a 17th century Italian pamphlet (Nuova e vera relatione, 1676), where the *text* clearly described the phenomenon as the explosion of a powder-magazine (Camassi and Castelli, 2005). Things can get more mixed up, however, when far-off countries are involved and there are political and human scores to settle, as we will now see.

4 Case Histories

4.1 The 1656 Tripoli Earthquake: A Middle East Earthquake?

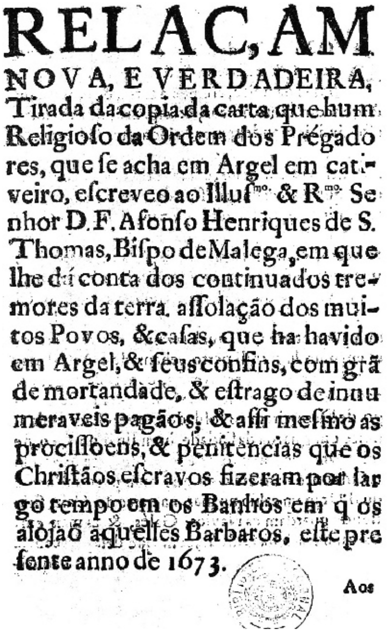
Can the actual location of the 1656 Tripoli earthquake be ascertained by a perusal of 17th century journalistic sources? There are few collections of Italian gazettes that cover the year 1656; moreover, most of these focused on the ongoing siege of Candia and the related military operations in the Eastern Mediterranean, rather than on north Africa. Among those sources that did report on Tripoli, there were the Genoa gazette and the Bologna, Genoa, Venice and Malta *Avvisi* (ASV, 1656ab; 1657a, b). These reported on several occurrences in Tripoli, but did not mention earthquakes either in Tripoli or elsewhere in north Africa during 1656 and 1657. However, there is contemporary evidence of earthquakes in Turkey and Syria. An *Avviso* written in Ragusa (now Dubrovnik) on April 13, 1656 (Dujcev, 1935) mentions an earthquake felt in Constantinople “on St. Gregory’s Eve”. Among the several St Gregory feast days of the Orthodox Church calendar, January 25 and January 30 are those that fall nearest to April 13. Then, taking into account the 10-day difference that existed between the Julian and the Gregorian calendars in the 17th century, the Ragusan *Avviso* could refer to an earthquake felt in Constantinople in early February, 1656, and about which no more is known. An almost contemporary missionary report (Besson, 1660; 1662) states that in 1657, “the earth shook four times in the space of two months in Aleppo and similar earthquakes occurred along the whole coast of Syria”.

In short, some new evidence has been collected that appears to make it likely that the *Dresdniche* Gelehrte Anzeigen (1756) mention of a 1656 earthquake in the Tripoli in Africa was actually related to a 1656 or 1657 earthquake in the Tripoli in the Middle East. However, this evidence is not conclusive enough to indicate that the 1656 earthquake should be removed from the catalogues relating to north Africa.

4.2 The 1673 Algiers Earthquake: Was it Part of a Larger Picture?

A search among the pamphlet collections of the main European national libraries led to the retrieval of a Portuguese pamphlet (Relaçam nova, e verdadeira…, 1673; Fig. 2) that if not quite the same as the Spanish pamphlet quoted by Ambraseys and Vogt (1988), appears indeed to be a closely related item. The news reported in this pamphlet seem to have circulated widely, as witnessed by an entry by a contemporary Mexican diarist (De Robles, 1665–1703) that relates the same tale presented in the Spanish pamphlet.

The text of Relaçam nova, e verdadeira… (1673) is presented as a letter that was written on May 30, 1673, by an enslaved Domenican Friar to Alonso Enriques de San Thomas, the Bishop of Malaga. This letter describes a long sequence of earthquake shocks that were felt in Algiers between May 10 and May 21, along with several astronomical phenomena that accompanied them, and the religious functions celebrated by the Catholic slaves in the Algiers slave quarters, or Bagnos (Table 2). All of these details that are easy to confirm (e.g., the name of the Bishop of Malaga, the existence of Catholic places of worship in the Bagnos) are correct and the circumstances described are known to be realistic. On the other hand, there is no mention of earthquakes in the Algiers news for March 1673 and the following months, as featured in the Genoa and Venice *Avvisi* (ASMo, 1673) and in the Gazette de France. By itself, however, this is insufficient to prove that the earthquake described in the Relaçam nova, e verdadeira… (1673) did not occur at all. The circumstances described in it could actually be related to a minor local



RELAÇAM
NOVA, E VERDADEIRA,
Tirada da copia da carta, que hum
Religioſo da Ordem dos Prégado
res, que ſe acha em Argel em cati-
veiro, eſcreveo ao Illuſ^{mo} & R^{mo} Se
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Thomas, Biſpo de Malega, em que
lhe dá conta dos continuados tre-
mores da terra, aſſolação dos mui-
tos Povos, & caſas, que ha havido
em Argel, & ſeus confins, com grã
de mortandade, & eſtrago de innu
meraveis pagãos, & aſſi meſmo as
prociſſoens, & penitencias que os
Chriſtãos eſcravos fizeram por lar
go tempo em os Banhos em q os
alojaõ aquelles Barbaros, eſte pre
ſente anno de 1673.

Aos

Fig. 2 Frontispiece of the Relaçam nova, e verdadeira…(1673)

Table 2 The occurrences of 1673 in Algiers (Relaçam nova, e verdadeira…, 1673)

Date	Time	Place	Occurrences
1673.03.10?		Algiers	A "fiery snake" (meteorite?) is seen plunging into the sea just before the first earthquake shock.
1673.03.10	9 h in the night	Algiers	The earth starts shaking.
1673.03.10	in the night	Algiers	18 earthquake shocks are felt.
1673.03.10/11	next day	Algiers	6 earthquake shocks are felt.
1673.03.11/12	next night	Algiers	47 earthquake shocks are felt.
1673.03	during the 24 h before	A place called "Arboleda" (possibly a Spanish rendering of the Arabic name "Bab el Oued", i.e. Algiers North gate)	A landslide or mudslide destroys 80 houses.
1673.03		Algiers	Catholic slaves celebrate the Church rituals prescribed in case of calamities (Rogations, Rosary) in the Bagnos[1] chapels.
1673.03.31		Southern end of Algiers beach	More than 200 dead "corvinas" (birds?) and fish found.
1673.04.2			Easter.
1673.04.10		Southern end of Algiers beach	More than 500 dead fish found.
1673.05.21	Pentecost Day ("Pascua de Espiritu Santo")	Algiers	Earthquake shocks felt up to this day.
1673.05.30		Algiers	Relaçam's writing date.

[1] slave quarters.

earthquake, or to one located inland from Algiers which could have set in motion a large landslide, which would be responsible in turn for the damage described. There is also the possibility that the phenomena described from the point of view of Algiers in the Relaçam nova, e verdadeira… (1673) are related to the aftermath of the 1672 Cabeço Gordo eruption (Fayal Island, Azores), which was also described by another, very detailed, 1673 pamphlet (Relaçam dos tremores de terra, e fogo…, 1673).

4.3 The Unlikely Tripoli Earthquake of 1685

The background of the details mentioned by Suleiman et al. (2004) concerning a possibly "unknown" 1685 earthquake in Tripoli is indeed authentic, but the story itself appears questionable. For one thing, the present study discovered another pamphlet (Tripoli, 1685a) that was printed in Milan and was purportedly based on "a private letter addressed to His Serene Highness the Grand-Duke of Tuscany

Tripoli li 4. Febraro 1685.
DISTINTO
RAGGVAGLIO
Gionto per lettera particolare all'Altezza Sereniſſima del Gran Duca di Toſcana, da vn Vaſcello mercantile arriuato nel Potto di Liuorno.

In Fiorenza, Torino, & in Milano,
Nella R.D.C., per Marc'Antonio Pandolfo Malateſta Stampator R.C.

Tripoli li 16. Maggio 1685.
DISTINTO
RAGGVAGLIO
Gionto per Lettera particolare
AD VN MERCANTE
Nel Porto d'. Ancona.

In Roma, & in Bologna, per l'Erede del Sarti, dal Monte delle Scuole, alla Roſa. *Con licenza de' Superiori.*

Algieri li 4. Luglio 1686.
VERA, E DISTINTA
RELAZIONE
DELL' HORRENDO, E SPAVENTOSO
TERREMOTO,
SEGVITO NELLA DETTA CITTA' D'ALGIERI,
Nella diſtanza di 50. miglia, eſſendo rimaſte, rouinate dalla mano poderoſa di NOSTRO SIGNORE quattro grandiſſime Terre di quei Turchi, e Cani, come leggendo intenderete.

IN ROMA MILANO, ET IN PARMA,
Per gli Heredi del Vigna. *Con licenza de' Superiori.*

Fig. 3 Frontispieces of the pamphlets on the apparemtly fictitious earthquakes of 1685–1686

from a ship just landed in Leghorn". Here, the same earthquake is described as having occurred on January 25 instead of May 25. This suggests a case of "pamphlet multiplication" (see also: Algieri, 1686, Fig. 3), which is all the more likely as there is no mention of any Tripoli earthquake in the Naples, Venice and Paris *Avvisi* for January–August 1685 (ASMo, 1685a, b). This despite all of these being extremely interested in news from Tripoli at the tme (which they received via Genoa and Marseilles) because of the ongoing French-Tripoli conflict that was to result in the French bombardment of Tripoli (June 22, 1685).

5 Evidence of New Earthquakes "On Paper" Only

By sifting through the collections of 17th century journalistic accounts that are available in a few of the main European libraries, several pamphlets were discovered that describe previously unknown, strong earthquakes as occurring in northwest African towns. However, pamphlets are an elusive kind of source, which have never been seriously studied before very recent times, and which were produced for commercial and/or ideological ends. While their declared aim was to describe "real" news, their contents could turn out to be a mix of truth and imagination, and indeed, even pure fiction. Thus, taking pamphlets at face value can lead to giving credence to fictional events, and to avoid this risk these pamphlets should first of all be positioned within the broader national (or even international) publishing context. In the present case, even a partial census of 17th century pamphlets allows us to identify groups of items that were printed between 1668 and 1694 for which common features abound, such that they are all clearly based on the same literary scheme (or even the same original text), which follows two main "traditions" (see also Appendix 1): The "A" group of pamphlets describe a seismic sequence that was concurrent with odd astronomical phenomena, and that had severe effects in Algiers (the destruction of 300 houses and the main Mosques) and surrounding villages. A

Seville-printed pamphlet (Assimismo se dà noticia de las cometas. . ., 1668) dates this between December 29, 1667, and January 10, 1668, and is supported by the Mexican Diario de sucesos notables (De Robles, 1665–1703). The earthquake apparently shifts to Tunis between April 27 and May 1, 1677, according to an Italian pamphlet (Tunisi 3 maggio 1677. Vera relatione e copia di lettera. . ., 1677), and then returns to Algiers in 1686 according to another pamphlet (Algieri li 4 luglio 1686. Vera e distinta relazione. . ., 1686). These A pamphlets are clearly based on a common template – a text that still remains to be identified – which they reproduce with slight variations for the epilogue (sometimes a new earthquake, sometimes a plague outbreak).

The "B" pamphlets describe an earthquake that occurred in Tripoli either in January 1685 (Tripoli, 1685a), or in May 1685 (Tripoli, 1685b), or even in September 1694 (Verissima relatione. . ., 1694). The B template is very similar to the A template, from which it differs only in the choice of the epilogue (the lightning-induced explosion of a powder-magazine which blows up a quarter of the city, causing thousands of deaths).

6 Hints of a Possibly Destructive Earthquake in Early 1640 (on the Algerian Coast)

Among so many fictional earthquakes, there is sometimes a real one. The historical and seismological literature (De Grammont, 1887; Ambraseys and Vogt, 1988; Cresti, 2005; Harbi et al., 2005) mentions a minor earthquake felt in Algiers some time in 1639. Contemporary *Avvisi* do not mention any earthquake as having occurred in Algiers in 1639 (which is not sufficient to conclude that the 1639 earthquake is fictional, of course), but they do give comparatively ample evidence of a possibly destructive seismic sequence that occurred in Algiers and its surroundings in February–March 1640 (Table 3). News of this earthquake (Fig. 4) first spread into Italy in a Genoese *Avviso* of April 6, 1640 (BAV, 1640a). This is certainly based on news that left Algiers after March 12 (as it describes earthquake shocks that occurred from February 26 to March 12), and which certainly reached Genoa by ship, possibly directly from Algiers as there is no mention in the *Avviso* of any other forwarding seaport. This earthquake is

Table 3 News of the 1640 Algiers region earthquake

Date	Place	Occurrences
Feb 26	Algiers' coast	Earthquake
After Feb 26	Near Algiers	Earthquake shocks demolish villages
Mar 12	Algiers	New earthquake felt; people afraid
Apr 6	Genoa	Earthquake news from Algiers published in Genoa *Avvisi*
Apr 14	Rome	Earthquake news from Algiers via Leghorn published in Rome *Avvisi*
Apr 21	Rome	Earthquake news from Algiers via Leghorn published in Rome *Avvisi*
May 6	Genoa	Earthquake news from Algiers published in Genoa *Avvisi*

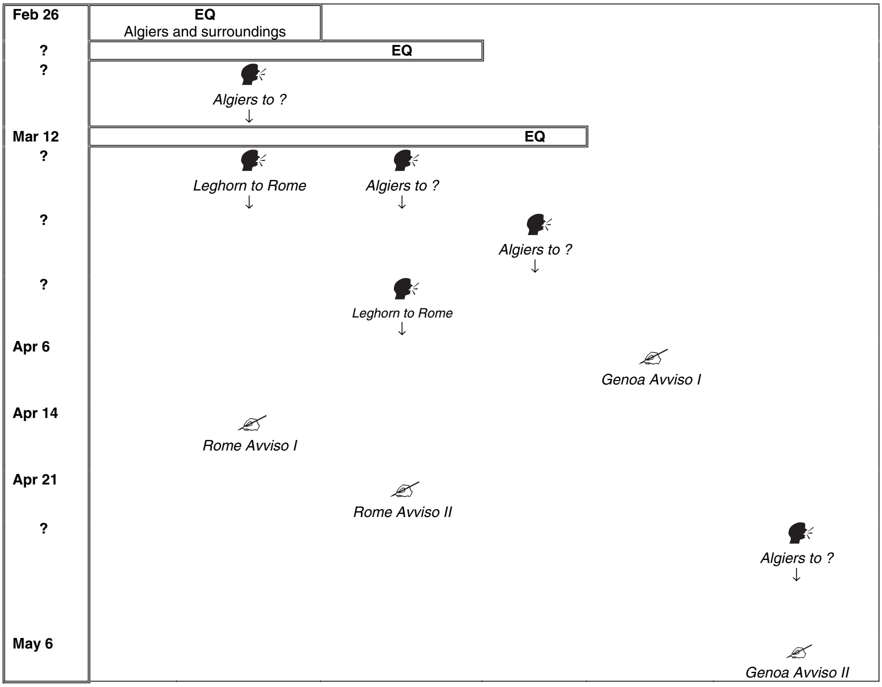

Fig. 4 Reports and news written about the 1640 earthquake[s]

also described in two Roman *Avvisi* (ASV, 1640a), released later than the Genoese one (April 14 and April 21) but carrying older news than it did. Their data, which had passed through the Tuscan seaport of Leghorn, appear to have arrived via a different channel to the one that supplied the Genoese news, as it mentioned only the February 26 event. Thus more than a month had elapsed from the start of the earthquake (February 26) to its first recording in an Italian *Avviso* (April 6). The seacrossing from Algiers to Italy would normally have taken less time than this, but in early spring bad weather could have delayed sea travel; moreover, there was at that time no regular mail service between Algiers and Italy, and the news would have had to wait for a chance carrier before setting out from Africa. It is quite likely that the length of this seismic sequence and its severe effects were what made its occurrence newsworthy enough to reach the Italian journalistic centres, as lesser earthquakes would probably not have managed this. Further Genoese and Roman *Avvisi* went back to describing this Algerian seismic sequence on April 21 and May 6 (ASV, 1640b; BAV, 1640b). Piecing together all of these available bits of information, it is possible to outline the picture of an earthquake that started on February 26 and was felt "over most of the Algerian coast". This wreaked havoc over some hamlets in the areas surrounding Algiers (BAV, 1640a), and possibly in Algiers itself, if the April 21 Roman *Avviso* and the May 6 Genoese *Avviso* are to be taken seriously. According to these latter, "in Algiers, part of the houses had collapsed and unnumbered people had died" (ASV1640b; BAV, 1640b).

At this stage, it would be interesting to know the sources that led to the identification of the 1639 earthquake that is already listed in the seismological literature, and which could perhaps turn out to be a foreshock of the 1640 earthquake.

7 Conclusions

Two out of three 17th century earthquakes that were previously believed to have occurred in north-west Africa turn out to be probably not true after this critical revision of the historical sources that were responsible for their inclusion in the local earthquake catalogue (Table 4). At the same time, however, new evidence of possibly significant earthquakes has come to light. The results of this very preliminary study confirm that there is room for interesting developments in the recostruction of the historical seismic records of the area. European researchers wishing to contribute to this historico-seismological venture must, of course, primarily rely on European sources, among which the European journalistic ones offer especially high potential (and particularly concerning the 16th–18th century time window). However, as there is no such thing as an impartial historical source, it should be kept in mind that the European journalistic sources can be biased in several aspects: politically, by being mainly focused on privateering semi-military actions ("guerra di corsa"); geographically, by being more interested in occurrences along the African coast rather than in its interior; and ideologically too, because after all, they wrote about "enemy" countries during times of violent religious and military strife. In any case, this complex game is worth playing, so that we can improve the perception of this time window of north African historical seismicity. Pursuing this goal does carry with it first of all the need to start afresh with systematic parallel analyses of primary historical records from both sides of the Mediterranean basin, a venture in which we would like to see contemporary European journalistic sources taking on a role.

Table 4 Real and fictional earthquakes of north-western Africa (according to the present study)

Date	Site	RMK	Sources
1639 1640 Feb 26	Algiers	Destructive earthquake?	Manuscript *Avvisi*, historiography, earthquake compilations
1656	Tripoli (Libya)	Doubtful news	Dresdniche Gelehrte Anzeigen (1756)
1673 Mar 10	Algiers	Doubtful?	Pamphlet; not reported in contemporary Italian *Avvisi* and gazettes
1676 Feb	Algiers	Doubtful?	Not quoted by Ambraseys and Vogt (1988)
1677 Mar 10	Tunis	Fictional news	Pamphlets
1685 Jan 24	Tripoli (Libya)	Fictional news	Pamphlets
1685 May 25	Tripoli (Libya)	Fictional news	Pamphlets
1686 Jun 27	Algiers	Fictional news	Pamphlets
1694 Sept 05	Tripoli	Fictional news	Pamphlets

Appendix

Appendix 1A Pamphlets wich follow the literary scheme "A"

	Algiers 1667	Algiers 1667	Tunis 1677	Algiers 1686
Frontispiece	*[P. Antonio de Robles, Diario de sucesos notables, 3 Vols. México: Editorial Porrúa, 1972]*	Assimismo se dà noticia de las cometas que aparecieron en la Ciudad de Argel, y las ruinas y lastimosos sucessos que causaron en dicha Ciudad en la distancia de cinquenta leguas, que destruyó la Magestad de Dios N.S. docientos y quatro Lugares, y la crueldad que hizieron los Barbaros con unos Christianos. Dase quenta de las cometas y lo que sucedió en la Ciudad de Argel, sacado de una carta que vino de dicha Ciudad.	Tunisi 3 maggio 1677. Vera relatione e copia di lettera scritta da D. Gio. Garzia dalla Ighiera. Naturale della città di Cadice. Nella quale dà conto a suo Padre delle rovine e compassionevoli prodigi succeduti nella detta Città di Tunisi, e nella distanza di cinquanta leghe da essa, essendo rimasti rouinati dalla mano poderosa di Nostro Signore ducento quattro Terre nello spatio di ventidue hore, con ammiratione, e spauento di quei Barbari infedeli.	Algieri li 4 Luglio 1686 Vera e Distinta Relazione dell'horrendo, e spaventoso Terremoto seguito nella detta città d'Algieri Nella distanza di 50 miglia, essendo rimaste rovinate dalla mano poderosa di Nostro Signore quattro grandissimi Terre di quei Turchi, e Cani, come leggendo intenderete.
Printer, printing date/place	*[24 de septiembre de 1668]*	En Sevilla 1668	In Venetia & in Bologna, per Giacomo Monti, 1677.	In Roma, Milano, et in Parma, Per gli Heredi del Vigna.
Introduction			So' che **il racconto de' prodigi** succeduti in questa Città di Tunisi **cagionerà** V.S. **non poco terrore, e compassione** [. . .]	So' che **il racconto de' prodigi** succeduti in questa Città di Algieri **cagionerà** Vosignoria **non poco terrore, e compassione** [. . .]
Forewarnings of following calamities		le daré a v. m. noticia de la ruina, que Sabado a 24 de Diziembre del año passado de 67 se vio en esta Ciudad, y fue en esta manera	Il giorno 16 Aprile dell'Anno presente 1677 si sentirono in questa Città i preludij delle rovine, che poi seguirono,	Il giorno 16 Giugno dell'Anno presente 1686 si sentirono in questa Città i preludij delle rovine, che poi seguirono.

Appendix 1A (continued)

	Algiers 1667	Algiers 1667	Tunis 1677	Algiers 1686
Comets and astral signs	Que en Argel el día 25 de diciembre del año pasado vieron **dos cometas**, el uno muy abominable y sus horas limitadas; la primera vez [. . .]	El día 25 del dicho se vieron **dos Cometas** en esta Ciudad, que al parecer era el uno muy abominable, y sus horas limitadas; la primera vez [. . .]	Ed il giorno 23 comparvero sopra questa Città **due Comete** d'aspetto terribile, l'una, e l'altra, e durarono alcune hore, cioè la prima volta [. . .]	Ed il giorno 23 comparvero su questa Città **due horrendi, e spaventevoli segni**, l'uno, e l'altro d'aspetto terribile, e durorono alcune hore, cioè la prima volta [. . .]
Christian slaves pray		**Estuvimos todos los cautivos** la [referida] noche **encomendandonos** muy de veras a **N. Señor IesuChristo**, y a N. **Señora de Guadalupe**.	**Stessimo tutti li Schiavi** la sudetta notte **raccomandandosi** di cuore à **Nostro Signor Giesù Christo**, & alla **Beatissima Vergine**.	**Stessimo tutti li schiavi** la sudetta notte **raccommandandoci** di cuore i **Nostro Signore Giesù Christo**, & alla **Beatissima Vergine Maria**.
Blood rain, darkening of the sun, storm:	el día 28 del dicho **llovió sangre tres horas, y se vio el sol eclipsado** que amenazaba la ruina;	Y el dia 28 del dicho **llovió sangre tres horas, y se vió el Sol eclypsado**, que amenazaba la ruina.	Il giorno 26 **piovette sangue per tre hore continue, e si vidde il Sole, che perduti i suoi raggi** naturali, minacciava qualche grand'infortunio;	Il giorno 23 piovete fittissima tempesta per un quarto d'hora, e **si vide il Sole, che perduti i suoi raggi** naturali, minacciava qualche grande infortunio,
An earthquake destroy 300 houses and Mosques	el día 29 con un **terremoto horrible destuyó** la majestad de Dios Nuestro Señor más de **trescientas casas, y las mezquitas** donde hacían oración a su falso profeta Mahoma quedaron demolidas y arruinadas,	Y el dia 29 del dicho **destruyó** la Magestad de Dios N. Señor **trecientas casas, y las Mezquitas** donde hazen o[r]acion a su falso Profeta Mahoma, quedaron demolidas, y arruinadas; [earthquake not explicitly mentioned]	& il giorno 27 seguente **atterrò da trecento case, e le Moschee** principali dove è solito orare questi barbari al suo falso Profeta Maometto. [earthquake not explicitly mentioned]	& il giorno 27 seguente **atterò il Terremoto trecento Case, e le Moschee principali**, dove è solito orare questi Barbari al suo falso Profeta Maometto.

More comets; villages destroyed	y el día 2 de enero de este año reinaban con las mismas crueldades los cometas; el día 3 del dicho **se destruyeron** en la distancia de cincuenta leguas en contorno **más de doscientos lugares** que quedaron demolidos [. . .]	Y el dia dos de Enero de este año sesenta y ocho, reynava con las mismas crueldades los Cometas. Y el dia tres del dicho mes **se destruyeron** en la di[s]tan[c]ia de cinque[n]ta leguas, **docientos y quatro Lugares**, que quedaron demolidos [. . .]	Il giorno 29 detto comparvero nel Cielo più Comete tutte di diversi, e spaventosi colori, e ne seguì il giorno appresso, ultimo del Mese, gli effetti nella **total destruttione di 204 Terre**, che qui chiamano Aduari, i quali si disfecero in cenere [. . .]	Il giorno 29 detto comparvero nel Cielo più segni tutti diversi, e spaventosi, e ne seguì il giorno appresso, ultimo del mese gli effetti nella **total distruttione di quattro Terre**, che qui si chiamano Aduari, i quali si disfecero in [. . .]
Wrath of local people against slaves		Y no ob[st]ante dare noticia de lo que suce[d]ió, y el r[i]g[ur]osissimo castigo que executa[r]on en quatro Christianos cautivos, que los **tres fueron quemados vivos** a fuego lento;	Mà ciò non ostante adirati questi Barbari sfogarono la loro rabbia, e furore contro d'alcuni Christiani qui Schiavi. **Brugiandone quattro à fuoco lento**	mà di ciò non ostanti adirati questi Barbari, sfogarono la loro rabbia e furore contro d'alcuni Christiani quì schiavi, **bruggiandone quattrocento à fuoco lento**,
The case of a slave		pero nuestro hermano **Manuel Sanchez** fue arrastrado, y quemado	fra quali **Emanuelle Sanchez**.	frà quali D. **Diego Rovis**,
who for killing a local notable		Y fue la causa, que los dichos Christianos entraron [. . .] **y a uno de los susodichos le hirió muy mal herido**, y era uno de los estimados en el Palacio, y murió dentro de tres horas,	E la cagione di sì rigoroso castigo fù, perche [. . .] il detto Emanuelle Sanchez **ferì d'una coltellata uno delli Infedeli** de più amati del Divano, il quale dalla ferita morì,	e la cagione di sì rigoroso castigo fù, perché [. . .] il detto D. Diego Rovis **ferì d'una coltellata uno delli Infedeli** più amati del Divano, il quale dalla ferita morì,

Appendix 1A (continued)

is arrested, dragged by horse to the execution ground	y los dichos Christianos fueron presos rigurosamente [. . .] y el dicho Hermano Manuel Sanchez fue arra[st]rado por toda la Ciudad [. . .]	per lo che essendo tutti fatti prigionieri [. . .] il detto Emanuelle Sanchez, essendo stato tirato à coda di Cavallo per la Città [. . .].	per lo che, essendo tutti fatti prigioni [. . .] il detto D. Diego Rovis, essendo tirato à coda di Cavallo per la Città [. . .].
and finally stabbed to death with a spear.	Pero en esta ocasion se halló, y le fue siguiendo las calles Fr. Francisco Garcia [. . .] pero uno de los verdugos con una lança le passó el cuerpo, y no murió tan presto [. . .].	E però vero, che l’accompagnò sempre consolandolo per le strade F. Francesco Garzia [. . .] poi finalmente da uno de’ Carnefici con una lancia fù trafitto, subitamente morì [. . .]	E’ però vero, che l’accompagnò sempre consolandolo per le strade il Padre Francesco del Migno [. . .] poi finalmente da uno de Carnefici con una lancia fu trafitto, e subitamente morì [. . .]
Oubreak of plague, another earthquake, many victims	**Al siguiente dia** Martes, que se contaron diez de Enero, **embió Dios el Contagio**, con que **ha padecido gran numero de gente**.	**il seguente giorno** primo di Maggio **si sparse per la Città un morbo contagioso** dal quale **morì gran numero di persone**.	**il seguente giorno successe per la Città un gran Terremoto**, nel quale **morì il numero di vintimilla persone**.

Appendix 1B Pamphlets wich follow the literary scheme "B"

	Tripoli 1685 Jan 16	Tripoli 1685 May 16	Tripoli 1694 Sep 5
Frontispiece	Tripoli li 4 Febraro 1685 Distinto Ragguaglio Gionto per lettera particolare all'Altezza Serenissima del Gran Ducato di Toscana, da un Vascello mercantile arrivato nel Porto di Livorno.	Tripoli 16 Maggio 1685 Distinto Ragguaglio Gionto per Lettera particolare ad un mercante Nel Porto d'Ancona.	Verissima Relatione Venuta dalla Città di Tripoli di Barbaria. Dove s'intende il grandissimo Terremoto, & le Comete apparse e le Ruine succese in quella Città, con la morte di 15 mille Turchi, e come si sono vendicati contro li Christiani. Seguita li 5 Settembre.
Printer, printing date/place	In Fiorenza, Torino, & Milano Nella R.D.C. per Marc'Antonio Pandolfo Malatesta Stampator R.C.	In Roma, & in Bologna, per l'Erede del Sarti.	In Venetia, 1694.
Sub-title	Distinto Ragguaglio seguito li 16 Genaro, 1685.	Distinto Ragguaglio. Seguito li 16 Maggio 1685.	Relatione venuta dalla città di Tripoli di Barbaria. Seguita li cinque settembre.
Introduction	So che il Ragguaglio de' castighi dal Sommo Iddio mandati in questa famosa Città di Tripoli cagioneranno alle vostre Signorie non poco timore, e compassion [. . .].	So che il Ragguaglio de' castighi dal Sommo Iddio mandati in questa famosa Città di Tripoli cagioneranno alle vostre Signorie non poco timore, e compassione [. . .].	So' che il Ragguaglio de' Castighi dal Sommo Iddio mandati in questa famosa Città di Tripoli cagioneranno alle vostre Signorie non poco timore, e compassione [. . .].
Forewarnings of following calamities	Il giorno **16 di Genaro dell'Anno presente 1685** s'udirono in questa Città i preludij delle rovine, che dovevano seguire [. . .].	Il giorno **16 Maggio dell'Anno presente 1685** s'udirono in questa Città i preludij delle rovine, che dovevano seguire [. . .]	Il giorno **5 Settembre dell'Anno presente 1694** s'udirono in questa Città i preludij delle rovine, che dovevano seguire [. . .].
Comets and astral signs	il giorno **23** sudetto si sono vedute apparir trè famose Comete d'aspetto terribile, la prima comparve alle hore due di notte, e durò sino alle 5, e svanita questa, si vidde una gran mutatione di tempo [. . .].	il giorno **23** sudetto si sono vedute apparir trè famose Comete d'aspetto terribile, la prima comparve alle hore due di notte, e durò sino alle 5, e svanita questa, si vidde una gran mutazione di tempo [. . .].	il giorno sudetto si sono vedute apparire trè famose Comete d'aspetto terribile, la prima comparve alle due hore di notte, e durò sino alle cinque, e svanita questa, si vidde una gran mutatione di tempo [. . .].

Appendix 1B (continued)

Christian slaves pray	Stettero quei miseri Schiavi tutta quella notte, pregando **caramente** la Beatissima VERGINE, che volesse intercedergli gratia dal suo carissimo Figlio GIESU di non voler gettare i suoi fulmini contro di loro, come così successe.	Stettero quei miseri Schiavi tutta quella notte, pregando **caramente** la Beatissima VERGINE, che volesse intercedergli gratia dal suo carissimo Figlio GESU' di non voler gettare i suoi fulmini contro di loro, come così successe.	Stettero quei miseri Schiavi tutta quella notte, pregando divotamente la Beatissima Vergine Maria, che voleese intercedergli gratia dal suo Carissimo Figliuolo Giesù Christo di non volere gettare i suoi fulmini contro di loro, come così successe.
Storm	Sù'l far del giorno si cominciò ad oscurar talmente, che pareva si fosse mutato da giorno in notte, e poi venne una gran pioggia accompagnata da una terribilissima tempesta, che ruppe tutti li Tetti delle Case, & uccise più di cinque milla di quei Barbari [. . .].	Sù'l far del giorno si cominciò ad oscurar talmente, che pareva si fosse mutato da giorno in notte, e poi venne una gran pioggia accompagnata da una terribilissima tempesta, che ruppe tutti li Tetti delle Case, & uccise più di cinque milla di quei barbari [. . .].	Sù'l far del giorno si cominciò ad oscurar talmente, che pareva si fosse mutato da giorno *in una oscurissima* notte, e poi venne una gran*dissima* pioggia accompagnata da una terribilissima tempesta, che ruppe tutti li Tetti delle Case, & uccise più di cinque milla di quei Barbari [. . .].
An earthquake destroys 200 Houses and Mosques	Il giorno seguente abbattè il Terremoto più di ducento Case, e frà queste le trè le più famose Moschee, che sono soliti orare questi falsi Maomettani.	Il giorno seguente abbattè il Terremoto più di 200 Case, e frà queste le trè le più famose Moschee, che sono soliti orare questi falsi Maomettani.	Il giorno seguente abbattè *à terra* il Terremoto più di doicento Case, e frà queste trè le più famose Moschee, che sono soliti Orare questi falsi Maomettani.
Moral consideration: prayers averted calamities.	E certo sarebbe sobissata tutta la Città, se non fosse stato i prieghi di quei miseri Schiavi Christiani, che in vedere sì grande spettacolo la compassion li mosse à pregare DIO nostro Signore che ci liberi da simili castighi.	E certo sarebbe subissata tutta la Città, se non fosse stato i prieghi di quei miseri Schiavi Christiani, che in veder sì grande spettacolo la compassion li mosse. **DIO nostro Signore ci liberi da simili castighi**.	E certo sarebbe subissata tutta la Città, se non fosse stato i preghi di quei miseri Schiavi Christiani, che in vedere sì grande spettacolo la compassione li mosse à pregare Dio Nostro Signore che ci liberi da simili castighi.
Wrath of local people against slaves	Mà non sapendo in che modo sfogare la loro Barbara crudeltà, si mossero a tormentare quei poveri Schiavi, che in breve tempo ne fecero morir più di cinquecento,	Mà non sapendo in che modo sfogare la loro Barbara crudeltà, si mossero a tormentare quei poveri Schiavi, che in breve tempo ne fecero morir più di cinquecento,	Ma non sapendo in che modo sfogare la loro Barbara crudeltà, si *missero* a tormentare quei poveri Schiavi, che in breve tempo ne fecero morire più di cinquecento,

The case of a slave	e frà questi vi fù un povero **Giovanni Dericos** [. . .].	e frà questi vi fù un povero **Giovanni Dericos** [. . .].	e frà questi vi fù un povero **Giovane** [. . .].
who is emprisoned, sentenced to death, dragged by horses through the city	fu carcerato in compagnia di molti altri, che *à tal ufficio attendevano*, alla fine del mese furono sententiati, & si esseguì il castigo, il quale fù rigoroso al detto **D. Gioanni Dericos**, essendo tirato à coda di **Barbari** [English “**Barbs**”] per la Città [. . .].	fu carcerato in compagnia di molti altri, che *à tal ufficio attendevano*, alla fine del mese furono sententiati, & si esseguì il castigo, il quale fù rigoroso al detto **D. Gioanni Dericos**, essendo tirato à coda **di Cavallo** per la Città [. . .].	fu carcerato in compagnia di molti altri, *che à tal ufficio attendevano*, alla fine del Mese furono sententiati, e si esserquì il castigo, il quale fù rigoroso al detto Giovane, essendo tirato à coda di **Cavallo** per la Città [. . .].
and finally executed by lapidation together with one of the clerics assisting him.	Fù assistito da due famosi Religiosi, che accompagnandolo ricevettero ancora loro molti pugni, e calci [. . .]. Giunto con salutevoli sospiri al luogo da loro destinato per il di lui *martirio*, e fu fatto bersaglio di quella Barbara natione per le sassate dateli, come pur restò feritò di colpo mortale uno de’ sudetti Religiosi, e con questo rese l’Anima à Dio il povero.	Fù assistito da due famosi Religiosi, che accompagnandolo ricevettero ancora loro molti pugni, e calci [. . .]. Giunto con salutevoli sospiri al luogo da loro destinato per il di lui *suplitio*, e fu fatto bersaglio di quella Barbara nazione per le sassate dateli, come pur restò feritò di colpo mortale uno de’ sudetti Religiosi, e con questo rese l’Anima *al Cielo* il povero.	Fù assistito da due famosi Religiosi, che accompagnandolo ricevettero ancora loro molti pugni, e calci [. . .]. Giunto con salutevoli sospiri al luogo da loro destinato per il di lui *supplicio*, e fu fatto bersaglio di quella Barbara Natione per le sassate dateli, come pur restò feritò di colpo mortale uno de’ sudetti Religiosi, e con questo rese l’Anima à Dio il povero **Giovine**.
A powder-magazin ignited by lightning blows up the fourth part of the city with thousands of victims.	Nel ritorno che facevano quella gente, da sì crudel *carneficina* caddè un folgore nel Magazeno della polvere, che fece saltare in aria la quarta parte della Città, con tutto quel Popolo, che aveva *martirizzato* il povero **D. Giovanni**, che ascendono al numero di **otto** milla.	Nel ritorno che facevano quella gente, da sì crudel *carnificina* cadè un folgore nel Magazeno della polvere, **che ve n’era più di cinquecento barili**, che fece saltare in aria la quarta parte della Città, con tutto quel Popolo, che aveva *martirizzato* il povero **D. Giovanni**, che ascendono al numero di **15** mila.	Nel ritorno che faceva quella gente, da si crudel *martirio* caddè un fulgore nel Magazeno della polvere, **che ivi era più di cinquecento barili**, che fece saltare in aria la quarta parte della Città, con tutto quel Popolo, che aveva tormentato il povero **Giovane**, che ascendono al numero di **quindeci** milla.

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Assimismo se dà noticia de las cometas que aparecieron en la Ciudad de Argel, y las ruinas y lastimosos sucessos que causaron en dicha Ciudad en la distancia de cinquenta leguas, que destruyó la Magestad de Dios N.S. docientos y quatro Lugares, y la crueldad que hizieron los Barbaros con unos Christianos. Dase quenta de las cometas y lo que sucedió en la Ciudad de Argel, sacado de una carta que vino de dicha Ciudad. En Sevilla 1668.

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Part III

Case Studies, New Data and Critical Analysis

The Case for Large (M > 7) Earthquakes Felt in the UK in Historical Times

R. M. W. Musson

Abstract Evidence from seismic and bathymetric surveys along the passive margin of NW Europe indicates that there are a number of features suggestive of large earthquakes having occurred in geologically recent times, although the exact timing of these events is difficult to establish. It might be thought that, although such large earthquakes may have occurred, for example, in immediate post-glacial times in response to rapid isostatic readjustment, no earthquake in the UK area in historical times has exceeded a value of around 5.7 Mw. However, in past interpretations of regional seismicity, the possibility that some known historical earthquakes were in fact passive margin events has not really been canvassed. A large, distant, offshore earthquake is likely to be felt only at moderate strength over well-populated areas without any observable damage concentration. In a period when documentation of earthquakes is always sparse, such an occurrence is likely to lead to vague reporting that will not be easily interpretable. Looking at the historical record with this in mind, it is possible to identify some earthquakes that are at least compatible with an offshore interpretation, as shown in a series of case studies. However, in no case is such an interpretation the only one viable. Also, some cases that initially appear to be potentially passive margin events can in fact be discounted. While there is no unequivocal evidence for large earthquakes having occurred on the NW European passive margin in historical times, neither can the possibility be rejected, and examination of the record shows one event in particular (in 1508) which may be a large passive margin event. Thus the regional maximum magnitude could possibly be larger than has hitherto been assumed.

Keywords Passive margins · historical earthquakes · maximum magnitude · seismic hazard · offshore earthquakes · water fluctuations.

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1 Introduction

The issue of maximum credible magnitude, important in seismic hazard analysis, has always been a difficult subject to handle in intraplate areas, where the seismic cycle is longer than the historical record. In this paper the issue of the possibility of large earthquakes in the UK is examined, with particular emphasis on the possibility that such a large earthquake may actually have occurred in historical times without being recognised from the earthquake record.

In considering this topic in the general sense, the occurrence of large (~ 7 Mw) earthquakes in quiet seismic areas (such as the 1989 Tennant's Creek, Australia earthquake or the 1993 Latur, India earthquake, to name but two) naturally raises speculation as to whether such events can occur in other low seismicity areas. The estimation of maximum magnitude cannot proceed on the basis of fault length, since the existence of ancient major faults (like the Great Glen Fault in Scotland) does not mean that these faults could reactivate along their whole length in a major earthquake in present day tectonic circumstances, quite different from those of the time they formed. One approach is through palaeoseimic investigation (e.g. (Camelbeeck and Meghraoui, 1996, 1998), (Camelbeeck et al., 2001)) though this can be difficult in glaciated areas. Attempts at palaeoseismic studies in Scotland (Davenport and Ringrose, 1985; Fenton and Ringrose, 1992) have been considered unconvincing by Stewart et al. (2001).

Examining the historical record for the British Isles, Ambraseys and Jackson (1985) write:

> The seismicity of the UK is clearly different from that of eastern USA or W Africa in that either (i) no earthquakes of $M \geq 6.0$ occur, or (ii) 700 years is not long enough to reveal such events in the UK, whereas 100 years is more than adequate in the eastern USA and W Africa. . . . Is there anywhere on the continents seismically quieter than the UK?

In some respects the comparison is unfair, since the eastern USA is over four times as large as the UK, and western Africa is larger still. One could easily find parts of the eastern USA or western Africa of equivalent size to the UK that have comparable or lower levels of seismic activity.

Nevertheless, the lack of even moderately large earthquakes with onshore epicentres in Britain is rather striking. Taking the period 1570–2005 one can distinguish eighteen events of magnitude 5.0–5.4 ML in Britain with epicentres onshore or just offshore to the west (i.e. excluding events in the North Sea and English Channel). The number of events larger than 5.4 ML in the same area is zero. The Gutenberg-Richter b value that one would derive from earthquakes ≥ 5.0 ML in this area (admittedly eighteen is a very small sample) is 1.8. However, in the same period, there are four earthquakes > 5.4 ML in the English Channel and North Sea (south of 60 °N). If one assumes that there is no difference between Great Britain and the offshore extension to the south and east as regards producing earthquakes larger than 5.4 ML, then the probability of all four larger events occurring in the offshore area by chance is about 0.015.

Before 1570 it is very difficult to estimate magnitudes. Thus some medieval earthquakes such as 20 February 1247 and 11 September 1275 were most likely over 5 ML, but it would stretching slender evidence to attempt to categorise whether they were larger than 5.4 ML (Musson, 1994).

On the available information, therefore, it does appear that there is a significant lack of earthquakes of 5.5 ML and over in mainland UK in the last 400 years (this is about 5.2 Mw). The purpose of this paper is to explore the possibility that there may actually be much larger earthquakes in the historical record of the UK, but which are hard or impossible to recognise because they have offshore epicentres. The reader is warned in advance that much of this paper is highly speculative. Given the difficulty of the subject matter this is unfortunately inevitable.

2 Passive Margin Seismicity

The first comprehensive study of intraplate seismicity worldwide, with a view to distinguishing areas most at risk from unexpectedly large events, was made by Sykes (1978). After a lengthy review of global intraplate seismicity, he concluded that a particular locus of large-magnitude intraplate events was on the passive margins of continents. He particularly considered that the intersection of passive margins and oceanic transform fracture zones marked locations of concern. He argued that such fracture zones initiated at the earliest stages of oceanic rifting at the sites of pre-existing weaknesses in the continental crust, and that these weaknesses continued to act as possible earthquake sources even when oceanic rifting was well advanced.

A subsequent major study of worldwide intraplate seismicity was commissioned by the Electric Power Research Institute in the US, which confirmed Sykes's findings that passive margins are significant, but without the emphasis on the intersection with oceanic fracture zones (Johnston et al., 1994). In a summary in Johnston (1989), it is noted that

> Of [the] eight largest SCI [Stable Continental Interior] earthquakes, seven occur at passive margins or in extended crust resulting from margin formation.

A classic example is the 18 November 1929 Grand Banks earthquake (7.2 Mw). This occurred off the coast of Newfoundland in an area with no previous or subsequent seismicity barring aftershocks of the 1929 earthquake itself. The earthquake triggered a large submarine slide on the continental slope, which in turn produced a damaging tsunami which killed 28 (Smith, 1966; Stewart, 1979; Fine et al., 2005). It was also widely felt over the onshore area (Smith, 1966). Sykes (1978) notes that the epicentre is near the intersection of the passive margin with the Newfoundland Fracture Zone.

This raises two questions with respect to north-west Europe: could an earthquake similar to the 1929 Grand Banks earthquake occur on the north-west European continental margin? And is there any evidence that such a thing might have occurred already? The question is particularly pertinent given recent concerns about whether tsunami warning systems should be implemented in the North Atlantic in the wake of the 26 December 2004 Sumatran earthquake (Kerridge, 2005).

3 Geological Evidence for Large Passive Margin Earthquakes Near Britain

That significant earthquakes have happened on the north-west European margin at some time in the past has already been mooted in the literature with regard to the triggering of submarine slope failures (Paul and Jobson, 1987; Baltzer et al., 1998; Holmes et al., 1998; Jackson et al., 1999). Submarine landslides are common features along passive margins (Embley and Jacobi, 1977; Embley, 1982; Mienert et al., 2003; Canals et al., 2004; Hühnerbach et al., 2004) and at least fifteen large slides or mass flows can identified along the NW European margin from 50 °N to 70 °N, including the massive Storegga slide (Bugge et al., 1987; Mienert and Weaver, 2003) as shown in Fig. 1. That large submarine slides may be due to earthquake triggering is well known (Hampton et al., 1996); the case of 1929 Grand Banks has already been mentioned, and some other cases are reviewed by Embley (1982). In the case of Europe, the relationship between seismicity and slides is ambiguous; it is suggested by Mienert et al. (2003) that earthquake triggering may not be the most important reason for slides. One other mechanism that has been suggested, for instance, is that slides may be triggered by escape of gas hydrates (Bugge et al., 1987; Vogt and Jung, 2002). Recent studies, though, incline towards viewing earthquakes as the most likely external triggering factor (Canals et al., 2004; Sultan et al., 2004). Holmes et al. (1998) consider that earthquakes may have triggered slide movements on the Barra Fan, and Baltzer et al. (1998) conclude that at least one earthquake (probably just before or during the early Devensian, i.e. around 70,000 years BP) was responsible for triggering the debris flows of the Sula Sgeir Fan. Strachan and Evans (1991) consider that earthquake triggering was the most likely explanation for the sediment failure below the Geikie escarpment. (These locations are close together; only the Geikie Escarpment is named on Fig. 1.)

The discussions of seismicity in these references unsurprisingly make most reference to known modern seismicity in the area, which is limited and of small magnitude. The existence of a few events like the 13 April 1980 Hebrides Terrace Seamount (4.0 mb) shows that the area is not entirely aseismic (Jacob et al., 1983). Paul and Jobson (1987) estimate that an earthquake of magnitude 6 could have caused failure on the Hebrides slope. Baltzer et al. (1998) then go on to say that a magnitude 6 might have taken place during times of major isostatic adjustment (i.e. the early Devensian). This is no doubt a sound argument; but by analogy with other passive margins, and given a long period of observation, it is not actually necessary to invoke greater isostatic adjustment in order to allow for the possibility of a large earthquake. The same is true of some the examples discussed in the COSTA Project (Canals et al., 2004); seismicity is considered to be strongly indicated as a causative factor in several examples, and where examination of modern

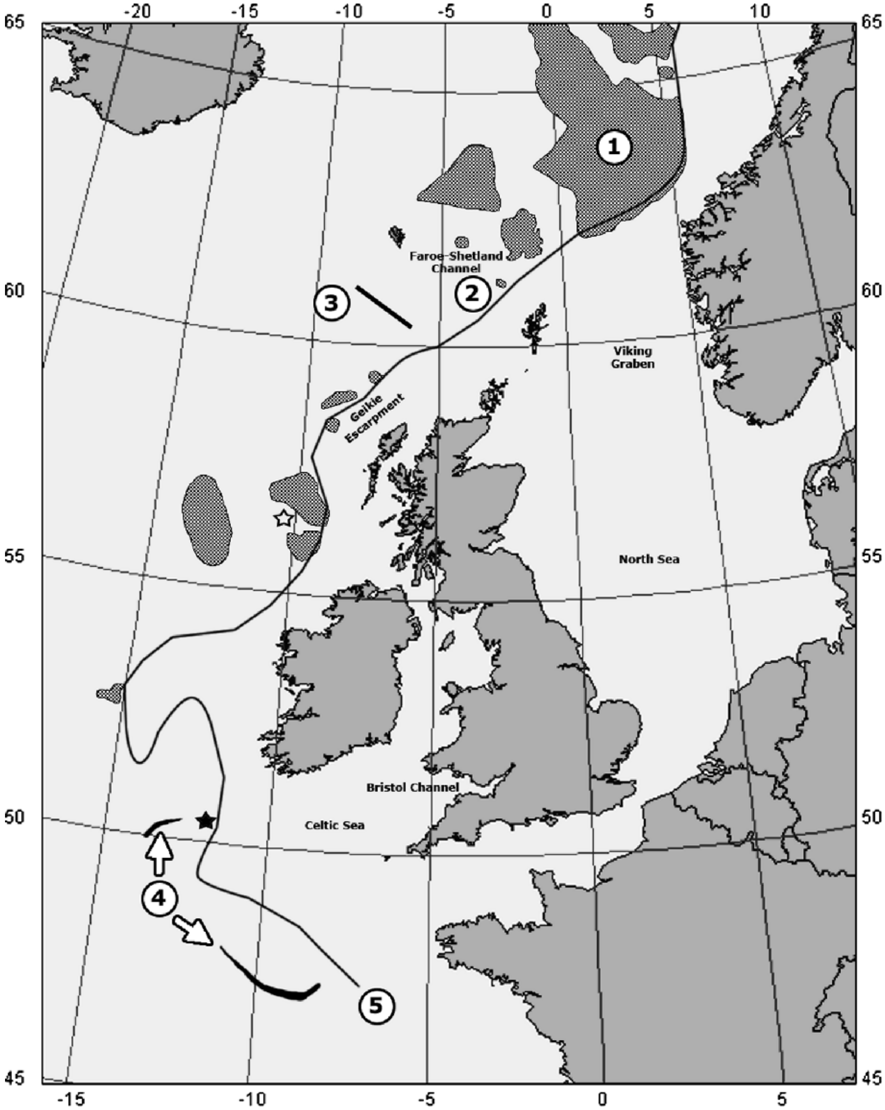

Fig. 1 Regional map showing principal geological features referred to. Stippled area marks extent of major submarine slides. 1: Storegga slide; 2: Afen slide; 3: Approximate position of fault on north side of Wyville Thompson ridge; 4: Areas of late or post Eocene compression; 5: Approximate location of edge of continental shelf (incompletely shown). White star: location of the Hebrides Seamount earthquake of 13 April 1980. Black star: location of earthquake of 17 February 1980

and historical data shows very low activity, it is suggested that seismicity may have been elevated in immediate post-glacial times. In fact, rare passive margin earthquakes are a possible factor even in periods where seismicity is not elevated as a result of deglaciation.

The most recent of these slides is probably the Afen Slide in the Faroe-Shetland Channel, which is not older than about 2880 years BP (Wilson et al., 2003, 2004), putting it within range of the historical period, though of course accurate dating is not possible. The morphology of the slide suggests that it was due to triggering by an earthquake, possibly associated with the Victory Transfer Zone (Canals et al., 2004; Sultan et al., 2004; Wilson et al., 2004), and an attempt has been made to model the effects of earthquake loading on slope stability in the area (Jackson et al., 2004).

Thus the existence of the various slides shown in Fig. 1 is evidence in favour of large earthquakes having occurred on the passive margin at least some time in the past.

Two other pieces of evidence can also be cited. The first is the existence of two deformation ridges off the continental slope south-west of the Celtic Sea. These were first shown by Masson and Parson (1983) and are also marked on Fig. 1. The southern feature is described by Masson and Parson (1983) as a complex faulted monocline, with crustal shortening accommodated by two zones of reverse faulting. Superficially, they resemble coseismic ridges which can develop in cases where faulting does not break through the surface in a fault scarp, as in the case of the Reelfoot Scarp, which was created by the 1812 New Madrid earthquake in Tennessee (Russ, 1979). They could therefore reflect large earthquakes. They are not easy to date. Masson and Parson (1983) consider that they must be later than the Early to Middle Eocene boundary. It has been suggested that they may be later than this (Tate, 2005, pers. comm.) but this is unproven.

The second is the existence of an apparent sea-floor-cutting fault on the northern flank of the Wyville-Thompson Ridge (Tate et al., 1999). This is shown on a seismic section (Figure 3 in Tate et al., 1999) as a steep, south dipping fault cutting the sea bed. Uplift of the Wyville-Thompson Ridge started in the late Eocene and continued intermittently throughout the Oligocene, and possibly until Recent times (Tate et al., 1999). This north-bounding fault is possibly the only known instance of seabed fault displacement in UK waters, and it does rather suggest palaeoseismic evidence of a large earthquake. Precise dating is not possible; it may be recent, but this is debatable. Other faults have been identified in the vicinity of the Afen Slide, with offsets of several metres, displacing Quaternary sediments and occasionally reaching the sea floor (Canals et al., 2004).

To sum up: it is probable, from physical evidence, that large earthquakes have occurred on the NW European passive margin, at least since Devensian times, and possibly more recently. The remainder of the paper will address the possibility that such an event may actually have occurred in historical times, and that such a large earthquake may be sitting in published earthquake catalogues without anyone having been able to recognise it.

4 Likely Effects of a Large Offshore Earthquake

We can begin by considering what might be expected to be observed and reported if a large earthquake occurred on the NW Europe passive margin, similar in magnitude to the 1929 Grand Banks earthquake. In Fig. 2, estimated isoseismals are plotted for such an event, based loosely on the isoseismals of the 1929 Grand Banks event (Smith, 1966) evened out to remove ellipticality, and with a notional epicentre near the Geikie Escarpment on the edge of the Hebrides Shelf. Obviously, actual isoseismals could vary in different ways, and these are intended only to be indicative. If such an earthquake were to have occurred in the late modern period when communications were good, one might expect the isoseismals would be such as could be reconstructed quite well from macroseismic data, as has been the case with other large British earthquakes. However, the impact on the historical record in earlier centuries could be expected to be different.

The area over which damage would be observed, within the isoseismals 6 and 7 EMS (European Macroseismic Scale), are in the remote north and north-west of Scotland. In this area, before the 18th century, the population consisted of subsistence farmers who spoke Gaelic rather than English, and were illiterate. The Gaelic language in Scotland never had a literary tradition in the way that other Celtic languages such as Welsh and Irish did have. Communications with the rest of Britain were very poor; there were no roads until the 18th century when the first roads into the Scottish highlands were built for military purposes. Thus, no information could be expected to come out of this area about the damage that occurred.

This can be illustrated by the case of the earthquake of 8 November 1608. A plot of places from which reports exist (Fig. 3) shows a dramatic divide along the "Highland Line" – the geological divide between the mountain country of the north of Scotland and the lowlands of the Central Valley. South of this line there are many reports; to the north there are none. This is nothing to do with the distribution of earthquake effects, but entirely to do with the distribution of literacy.

Returning to Fig. 2, over the rest of the British Isles the shaking would vary from strong (5 EMS) but not damaging in the Scottish cultural centres (Stirling, Edinburgh, St Andrews, Glasgow) to weak (3 EMS) over most of the wealthiest (the southern) parts of England.

Therefore, for the period before the 17th century (and one might except the later 16th century as well) the sort of report that one might *expect* to survive would be along the lines of information that an earthquake was felt over a very wide area, but without any description of effects such as damage (since there would be no notable effects in the areas from which one might expect reports to come). One might also find it reported that the earthquake was stronger in Scotland; however, generally historical reporting is less good for Scotland than it is for England, partly due to the loss of documents in the violence of the Scottish Reformation.

In fact, there are a number of earthquakes that more or less meet this description, especially for the medieval period. Clearly, though, in the case of an earthquake that is mentioned in chronicles as "felt throughout England" with no further detail,

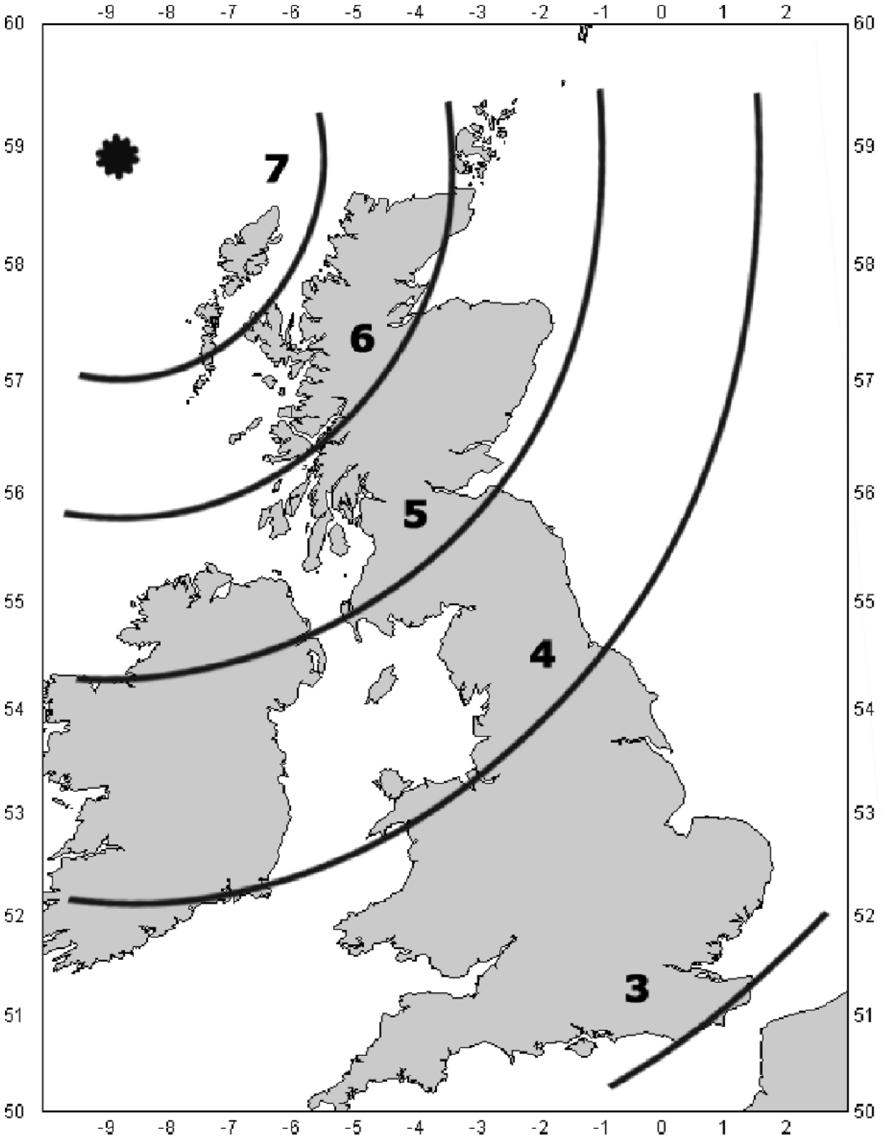

Fig. 2 Likely extent of isoseismals from a 7 Mw earthquake located on the edge of the Hebrides Shelf

there are plenty of alternative explanations, including (a) that the epicentre was in a remote part of England or Wales; (b) that the chronicler felt it not worth mentioning that the cottages of mere peasants were thrown down; (c) "throughout England" is an exaggeration for "here and in the next town as well".

In the next section some particular case studies are considered in detail (see Table 1).

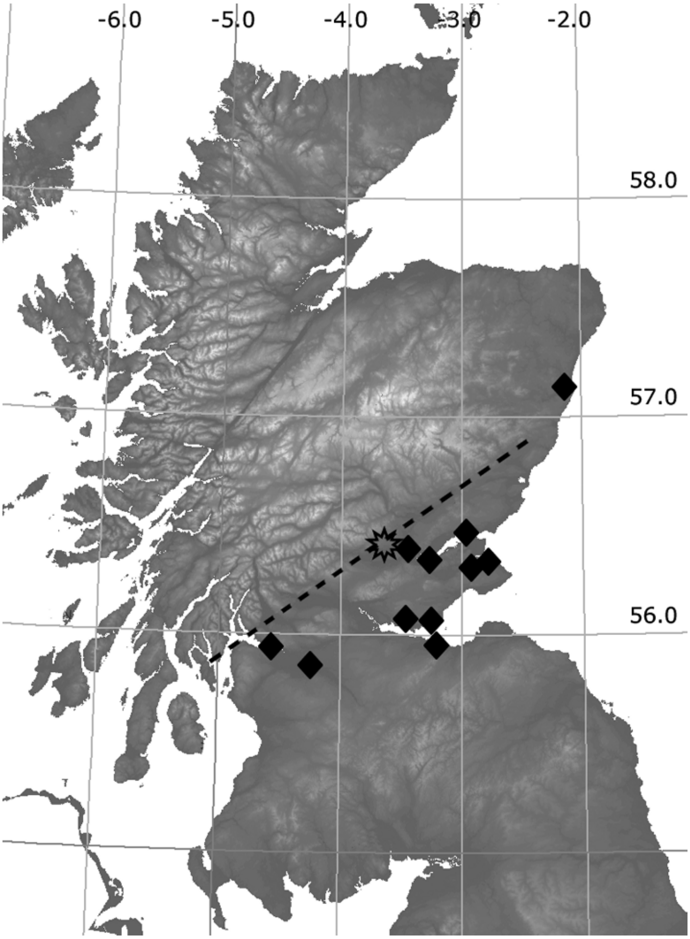

Fig. 3 Distribution of felt reports of the 8 November 1608 Comrie earthquake in relation to topography. The *dashed line* indicates the "Highland Line", which also coincides with the Highland Boundary Fault. The only place to the north of this from which the earthquake is reported is Aberdeen, which lies in the English-speaking lowlands *east* of the Gaelic-speaking Highlands. *Star* indicates the position of the epicentre

Table 1 Synopsis of case studies

Date	Entry in Musson (1994)	Revised conclusion
11 August 1089	England, probably > 4ML	No change
19 September 1508	Viking Graben?	Possibly passive margin event
20 January 1607	Not considered	Not an earthquake
1686	Not considered	Epicentre near St Kilda, probably > 3.5 ML
23 May 1847	Below magnitude threshold	No change

5 Case Studies

It is all too easy, in considering a subject such as this, to extend an idea too far and start to interpret all obscure earthquake reports as possible large distant events, when there are much more straightforward explanations that don't require large earthquakes.

A general consideration is the difficulty of interpreting any historical offshore earthquake from sparse macroseismic data on a single coast. In the absence of other information, one can usually posit either a small earthquake just offshore, or a larger one further out to sea, and there may be no constraints on how one interprets this other than the general rule that small earthquakes are inherently more common phenomena than large ones. In assigning epicentres to historical offshore earthquakes in the UK earthquake catalogue (Musson, 1994), the standard practice was to adopt the closest credible epicentre to shore and thus the smallest probable magnitude.

An interesting case in point is the earthquake of 4 January 1879. This was weakly felt on the island of Unst, which is the most northerly of the Shetland Isles. This was the only place in the UK where it was felt, but it was also felt in Norway (Kolderup, 1913) at Flesje, on the other side of the North Sea. We can thus be certain that this was a moderately large earthquake between Shetland and Norway, most likely in the Viking Graben, and with an estimated magnitude of around 4.8 ML. Now, there are also a number of other reports of earthquakes felt only on Unst at around the same period, and these are not matched with Norwegian records. Are these other largish events in the North Sea which were less strong to the east? Or similar events to the north or west of the Shetlands? Or small local earthquakes? It is not possible to tell, although given that seismicity in the Viking Graben and South Møre Basin is much greater than any other seismicity in the area, one is inclined to suspect that these solitary reports from the Shetlands (often from lighthouses) represent earthquakes > 4.5 ML at some distance to the east and north-east of the point of observation.

5.1 11 August 1089

This earthquake will stand for some other medieval cases. Like so many medieval events in the UK, the available information is brief and unsatisfactory. The account in the Anglo-Saxon Chronicle (Ingram, 1823), one of the major sources of information for the 11th century, reads

> There was also over all England much earth-shaking on the third day before the ides of August. . .

The fullest account is by the chronicler William of Malmesbury (Stevenson, 1853–1856), who writes:

> . . . a great earthquake terrified all England with a horrid spectacle; for all the buildings were lifted up, and then settled again as before.

The same information from these two accounts is repeated with some minor variation in various other chronicles, evidently with much copying. These include the two surviving monastic chronicles from Scotland, the Holyrood Chronicle (Anderson, 1938) and the Melrose Chronicle (Stevenson, 1839). The significance of this is open to question. The MS source of the Holyrood Chronicle is 13th century, and the entries for the 11th century need not reflect local information. The Holyrood entry is very terse. The entry in the Melrose Chronicle reads,

> There occurred a very great earthquake throughout the whole of England about the third hour of the day.

The Melrose Chronicle is only a contemporary narrative after 1172, and for the 11th century it is clearly based on English sources. Thus one notes that the "whole of England" is mentioned without any reference to Scotland.

All one has for this earthquake, therefore, is that it was widely felt throughout England, and buildings were shaken but not (so far as is noted) damaged. The mention in two Scottish chronicles is inconclusive, as the transmission into these two sources is most likely just a product of the copying of English sources without regard for local interest. This does not rule out the possibility that the earthquake was indeed also felt in Scotland.

This earthquake is thus more or less consistent with Fig. 2, and so are a number of other medieval events that are similarly reported. In this particular case, the use of words like "great" and "terrified" suggest higher intensities in England than are shown in Fig. 2. It could be speculated, though, that in the case of a large, distant earthquake, long-period effects on castles and cathedrals and other monumental structures could produce alarm even at considerable distances.

Of course, there are other possible explanations, and it does not seem possible that one could ever resolve the issue.

For Ireland, there are no mentions of this earthquake in any of the Irish Chronicles. The situation with regard to medieval Ireland should be commented on. In the Annals of Ulster (Balé and Purcell, 2003) there are a number of references to earthquakes before 1000 AD which are the earliest mention of any earthquake in the British Isles. However, given accounts that say no more than "earthquake in Ireland" one cannot be sure whether these really refer to earthquakes as we use the word, since the term was also used for landslides and other similar phenomena. Given the fact that Ireland is one of the most aseismic countries in the world, it would not be surprising if most of these records were actually not earthquakes. It is also not surprising that few other mentions of earthquakes appear at all in the Irish records of the post-millenial period. In fact there are just two. The earthquake of 20 February 1247 is mentioned by both the Annals of Inisfallen (Färber, 2000a) and the fragmentary annals (Färber, 2000b). The former misdates the year as 1249 and states that it was felt in Ireland and Wales; the latter describes it as affecting Ireland, Scotland and Wales. The other Irish earthquake for this period is dated 1269; there are no details, and the source, Dowling's Annals (Butler, 2003) is not contemporaneous.

The 1247 earthquake is the only earthquake before the 19th century that one can say was certainly felt in England, Scotland, Ireland and Wales. It was particularly strong, and even damaging, in Wales, and there seems little doubt that this was a Welsh earthquake and one of the largest known in Wales.

5.2 19 September 1508

The source material for this earthquake has already been published and discussed at length in Musson (2004) and will be summarised only briefly here. There are only three sources, none of them contemporary. Two are Scottish and one is English, and the English one may have used one of the Scottish ones. The combined information yields the following points:

- The earthquake was reportedly felt over all England and Scotland.
- People were much frightened.
- The shock lasted 6 min.
- The earthquake particularly shook churches.

As in the previous case, we have an earthquake with a large felt area, this time explicitly including Scotland as well as England, plus a description of shaking buildings without any mention of damage. It is interesting to note that churches were most affected; this again might be consistent with the effect of long-period shaking on the highest buildings around. It would probably be dangerous to try and read much into the estimate of 6 min duration, as such estimates are usually unreliable. Enormously exaggerated durations ("the shock lasted for half an hour") can be interpreted as referring to the main shock plus several aftershocks. Six minutes is not gross exaggeration, and may be taken as indicating at least that what was perceived was not a short sharp shock – again, consistent with a distant event.

The fact that Scottish sources here have prime place does lead one to infer that the shock was stronger in Scotland than in England. There are not many interpretations that are consistent with the evidence, slender though it is. (Musson, 1994) treats this earthquake as a probable Northern North Sea earthquake, analogous to that of 24 January 1927; this possibility is compared to the passive margin hypothesis in Musson (2004). There is no information forthcoming from Norway, but given the historical period, this is not very likely anyway.

Probably, of all events in the UK earthquake catalogue, this is the one that conforms best to the pattern of Fig. 2. What is missing is any report from Ireland. If it were known that the earthquake had also been felt in Ireland, the implication that this was likely to have been a large passive margin event would be strong. Historical earthquakes in Ireland were investigated 30 years ago by Richardson (1975), and his report does not include any entry for 1508. No more recent search of the Irish archives for earthquake data has been undertaken. Considering known sources for this period, the Annals of Ulster make no mention of any earthquake, but at this period it is a record of raids and deaths of eminent people (Balé and Purcell, 2003).

The same is true of the Annals of Loch Cé (Färber, 2005), the Annals of Connacht (Bambury, 2001) and the Annals of the Four Masters (Ryan, 2002). None of these chronicles mention the Welsh earthquake of July 1534 which was definitely felt in Dublin (Ware, 1662).

5.3 20 January 1607

In January of 1607 a sudden inundation in the Bristol Channel flooded an area of countryside around the town of Burnham-on-Sea to a depth of 3–4 m, and caused damage at Barnstaple, Bridgewater, Bristol, Glastonbury and Kingston Seymour (Horsburgh and Horritt, 2006); South Wales was also affected (Fig. 4). There was some loss of life. It has been suggested (Bryant and Haslett, 2003; Disney, 2005) that this flooding was due to a tsunami, though no earthquake is reported as having been felt on this date. An earthquake is known to have affected Barnstaple and the adjacent area on 12 May 1607 (Musson, 1989) and it would be surprising if this small local event were known and a more generally felt larger one very close in time was not.

Therefore, if this event was a tsunami, it must have been caused by an earthquake sufficiently far offshore not to have been felt in England. One can posit an epicentre

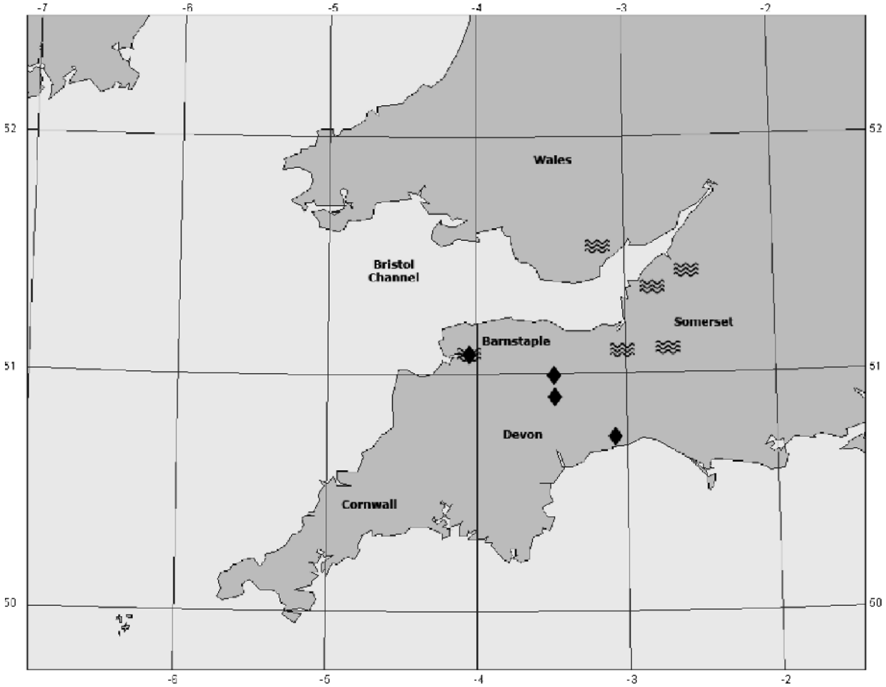

Fig. 4 Water symbol: places affected by the inundation of 20 January 1607. Lozenge: felt reports of the 12 May 1607 Barnstaple earthquake

south-west of the Celtic Sea such that a large earthquake might be felt weakly in south-west Ireland but not elsewhere. And the likelihood of finding felt reports from south-west Ireland at this period is very low.

Furthermore, although the edge of the Celtic sea is a very low seismicity area, one anomalous earthquake has been observed there on 17 February 1980, with a reported magnitude of 4.5 ML (according to the agency LDG - Laboratoire de Détection et de Géophysique, France, as reported in the bulletin of the International Seismological Centre). This seems to show that some structure in this area is capable of reactivation. The event is too poorly recorded for a focal mechanism to be possible. Alternatively, this could possibly be an explosion from underwater disposal of munitions, but the records seen do not suggest that this is likely.

Consequently, one cannot rule out a passive margin tsunamigenic earthquake as impossible on seismological grounds. Whether the 1607 event *was* a tsunami or not is another matter. The alternative is that the inundation was a storm surge. Horsburgh (2006) has shown that contemporary weather records mention prolonged high winds before 20 January 1607, and that other parts of England also suffered from flooding. Tidal conditions for 20 January 1607 can also be calculated, and they were particularly high (Horsburgh, 2006). Thus the conditions were in place for a storm surge event, and consequently there is no need to invoke any tsunami to explain the historical observations.

It is concluded, therefore, that there was no large passive margin earthquake on 20 January 1607.

5.4 1686

The remotest inhabited place in the British Isles used to be the island of St Kilda (it was evacuated in the mid 20th century), 170 km west of the Scottish mainland. In historical times the island was home to a small community of illiterate subsistence farmers who lived almost without any contact with the outside world. Given that the seismicity of mainland Britain is not that well known for the 17th century, it would seem amazing that one could know anything about an earthquake in this period felt on St Kilda, yet by strange chance this is the case.

In 1697 an estates administrator called Martin Martin, an aspiring naturalist with a university education, travelled to St Kilda to make notes on natural history. In the course of his excursion, he learnt from the islanders that they had felt an earthquake in 1686 (Martin, 1716; Musson, 1998). Since Martin worked on the Outer Hebrides, the nearest islands east of St Kilda, and seems to have been unaware of this 1686 earthquake previously, it may be taken that St Kilda was the only place where it was felt. Thanks to the chance visit of Martin to St Kilda, and the fact that he published what he learnt there, we know today, against all odds, that this earthquake took place.

This earthquake presents an extreme case of the coastal problem. The only report is from a speck of an island surrounded by sea, and one cannot tell whether the epicentre was north, south, east or west, never mind how far from shore it was. One can guess it was less likely to be to the east, as this would put it closer to the Outer Hebrides and the mainland.

Clearly this cannot have been a large earthquake of 6 Mw or greater, as then it would certainly have been more widely observed. However, it shows that, despite contemporary aseismicity, the Atlantic waters west and north-west of Scotland have produced earthquakes in the past large enough to be felt. It also shows how much of a lottery is the preservation of historical records of such events.

5.5 23 May 1847

In the course of the 19th century, a number of anomalous tidal fluctuations in the south-west of England were reported, some of which resemble weak tsunamis, and which were considered to be earthquake-related at the time. These were particularly chronicled by Richard Edmonds (Edmonds, 1846, 1856, 1860, 1869) and all have recently been listed and reviewed by Dawson et al. (2000). Some of these may be due to storm surges. It is curious that so many are reported from Cornwall and yet not from south-west Ireland or from Brittany.

One such event will be considered in detail here, which is particularly significant as it was accompanied by an actual earthquake report. This is the event of 23 May 1847. On this day strange tidal fluctuations were observed along the coast of Cornwall and Devon, as far east as Plymouth and also in the Scilly Isles. The maximum amplitude was from 1.0 to 1.6 m (Edmonds, 1869). In the Scilly Isles a strange noise was heard, as if underground (Falmouth Packet 5 June 1847 p8). The previous evening a slight earthquake was felt by many people in the Penzance district (Falmouth Packet 29 May 1847 p8).

This is another case of an offshore event where one has a choice between adopting a small near-shore solution or a larger event further away. How close to the Scilly Isles was the epicentre? The very fact of a marine disturbance makes a small near-shore earthquake less likely. The generally flat bathymetry of the coastal waters around England make slumping-induced events unlikely, so either the marine disturbance was not seismic, or the earthquake was probably distant, and therefore fairly large. One can hypothesise a large earthquake on the passive margin south-west of the Celtic Sea with an elliptical felt area that reached to the Scilly Isles without touching Ireland or France (Fig. 5).

There are still two problems. The first is the Penzance earthquake the night before, which appears must have been a local event the timing of which just before a larger offshore earthquake was complete coincidence. This is the solution proposed by Musson (1989). The other is the duration of the marine disturbance. According to Edmonds (1869) the fluctuation began as early as 05 h near Penzance, reached a peak at 17 h, and at Plymouth did not peak until between 20 h and 21 h. This duration is too long to be credible for a tsunami. Even if, say, the time of the onset was misreported, the fact that the disturbance continued all day with varying magnitude and peaked late, rather than peaking with one of the first waves, is inconsistent

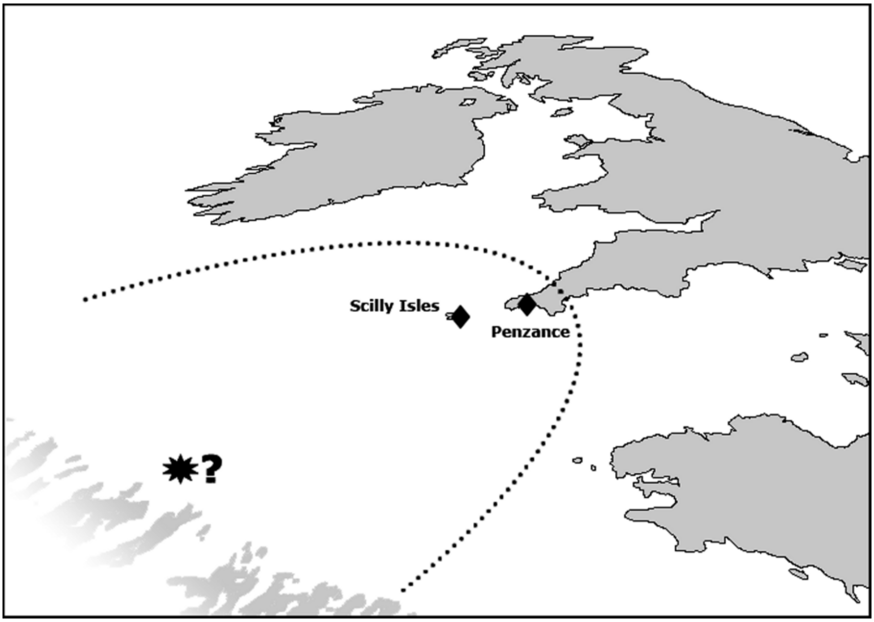

Fig. 5 Sketch showing a notional (and not very likely) reconstruction of the 23 May 1847 event. Stippled area is the continental slope; lozenges indicate earthquake felt reports

with what one expects from a tsunami and suggests instead some meteorological phenomenon. In this case, *both* earthquake reports are coincidences.

What happened on 23 May 1847 is thus enigmatic.

6 Discussion and Conclusions

From what is known about patterns of intraplate seismicity, the possibility of a large earthquake on the passive margin of north-west Europe has to be considered. Physical evidence on the sea floor suggests that such events have occurred in the past, at least in geologically recent time, since it may be the case that at least some of the observed slides were earthquake-triggered.

Asking the question as to whether such an event could have occurred in historical time without this having been recognised from existing reports, the answer appears to be yes. There exist poorly documented earthquakes that were widely felt with no evidence that they were strong or damaging in what might be the epicentral area. Until now, the question as to whether any of these might be a large passive margin earthquake has not been raised. There is no conclusive evidence that any of these earthquakes are passive margin events; one can only say that it is conceivable that they might be. The best candidate is probably the earthquake of 19 September 1508; but even with this one there are alternative interpretations that are also consistent with the evidence.

Positive identification might be achieved if evidence from Ireland could be obtained, but the limitations of the documentary record from Ireland before the 18th century makes this unlikely. A sequence of chance events preserved a piece of oral history that an earthquake was felt in Antrim (Northern Ireland) around 1600 by Sir Hugh Clotworthy. A woman was told that this happened before she was born; in her old age she passed the information to someone else. Because an earthquake was felt in Dublin in 1690, that someone (Sir Thomas Molyneux) thought to include the information in a letter to his brother; the letter survived and was published in a university magazine in the mid 19th century (Marsh, 1841). There is no other information on this earthquake (unless it is a distant report of the 23 July 1597 earthquake felt over much of the north of Scotland). It is only by this chain of happenstance that there is any information at all, and if information from Ireland c. 1600 survives only through luck, one cannot read much into the absence of reports from Ireland in 1508. The story of the 1686 earthquake, given previously, is another example of how the historical seismologist is dependent on luck.

What are the consequences of all this? Firstly, the judgement of Ambraseys and Jackson (1985) previously quoted is in need of revision, at least to the extent that large magnitude earthquakes may have occurred in the British Isles in the last 1000 years – we are just not able to recognise them for what they are with the evidence on hand. To generalise from this that an earthquake with magnitude $> 6\,\text{Mw}$ or even $7\,\text{Mw}$ is possible in mainland Britain (which would have some implications for seismic hazard) is another matter.

If we assume that large magnitude earthquakes can affect the British Isles, but only from the passive margin, the effect on hazard assessment for onshore structures would be very limited. In intraplate areas in general, probabilistic seismic hazard assessment (PSHA) is not very sensitive to decisions made about maximum magnitude, except perhaps at very long return periods. This is because even if one allows the possibility of large earthquakes, they must be such rare events that they contribute little to the hazard compared with more moderate-sized earthquakes that are much more common, and may still produce high ground motion values through scatter. If one introduces large magnitude earthquakes that are also at a considerable distance offshore, the effect is infinitesimal.

The implications are much more significant with respect to offshore hydrocarbon exploration, as a large earthquake could either directly damage offshore installations, or cause damaging submarine slope failure. However, this danger is already recognised (Baltzer et al., 1998).

The other potential issue is tsunami hazard. One cannot tell how rare large passive margin earthquakes in north-west Europe are, beyond saying that the earthquakes themselves are rare, and that should one occur, the chances of it being also tsunamigenic are low. Therefore the conditional probability of a tsunami occurring could be very low indeed. Even so, given the danger to human life, and the fact that tsunami warning systems can be fairly inexpensive if combined with other monitoring systems, it may still be advantageous to pursue such a system for the north-east Atlantic (Kerridge, 2005).

Acknowledgments This paper grew out of a presentation to the International Seminar in Memory of Jean Vogt (1929–2005), and I would like to pay tribute to Jean Vogt as one of the outstanding contributors to the study of historical seismology. As mentioned above, discoveries in historical seismology often depend on serendipity, and Jean Vogt had a remarkable gift for discovering key documents in unpromising archive collections. This paper also draws upon my contribution to a study commissioned by the Department for Environment, Food and Rural Affairs (Defra) on tsunami risk to the UK, published as (Kerridge, 2005). I would like in addition to thank Michael Tate of Tate Exploration Consultants Ltd for drawing my attention to some of the offshore evidence cited in this paper, and also Kevin Horsburgh of Proudman Oceanographic Laboratory for discussions of the 1607 event; also Dave Long and Ken Hitchen of BGS for helpful discussions on various aspects of this work. Comments from Michel Cara and Gottfried Grünthal improved the quality of this paper. This paper is supported by the Natural Environment Research Council and is published with the permission of the Executive Director of the British Geological Survey (NERC).

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The 18 September 1692 Earthquake in the Belgian Ardenne and Its Aftershocks

P. Alexandre, D. Kusman, T. Petermans and T. Camelbeeck

Abstract New discoveries in different record-offices provide additional information on the effects of the 18 September 1692 earthquake, mainly for localities in the epicentral area and in Germany. In the northern part of the Belgian Ardenne, substantial to heavy damage and sometimes complete destruction of houses and large buildings (castles and churches) is described, suggesting intensity values on the EMS-98 macroseismic scale ranging from VII to VIII. German records allowed also to improve the assessment of the intensities in large cities like Köln, Mainz, Trier and Frankfurt and thus allowed to better delimitate the isoseismals of intensities V and VI towards the East. Based on the intensity evaluation for the 220 localities for which contemporary information is available, the magnitude of the earthquake has been evaluated to range between 6 and $6^1/_4$.

A new list of the known aftershocks of the 18 September 1692 earthquake is presented together with maps indicating the localities in which these have been reported.

1 Introduction

The most seismic active region of the northwest of Europe (Fig. 1) is the bordering region between Belgium, the Netherlands and Germany. A general overview of the seismicity and the seismotectonics of this region is given in Camelbeeck et al. (2007) and Hinzen and Reamer (2007). The strongest known seismic event occurred on 18 September 1692 approximately at 14:15 (local time). The earthquake produced significant destructions in the northern part of the Belgian Ardenne and caused widespread damage from Kent in England to the Rhineland in Germany and to Champagne in France.

The traditional catalogues and compilations of historical seismicity give an overview of this earthquake from a limited number of sources contemporary of the event. Moreover, in these catalogues the difference between an original document

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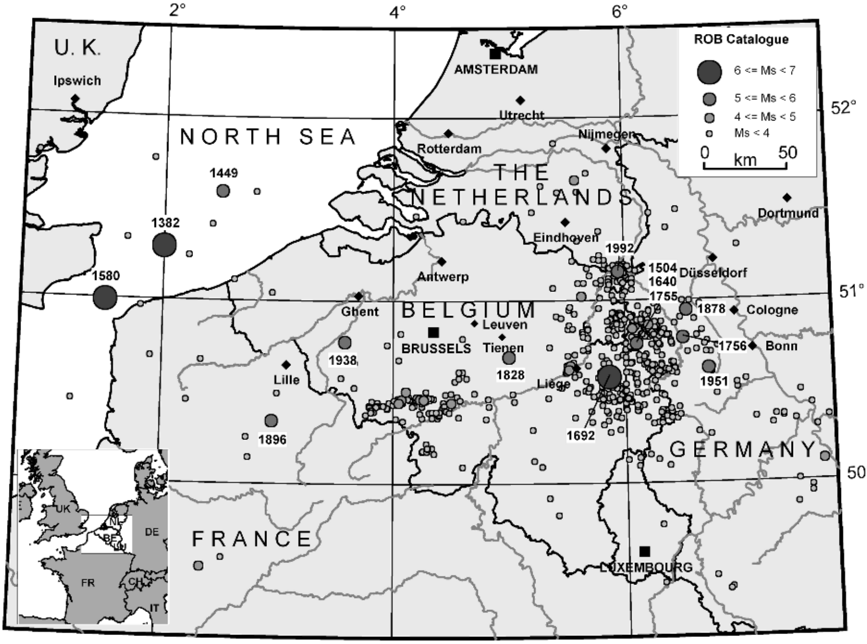

Fig. 1 Seismic activity in northwest Europe (1350–2006)

and a later copy is not clearly specified. This lack of the rules of historical criticism was the cause of many mistakes (Alexandre 1990).

In two of the famous catalogues of Alexis Perrey (1845, 1847), the shock of 18 September 1692 appears as a phenomenon located in the eastern part of the Belgian province of Brabant, in the area between Brussels and Antwerp (Fig. 2). According to Perrey, the perceptibility area included Paris, Normandy, the coasts of England, the Netherlands, Frankfurt/a.M. and towards the southeast the Swiss cantons of Vaud and Valais. This mention of Switzerland comes from the work of Gueneau de Montbéliard (1761), an author who does not quote his sources, and has not been confirmed by contemporaneous texts. In fact, up to now, there is no original text known confirming such a distant extension of the 1692 earthquake in this direction. This example illustrates the methods of Perrey and other compilers: they mention their sources, but some of them are unverifiable by the reader. Similar examples are the catalogues of Von Hoff (1840) and Mallet (1852), which give the same description of the earthquake under discussion, nearly from the same sources.

The Belgian catalogue of Lancaster (1901) does not bring any new data and also locates the epicentre of the shock in the Belgian province of Brabant. The catalogue of Lemoine (1911) gives an epicentre near Mechelen (Fig. 2), without explanation. Davison (1924), in his English catalogue, files the 1692 event among the "earthquakes of unknown epicentres in England".

In their regional works, Villette (1904–05) and Van Rummelen (1943) supply some new data from original sources for the Champagne and the Dutch Limburg.

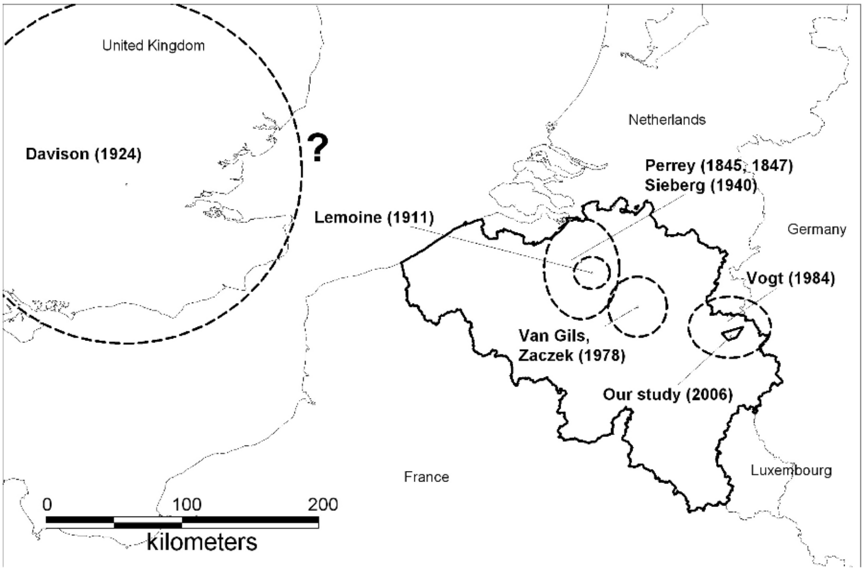

Fig. 2 Epicentre locations of the 18 September 1692 earthquake as defined in the different studies of the earthquake

A more important compilation is the well-known catalogue of Sieberg (1940) on the historical earthquakes in Germany and neighbouring areas (Fig. 3). It contains new data and clearly some of them come from original sources, but without specific references. Sieberg's map of the earthquake of September 1692 (Fig. 3) shows an isoseismic curve of "strong damages" ("*kräftige Gebäude-Schäden*") which surrounds the area between Brussels and Antwerp, and a curve of "light destructions" ("*leichte Zerstörungen*") from Oudenaarden in Flanders to Spa, Stavelot and Aachen.

Finally, the paper of Van Gils and Zaczek (1978), which is a summary on the seismicity of Belgium, localizes the epicentral area near the town of Tienen (Fig. 2), with a M.S.K. maximum intensity level of VII; these authors put the earthquake of September 18, 1692, in a table of the seismic events of the "area of Flanders and Brabant". It does not become clear on what this hypothesis of an epicentre in Tienen. The two authors do not explain their choice, however it can be assumed that they made their comment in analogy to other earthquakes supposedly located in the same area, for example the earthquake of 23 February 1828 in eastern Brabant, and also the shock of 13 January 1714 (supposedly near Tienen, but in reality in eastern Belgium). Thus, a real myth of a particular seismic area around the town of Tienen was created (Alexandre and Kupper, 1997).

The first one who called the Brabant epicentre into question is the Alsatian scientist Jean Vogt (1984). He was also the first one who undertook a new research towards original sources in the European archives. At last it was possible to get out of the process of compiling previous catalogues. According to the analysis of so for

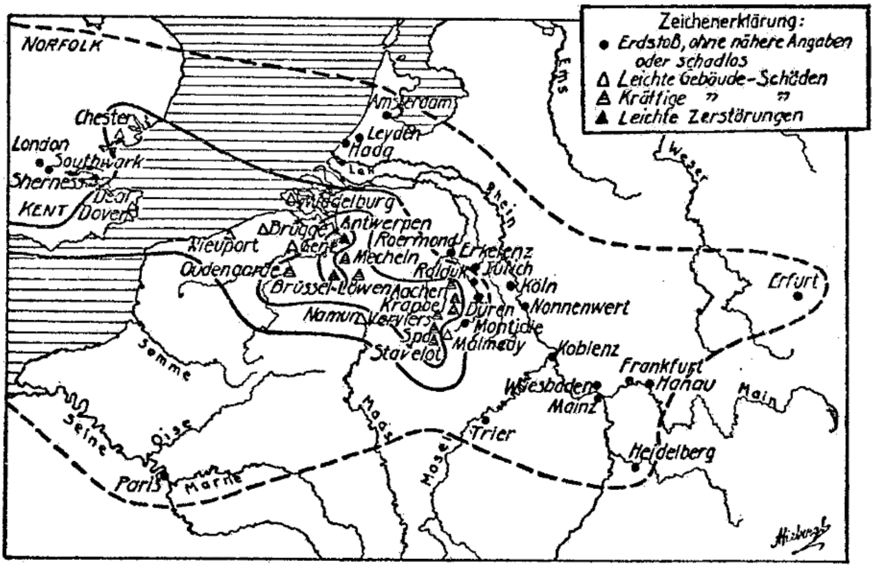

Fig. 3 Macroseismic map of the 18 September 1692 by Sieberg (1940)

unnoted documents, Vogt assumes that the epicentral area is not in the province of Brabant, but is located in a triangle Liege – Verviers – Aachen (Fig. 2). Vogt remarks the importance of the damage in castles, churches and houses in the Verviers area, where he suggests intensities VII–VIII or VIII in the M.S.K. scale. He also provides new elements for estimating the other local intensities and determining the boundaries of the perceptibility area.

As far as the effects of the shock in England are concerned, new original data were supplied from English records and newspapers by Morse (1983) and also by Melville and Ambraseys (1983).

The catalogue of Van Gils and Leydecker (1991) does not at all take the Vogt's new research into account and still locates the epicentre of the 1692 earthquake at the coordinates of the town of Tienen.

At the same time, a new catalogue of the earthquakes in Belgium and neighbouring areas was elaborated in the Royal Observatory of Belgium, and the study of Alexandre and Kupper (1997) presents a critical account of all the known records concerning the earthquake of September 1692 and the ensuing pilgrimage to Our Lady of the Récollets in Verviers.

Since then some new material about this event was provided in different papers by Camelbeeck et al. (1999, 2000), and Alexandre et al. (2005). The last paper discusses the damage to the architectural heritage.

The purpose of the present paper is to describe on (1) the results of new investigations in old written evidence – for instance in a very useful source, the "*Unglücks-Chronica*", a book already published at the end of the year 1692, which contains contemporaneous reports from local newspapers –, (2) to discuss the problems of the local epicentral intensities and of the aftershocks, (3) to provide (Table 1) the complete set of intensities, locations and coordinates, and (4) to draw a new map of the macroseismic area of this "Verviers" earthquake.

Table 1 Localities for which contemporaneous historical sources provide information on the effects of the 18 September 1692 earthquake

CITY	Country	Imin	Imax	Lat N	Long E
ENSIVAL	B	8		50,5822	5,8433
HERVE	B	8		50,6333	5,8000
SOIRON	B	8		50,5928	5,7922
WALHORN (CRAPOEL)	B	8		50,6756	6,0467
ANDRIMONT	B	7	8	50,6147	5,8842
HUY	B	7	8	50,5175	5,2386
LIEGE	B	7	8	50,6481	5,5764
LIMBOURG	B	7	8	50,6136	5,9416
MONTZEN	B	7	8	50,7089	5,9631
ONEUX	B	7	8	50,5500	5,8330
POLLEUR	B	7	8	50,5389	5,8828
SPA	B	7	8	50,3950	5,9314
STAVELOT	B	7	8	50,3950	5,9314
BATTICE	B	7		50,6483	5,8231
BOIRS	B	7		50,7519	5,5811
CHARNEUX	B	7		50,6697	5,8061
CLERMONT-SUR-BERWINNE	B	7		50,6670	5,8830
EMAEL (EBEN)	B	7		50,7950	5,6692
GLONS	B	7		50,7517	5,5475
MALMEDY	B	7		50,4275	6,0297
MONS	B	7		50,4547	3,9483
OUDENAARDE	B	7		50,8500	3,6000
THEUX	B	7		50,5281	5,8247
VERVIERS	B	7		50,5942	5,8606
VILLERS-LE-TEMPLE	B	7		50,5083	5,3706
AACHEN	G	7		50,7700	6,1000
BRUEST (EIJSDEN)	NL	7		50,7830	5,7000
KERKRADE (ROLDUC)	NL	7		50,8667	6,0667
ROERMOND	NL	7		51,1200	6,0000
BRUXELLES	B	6	7	50,8486	4,3617
GENT	B	6	7	51,0542	3,7289
HASSELT	B	6	7	50,9333	5,3333
LEUVEN	B	6	7	50,8806	4,7025
MECHELEN	B	6	7	51,0300	4,4797
TIENEN	B	6	7	50,8072	4,9400
WETTEREN	B	6	7	51,0086	3,8872
LILLE	F	6	7	50,6333	3,0667
LOOS	F	6	7	50,6167	3,0167
VOERENDAAL	NL	6	7	50,8833	5,9333
ANTWERPEN	B	6		51,2153	4,4142
DEINZE	B	6		50,9833	3,5333
DENDERMONDE	B	6		51,0306	4,1006
FELUY	B	6		50,5628	4,2517
FLERON	B	6		50,6231	5,6850

Table 1 (continued)

CITY	Country	Imin	Imax	Lat N	Long E
IEPER	B	6		50,8519	2,8864
LAARNE	B	6		51,0308	3,8522
MESEN	B	6		50,7670	2,9000
POPERINGE	B	6		50,8553	2,7275
TONGEREN	B	6		50,7814	5,4667
TOURNAI	B	6		50,6053	3,3886
WAARSCHOOT	B	6		51,1500	3,6000
CONDE SUR L'ESCAUT	F	6		50,4500	3,5833
HOUPLIN	F	6		50,5667	3,0000
NIEPPE	F	6		50,7000	2,8330
NOORDPEENE	F	6		50,8000	2,4000
SAINT-AMAND	F	6		50,4500	3,4300
SOCX	F	6		50,9333	2,4167
SPYCKER	F	6		50,9667	2,3167
UXEM	F	6		51,0167	2,4833
VALENCIENNES	F	6		50,3667	3,5167
WARHEM	F	6		50,9833	2,5000
BRAUWEILER	G	6		50,9670	6,7830
KÖLN	G	6		50,9333	6,9833
TRIER	G	6		49,7500	6,6333
VIANDEN	LU	6		49,9333	6,2000
RAVENSTEIN	NL	6		51,8000	5,6500
KORTRIJK	B	5	6	50,8289	3,2647
AIRAINES	F	5	6	49,9667	1,9500
BÉTHUNE	F	5	6	50,5333	2,6333
COUCY	F	5	6	49,5167	3,3167
LAON	F	5	6	49,5667	3,6667
LIRY	F	5	6	49,3167	4,6667
MARQUETTE-LES-LILLE	F	5	6	50,6667	3,0833
PROVINS	F	5	6	48,5500	3,3000
MAINZ	G	5	6	50,0167	8,2667
FRANKFURT	G	5	6	50,1167	8,6667
MIDDELBURG	NL	5	6	51,5000	3,6167
DEAL	UK	5	6	51,2333	1,4000
BRUGGE	B	5		51,2125	3,2306
RULLES	B	5		49,7178	5,5617
SINT-TRUIDEN	B	5		50,8000	5,2000
VEURNE	B	5		51,0667	2,6667
ARRAS	F	5		50,2833	2,7833
CAPPELLE-BROUCK	F	5		50,9000	2,2167
CHÂTEAU-PORCIEN	F	5		49,2833	3,2333
DOUAI	F	5		50,3667	3,0833
DUNKERQUE	F	5		51,0333	2,3833
METZ	F	5		49,1140	6,1770
ESSEN	G	5		51,4500	6,9500
GRAMMENE	B	5		50,9769	3,4744
LUXEMBOURG	LU	5		49,6000	6,1500
AMSTERDAM	NL	5		52,3667	4,8833
BREDA	NL	5		51,5833	4,7667
DEN HAAG	NL	5		52,0830	4,3000
HERTOGENBOS	NL	5		51,4500	4,9333

Table 1 (continued)

CITY	Country	Imin	Imax	Lat N	Long E
KAMPEN	NL	5		52,5500	5,9167
ZALTBOMMEL	NL	5		51,8000	5,2500
CANTERBURY	UK	5		51,2700	1,0700
COLCHESTER	UK	5		51,8900	0,8900
LEEDS CASTLE	UK	5		51,2333	0,6167
LONDON	UK	5		51,5067	–0,1300
MAIDSTONE	UK	5		51,2833	0,5333
ROCHESTER	UK	5		51,3800	0,5000
SANDWICH	UK	5		51,2700	1,3400
SOUTHWARK	UK	5		51,5000	–0,0833
ROTTERDAM	NL	4	5	51,9167	4,4667
SEVENUM	NL	4	5	51,4170	6,0330
PARIS	F	4		48,8667	2,3333
DIEPPE	F	3		49,9333	1,0833
ROUEN	F	3		49,4300	1,0800
BATH	UK	3		51,3833	–1,6333
BRISTOL	UK	3		51,4500	–1,4167
WOTTON	UK	3		51,2167	0,3833
AHIN	B	M		50,5167	5,2167
ATH	B	M		50,6333	3,7833
BAELEN	B	M		50,6333	5,9677
BRECHT	B	M		51,3531	4,6444
CAMBRON (CASTEAU)	B	M		50,5892	3,8800
CHIMAY	B	M		50,0500	4,3167
DIKSMUIDE	B	M		51,0347	2,8656
FAGNES	B	M		50,3667	5,6667
FOREST	B	M		50,8000	4,3167
FRANCHIMONT	B	M		50,2000	4,6330
GEMBLOUX	B	M		50,5667	4,6833
GERONSTERE	B	M		50,4667	5,8667
HAUTE-MARLAGNE (BUZET)	B	M		50,4167	4,7833
HENRI-CHAPELLE	B	M		50,6667	5,9333
JUZAINE	B	M		50,3667	5,5333
LAMBERMONT	B	M		50,5833	5,8333
LESSINES	B	M		50,7167	3,8330
LIERNEUX	B	M		50,2833	5,8000
LOUVEIGNE	B	M		50,5330	5,7000
NAMUR	B	M		50,4656	4,8642
NIEUWPOORT	B	M		51,1333	2,7500
OOSTENDE	B	M		51,2290	2,9090
ORGEO	B	M		49,8344	5,3078
REULAND	B	M		50,2000	6,1500
RONGY	B	M		50,5000	3,8330
STINVAL	B	M		50,5333	5,7000
VILLERS-SUR-SEMOIS	B	M		49,7000	5,5667
WANNE	B	M		50,3500	5,9167
ABBEVILLE	F	M		49,5167	2,1667
AIRE	F	M		50,6330	2,4000
AMIENS	F	M		49,9000	2,3000
BEAUCAMPS	F	M		50,0333	3,8000
BERGUES	F	M		50,0333	3,7167

Table 1 (continued)

CITY	Country	Imin	Imax	Lat N	Long E
BOUXWILLER	F	M		48,8167	7,4833
CAMBRAI	F	M		50,1667	3,2333
DAMOUZY	F	M		49,8000	4,6670
FENAIN	F	M		50,3667	3,3000
LE HAVRE	F	M		49,5000	0,1333
LINSELLES	F	M		50,7333	3,0833
MANICAMP	F	M		49,5667	3,1667
MARLY	F	M		48,8670	2,0830
NEUVILLE-LES-WASIGNY	F	M		49,6330	4,3000
ROUBAIX	F	M		50,7000	3,1667
RUMEGIES	F	M		50,4833	3,3500
SAINT-MARD	F	M		49,3833	3,5833
STEENBECQUE	F	M		50,6833	2,4833
TROYES	F	M		48,3000	4,0833
VERSAILLES	F	M		50,3500	3,5330
BAD HONNEF	G	M		50,6333	7,2333
EMMERICH	G	M		51,8333	6,2500
ERKELENZ	G	M		51,0833	6,3167
FRANKFURT	G	M		50,1167	8,6667
HANAU	G	M		50,1333	8,9167
HEIDELBERG	G	M		49,4167	8,7167
IBURG	G	M		52,1667	8,0500
KLEVE	G	M		51,7833	6,1500
KÖLN	G	M		50,9333	6,9833
KOBLENZ	G	M		50,3640	7,5910
NIDDA-ULFA	G	M		50,4167	9,0000
OSEDE(NSIS)	G	M		52,2167	8,0667
OSNABRUCK	G	M		52,2667	8,0500
ROLANDSWERTH	G	M		50,6330	7,2000
TRIER	G	M		49,7500	6,6333
WESEL	G	M		51,6667	6,1667
BRANDENBOURG	LU	M		49,9130	6,1400
ELVANGE-LES-BECKERICH	LU	M		49,7247	5,9178
ARCEN	NL	M		51,4833	6,1833
BRIELLE	NL	M		51,9000	4,1667
CADZAND	NL	M		51,3670	3,4090
GOES	NL	M		51,5070	3,8920
HAARLEM	NL	M		52,3667	4,6500
HOORN	NL	M		52,6333	5,0667
LEIDEN	NL	M		52,1500	4,5000
MAASTRICHT	NL	M		50,8500	5,6833
PURMEREND	NL	M		52,5167	4,9500
SITTARD	NL	M		51,0000	5,8667
T GOOI	NL	M		52,3000	5,1500
UTRECHT	NL	M		52,0833	5,1333
VLISSINGEN	NL	M		51,4440	3,5760
ZIERIKZEE	NL	M		51,6500	3,9167
ASHFORD	UK	M		51,1330	0,8330
BARNET	UK	M		51,6500	–0,2000
BRAINTREE	UK	M		51,8833	0,5667
BRENTFORD	UK	M		51,5000	–0,3167

Table 1 (continued)

CITY	Country	Imin	Imax	Lat N	Long E
BROOMFIELD	UK	M		51,7667	0,4667
BUCKDEN	UK	M		52,2830	–0,2500
CAMBRIDGE	UK	M		52,2000	0,1100
CHATHAM	UK	M		51,3833	0,5333
COGGESHALL	UK	M		51,8667	0,6833
DEPTFORD	UK	M		51,4833	–0,0333
DOVER	UK	M		51,1200	1,3000
ELY	UK	M		52,4000	0,2667
ENFIELD	UK	M		51,6667	–0,0667
EPSOM	UK	M		51,3333	0,2667
HATFIELD	UK	M		51,7667	–0,1667
IPSWICH	UK	M		52,0667	1,1667
KENSINGTON	UK	M		51,4833	–0,1833
MANNINGTREE	UK	M		51,9500	1,0667
NORWICH	UK	M		52,6333	1,3000
OXFORD	UK	M		51,7667	–1,2500
PORTHTMOUTH	UK	M		50,8000	–1,0900
RYE	UK	M		50,9500	0,7330
SAINT-ALBANS	UK	M		51,7500	–0,3333
SHEERNESS	UK	M		51,4400	0,7500
TWINEHAM	UK	M		50,9500	–0,2167
WESTMINSTER	UK	M		51,4980	–0,1290
WITHAM	UK	M		51,8000	0,6400

Countries: B = Belgium; NL = The Netherlands; F= France; LU = Grand Duchy of Luxembourg; UK = United Kingdom

Imin: Minimal EMS-98 intensity based on historical texts. M = Event only mentioned without any details.

Imax = Maximal EMS-98 intensity based on historical texts.

2 Intensity in the Epicentral Area

In the epicentral area, substantial to heavy damage and sometimes complete destruction are described as a matter of fact for large buildings (castles and churches) and for houses. The ground shaking also appeared as violently felt by the people and it produced effects on the environment. From many sources reporting about the earthquake, it appears possible to classify the effects of the earthquake and to suggest ranges of intensity values on the EMS-98 macroseismic scale (Grunthal ed. 1998).

For the most affected villages (Fig. 4), the descriptions mention that some number of houses was ruined with the consequence that inhabitants were injured or died. This is the case in **Herve** "*... en die [Aardbeving] van voorleden Donderdag heeft tot Herpf in Limburgerlandt eenige Huisen omverre geworpen, en verscheide Menschen gedoodt.*" ["and the earthquake of Thursday last threw some houses down and killed several people as far as Herve in Limbourg country"] (Naawkeurige Beschryving van de Aardbevinge ..., Amsterdam 1692); **Ensival**, "*plusieurs maisons furent écrasées*" ["several houses were flattened"] (Remy Du Pont, Chronique); **Soiron**, "*un tremblement de terre espouvantable qui a abbatu les maisons, cheminées dont les miennes l'ont esté*" ["a terrible earthquake which

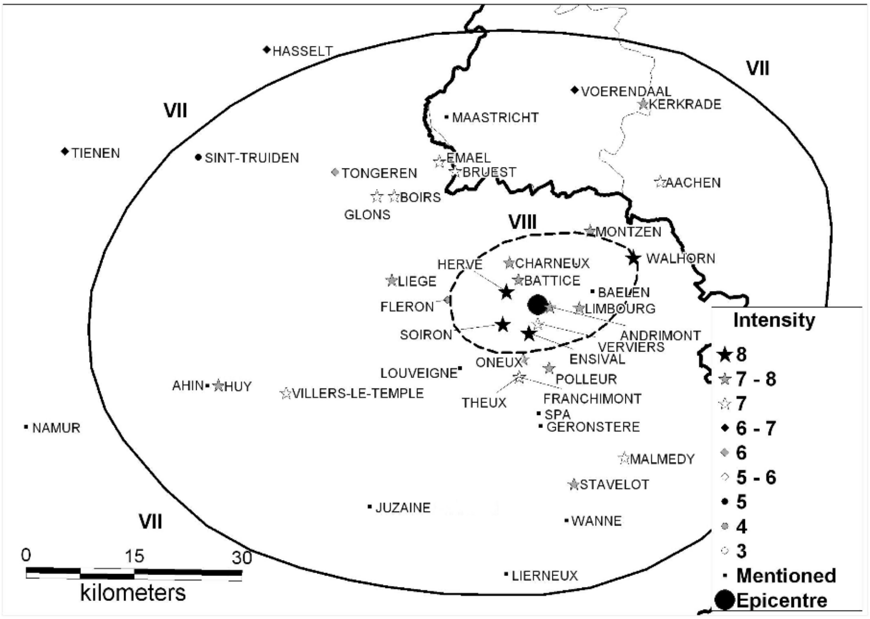

Fig. 4 Epicentral area of the 18 September 1692 earthquake with all associated locations where intensity could be defined. The full line and the dashed line give the isoseismals of intensity VII and VIII, respectively

knocked down houses, chimneys among which were mine"] (Servais Ronval, Notes); **Charneux**, "*la maison de Lambert Halleux fut culbutée de fond en comble*" ["Lambert Halleux's house was knocked over from top to bottom"] (Nicolas Ernolet, Chronologie); **Waucomont-Battice**, the buildings of a house are "*inhabitables, renversés et ruinés par ce violent tremblement de terre*" ["uninhabitable, upturned and wrecked by this violent earthquake"] (Minute du notaire Detiège à Battice); **Walhorn**, "*In diversis locis domus fuerunt eversae et homines occisi*" (Walhorner Kirchenbuch); in the **Limbourg** Duchy, "*In dem Limburger Lande aber war es an vielen Orthen sehr starck gewesen und hatte viele Häuser mit Macht über einen Hauffen gestossen wobey denn auch einige Menschen getödtet worden*" ["But in Limbourg country it was very strong in many places and violently overturned many houses, thereby killing a number of persons"] (Unglücks-Chronica 1692). A text written in **Kerkrade** (Nicolas Heyendahl, Annales Rodenses), for which it is difficult to say if it refers to the locality itself or if it has a more general character "*... fuit vehementisssimus terrae motus, qui pluribus in locis castella et domus subversae sunt, fontes exaruerunt, prata in paludes versa sunt. Ecclesia monasterii tam valide concussa fuit, ut fastigium frontispicii pasculum respicientis deciderit, et fornices centenas fissuras receperint*".

The terminology used in the sources "to fall, to collapse, to thrown down, to break down, ..." suggests that some buildings suffered damage of grade 4–5 in the damage classification of the EMS-98 macroseismic scale (Grunthal ed. 1998). An important problem for a reliable assessment of intensity, which will have to be considered in future studies on the earthquake, is the assessment of the vulnerability of the different types of constructions at the epoch of the earthquake. It is generally accepted that the vulnerability classes of traditional houses range from A to B. Considering that houses are of vulnerability class A, "few" damage of grade 4 means intensity VII, "few" damage of grade 5 corresponds to intensity VIII.

For some localities damage to monumental buildings is described. In **Soiron**, the castle and the church suffered from heavy structural damage and, with the exception of the tower of the church, had to be torn down completely and were rebuild a few years later. In **Walhorn**, the castle of Crapoel suffered from the same kind of building damage. If we consider that monumental buildings are generally better built and better-maintained, their vulnerability should be less than traditional houses. Thus, we suggest attributing intensity VIII to these two localities, but also to **Herve** and **Ensival** where several houses collapsed. For the other localities, we prefer to give intensity VII or VIII. In the case of **Charneux** and **Waucomont-Battice**, the source noticed a single description of destruction and consequently they are perhaps isolated cases in these localities. For **Kerkrade** and **Limbourg** the description is more general and is perhaps not related to the city itself.

In **Soiron**, the owner of the castle provided also an impressive description of the earthquake effects that could be evaluated as intensity IX in EMS-98 "*Ce tremblement venait du septentrion et … fait à fait qu'il s'avançoit on voyait hausser la surface de la terre, en sorte que plusieurs personnes et animaux en furent culbutez et les arbres et la haie se courboyent comme s'ils avoyent fait la reverence et puis se jettoyent dans leurs place avec grande violence*" ["The tremors came from the septentrion and as they were getting closer, you could see the earth rise up, so much so that several people and animals fell over and trees and hedges bowed down as though in reverence and then were thrown back with great violence"] (Nicolas Ignace de Woelmont, Histoire de la maison de Woelmont). This source supports our previous intensity evaluation.

For other localities, the descriptions are more concentrated on the amount of damage to the chimneys and do not mention necessarily the collapse or complete destruction of houses. Thus, this suggests that degree of damage is 2 and 3 and could be widespread in these cities. If buildings are of vulnerability A, the corresponding intensity should be VII. If they are of vulnerability B, intensity could be also VIII. This is the case in **Montzen**, "*seint alle Schornsteinen oder Caminen abgefallen*" ["reports that all chimneys have fallen down"] (Comptes de l'église paroissiale de Montzen); **Stavelot** et **Malmédy**, "*il y a eu plusieurs édifices endommagez et beaucoups de cheminées bouleversées à Malmedy, Stavelot et ailleurs*" ["several buildings were damaged and many a chimney was toppled over in Malmédy, Stavelot and other places"] (Note du Registre paroissial de Malmédy); **Aachen**, "*die Caminnen oder Schornstein sein heruntergefallen und geborsten, auch etliche Häuser*" ["the chimneys fell down and broke, together with a number of houses"] (Janssen, Aachener Chronik); **Polleur**, "*In dem Dorffe Bleur so auff einem Felsen eine Stunde von Verviers gelegen war nicht ein Schorstein gantz geblieben*" ["In the village of Bleur situated on a cliff one hour from Verviers not a single chimney remained standing"] (Unglücks-Chronica 1692); **Villers-le-Temple**, "*Lorsqui at abatu beaucou de cheminées et vielles murailles et les disloques*" ["then were pulled down a great many chimneys and old walls and were taken to pieces"] (Note du Registre paroissial de Villers-le-Temple); **Huy**, "*Les briques de presque toutes les cheminées furent projetées à terre, entraînant dans leur chute des ardoises et des tuiles. De grosses pierres se détachèrent de la tour principale de l'ancien château et l'une d'elles tua une sentinelle* ..." ["the bricks of almost all the chimneys were thrown to the ground, dragging slates and tiles down in their fall. Large stones came off the main tower of the old castle and one of them killed a sentry"] (Noël, Note dans un Registre de la Cour d'Ahin); **Liège**, "*il n'y eust pas une maison dans cette ville qui n'en eust ressenty du dommage; il y eust plusieurs personnes écrasées et quantité de blessées par les débris des cheminées et des toicts*" ["there was not a single house in this town that did not suffer much damage; several people were crushed and many were injured by the debris from the chimneys and roofs"] (Albert Joseph Gossuart, Chronique); "*toute la ville de Liege fut forte ebranlée, il y eut plusieurs morts, et beaucoups des dégats sur tout par les cheminées renversées*" ["the whole city of Liège was deeply shaken, there were several dead and considerable damage mostly by toppled chimneys"] (Chronique des Célestines d'Avroy).

Many patrimonial buildings suffered also strongly and have been refreshed during the years following the earthquake event: the churches of **Andrimont, Verviers, Oneux, Theux, Stavelot, Fléron, Montzen, Aachen, Emael, Boirs, Glons and Liège** (St-Lambert cathedral, St-Laurent abbey, etc.); abbey buildings in **Stavelot** and **Malmédy**; the castle of **Franchimont**. For these localities, we evaluated intensity as being at least VII. For some of them we gave also the range VII–VIII.

Curiously, there is little information concerning the behaviour of the houses in the city of **Verviers**, "*un gros tremblement de terre qui abattit plusieurs cheminées de maisons* ..." ["A violent earthquake which sent down several chimneys"] (Henri De Sonkeux, Chronique), where the panic of the population is at the origin of the "miracle" of Our Lady of the Récollets church.

3 At Larger Distance

During the last years, our specific searches in different offices of records allowed to improve the knowledge of the earthquake effects in several localities outside the mainly affected area (Fig. 5).

In **Mons** (intensity VII), additional information confirms the importance of damage to houses and that some dozen of people were killed or seriously injured: "*Eben zu der Zeit und Stunde war auch das Erdbeben zu Bergen in Hennegau verspühret worden wodurch viel Häuser Kirchen und andere Gebäue beschädiget und halb ruiniret auch über 80 Menschen theil getödtet theils beschädiget worden*" ["At exactly the same time and hour, the earthquake was also felt in Mons in Hainaut where many houses, churches and other buildings were damaged and half ruined and more than 80 people were either killed or injured"] (Unglücks-Chronica 1692); "... *il ébranla plusieurs bâtiments; il en ouvrit d'autres qu'il fallut démolir, et plusieurs cheminées*

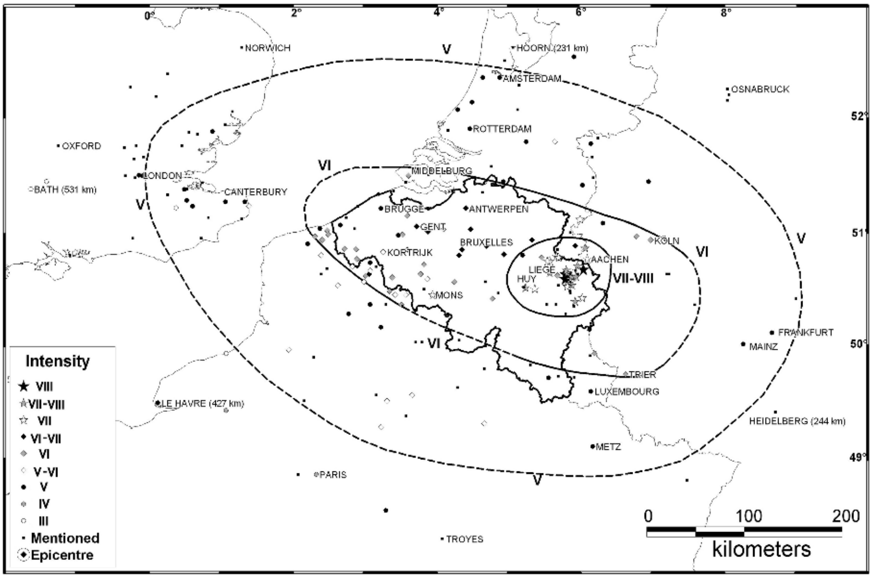

Fig. 5 Macroseismic map of the 18 September 1692 earthquake. Intensity is given in terms of the EMS-98 scale

foncèrent les toits, tuèrent quelques habitants et blessèrent les autres" ["several buildings were shaken; others were torn open which had to be pulled down; and several chimneys smashed through the roofs, killed some inhabitants and injured many others"] (G.-J. de Boussu, Histoire de la ville de Mons).

In **Middelburg** (intensity VI) "Die Strassen bogen sich als Wellen in der See also dass ein jeder auff der Gassen ergriff was er kunte um sich veste zu halten. Die Schiffe wurden mit grosser Gewalt hin und her gerworffen gleich als wenn ein Abgrund auffgebrochen wäre. Giebel, Dächer, Schorsteine und Fenster fielen herab; und vermeynte man auch gäntzlich es würde dem grossen und starcken Abtey-Thurme wegen seines hin und her wanckens nicht besser ergehen. Das Uhrwerck wurde dadurch auch gäntzlich verrücket dass es gantz irrig und falsch ging" ["The streets moved like waves in the sea so that anyone who found himself out on the streets was obliged to hold on. The ships were thrown hither and thither with great violence just as if an abyss were being created. Gables, roofs, chimneys and windows fell down; and it was supposed that the same fate awaited the great, strong tower of the abbey since that was also shaken to its foundations. The clock was so completely shaken that it ceased to show the correct time and went completely crazy"] (Unglücks-Chronica 1692).

German documentation and mainly the already cited "Unglücks-Chronica" allowed us to evaluate intensity in some German cities and thus providing a real improvement of our knowledge on the extension of the earthquake to the east (Fig. 5).

In **Mainz** (intensity V) "*Ist die Erschütterung des Erdbebens auch zu Maynz verspühret worden* [. . .] *dass einige Sachen in Kirchen und Häusern davon über einen Hauffen gefallen*" ["The effects of the earthquake were also felt in Mainz [. . .] to such an extent that some objects in homes and churches fell to the ground in a heap"].

In **Frankfurt/a.M**. (intensity V) "*Ist das Erdbeben auch zu Franckfurth und in der Gegend observiret worden welches denn als etwas ungewöhnliches einen grossen Schreck und Entsetzen unter den Einwohnern verursachet, indem die Häuser selbigen Orthen dermassen commoviret wurden das die Tinten-Fässer Gläser und andere Sachen von den Tischen* [. . .] *herunter fielen*" ["The earthquake was noticed in Frankfurt and the surrounding area where, as something totally unusual, it caused great shock and horror among the inhabitants; as the homes in these places were so shaken that ink pots, glasses and other things fell down from the tables"].

In **Trier** (intensity VI) "*Eben auff die Zeit und Stunde ist solches auch in Trier und an dem Mosel-Strohme sehr hart und zwey mahl nacheinander verspühret worden also dass kein Mensch daselbst wie alter auch immer gewesen dergleichen erlebet hätte. Es waren unterschiedene Giebel und Schorsteine eingefallen und hatten einige Häuser und Gebäue Risse davon in den Mauren bekommen welches unter den Leuten eine grosse Consternation erwecket*" ["At exactly the same time and hour the same thing was felt in Trier and at the Mosel river – a very violent shock, one after another that none had ever experienced anywhere else before. Various gables and chimneys fell and some houses and buildings had great cracks in their walls which caused great consternation among the people"].

In **Köln** (intensity VI) "dieses Erdbeben . . . wodurch über 50 Schorsteine die man würcklich gesehen und durch dero Fall viele Dächer und niedrige Gebäue versehret und beschädiget worden. Es haben sich in wenigen Minuten die Häuser etliche mahl hin und wieder gleichsam Creutzweise und so gar auch die Glocken auff dem Thürmen beweget wodurch solch geprassel entstanden dass sich die Leute eiligst und in grosser Confusion auff die Strassen retiriret, um ihr Leben von den besorglichen Ruinen der Häuser zu salviren" ["This earthquake . . . . whereby 50 chimneys were seen to fall and harm and damage many roofs and low buildings. In a matter of moments the houses moved this way and that and even the bells in the towers moved in such a way that the din they occasioned caused the people to rush out into the streets in great confusion in order to save their own lives from the ruins of their homes"].

The 1692 earthquake macroseismic map (Fig. 5) is instructive by two aspects. First, it is clear that very few notices exist in localities where intensity is less than V. Thus, it is difficult to evaluate correctly the felt area of the event and to deduce its magnitude from this. Secondly, the isoseismals of intensities V and VI are not concentric, but have a more elongated shape to the west-northwest. Recent investigations (Nguyen et al., 2004) showed that site effects due to the Meso-Cainozoïc cover sediments onto the London-Brabant Massif could be responsible for the amplification of earthquake strong ground motions. This problem has not been considered in the present study but should be included in future investigations.

4 Epicentre

The macroseismic epicenter of an earthquake can be defined as the centre of the area with maximal intensity. Considering the type of information at our disposal, with a strong uncertainty on the intensity in many towns, which is expressed by a range of values, the epicenter will depend on the choice of the epicentral intensity. Fortunately, our extensive search of historical data allowed us to collect information from many localities in the epicentral area.

We based our epicenter evaluation on two hypothesis by respectively considering the barycenter of the epicentral area of I = VIII (4 localities) and I = VIII and VII – VIII (15 localities). The obtained respective coordinates are very close to each other: 50.62° Lat N – 5.87° Long E and 50.62° Lat N – 5.83° Long E. These locations are around the village of Dison, a few kilometers north of the city of Verviers. Because of the uncertainties, the epicentre of the 1692 earthquake can be considered to be located within the area of Verviers-Soiron-Herve-Montzen.

Of course, this conclusion could be revisited in the light of possible new discoveries in the archives.

5 Magnitude

The magnitude of historical earthquakes can be evaluated by means of the spatial distribution of the evaluated intensities compared to that of recent earthquakes for which a magnitude has been instrumentally determined.

A relatively simple way to evaluate the magnitude is to determine the radius of the different isoseismals and to compare them to relationships established between average macroseismic radii and magnitude. Ambraseys (1985) calculated laws valid for northwestern Europe whereas Johnston (1996) established relationships with the data from stable continental regions. Levret et al. (1994) developped also a relationship based on historical earthquakes in France. Johnston (1996) considers estimation of the seismic moment magnitude, M, of Hanks and Kanamori (1979). Ambraseys (1985) established his laws by using instrumental earthquakes for which the magnitude is defined as M_S by the Prague formula (Vanek et al., 1962). The magnitude provided by Levret et al. (1994) is similar to the one defined by Ambraseys (1985). In the following of the text, M will be used for these three different evaluations of the magnitude, because for the magnitude range considered here M_S is relatively equivalent to M.

With a smaller dataset, Camelbeeck et al. (2000) used the Johnston laws to estimate the magnitude of the 1692 earthquake suggesting a magnitude ranging from M = 6.0 to 6.5.

A more recent method to evaluate the magnitude for historical earthquakes is that of Bakun and Wenthworth (1997). The source parameters are directly derived from the individual intensity observations. Hinzen and Oemisch (2001) applied this method to the location and magnitude of recent and historical earthquakes in the Northern Rhine area. They calculated those parameters for the 1692 Verviers earthquakes by using the data from Alexandre and Kupper (1997). They obtained a magnitude $M_L = 6.8$, which corresponds to $M_w = 5.7$ by applying the relationship between M_L given by the Bensberg network and M_W (Reamer and Hinzen 2004). Their location is in the locality Esneux, some 30 km to the southwest of Verviers. Both of our epicenters are within their 80% confidence limit.

Gasperini, Bernardini, Valensise and Boschi (1999) presented a method that assesses the location, the physical dimensions and the source orientation of large historical earthquakes by the use of macroseismic intensity data. They applied in a systematic way this program called BOXER to all $M > 5.5$ earthquakes having occurred in the central and southern Apennines in Italy during the past four centuries. The method computes the macroseismic epicentre and the magnitude as well as the azimuth, the length and the width (down dip) of the box representing the seismogenic fault having generated the earthquake We will not take into account the latter parameters because we consider that our macroseismic data are unable to furnish such information.

As intensity attenuation with distance, magnitude-epicentral intensity and magnitude-macroseismic radii relationships are different in northwestern Europe compared to those in Italy, it was necessary to modify the parameters of these laws in the BOXER program. We approximated the Ambraseys (1985) laws relating magnitude to isoseismal areas by a mathematical formulation which can be used by BOXER. We considered an equation of the type: $M = a_i + b_i \log^2 A_i$; where A_i is the area (expressed in km^2) of the isoseismal of intensity I and a_i, b_i are coefficients depending of the considered intensity. The values of these coefficients are indicated in Table 2.

To calculate the magnitude of the 1692 earthquake with BOXER, two datasets have been considered (Table 1). The first (Imin) considers only the minimal intensity evaluation for localities for which a range of intensity values is given. The second one (Imax) considers the maximal values of the intensity ranges. Localities with a single value are included in the both datasets with this single value. We calculated also the magnitude with attenuation valid for Italy for comparison. Magnitude has also been determined by using the Ambraseys (1985) and Levret et al. (1994) attenuation laws calculated on the three isoseismals (intensities V, VI and VII) traced on Fig. 5. All these results are presented in Table 3.

Attenuation laws generally take into account the earthquake focal depth. Thus, the focal depth is a parameter that should be determined using intensity data. We consider that for historical earthquakes, the reliability of macroseismic data is not sufficient to allow depth determination. Thus, we used the Ambraseys and Levret

Table 2 Coefficients used in the Boxer program to approximate Ambraseys laws

Intensity	a_i	b_i
IV	2.306	0.119
V	2.926	0.119
VI	3.546	0.119
VII	4.166	0.119

Table 3 Magnitude evaluation for the 18 Septembre 1692 earthquake (1) with the Boxer program on the minimum/maximum intensity (I_{min}/I_{max}) data for Belgian and Italian attenuation laws. RI_{min} and RI_{max} are the mean radii for the two datasets, respectively; (2) with the Ambraseys and Levret et al. attenuation laws on the traced isoseismals of Fig. 5, considering a focal depth of 15 km. R is the mean radius of the enclosed area of the considered isoseismal

Intensity	I_{min} Belgium	I_{min} Italy	RI_{min} (km)	I_{max} Belgium	I_{max} Italy	RI_{max} (km)	Ambraseys laws	Levret et al. laws	R (km)
V	M = 6.05	M = 6.75	205	M = 6.08	M = 6.78	213	M = 6.22	M = 6.23	252
VI	M = 6.29	M = 6.40	142	M = 6.52	M = 6.54	179	M = 6.19	M = 6.24	127
VII	M = 5.26	M = 5.81	18	M = 6.15	M = 6.49	62	M = 6.12	M = 6.04	45

et al. relationships by considering a depth of 15 km. Such a value seems coherent with the large geographical extension of the effects of the 1692 earthquake and also of the probable fault surface for an earthquake of this importance. For the Italian relationships, the depth is implicitely fixed at 10 km.

The magnitude of the earthquake ranges from 5.3 (5.26) to 6.5 (6.52) when using minimum or maximum intensity evaluations and the attenuation laws valid for northwest Europe and France. The range of values obtained by BOXER are excessive in the two directions because the reality is surely in between because considering only minimum (maximum) intensity evaluation minimizes (maximizes) the real effects of the earthquake. Taking the average value gives $M = 6.1 \pm 0.4$. Using the isoseismals of Fig. 5 and the Ambraseys and Levret et al. laws, the evaluation gives identical result: $M = 6.1 \pm 0.1$.

These evaluations suggest a magnitude value in the range 6–6 1/4.

Using attenuation laws for Italy provide magnitude values 0.5 higher as if the corresponding relations for Northwestern Europe are applied. This observation justifies the choice to modify the attenuation laws in the BOXER software.

6 The Aftershocks of the 1692 Earthquake

The same day that the main shock occurred, two major aftershocks were felt from Liège to Essen. Even the following days, shocks were still felt in the neighbourhood of Verviers and one major important shock on 28 October was even felt up to Brussels. On 19 March 1694, another strong shock occurred. At the exception of the fourth aftershock, only mentioned in Aachen, the other earthquakes have been reported from different localities, indicated in Fig. 6. Table 4 provides the location of the barycenters of the coordinates of the towns where the earthquakes have been noticed and the distance of the farthest of these cities to this barycenter and to the epicenter of the main schock.

There are not enough data to certify that these earthquakes are really originated from the mainshock area. Aftershocks 1, 2 and 3 have been reported in distant German towns whereas up to now, no mentioning has been found to the west in the Belgian province of Brabant though the mainshock was here strongly felt. Perhaps these earthquakes occurred more to the east in the Lower Rhine Embayment

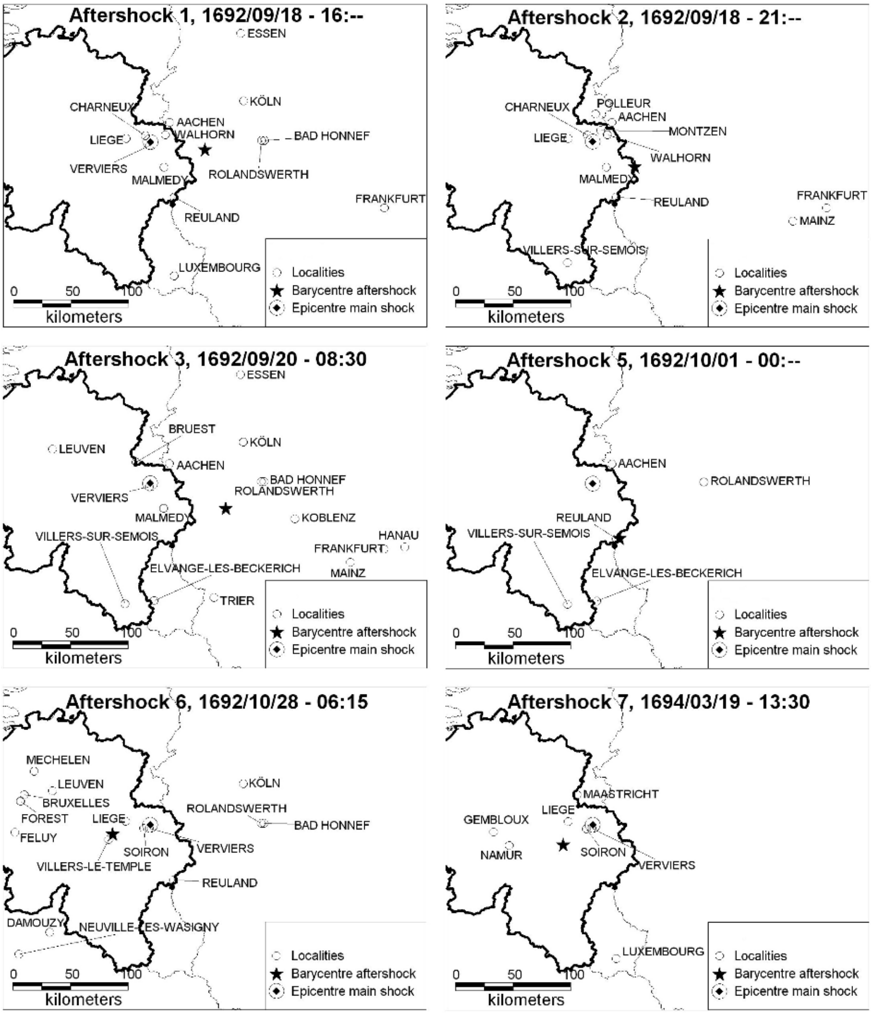

Fig. 6 Maps of 6 of the 7 "aftershocks" of the 18 September 1692 earthquake. Localities are places, where the earthquakes were mentioned

Table 4 Aftershocks of the 18 September 1692 earthquake

	Date	Time (local)	Lat N barycentre	Lon E barycentre	Distance from barycentre	Distance from Main shock
Event 1	1692/09/18	16 h	50.57	6.52	160 km	206 km
Event 2	1692/09/18	21 h	50.43	6.37	167 km	206 km
Event 3	1692/09/20	8 h1/2	50.43	6.77	156 km	227 km
Event 4	1692/09/23		50.77	6.10	0 km	23 km
Event 5	1692/10/01	0 h	50.21	6.19	86 km	105 km
Event 6	1692/10/28	6 h1/4	50.55	5.42	130 km	157 km
Event 7	1694/03/19	13 h1/2	50.49	6.23	107 km	115 km

and are not real aftershocks, but represent seismic activity triggered there by the strong mainshock. Even for Aftershock 4, only reported in Aachen not very far from the main shock epicenter, it is impossible to certify if it is a real aftershock or an event that occurred along the border fault zone of the Roer Graben, very close to Aachen.

On the other hand, due to the geographical repartition of its felt area and the description in Soiron, aftershock 6 appears as a real one.

7 Conclusion

The knowledge of the 18 September 1692 September has greatly improved during the last ten years by the numerous new documents found in different record-offices in Belgium, Germany, The Netherlands and France. In this publication, we propose a new macroseismic map of the earthquake in terms of the EMS-98 macroseismic scale, from which it is suggested a better epicenter location, than in previous investigations, within the area of Verviers-Soiron-Herve-Montzen. However this conclusion should be revisited in the light of possible new discoveries in the archives for localities in the Belgian Ardenne and the Eifel mountains.

With a magnitude between 6 and 6 $^1/_4$, it is the largest known historic earthquake which occurred in Northwest Europe. Thus, it is an earthquake of reference for the assessment of seismic hazards and risks. For the purpose of evaluating the risks on buildings, it is now important to undertake investigations on the vulnerability of typical constructions of the end of the 17th century to more precisely assign intensities in the epicentral area.

The earthquake had a strong impact on patrimonial buildings, destroying churches, and castles in the epicentral area, but provoking also heavy damage at larger distances. It is important to analyse these damages and destructions more carefully to improve the knowledge on the effects of earthquakes to the patrimonial buildings with the objective of incorporating paraseismic design when a costly repair is undertaken on a specific building.

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The 1855 Visp (Switzerland) Earthquake: A Milestone in Macroseismic Methodology?

M. Gisler, J. Kozák and J. Vaněk

Abstract The first attempts to establish macroseismic intensity reach back to the 17th century. But it was not until the late 19th century that seismic intensity scales, tectonic faults and individual types of seismic waves were routinely studied and recorded. Observational seismology, macroseismic observation and earthquake classification in the early 19th century was so cumbersome and slow that these data were not commonly used and often forgotten. In mid 19th century, two researchers, G.H.O. Volger and A. Petermann, made a fundamental contribution to macroseismic damage classification by plotting the 1855 Visp earthquake; an endeavor that can be seen as the beginning of macroseismic methodology. In this essay we follow the thread of this early contribution to macroseismology, and ask for its impact and its early successors.

1 Introduction

It is well known that strong and disastrous seismic events stimulate the increased interest and professional attention of naturalists, scholars, philosophers, engineers and other intellectuals. It follows that large seismic disasters are often regarded as important milestones in the process of a more advanced and scientific understanding of the Earth. In 2005 we commemorated the anniversary of the 1855 Visp earthquake in the Valais, Switzerland, which gave us the opportunity to study the event and the question of its incentive on macroseismic methodology. In what follows, we present an historical survey of the endeavors before the 1855 earthquake and discuss its effects on the work of G.H.O. Volger and A. Petermann, who took the initiative to establish a measurement scale of the event and plot it on geographical maps, endeavors that are still widely used today.

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J. Fréchet et al. (eds.), *Historical Seismology*,

2 Macroseismic Endeavors Before 1850

The first attempts to establish macroseismic intensity go back to Italy in the 17th century. After the Capitanata earthquake of 1627, the Italian Matteo Greuter designed an earthquake map in which damage was subdivided into four classes. It was the large 1755 Lisbon earthquake however, which forged new methodologies enhancing the study of earthquakes. The event, felt all over Europe as well as Northern Africa, stimulated European intellectuals to produce hundreds of treatises describing and analyzing the event (Braun and Radner 2005; Kozák et al. 2005; Löffler 1999; Kendrick 1956) (Fig. 1). It is not easy to judge the degree to which the Western European Enlightenment influenced and encouraged the scientific study of the Lisbon earthquake, or – vice versa – how much the Lisbon earthquake and the new approach to its analysis shaped the new studies of natural phenomena. Two outstanding European naturalists turned their attention to the phenomenon of earthquakes, namely John Michell (1724–1793), Woodwardian professor of geology at Cambridge, and Elie Bertrand (1713–1797), Swiss naturalist and geologist, pastor at Berne and member of several Academies of Sciences. The latter composed and published his famous treatise *Mémoires historiques et physiques sur les tremblements de terre* (Bertrand 1757), in which he presented a physical approach to the movements of the earth. Both naturalists were later called founders of seismology by Davison (1978). The analysis of natural events, and the principles of investigation set down after the 1755 Lisbon event and improved after the 1784 Calabria earthquake, evolved and grew to the present; observing, measuring, collecting and analyzing the data, building relations among the data and comparing them with other known results and facts.

The procedure laid out by the 18th century naturalists was gradually improved and refined in the course of the 19th century (we have to keep in mind that seismology as a scientific geo-discipline did not exist prior to circa 1880; the first professor of seismology was Seikel Sekiya (1834–1896) at the University of Tokyo in 1886; Emil Wiechert (1861–1928) was appointed professor of seismology at the University of Göttingen as late as 1901). In this century most of the macroseismic terminology was specified and labeled, their definition described and identified in such terms as: epicenter, hypocenter, earthquake intensity, isoseismic lines, seismic wave ‘direction’, velocity of seismic waves, etc. Not until the late 19th century were seismic intensity scales, tectonic faults and individual types of seismic waves commonly measured, accepted and taken into consideration.

The use of cartographic tools to evaluate the distribution and degree of seismic damage, known already since the early Mogiol seismic map of the 1564 Nice earthquake (Stucchi and Morelli 1992), improved considerably in the course of the 19th century. Thematic cartography was a broadening field at the time (Robinson 1982), and it was only reasonable that isoseismal mapping profited from this innovation and adapted the methods of this discipline. Earthquake maps of this kind show how macroseismic data was plotted onto suitable geographic maps as a helpful form to describe the effects of an earthquake. The early earthquake maps eventually developed into the present maps of seismicity, which today represent an important tool in earthquake engineering.

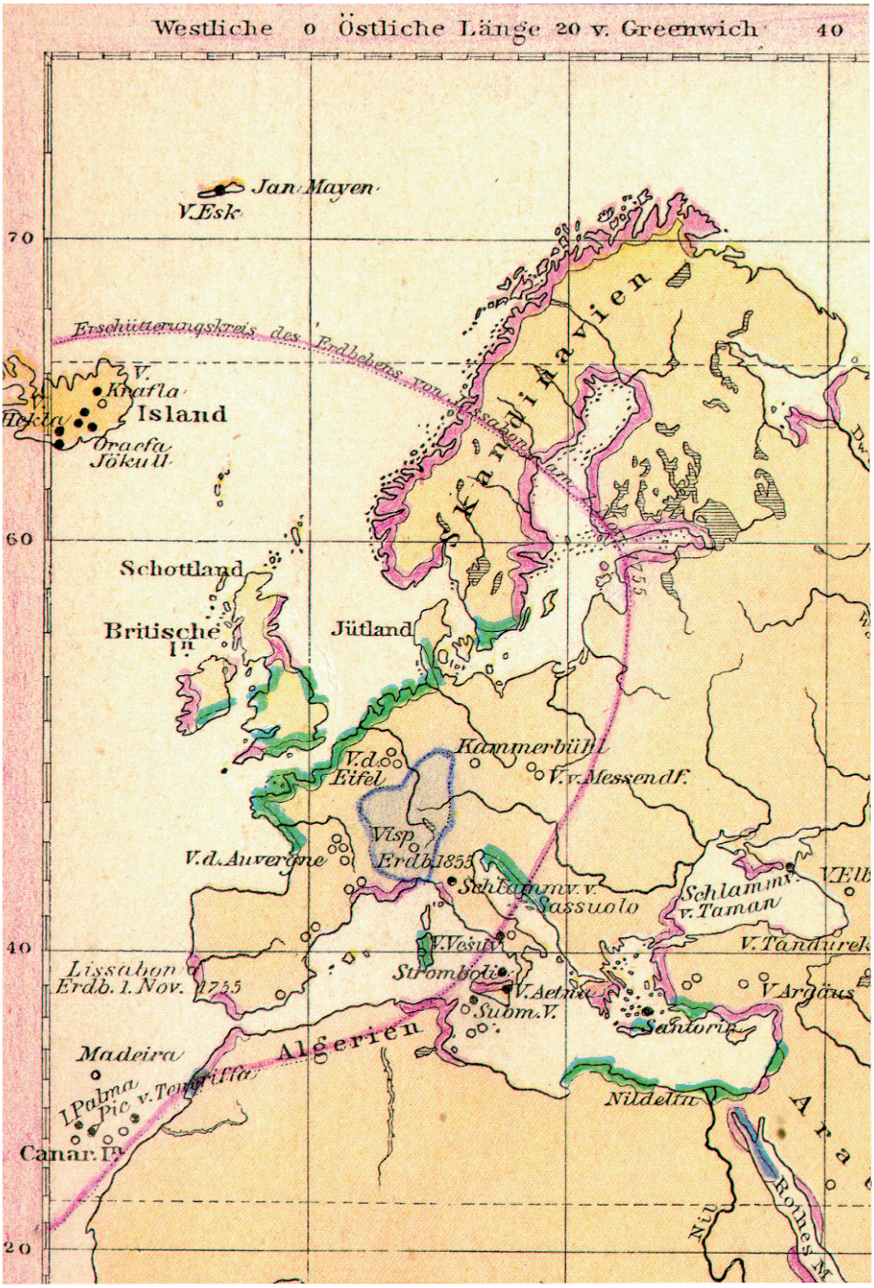

Fig. 1 Segment of map taken from the *Physical Atlas* (Section *Geology*) by Hermann Berghaus (1888), issued by J. Perthes editorial house, Gotha. In the map, limits of the perception of two important European earthquakes (Lisbon 1755 and Visp 1855) are drawn. Private collection, Prague

Several names can be connected to this effort. Schiantarelli in Italy was the first to make simple quantifications of damage in 1783 after the Calabrian earthquake of that year. It was the German geologist Christian Leopold von Buch (1774–1853) who considerably improved the endeavor in macroseismic analysis by studying the 1799 Silesian earthquake: he collected macroseismic observations from the residents of the affected region and plotted the obtained data into local geographical maps. This enabled him to determine the size and shape of the zone in which the earthquake was experienced, and hence to locate the ‘epicenter zone’ of the respective earthquake (Buch 1801). Günther (1897) names the German mathematician and naturalist P.N.C. Egen as the author of the first macroseismic map. Egen (1828) analyzed the February 28, 1828, North Rhine earthquake by using a large set of macroseismic data collected from local inhabitants. He was able to delineate the zones of the strongest effect. By doing so, he located the epicenter zone of the earthquake. He defined and applied the first empirical scale of macroseismic intensity, and in his earthquake map he recorded the directions of seismic movements, an endeavor that has already been undertaken in Hungary by Kitaibel and Tomtsányi (1814), who analyzed the 1810 Mór earthquake in central Hungary. For the ellipse of the largest seismic effects, Egen marked its two main axes; the longer axis coinciding with the longitudinal direction of the affected part of the Rhine Valley. However, the proposed scale has failed to receive widespread acceptance, as has the one by Robert Mallet, and as a result was of limited use in comparing earthquakes from different regions (Valone 1998). In Germany, Johann Jakob Nöggerath (1788–1877), professor of mineralogy and mining at the University of Bonn, presented a ‘modern’ map of the July 29, 1846 Rhine-region earthquake (Nöggerath 1847). Therein he depicted isoseismic lines, using several reports from the public (Davison 1978).

It was the German mineralogist and geologist Georg Heinrich Otto Volger (1822–1897) and the geographer and cartographer August Petermann (1822–1878) who presented an important study on the earthquake series after the July 25, 1855 Visp event. Their modern approach to the subject significantly enhanced this emerging discipline. In what follows, we will discuss their endeavor in detail, starting with a short outline of the 1855 Valais event.

3 The July 25, 1855 Valais Event: Synopsis and Overview

On July 25, 1855, a strong earthquake struck the southwestern region of Switzerland, the Valais, causing heavy damage in a wide range around Visp. It is known as one of the strongest earthquakes within Switzerland. The event was widely commented on and discussed in these regions as well as in border areas such as Northern Italy and Eastern France. According to modern classification the main shock occurred at 11 h 50 min UTC on July 25, 1855, with epicenter coordinates 46.23°N, 07.85°E, ± 20 km, near the village of Törbel. It was a deep event ($h = $ ca. 12 km); its epicenter intensity I_0 reached VIII (± 0.5) according to the EMS-98 scale (Grünthal 1998). Moment magnitude M_w is parameterized as 6.4 (± 0.5); additional macroseismic intensity magnitude M_m, determined by Swiss and Italian agencies, range between 6.2 and 6.4. The seismic analysis was set using 310 macroseismic intensity site-points (Fritsche et al. 2006).

The main shock of July 25th, 1855, at 11 h 50 min was followed by a series of aftershocks, the strongest one on July 26 at 9 h 15 min ($I_0 = 7^0$), another one at 13 h 20 min the same day ($I_0 = 6^0$). Other large aftershocks were detected on July 28 at 10 h ($I_0 = 7^0$), August 24, October 28 at 1 h 30 min, and November 6, at 3 h 30 min, all of them reaching an intensity of $I_0 = 6$ at least. The majority of this information comes from Volger's extensive study of the event, where he collected hundreds of observations in the epicenter area but also farther away.

The most affected region was the center of the Valais, at the border of the Rhone-Valley plane, with heavy damage of buildings and the environment. Visp, a village of about 130 buildings, was destroyed. People had to leave their buildings and live in tents for several days (Fig. 2). Houses built of stones were heavily damaged, many of them completely destroyed, and even wooden buildings suffered much harm (Fig. 3). Secondary effects impacted the environment of Visp. Several kinds of cracks, as well as clefts in the rocks, emerged from the seismic shocks (Fig. 4). In the area of Stalden, St. Niklaus and Grächen, effects of rock falls, landslides, cracks and rifts in the ground and newly emerged sources were easily identified. Thanks to particular contemporary sketches of the scene we know of a storehouse that was destroyed by a rock fall and a similarly destroyed stone house in St. Niklaus, the village that is supposed to have suffered most. Significant damage was also reported for Stalden, where the destruction was less than in Visp because of the large

Fig. 2 Local inhabitants at a mass served under the open sky near Visp ("in den Baumgärten"). Xylographic newspaper illustration, reproduced from an unidentified German journal of the time. Depicted by R. Kummer. Private collection, Prague

Fig. 3 Lithographic illustration showing heavily damaged stone house and timber structure in the Visp Valley. Heusser, 1856, ETHZ RARA: Geol P 173: 58 (1856)

Fig. 4 Lithographic illustration showing earthquake cracks and fallen stone blocks in the Visp area. Heusser, 1856, ETHZ RARA: Geol P 173: 58 (1856)

proportion of wooden buildings, but the stone houses suffered at least as much as those in Visp. For many other villages that underwent severe damage, the available information is much more fragmentary. Whereas Visp, Stalden, St. Niklaus and Naters were described as having suffered enormously, for other villages such as Grächen, Törbel, Visperterminen and Brig we know of little damage only, due to a neglect of descriptions. The extent of harm was remarkable, however, and has no parallels in Switzerland until the present (Fritsche et al. 2006).

4 G.H. Otto Volger's Depiction of the Event

At the time of the 1855 event the German geologist Georg Heinrich Otto Volger was committed to the study of the causes of seismic phenomena. Born in 1822 in Lüneburg, Volger studied natural sciences in Göttingen and qualified as a lecturer in 1847. He later taught natural history in a monastery in Muri (Aargau, Switzerland), and in 1851 became a high school-professor in Zurich. Since his student years in Göttingen he was seriously interested in mineralogy, crystallography and geology. Living in Frankfurt between 1856 and 1860, Volger taught at the Senkenberg Museum. He died in Sulzbach in Taunus on October 18, 1897 (Oeser 2003).

Independently of Robert Mallet (1810–1881) he developed a neptunist theory of wave propagation of earthquakes, adapted from the idea of the analogy of water waves to sound waves (hence the name neptunist). Volger assumed that most earthquakes in Switzerland were subsidence earthquakes, and were thus caused by the collapse of extensive hollow strata. The immediate opportunity to validate his theory was the Valais 1855 earthquake. As Volger reports in his monograph devoted to this event, he visited the earthquake site immediately after the main shock, collecting reports and observations from the affected population. Furthermore, he also created a broad correspondence network among people from more distant localities in order to complete the macroseismic data series for the earthquake area. Volger's collection of these genuine macroseismic data, complete with his interpretations, were published in 1858 (Volger 1857–1858).[1] In his conclusions he discusses origin and occurrence of earthquakes. The detailed description of the earthquake and the subsequent discussions on earthquake phenomena show how much an anticipated hypothesis or theory might influence the observation process, as Volger not only presents eyewitness records, but also selects and comments them or even corrects them from the viewpoint of his neptunist theory.

His neptunist subsidence theory assumes extensive wash out in the lower strata of the crust prior to an earthquake. Volger thus starts his discussion of the Valais earthquake with an account of the weather conditions before the actual event. His description of the main shock contains clear references to his theoretical explanation of this event as a subsidence earthquake. The noise that could be heard from the Earth

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[1] In the first Volume *Chronik der Erdbeben in der Schweiz* (1857), the author gives an historical survey of the earthquake occurrence in the Alpine zone and in adjacent regions; in the second one *Die Geologie von Wallis* (1857) he describes the geology of the respective regions. The third one *Die Erdbeben im Wallis* (1858) deals with the 1855 event.

in the epicenter area in the Visp valley during the first shock of the ground – often reported as detonations or cracking shocks – was evidence enough for the geologist to consider the hypothesis that the subterranean hollow stratum would lead to a subsequent undulating movement of the surface in the neighboring countries, moving towards the north much farther than towards the south. His basic assumption, still accepted today, is based on the idea that earthquakes depend on definite conditions that are present in the ground. In terms of these ideas, the cause of the shock is explained by the fall of a heavy body from the vault of a cave, or the collapse of a mountain rock to the base of a hollow layer. The direct effect of such a subterranean shock is similar to a shock to water covered with ice. Since the ground can be more easily compressed than water, the shock will propagate deep downward. But since the static vault of the ground prevents the shock to reach the Earth's surface, the undulation will, in contrast to an uncovered fluid, propagate also horizontally in all directions. The direct shock can thus be felt only under the location of the shock, at any other place it is covered by the undulation that already has started. It might have been this hypothesis that led Volger to scale the damage and plot a map. This very precise map evidently shows that the propagation of the main shock on July 25, 1855 was at least three and a half times stronger towards the north than the south. Volger assumed that this effect was caused by the washout of strata in the structure of the northern wing of the basin below the Gorner-Visp valley between St. Niklaus and Stalden. On the other hand, Volger strongly denied the explanation that earthquakes are cut off by mountain ridges, in this case by the Jura and the Alps. In the framework of his collapse theory, Volger provided the following plausible explanation of different behaviors of mountains and buildings during earthquakes: while mountains are comparable to large ships, below which several seismic waves propagate simultaneously so that the mountains as such cannot start to vibrate themselves, in contrast to high buildings and in particular towers, which are subject to different processes due to their small ground area in comparison to their height. With this hypothesis Volger reassessed Werner's (Abraham Gottlob Werner, 1749–1817) original idea of the collapse of whole strata rather than providing new ideas to the causes of earthquakes (Oeser 2003).

5 Early Macroseismic Maps

On the other hand, the depiction of macroseismic maps is the most fascinating part of Volger's work. Equivalent with the collection of seismic data, earthquake-map plotting has its history, too, going back to the above mentioned map design by Mogiol for the Nice earthquake of 1564. In the first half of the 19th century, P.N.C. Egen and J.J. Nöggerath already drew earthquake maps showing seismic intensity. After these pioneer cartographic earthquake portrayals, the two maps of the Visp 1855 event, both designed by A. Petermann, the first based on preliminary, the second on detailed macroseismic information provided by Volger, led to an advanced step of macroseismic study both concerning the collection of data as well as map plotting.

It follows from the biography of Petermann that the creation of geophysical maps was an inherent part of his work. As his many maps document for inner Africa, northern parts of the Russian Empire, and the Arctic regions, he showed an extraordinary ability to transform data, usually provided by travel accounts, into cartographic form. Along with his military maps, as for example his excellent map of the battle near Hradec Králové, North Bohemia in 1866, he mainly produced geographical and geophysical maps, among them maps of volcanic and seismic activities. These areas of interest resulted from his cartographic education in the Cartography Art School in Potsdam, founded and directed by Heinrich Berghaus (1797–1884), author of the famous Physical Atlas published by J. Perthes in Gotha between 1837 and 1848 (Kozák and Vaněk 2002). After 1840, Petermann continued this endeavor in London. After his return to Germany in 1854, he became engaged in drawing both geographical and physical maps for the publishing house of J. Perthes in Gotha. It seems that Petermann was not specialized in seismological research of individual earthquakes. On the other hand, the field was familiar to him due to his long-term engagement in constructing numerous world and regional physical maps, in which the effects of earthquakes were shown.

Volger, on the other hand, had most probably no special cartographic education at all. From the preface of the third volume of his monograph (Volger 1858) it can be concluded that he contacted the editorial house of Perthes in Gotha or its chief cartographer Petermann, feeling the need to interpret the results of his earthquake studies as a geophysical map. When studying the Visp earthquake, Volger invented and utilized a seismic intensity scale for his own purposes. He subdivided the effects into seven categories, designating degree zero for the epicenter region, and degree 6 for the lowest intensity site (Fig. 5). Since Volger designed the scale exclusively for this one particular event of July 25, 1855 it was not suitable for classifying other earthquakes, unless one would have accepted higher degrees of Volger's scale for the classification of weaker events or degrees of negative values of Volger's scale for the description of stronger events.

The first Petermann map was published in 1856 by Volger as part of a paper that gives a short overview of the event and lays the foundation for his extensive studies in the future (Volger 1856; as for the next paragraph see also Kozák and Vaněk 2006). Petermann's data comes from a collection that Volger started right after the earthquake (Volger 1855).[2] In this map, the intensity of earthquake effects is classified in five degrees, according to five defined levels of seismic damage:

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[2] "Durch einen bereits am 27. Juli erlassenen und in alle Blätter der Schweiz verbreiteten Aufruf habe ich möglichst viele Leute der gebildeten Stände zu veranlassen gesucht, ihre Beobachtungen sogleich niederzuschreiben und mir einzusenden. Diese Bemühung hat, besonders in der Deutschen Schweiz, ziemlich reichlichen Erfolg gehabt, die Zusendungen gehen noch immer fort, es giebt ein beträchtliches Material zu verarbeiten. [On July 27, I caused an investigation to be made by as many sophisticated people as possible. I enquired them to give notice of their observations, and send these to me. This endeavor was quite successful, particularly in the German part of Switzerland, the returns still incoming; I received considerable material to process.]" (Volger, 1855).

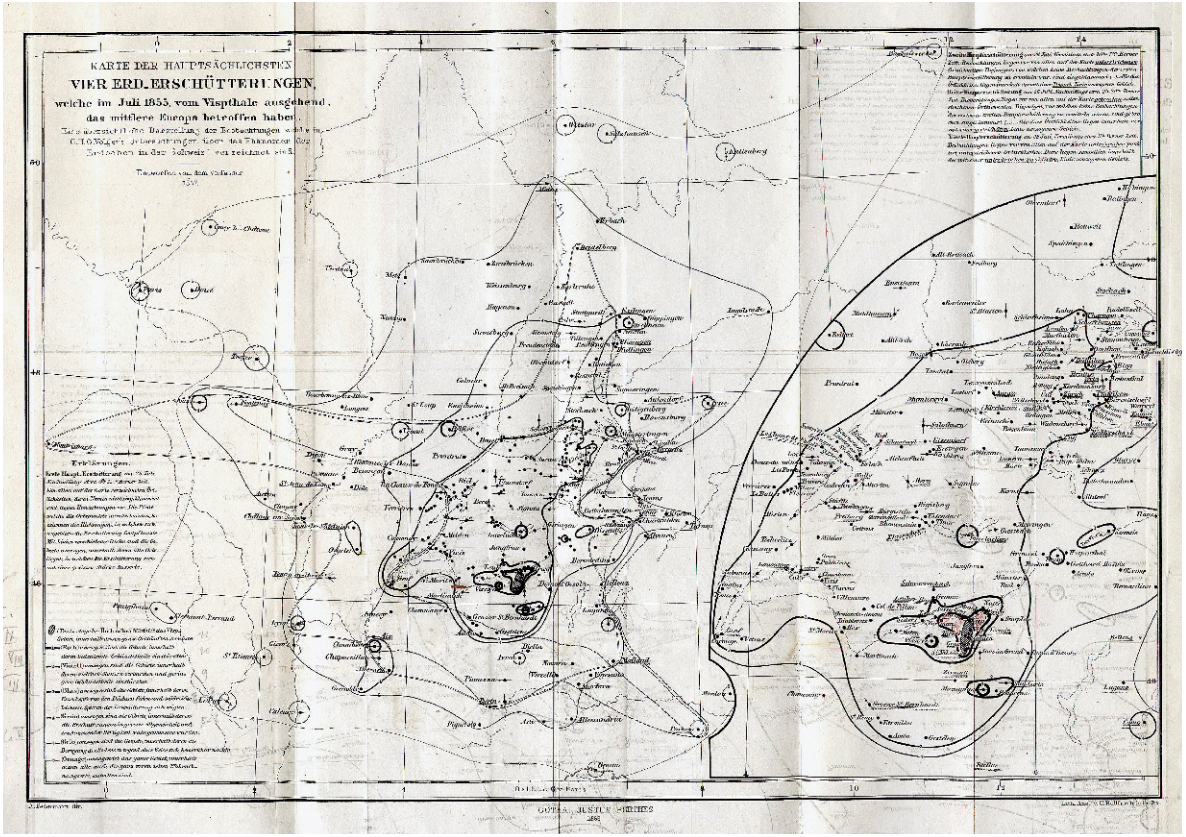

Fig. 5 Detailed map of the effect of four principal earthquakes in July 1855 in the Visp Valley. For the main shock the isoseismal lines (0, 1, 2 . . . 6) are given while for three aftershocks the limits of perception are plotted. Volger, 1858, ETHZ RARA: 8096 1–3

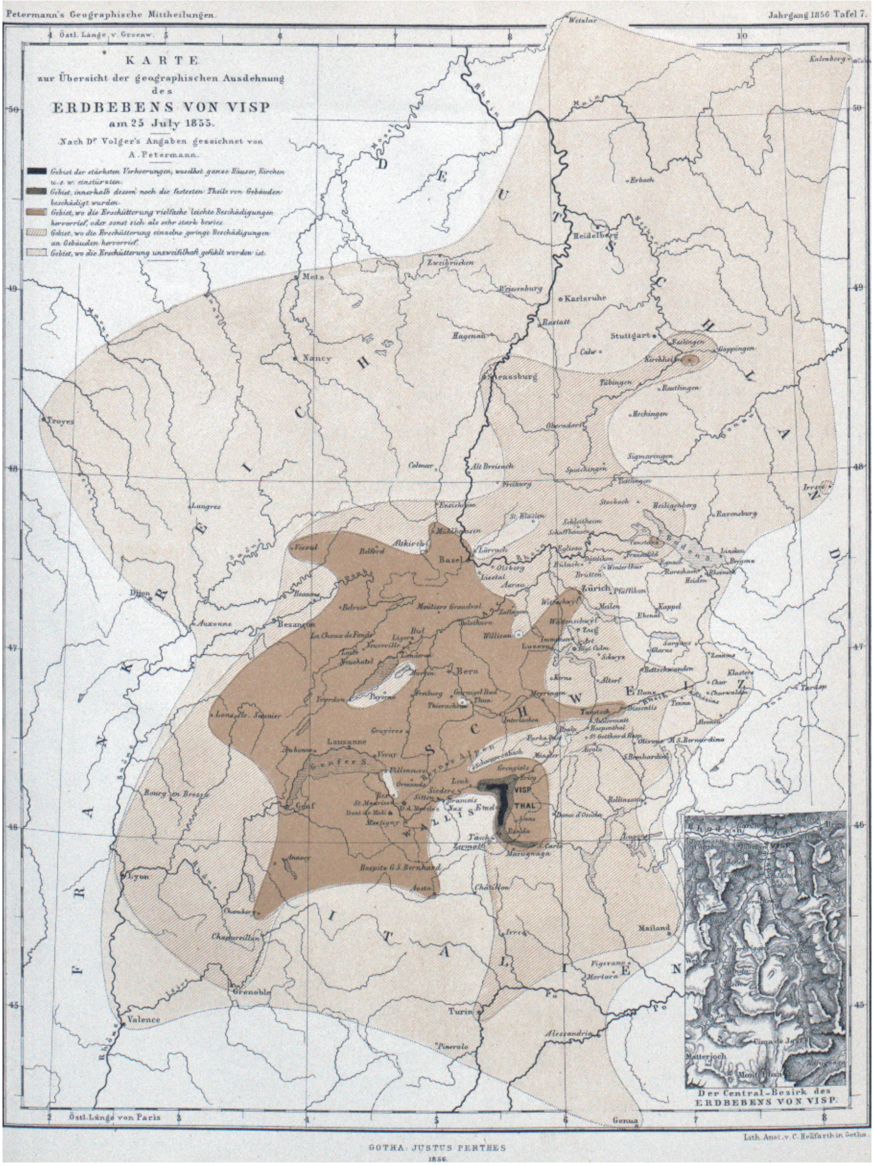

Fig. 6 Map with survey of the geographic perception of the 1855 July 25th Visp earthquake. Drawn by A. Petermann after data submitted by O. Volger. Zones of different level of seismic damage are given by five tones of brown. Volger, 1856, ETHZ RARA: 1058: 1856

different tones of brown colors designate the relevant zones (Fig. 6). The author did not assign values to the individual earthquake damage degrees, which makes his classification more general; the largest damage was related to the Visp 1855 highest intensity. However, he did not realize that no data was obtainable from uninhabited zones. He thus erroneously classified several of the mountain regions (e.g., the zone westward of the epicenter region between Aosta, Sitten and Zermatt in his map) as being of low intensity. This flaw might be a result of a lack of experience when designing seismic maps for the Alpine region, where the bulk of population inhabited the bottoms of mountain valleys.

The second isoseismal map of the 1855 Visp event (Fig. 5), published by Volger two years later (Volger 1858) seems to be outlined with greatest care and attention. The author used the detailed data collecting campaign and plotted the isoseismal lines according to the classification (intensity/damage scale) from 0 (strongest effects) to 6 (limit of perceptibility). Whereas the first map showed a distinction of five degrees only, this latter one showed six different intensity degrees. Volger considered all individual reports – sometimes contradictory for one region – which resulted in numerous 'islands' of higher intensity in fields of lower ones. Such a regional exactness in following the reported information for individual localities (mostly distributed non-regularly in mountain valleys) produced a rather complicated pattern of isoseismal lines, from which the general shape of the shaken region is difficult to be read. In this respect the simple and more generalized first map by Petermann (Fig. 6) seems to be more instructive.

The high level of the maps shows that the cartographic representation of the macroseismic field was undoubtedly proposed and constructed by Petermann. The mode of expression of the distribution of the macroseismic effects in the maps is completely different: whereas in the preliminary map (Fig. 6) Petermann applied five tones of the same color, in the final map (Fig. 5) isolines dividing regions of different degree of macroseismic effects were used.

Volger defined degrees of his 'intensity scale' in the legend of his macroseismic map as follows:

(0) in the hatched zone . . . the whole settlements were ruined
(1) in the zone limited by line 1 . . . the most important parts of buildings collapsed
(2) in the zone limited by line 2 . . . numerous walls cracked, smaller parts of buildings collapsed
(3) in the zone limited by line 3 . . . chimneys toppled, numerous traces of minor damage occurred
(4) in the zone limited by line 4 . . . tremors to be felt strongly
(5) in the zone limited by line 5 . . . ground movements to be observed
(6) entire zone limited by line 6 . . . from which observations – of any kind – were reported.

Even though Volger never used the term 'macroseismic intensity', he obviously succeeded in creating one of the first applicable macroseismic scales based on the observation of damage, the behavior of objects and the perception of the people, i.e. upon principles that are applied in all later intensity scales developed up to the present (Kozák and Vaněk 2006).

It should be noted that the classification degrees used in Petermann's preliminary map are slightly different from those applied in the final macroseismic map. The zones of different tone of color in Fig. 6 are defined as follows:

Zone 1 . . . of the strongest movements, where whole buildings, churches, etc. collapsed. It is denoted by the darkest tone of brown
Zone 2 . . . where large parts of buildings were damaged
Zone 3 . . . where shaking caused small damage but in general the earthquake appeared as strong
Zone 4 . . . where individual small damage to buildings was mentioned
Zone 5 . . . where tremors were undoubtedly felt. It is denoted by the palest tone of brown.

A comparison of the macroseismic classification at the corresponding sites in both maps is given in Kozák and Vaněk (2006). The highest degrees of both scales were defined by construction damage, while only limits of the smallest effects considered human responses. Both scales were fully based on classification of damage to constructions, and no ground effects were taken into consideration, even though rock falls and ground fractures and cracks occurred in the region (Fig. 4).

Despite these weak spots, both the preliminary Petermann map and the enhanced map of Volger's intensity classifications can be seen as an important step forward, namely a more detailed damage-to-construction-classification, which became even more important in later macroseismic scales. The distortion of the damage scale appeared partly due to Volger's possible overestimation of many reports coming from the densely inhabited regions of Baden, Zurich and Winterthur, where the level of damage reports did not correspond to actual degree of damage in this area; Volger apparently attributed his earthquake-effect class 3 (instead of class 4) to numerous such localities. It should be taken into account that a more detailed definition of Volger's categories – in general – was not possible due to his neglect of different types of construction, considered in later macroseismic intensity scales (Kozák and Vaněk 2006).

6 Impacts

It is now very interesting to follow the thread of the impact and reception of Volger's ideas and inputs. Four years after the issue of Volger's monograph, Robert Mallet, a practical engineer, presented a coherent system of macroseismic earthquake investigation of the December 16, 1857, Basilicata (central Italy) earthquake (Mallet 1862). No direct evidence has been found that Mallet knew and made use of Volger's construction of isoseismal lines; however, Mallet – in 1862 – evidently used almost identical methods for the construction of isoseismals, as Volger did four years earlier.

In the last quarter of the 19th century reference to earthquake intensity became widespread. Let us thus focus on a closer geographical circle: Switzerland and Italy. Francois Alphonse Forel (1841–1912) proposed a ten-degree scale in 1880 (2 years after the establishment of the Swiss Seismological Commission in 1878) and plotted an isoseismal map of the earthquake of December 30, 1879 in the Valais. Albert Heim (1849–1937) was then the first to use it for the interpretation of an earthquake (Société helvétique 1880). In 1881 Forel discussed his scale to gain a more accurate and simplified methodological approach when collecting observational data (Forel 1881). He proposed his scale to evaluate the seismic events in Switzerland in 1879/1880. He soon became acquainted with the scale suggested by the Italian Michele Stefano de Rossi. On the invitation of de Rossi, the two seismologists met, in order to agree on a single scale for earthquakes occurring on both sides of the Alps (Forel 1880; Davison 1978).[3]

In the following years, Forel and others published yearly reports on seismicity in Switzerland, and larger earthquakes of the respective year. In 1884 Forel discussed the collaboration with Rossi and published the joint Rossi-Forel-Scale with ten degrees of intensity, designed in 1883 and 'bien adaptée par les sismologistes suisses et italiens [well adapted by the Swiss and Italian seismologists]' (Forel 1885).[4] This was the first scale to be widely used internationally, whereas a common feature of all former scales was that none of them was used by anyone but their authors. In fact, the Rossi-Forel scale was extended to the United States of America, since Edward

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[3] "Depuis que cette échelle a été proposée, j'ai reçu connaissance d'une échelle analogue établie déja en 1875 par M. M.-S. de Rossi, de Rome, et adoptée par les sismologues italiens. Devant les droits de priorité évidents de M. de Rossi j'aurais immédiatement retiré l'échelle que j'avais établie, si nous n'avions reçu de MM. de Rossi et Gatta la proposition d'étudier en commun une révision de ces échelles d'intensité, en tenant compte de l'experience des années écoulées. Nous avons accepté avec empressement cette offre; mais le travail de révision est assez long, et nous ne pourrons l'utiliser que pour le rapport de l'année prochaine. [After this scale has been proposed, I learned that an analogous scale has been established in 1875 by Mr. M.-S. de Rossi, from Rome; the scale being used by Italian seismologists already. As Mr. Rossi has the privilege for having been the first one to establish the scale, I would have immediately withdrawn mine if there were not Messrs. Rossi and Gatta to offer to work on a common scale, making use of our experiences of the past years. We have zealously accepted this offer, even though the revision seems to be extensive, and we thus can only adapt it next year.]" (Forel, 1881). As a matter of fact, Rossi had composed his first scale in 1873.

[4] Comparision of the Forel and the Rossi-Forel scale; I being the lowest, X the highest intensity (Forel, 1884).

Échelle Forel 1881	Échelle Rossi-Forel 1883
I / II	I
III	II / III
IV	IV
V	V / VI
VI	VII
VII	VIII
VIII / IX	IX
X	X

S. Holden (1846–1914) (Holden 1898) used it in his catalog of earthquakes in the western USA, from which it descended to the listing of Townley and Allen (1939).

Compared to the former scales a refinement is clearly to be observed when it comes to the description and perception of damage. Description of damage starts with intensity VI, degree X meaning completely destroyed. In Volger's scale, degrees 0–4 relate to damage zones, whereas degrees 4, 5 and 6 reflect merely perception by humans. In the following years, all discussed events were given with intensity degrees according to the Rossi-Forel scale. Forel even modified the events he had already interpreted with the Forel-scale. This scale was in use until the first third of the 20th century (Valone 1998). Giuseppe Mercalli (1850–1914), who published a modified version, still with ten degrees, improved the scale. (He had also published an earlier scale of six degrees, which was a modification of Rossi's first scale). It appeared, though, that ten degrees were insufficient for expressing the whole range of effects from the weakest to the calamitous. The Italian Adolfo Cancani (1856–1904) therefore proposed the extension of the scale to twelve degrees. However, he omitted to flesh out his twelve degrees with full descriptions, and restricted himself to titles for each degree (like 'destructive'), and estimated ground acceleration values (Musson 2005).

What about the use of Volger's scale by his colleague Forel? The latter was very well acquainted with Volger's work as he used it for statistical purposes (Forel 1884). As what concerns the development of his own scale or the plotting of intensity maps, it seems that Forel neglected Volger's contribution entirely. Volger was never acknowledged by Forel or his collaborator Rossi. What's more, despite these endeavors, August Sieberg in 1904 laments about the lack of any conventional and internationally approved quantitative scale, analogous to those used in meteorology (Sieberg 1904). Volger's work, we must conclude, was highly recognized and debated by his contemporaries and successors in favor of his accomplishments regarding earthquake theory, and the broad collection of his earthquake data (Tams 1952), but not in matters pertaining to intensity scales and map plotting.

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In Troubled Times, in a Divided Country: The 1789 Valtiberina Earthquake

V. Castelli

Abstract The Valtiberina region (central Italy) has a seismic record going back to the Middle Ages and including five Io>VIII MCS earthquakes, the earliest of which (1352, 1389, 1458), though recently and extensively studied, remain rather poorly known. This makes it all the more important to ensure that the later ones (1789, 1917) are as thoroughly studied as possible. The 1789 earthquake is listed by the current Italian catalogue (CPTI Working Group 2004) with Io VIII-IX MCS and Mm 5.8. These parameters were assessed from a database of twenty-eight macroseismic intensity data points (Castelli et al. 1996), which is less than plentiful for a late 18th century earthquake. An analysis of the historical context of the 1789 earthquake and its influence on the production of contemporary accounts evidences a few research paths that previous studies either did not or could not take. Following them, the macroseismic database of the 1789 earthquake can be noticeably improved, providing the catalogue compiler with a mean to check the reliability of its current parameters.

1 Introduction

Late in the morning of September 30, 1789 a strong earthquake hit Valtiberina, the upper valley of the Tiber, in central Italy. The seismic history of this area goes back to the Middle Ages, with at least nine Io≥VII MCS regional earthquakes (Fig. 1).

The 1789 earthquake – listed by (CPTI Working Group 2004) with Io VIII-IX MCS and Mm 5.8 – is one of the five strongest regional earthquakes (Table 1). Though recently and extensively studied (Boschi et al. 1995; Boschi et al. 1997; Boschi et al. 2000; Castelli 2002; Guidoboni and Comastri 2005) the earliest of these earthquakes (1352, 1389, 1458) remain rather poorly known, with less than ten macroseismic intensity data points (MIDP) available for each (Table 1). This makes

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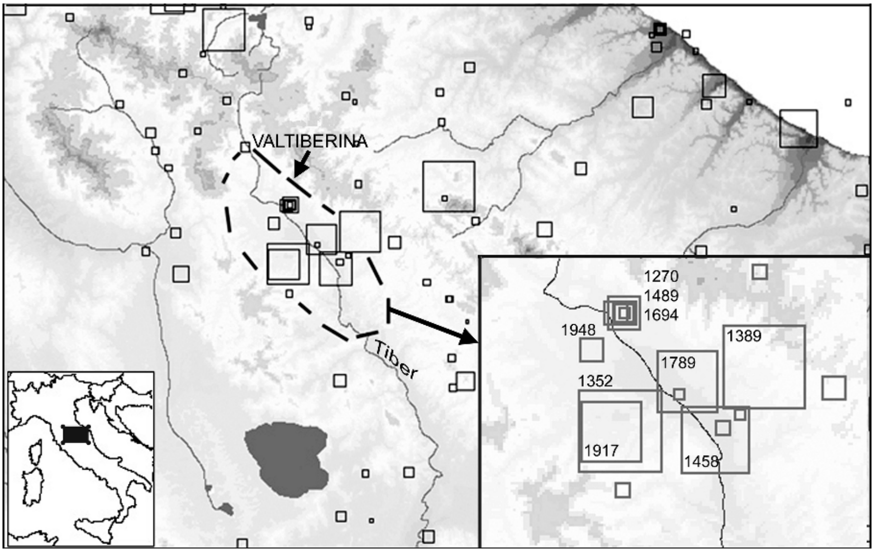

Fig. 1 Valtiberina historical seismicity according to the Italian catalogue (CPTI Working Group 2004)

Table 1 Valtiberina major historical earthquakes according to the Italian catalogue (CPTI Working Group 2004)

Year	Mo	Da	Epicentral zone	MIDP	Io MCS	Lat	Lon	Mm
1352	12	25	Monterchi	7	IX	43.465	12.127	6.0
1389	10	18	Bocca Serriola	9	IX	43.523	12.295	6.0
1458	04	26	Città di Castello	5	IX	43.456	12.239	6.0
1789	09	30	Valtiberina	28	VIII-IX	43.505	12.208	5.8
1917	04	26	Monterchi-Citerna	128	IX	43.465	12.125	6.0

MIDP: Macroseismic Intensity Data Points

it all the more important that the two later ones (1789 and 1917) are as thoroughly studied as possible. This paper deals with the 1789 earthquake, whose current epicentral parameters have been assessed from a database of 28 MIDP (Fig. 2). Taking into account the MIDP-per-earthquake ratio in the 18th century time-window of the Italian catalogue (Table 2), a database of this size suggests that the 1789 earthquake is better known than most 18th century events but not quite as well as a good many of them. Moreover, the MIDP distribution in the 1789 intensity map (Fig. 2) seems sparser in the lesser damage intensity ranges (VII and VI MCS), than in the higher damage ones (VIII and IX MCS), most MIDP being located south of the border which runs through the Figure, marking the present administrative boundary between Tuscany and Umbria (or, in 1789, between the Grand-Duchy of Tuscany and the Papal States). Both circumstances seem to hint that part of the information pertaining to this earthquake could be lacking. Why should it be so? And what could be done to improve this situation?

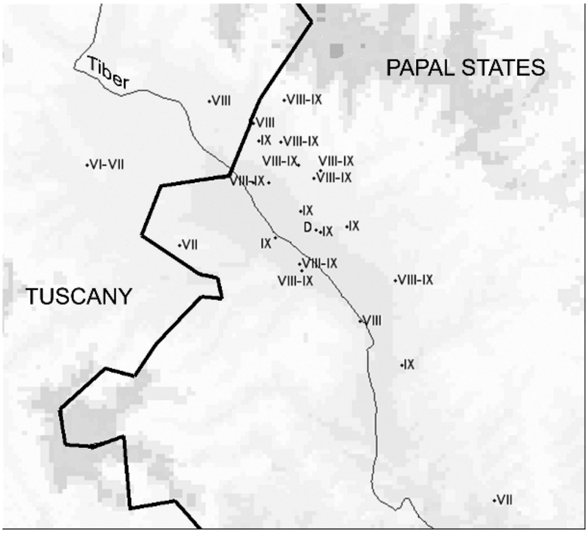

Fig. 2 Current macroseismic data base for the 1789 earthquake (Castelli et al. 1996)

Table 2 MIDP per-earthquake in the 18th century time-window of the Italian catalogue (CPTI Working Group 2004)

18th century earthquakes (CPTI Working Group 2004)	≤ 10 MIDP	11–30 MIDP	31–100 MIDP	101–357 MIDP
126	79	19	16	7

MIDP: Macroseismic Intensity Data Points

As many outstanding methodological contributions pointed out along the years (Ambraseys and Melville 1982; Gisler 2003; Guidoboni 2000; Guidoboni and Stucchi 1993; Gutdeutsch and Hammerl 1988; Musson 1998; Vogt 1993 to name but a few) to answer these questions one should, first of all, consider the historical circumstances within which the earthquake took place, and in which way they could have influenced (i.e. furthered or hindered) the production of contemporary written accounts of the earthquake itself and their preservation for future use by historical seismologists.

2 The Historical Context Within Which the 1789 Earthquake Took Place

The 1789 earthquake occurred across what was then the frontier between two independent countries – the Grand-Duchy of Tuscany and the Papal States – and at a time of European strife. Both circumstances influenced the way in which contemporary observers perceived the 1789 earthquake and recorded its effects for future memory.

The involvement of two countries implies that earthquake victims asked for help to two distinct rulers (Pope Pius VI and Grand Duke Pietro Leopoldo I of

Habsburg-Lorraine), and that there were two independent official responses to the emergency. Letters were exchanged between the earthquake-affected area and two capital cities (Florence and Rome); damage surveys had to be made, relief measures taken, restoration work done, and financial accounts totted up. Each of these actions would leave a paper trace in written records destined to be stored, in local and central archives. Once there they would undergo all the vicissitudes that archives are exposed to and which sometimes lead records to be lost, either temporarily or for good; for more on this subject see (Vogt 1993) (chapter on "Archives: general considerations").

Contemporary perception of the 1789 earthquake is also likely to have been influenced by an earthquake of another kind. Two month and a half before September 30 a Parisian mob had stormed the Bastille and, in quick succession, King Louis XVI of France was forced to acknowledge the National Assembly, panic swept through France, and the Déclaration des Droits de l'Homme et du Citoyen was issued. By the end of September 1789, the French revolution and its repercussions on European politics had become the major focus of attention for most European observers; additional interest was provided by the Balkans (where an Austro-Russian army was confronting Turkey) and by the Austrian Low Countries (which had revolted against Habsburg rule).

The international situation is the likeliest responsible for the lack of interest shown by learned members of the Italian intelligentsia, for the 1789 earthquake, as witnessed by the fact that no scientific treatises were written on the 1789 earthquake, contrarily to what had happened in the wake of many comparatively minor earthquakes occurred in Tuscany and the Papal States in the 1780s (Augusti 1779; Augusti 1780; Augusti 1785; Canterzani 1779; Cavalli 1785a; Cavalli 1785b; Della Valle 1781; Gilii 1786; Parere 1787; Rinieri de' Rocchi 1788; Saggio 1787; Sarti 1783; Vannucci 1787). Newspapermen showed more interest in the 1789 earthquake. The earliest gazettes to report on the 1789 earthquake were those printed in Florence and Rome (Gazzetta Universale 1789a; Notizie politiche 1789a): second-hand accounts based on letters received from the provincial capitals of the afflicted districts (Tuscan Sansepolcro and Papal Città di Castello), which would in their turn become a source for other Italian (Avvisi di Genova 1789; Gazzetta di Bologna 1789a, 1789b, 1789c; Gazzetta di Mantova 1789d; Notizie del Mondo 1789a, 1789b, 1789c) and foreign gazettes: by November 1789 the news had reached London (Gentleman's Magazine 1789), Madrid (Mercurio de España 1789a, 1789b) and Paris (Gazette de France 1789).

3 The 1789 Earthquake in the Eye of Contemporary Newspapermen

From mid-19th century onwards the 1789 earthquake became a subject for historical reconstruction, first on the part of local erudites (Muzi 1842-1844) then by seismologists (Baratta 1901; Boschi et al. 1995; Boschi et al. 2000) and architecture historians (Giovanetti 1992). All these reconstructions have in common an almost total reliance on contemporary journalistic sources as their providers of raw data. To understand how this can have influenced the resulting depiction of the 1789 earthquake, it is necessary to consider how exhaustive a view of the 1789 earthquake can be derived from contemporary journalistic sources.

A comparison between earthquake reports printed in a large sample of gazettes published in October/November 1789 (Avvisi di Genova 1789; Diario Estero 1789; Diario Ordinario 1789a, 1789b, 1789c; Gazette de France 1789; Gazzetta di Bologna 1789a, 1789b, 1789c; Gazzetta di Mantova 1789d; Gazzetta Toscana 1789a, 1789b; Gazzetta Universale 1789a, 1789b, 1789c; Gentleman's Magazine 1789; Mercurio de España 1789a, 1789b; Notizie del Mondo 1789a, 1789b, 1789c; Notizie politiche 1789a, 1789b) allows to identify a few descriptions that, judging from their wide circulation, must have been particularly influential in creating a "popular image" of the 1789 earthquake:

a) the earliest Florentine report, dated October 2 (Gazzetta Universale 1789a). It was taken up by (Gazette de France 1789; Gazzetta di Bologna 1789a; Gazzetta di Mantova 1789d; Gazzetta Toscana 1789a; Gentleman's Magazine 1789; Mercurio de España 1789a; Notizie del Mondo 1789b); a summary of effects in Sansepolcro with a few rumours about effects in the Papal States;
b) the earliest Roman report, dated October 7 (Notizie politiche 1789a). It was taken up by (Gazzetta di Bologna 1789a; Notizie del Mondo 1789a); a summary of effects in Città di Castello and district, with a few hints on Tuscany;
c) an anonymous report, published in Florence on October 17 (Gazzetta Toscana 1789b), whose author was one abbé Lampredi of Anghiari, a village near the Tuscan-Papal border (Lampredi 1789). On October 1, 1789 Lampredi crossed the border, walked as far as Città di Castello and went back home to write a stirring tale of devastation. The report printed in (Gazzetta Toscana 1789b) would also be reprinted, verbatim, by the Roman periodical (Notizie politiche 1789b);
d) a journalistic pamphlet (Brami 1789) printed in Città di Castello, probably at the end of October 1789, on behalf of the Municipality that wished "to set right many errors seen in previous reports" (a possible reference to Lampredi's one). It details the damage suffered by the main monuments of Città di Castello, with special reference to the loss of important artworks, adding summary descriptions of earthquake effects in a few minor localities of the district and information on the official response to the emergency.

All these accounts agree in presenting the 1789 earthquake as a shocking drama whose main protagonist is Città di Castello, though a few other affected localities are also singled out for consideration (Sansepolcro, San Giustino, Selci, Cospaia). The damage sustained by the main public and private buildings of Città di Castello is extensively detailed, while descriptions of earthquake effects in the lesser localities tend to be global and to privilege the most dramatic episodes.

4 Archive Records and Their Relevance in Reconstructing the 1789 Earthquake

The first study to make a comparatively extensive use of contemporary archive records for the reconstruction of the 1789 earthquake was (Castelli et al. 1996). It hardly needs to say that this statement does not imply any criticism whatsoever of previous reconstructions. Local erudites – in whose eye the 1789 earthquake was no more than an anecdote – relied on newspaper accounts as a matter of opportunity rather than choice. The classical national-scale earthquake compilation by (Baratta 1901) was largely dependent on contributions by local erudites, whose methodological biases it inherited. Finally, the 1789 studies by (Boschi et al. 1995; Boschi et al. 2000) were preliminary ones, based on the "critical revision of existing bibliography and of selected sources" (Boschi et al. 2000, p. 843) and not required to perform any systematic archive research at all, though in fact their references include some archive records together with a good sample of contemporary newspapers. However, the importance of archive records for the study of historical earthquake cannot be overstated, as a quantitative comparison between the 1789 earthquake intensity map provided by (Boschi et al. 1995) and the one by (Castelli et al. 1996) (Fig. 3) shows.

Unfortunately, using archive records has some drawbacks too. As Jean Vogt brilliantly put it in (Vogt 1993), finding out exactly which records were produced after a given earthquake and discovering their present whereabouts can be a slow, complicated, and even frustrating task. Now, earthquake historians, particularly if they are taking part to the compilation of a new catalogue, will sooner or later have to find an acceptable compromise between thoroughness and the meeting of deadlines. In the case of the 1789 study by (Castelli et al. 1996) the compromise was reached by giving priority to the records stored in the central archives of the involved gov-

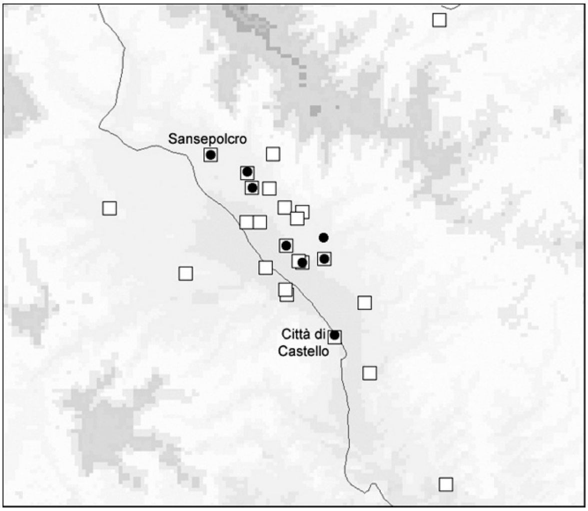

Fig. 3 1789 intensity maps: a comparison between (Boschi et al. 1995) and (Castelli et al. 1996)
Note: *Black dots*: (Boschi et al. 1995) *White squares*: (Castelli et al. 1996).

ernments, which – as a general rule – are richer, better preserved, easier to find and more accessible to researchers than most municipal archives. The records produced by Papal officials that had dealt with earthquake effects in the Papal States were easily retrieved (ASRM [Archivio di Stato, Rome] 1789–1795) but their Tuscan homologues – the damage surveys made in Sansepolcro and its district – could not be located in the Archivio di Stato of Florence, owing to damage suffered by the relevant holdings in the Great Flood of 1966 (a loss reflected by the paucity of Tuscan data mentioned in 1). It was also impossible to retrieve a most important document mentioned in Roman records, a damage survey of the whole Governatorate of Città di Castello, which had been made during the 1789–1790 winter and, after having been originally stored in Rome, had been later on sent to Città di Castello, in whose municipal archives it should have been preserved. Unfortunately, when the (Castelli et al. 1996 study was carried out, the historical section of the archives was still uninventoried, and therefore unavailable to researchers. It took six or seven years more before an inventory was started and reached an advanced enough stage to identify one of the three ledgers originally composing the survey (ASCC [Archivio storico comunale, Città di Castello] 1790). Though incomplete, this document gives information on about 85% of the buildings of Città di Castello itself (Castelli 2002) and on several outlying hamlets. More or less at the same time, and by a mere chance, a list of names and addresses of the householders who had been subsidized by the State on account of damage suffered during the 1789 earthquake was discovered in the municipal archives of Sansepolcro (ASCS [Archivio storico comunale, Sansepolcro] 1789–1791). Though this kind of information cannot make up for the loss of the actual damage surveys, it gives at least the location of single damaged buildings and can therefore be used for a preliminary identification of affected localities. The input of these data allows to add another forty-five previously unknown affected sites to the macroseismic database of the 1789 earthquake (Fig. 4, Table 3).

5 Why to Tell This Story?

How does this story end and why to tell it at all? The referees who read its first draft asked to know whether the increase in MIDP improves the parameters of the 1789 earthquake. A fair question, which the author must leave unanswered: pending the revision of the current Italian earthquake catalogue, the "new" 1789 earthquake database was turned in to the people in charge and the judgment is now up to them. However, it can at least be pointed out that – for what concerns the town of Città di Castello itself – the evidence of a contemporary damage survey (ASCC [Archivio storico comunale, Città di Castello] 1790) allows to draw a much more reliable image of urban damage than previously available and to refute the catastrophic scenario depicted by (Giovanetti 1992), according to which the 1789 earthquake "rase al suolo una gran parte degli edifici e [. . .] risparmiò solo quelli di più recente costruzione" [razed to the ground a great many buildings, leaving untouched only

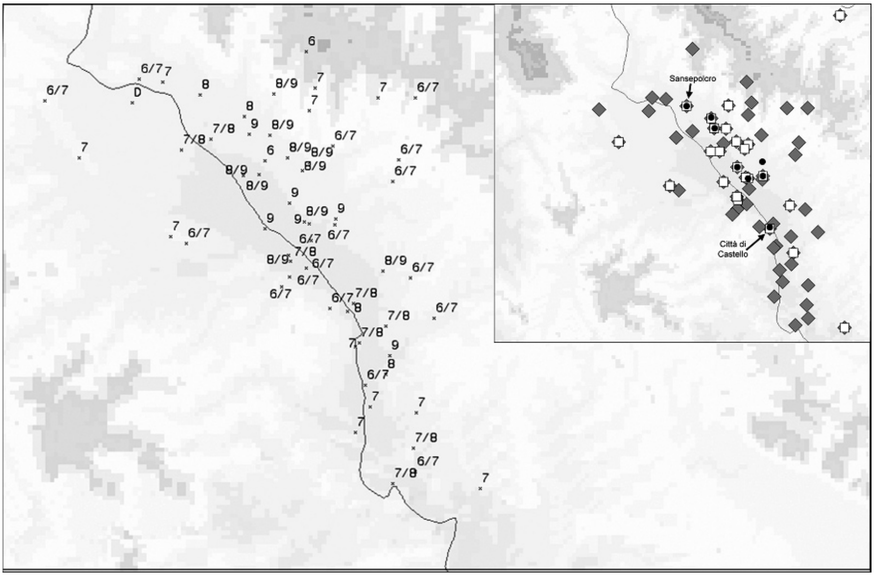

Fig. 4 Figure 4 The 1789 earthquake according to this study
Note: Intensity expressed in MCS scale. Inset: a quantitative comparison between (Boschi et al. 1995) (*black dots*), (Castelli et al. 1996) (*white squares*) and this study (*grey diamonds*).

Table 3 Intensity table for the September 30, 1789 earthquake (this study)

Locality	Class	In previous studies?	Latit	Long	I MCS (this study)
Turicchio		Y	43.433	12.267	IX
Selci		Y	43.500	12.183	IX
San Giustino		Y	43.549	12.174	IX
Lama		Y	43.513	12.201	IX
Grumale		Y	43.504	12.233	IX
Cerbara		Y	43.502	12.214	IX
Bagnaia		Y	43.528	12.180	VIII/IX
Belvedere		Y	43.476	12.265	VIII/IX
Capanne		Y	43.528	12.169	VIII/IX
Celalba		Y	43.536	12.201	VIII/IX
Corposano		Y	43.569	12.193	VIII/IX
Montione		Y	43.533	12.216	VIII/IX
Piano di Grumale	SS	Y	43.503	12.211	VIII/IX
Piosina		Y	43.486	12.199	VIII/IX
Pitigliano		Y	43.529	12.211	VIII/IX
Sant'Anastasio		Y	43.548	12.189	VIII/IX
Sansepolcro		Y	43.570	12.141	VIII
San Donnino	MS	N	43.423	12.264	VIII
Cospaia		Y	43.558	12.171	VIII
Città di Castello		Y	43.456	12.239	VIII
Giove		Y	43.483	12.200	VII/VIII
Bisacchi	MS	N	43.448	12.265	VII/VIII

Table 3 (continued)

Locality	Class	In previous studies?	Latit	Long	I MCS (this study)
Chiesa di Marchigliano	SS	N	43.385	12.281	VII/VIII
Il Peglio	MS	N	43.440	12.246	VII/VIII
Il Trebbio	MS	N	43.547	12.147	VII/VIII
Meltina	SS	N	43.460	12.243	VII/VIII
Promano		N	43.367	12.266	VII/VIII
San Marino		N	43.542	12.126	VII/VIII
Bisacchio	SS	N	??.???	??.???	VII/VIII
Fiorentina di Sopra	MS	N	??.???	??.???	VII/VIII
Valdimonte	MS	N	43.560	12.217	VII
Seripole		N	43.403	12.284	VII
Sant'Onda	MS	N	??.???	??.???	VII
San Martino d'Upo	MS	N	43.438	12.243	VII
San Martino di Castelvecchio	SS	N	43.394	12.241	VII
Ponte d'Avorio		N	43.407	12.252	VII
Pocaia	SS	N	43.577	12.115	VII
Passano		N	43.571	12.222	VII
Montone		Y	43.363	12.327	VII
La Grillaia	SS	N	??.???	??.???	VII
Germagnano	MS	N	43.622	12.151	VII
Citerna		Y	43.498	12.116	VII
Cantone	MS	N	43.565	12.266	VII
Anghiari		Y	43.540	12.054	VII
Barzotti	SS	N	43.451	12.299	VI/VII
Case Salebio	SS	N	43.472	12.284	VI/VII
Fuscagna		N	43.501	12.232	VI/VII
Gragnano	SS	N	43.579	12.098	VI/VII
Lerchi		N	43.475	12.199	VI/VII
Micciano	MS	N	43.570	12.031	VI/VII
Nuvole		N	43.470	12.193	VI/VII
Palmolara		N	43.541	12.233	VI/VII
Parnacciano		N	43.564	12.292	VI/VII
Parrocchia Colledipozzo	SS	N	43.373	12.282	VI/VII
Pieve delle Rose		N	43.522	12.274	VI/VII
Regnaldello		N	43.458	12.226	VI/VII
Regnano		N	43.493	12.215	VI/VII
Riosecco		N	43.479	12.211	VI/VII
San Savino	SS	N	??.???	??.???	VI/VII
Santa Lucia		N	43.418	12.249	VI/VII
Vallurbana		N	43.533	12.279	VI/VII
Carsuga	SS	N	43.494	12.127	VI/VII
Fiorentina di Sotto	MS	N	??.???	??.???	VI/VII
San Patrignano	SS	N	??.???	??.???	VI/VII
San Vincenzo		N	??.???	??.???	VI/VII
Madonna di Altomare	SS	N	43.535	12.185	VI
Case Valghisola		N	43.590	12.217	VI
Falcigiano	SB	N	43.567	12.093	D
Castiglion Fiorentino		Y	43.341	11.923	IV/V
Mercatello sul Metauro		Y	43.647	12.337	IV/V
Siena		Y	43.321	11.328	IV

Table 3 (Continued)

Locality	Class	In previous studies?	Latit	Long	I MCS (this study)
Firenze		Y	43.777	11.249	IV
Cortona		Y	43.274	11.986	IV

Y: yes
N: no
SS: small settlement (<30 buildings)
MS: multiple settlement: (buildings scattered over an expanse of land)
SB: solitary building (church, monastery, castle, villa, farm etc.)
D: generic damage

those recently constructed]: a statement which gives too much credit to the moving stories circulated by 1789 newspapers.

As to the reasons for telling this story: there is none really, apart from the wish to keep a record of an intricate investigation that would else have remained hidden behind a catalogue string of earthquake parameters. I hope the late Jean Vogt would agree that sometimes "ce n'est pas l'histoire des succès, c'est l'histoire des épreuves qui mérite d'être racontée"[1]; I just tried to do that.

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[1] Adapted from Jules Verne's Michel Strogoff

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Review of the 1755 Lisbon Earthquake Based on Recent Analyses of Historical Observations

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Abstract The importance of the 1755 Lisbon earthquake is known worldwide not only among the scientific and technical communities but also in many other disciplines of human kind related to the effects and consequences of the earthquake. A re-visiting of the 1755 Lisbon earthquake is made based on the historical descriptions in what regards the multiple aspects of scientific and technological background in his smaller details as, for example, the predominant direction of shaking, the duration of the event, the anisotropy in propagation, the enormous area of perception with its direct effects along all the Iberian Peninsula and Morocco, the water movement in Scotland (seiches), the enormous tsunami that affected the Portuguese, Spanish and Morocco coast, being remarkable the waves in the other side of the Atlantic, in New Jersey. These examples illustrate that the 1755 earthquake was a unique seismologic event for which a great deal of information already exists but, on the other hand, still contains many unresolved problems.

We review the historical descriptions of several different physical phenomena, compiling available data and discussing models proposed recently in the literature, with the aim of contributing to a better characterization of the seismic source, the wave propagation, and also to the causes behind the observations in nature, in housing and population. The interpretations are supported, as much as possible, on physical evidences such as the structural characterization of simple objects and structures for which it was possible to partially recover the seismic input acting at the foundation level. The analysis of the tsunami, of several monumental structures, and especially the "Aqueduto das Águas Livres", the damage inflicted to different types of buildings, etc., represent the essential basis to place a few pieces to reconstitute the large and intriguing puzzle that the 1755 earthquake still is. Though science has already given many important clues, there are yet a large number of questions to be answered which will contribute to a full comprehension of the phenomenon and to the definition of future hazards.

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Keywords Historical earthquakes · 1755 Lisbon earthquake · source mechanism · attenuation · damage · inverse problems

1 Introduction

The importance of the 1755 Lisbon earthquake is known worldwide not only among the scientific and technical communities but also among many other disciplines of human kind related to the effects and consequences of the earthquake. The 1755 earthquake was perceived in an enormous area with direct effects along all the Iberian Peninsula and Morocco, the water movement in Scotland (seiches), the enormous tsunami that affected the Portuguese, Spanish and Morocco coast, being remarkable the waves in the other side of the Atlantic, in New Jersey. This example illustrates clearly that the 1755 earthquake was a unique seismologic event for which a great deal of information already exists but, on the other hand, still contains many unresolved problems. But, on the other hand, this event was perhaps the first one in history that gathered a large amount of important data which can be used to understand many of the scientific and technical aspects related to it.

In the year when we evocate the remembrance of Jean Vogt, we want to pay our tribute to one of the individualities that most contribute to the history of seismology across Europe, bringing to the reader some new facts important to the interpretation of this historical earthquake that marks the European scientific society for many decades and centuries. It is compulsory to give continuity to the different studies that have been developed, with the intention of learning as much as possible about the phenomenon, but also to make an efficient strategy of prevention and action in the case of a tragedy of big dimensions.

Since it happened until today, many were the authors that studied the 1755 earthquake, and, in the future, a lot more will dedicate his attention to this event. Also commissions, work groups and investigation programs, etc., have been given an enormous contribution for the understanding of the phenomenon. The joining of different specialities, from seismology to the engineering seismology, through the history and sociology, etc., brought an important number of results in the search of more and better data.

Concerning only the geophysics and the seismic engineering aspects of the problem, we can refer the following authors (by chronological order) as a strong base to the study of the earthquake in Portugal, Spain and Morocco:

Moreira de Mendonça (1758), Montessus de Ballore (1906), Pereira de Sousa (1919–1932), Choffat (1904), Diniz (1910), Reid (1914), Miranda (1931), Rosas da Silva (1939), Machado (1966), França (1977 and 1978), Moreira (1979 and 1984), Rómulo de Carvalho (1987), Brazão Farinha (1990) and Campos (1998).

The 200th anniversary of the earthquake in 1955 was another occasion for using the date to launch the first modern hazard map of Portugal, *in* Simpósio sobre a Acção dos Sismos (1955), and the first modern seismic code.

In the field of historical studies, a Portuguese Commission for the Seismic Catalogue, “Comissão do Catálogo Sísmico Nacional (1980–1990)”, composed by a group of historians, sociologists, among which L. Runa, A. Freire, T. Barata, L. Braga, M. Wagner, has made considerable contributions to several aspects of the historical seismicity of Portugal including the 1755 earthquake.

Martinez-Solares (2000), Rodriguez de la Torre (1981–1993), Mezcua (1982) studied in great detail the effects of the 1755 earthquake in Spain), and Levret (1991) in Morocco.

After 1990, many contributions in the field of geophysics, seismology, tsunami science and earthquake engineering were made, namely by: M. Baptista, M. Bezzeghoud, F. Borges, E. Buforn, F. Carrilho, J. Fonseca, L. Matias, J. Mezcua, A. Paula, L. Senos, P. Terrinha, P. Teves-Costa, A. Ribeiro, A. Udias, L.M. Victor, S. Vilanova, N. Zitellini, C.S. Oliveira, J. Vieira de Lemos, J. Azevedo, etc. Among these, we should emphasize the geophysical campaigns (seismic reflection profiles), done in the transition of the oceanic to the continental shelf since 1970, which were greatly increased in the last 15 years. These were essential for the knowledge of the bottom of the ocean and of the crustal morphology, which, in association to the historical and instrumental seismicity, the tsunami studies for constraining the source mechanism and the wave propagations modelling to estimate the ground motion at different locations of the Iberian Peninsula have given a new breath to understanding this complex zone. Re-visiting the historical documents has been made by many experts to extract more reliable information by interpreting the existing descriptions under all new advancements in science and technology. In the present paper, following this line of thought, we will use a few examples to illustrate how historical descriptions can be extremely helpful to develop new understandings of a complex event of huge proportions such as this one.

The earthquake of 1755 gave origin to a wide range of contemporaneous writings, with the descriptions of the effects over the people, the houses, the monuments, the economic activities, the existing tax regulations, etc., leading to the most different interpretations. This enormous range of documents includes letters from foreigners living or travelling by Lisbon, pictures testifying the horrors of the shock, etc. After the M6.3 earthquake of 1909 in Benavente, 30 km to the NNE of Lisbon, ulterior studies about the earthquake of 1755 were retaken by different authors. Meanwhile, all the XIX century is full of literary works describing scenery where we understand many of the urban developments done in the City of Lisbon.

In the last few years, with the evocations of the 250 anniversary of 1755 earthquake, an increase of interest in the above mentioned areas, as well as the arise of studies in other areas of knowledge including paleoseismology, geography, economics, religious and political science, with contributions of experts from all over the world, has given a considerable push towards a better knowledge of 1755. This occasion was also important for the publication of other types of works related with 1755. Some are of literacy contents, romance addressing the life style at the time and describing the aftermath of the event (Chantal 2005, Quenet 2002, Tavares 2005). Others are full of historical documentation (Amador 2007, Pararas-Carayannis 1997).

It was also an opportunity to re-publish writings which were out of print or not published due to censorship. A vast bibliography was compiled by Oliveira (2005).

Another area of great interest but not dealt with in this paper is what concerns the reconstruction of the City of Lisbon. This involved a great number of discussions and developments in the most varied topics from urban planning passing by seismic resistant construction to rationalisation of construction practices.

2 Contemporaneous Information

Most of the existing information obtained at the time of the earthquake was compiled in a questionnaire with 13 questions, enquiring different aspects of the event such as how it was felt, how long the vibration last, the direction of propagation and the type of damage inflicted. Marquis of Pombal decided to promote this inquiry across the parishes of the country, using the religious authorities (Pereira de Sousa 1919–1932; Table 1).

We must sign the remarkable way how these 13 questions were elaborated (the number of victims and the ruins produced in each parish of the country), in many instances similar to the macroseismic information developed 150 years later and still used nowadays.

It is also remarkable that in Spain during the reign of Fernando VI a very similar inquiry with the same purpose was produced by the "Real Academia de la História". This inquiry was found just a few years ago and is opened to the scientific commu-

Table 1 Questionnaire sent, by order of the Marquis of Pombal, after the earthquake of 1755, to the different parishes of the country

1°	At what time did the earthquake started and how much did it last?
2°	Did you notice a bigger impulse in one side than in the other? From north to south, or, in the contrary, did you notice that ruins felt more to one side than to the other?
3°	Number of houses ruined in each parish; where there any special buildings and what is their state now?
4°	What kind of people died? Were there any nobles?
5°	Which novelties were seen in the sea, rivers or fountains?
6°	Did the tide get low or high first; how much did it grown more than normal, how many times was the flow or unusual reflux noticed; how much time took the water to get lower and how much to get higher?
7°	Were there any cleavages in the ground, what was seen there, and did any fountain came out again?
8°	What were the measures taken locally by the priest, by the soldiers and by the ministers?
9°	Were aftershocks felt? When? Which damages caused?
10°	Do you remember any other earthquake and what damages did it cause?
11°	What is the number of people in each parish, declaring when possible how many women and men?
12°	Was there any kind of lack of food?
13°	Where there any fire, for how long and what kind of damages caused?
extra	Were you victim of any ruin from the earthquake of 1755, what kind and is it already repaired?

nity (Martinez-Solares 2000). Coelho (2007), in studying the possible origins of both inquiries, classifies this accomplishment as the first scientific quantification of earthquake damage in history.

Based on the inquiries of the Marquis of Pombal and of the "Memórias Paroquiais" (Parish Memories), Pereira de Sousa (1919–1932) compiles a remarkable amount of information about the damages occurred in the construction and mainly in the monuments, developing at the same time maps of Mercalli Intensities, assigned in different geographical scales, but always with a strong connection with the geological units in which they were built. For Lisbon, Pereira de Sousa works with the map drawn by Filipe Folque in a scale of 1:10,000, identified the location of the existing monuments and classified them by damage classes.

In 1986, Oliveira tried to systematise the information about the damages occurred in the monumental constructions by the time of the earthquake. Using a wide bibliographic list, with special incidence on the work of Pereira de Sousa, he builds up a new file of information and presents a new classification of the damages. His work is supported in traditional methods of organization and registration made on cards and manual charts using the same cartographic base of Pereira de Sousa.

All this work is now under a final revision, with a transfer of treatment to modern tools of Geographical Systems of Information (GIS) to proceed to an accurate location of the monuments worked in the 1980s (San-Payo *et al.* 2005) and with the possibility to easily correlate the class and degree of damage for each structural typology with other local parameters, such as geotechnical strata, soil frequency, topography, etc.

3 Description of the Earthquake

The earthquake of 1755, better known as "Terramoto de 1755", is considered as the biggest earthquake historically known. It was strongly felt in Lisbon, Algarve, South of Spain and Morocco. Although without causing any damages, it also left signs of its occurrence in almost all Europe and in the Azores and Madeira Islands.

The seismic activity during the years that preceded the great quake of November 1st, 1755 was not intense, although references can be found to small quakes from 1750 (the day King John V died). It is interesting to note (National Archive of Torre do Tombo) that "the day before, meaning October 31st, something happened that pre-announced this catastrophe. I am referring to the fact that, during that day, the tide was delayed in more than two hours, fact that was noticed by a pilot, who, noticing the same during December 10th, shouted throughout Lisbon for people to stay out during that night because another earthquake could happen". This prophecy seemed to be accurate, and if so a good sign of immediate foreshock, as a similar observation was made on the eve of December 11th, when the earth trembled twice, violently at 4h:55 in the morning.

On November 1st 1755, Saturday, the weather was too hot for the epoch, with a temperature of 14°C and a weak wind from NE. The main shock happened at 9h:40

(the origin time of the earthquake is a matter of some controversy, with variations between 9h:30 and 10h:00, with a better possibility between 9h:35 and 9h:45) with essentially three phases, and preceded by an underground snore or simultaneous to an "underground boom that lasted the time of the vibration sounding like a far away thunder". The phases and respective durations vary from place to place, according to testimonies from the entire Iberian Peninsula. In Lisbon, the first phase, with duration of about one and a half minutes, not very violent, was followed, after a period of 1 min, by a more intense movement with duration of two and a half minutes causing serious damages. After another pause of one minute, there was a third phase, with a duration of 3 min, more violent that before. The earthquake lasted for about 9 min. The vibrations of the first phase were essentially vertical and of higher frequency than the others.

Duration of motion in other locations will be discussed later, Section 3.2.2. It is difficult to establish the direction of the movement: some say it was N–S, others, possibly in other places, indicate E–W. However, the preferential direction of the movement of SW–NE deserves some consideration, according to the fact that the downtown streets with that orientation did not suffer great damage, as houses give better support to each other in the direction of the streets axes, functioning as aggregates.

To support this interpretation two other facts should be mentioned: the reconstruction of the new City of Lisbon developed the streets with alignment of the longer axis of building blocks in the N-S direction; the small damage inflicted to the "Aqueduto das Águas Livres", as will be discussed in Section 5.1 may be not only due its good construction but also due to the predominant N–S direction of waves.

Some eyewitnesses refer that houses were wagged like carriages going in high speed on a street full of stones. Rómulo de Carvalho (1987) goes a bit far in his description stating that the movement in Lisbon starts with a "slow shake but increasing intensity. The walls of the buildings start to crack, to open crevices and soon collapse, falling on people running away through the streets." ... "The stones of the temples vaults where Catholic mass was being prayed, the columns of the altars, the surrounding walls, etc. fall violently on people, raising dust clouds that suffocate the few survivors".

Besides the damages caused by the seismic movement (partial or total collapse of the buildings), a great fire, caused by the several fires that exploded downtown, burned during 6 days, increasing substantially the number of deaths and the material damages.

During the first 24 h, the earth trembled in an almost continuous shaking. The first aftershock, rather violent but of shorter duration, was felt around 11h:00. During the first 8 days, more than 28 aftershocks were felt, 250 aftershocks during the first 6 months and 500 aftershocks until September 1756 (Table 2). The main shocks were: 8/11/1755 at 5h:30, 15/11/1755 at 5h:00, 16/11/1755 at 3h:30 (with tsunami), 18/11/1755 early in the morning, 8/12/1755 by the end of the morning, 11/12/1755 at 4h:55 and on the 21/12/1755 at 9h:00 with two shocks of 1 min each. On 31/03/1761 another important earthquake was felt in Lisbon, an off-shore earthquake of the Portuguese coast, causing seiches and a visible tsunami.

Table 2 Main aftershocks with epicentres around Lisbon

Date	Hour	Observations
1-11-1755	10h30m	it lasted 2 minutes without damages
1-11-1755	11h	light
1-11-1755	12h	weak
1-11-1755	22h	short
2-11-1755	3h	strong
2-11-1755	21h	light
3-11-1755	7h	
4-11-1755	14h	light
5-11-1755	20h	moderate
6-11-1755	4h30m	
8-11-1755	5h30m	violent
8-11-1755	9h	strong
9-11-1755	9h30m	light
15-11-1755	5h	
16-11-1755	3h30m	very sensible
18-11-1755		
9-12-1755		violent in Lisbon
11-12-1755	5h	violent, Felt in some places of Andalusia, Extemadura and center
21-12-1755	9h	strong in Lisbon
25-11-1755	2h	
18-01-1756		
22-01-1756		
18-02-1756	morning	
01-03-1756		strong in Lisbon
07-03-1756		
11-03-1756	21h	collapse of few houses in Lisbon
24-04-1756		very strong
27-01-1756	14h15m	
30-04-1756		violent
3-07-1756		violent
10-07-1756	22h30m	strong in Lisbon
18-07-1756		strong
26-08-1756		weak
25-09-1756	14h30m	
15-01-1756		strong in Lisbon
29-10-1756	2h	strong. It caused fear in Lisbon
6-11-1756	8h15m	small in Lisbon

Two other notes worth mentioning are as follows:

- The 1755 earthquake was followed by many important earthquakes throughout Europe and also in America by the Boston earthquake Nov 18, 1755. A large event occurred in Morocco 18/19 days past the November 1st shock, causing large damage in Fez and especially in Meknez, where over 50,000 victims are accounted. This event, with epicentre in the southern edge of the Atlas, sometimes confuses the specialists which wrongly associate it with the Lisbon event.
- In Europe more than 17 events were referred in the first year post November 1755. Locations in the UK, Italy, Constantinople, were among the places

Table 3 Other events in Europe an USA in the aftermath of the 1755 earthquake (after Braga 1989)

Year	Day/Month	Hour	Location
1755	9/December		Switzerland
1756	18/February	7–8	Paris, Luxembourg
		8	Cologne, Bonn, Versailles, Brussels, Amsterdam, etc.
		9	Liége
		morning	The Hague
1756	17/August	11.30	Padova
1756	28/August	5.30	France
1757	8/February	6	Parma
1758	3/December	Night	Constantinople
1758	6/December	Afternoon	Kola (Laponia)
1759	18/March		Listoia, Toscara
1759	10/August	21.15	Bordeaux
1759	23/August	2	Cologne, Denmark
		3	Breda
1760	9/November	8	Boston, USA
1761	31/March	12	Bayona, Spain
		12.30	Cork, Ireland
		14.30	Lake Ness, Scotland
1761	1/April	13	Bordeaux
1761	20/April	13.15	Barcelona
1761	20/May	13	Rossilon
1761	10/June		Pesaro
1761	20/June	Night	Florence,Bagno, Romania
1761	9/December	20	Barnau, Siberia
1762	18/October		Roma
1763	11/July		Komore
1765	13/January		Prand, Austria

of shaking (Table 3). The most important were in Switzerland (Dec 9, 1755), Luxembourg (Feb 18, 1756) and Cologne/Denmark (Dec 23, 1759).

Interesting to note that the 1755 earthquake with the high magnitude we attribute, not only released more energy than the total of all earthquakes occurring in Europe in the first two millennium AD, but was followed during the next years by a set of important events throughout Europe.

In what concern foreshocks, besides the note already mentioned on anomalous tide behaviour, the only existing reference is the one of a small seismic movement felt in Villablino in the province of Lion in Spain (near Galiza) on October 31/1755 between 22 and 23 h or at 2 h:00 (Anonymous 1756). Some precursory phenomena of 1755 event may have take place 3–7 days before in several locations mainly in the centre-north littoral. Muddy waters, smell to sulphur, and even anomalous animal behaviour and a crack in the soil were part of those manifestations (Moreira *et al.* 1989).

But in the years prior to 1755 there were plenty of seismic activity such as in Valencia-Murcia, Spain in May 5, 1748, Madeira Island in May 31, 1748, in Africa 1751, in Belgrade in October 30, 1752, in Tunes in December, 9, 1752 and in

Comarca de Valença, Braga, northern Portugal in February 13, 1754 (*in* Biblioteca da Ajuda, quoted by Amador 2007).

Around 11h:00 in the morning of November 1st, the waves of a tsunami caused by the main shock of 9h:40 arrived in Lisbon. The Tagus waters initially run-down, dragging the boats anchored near the harbour. Then, they started to increase its level, passed over the walls of the port and invaded downtown in 300–400 yards ("Terreiro do Paço" and streets near the river banks). According to the testimony of the captain of an English vessel, the waters raised about 16 feet, three times, during 15 min. Only at 7h:00 in the morning of Sunday (November 2), the tide went back to normal.

However, as a result of the tsunami, during the first 10–12 days the tides did not have a regular course, as some times they came earlier, other times were delayed, and took 7–8 h to reach high tide and 3–4 h to reach low tide.

The impact of the tsunami of 1755 in Lisbon is described in various testimonies of that time, such the one following (in Emergency Plan for the Seismic Risk in Lisbon): "(. . .) Suddenly the sea enters the harbour with a furious inundation of water (. . .); Surpassing it ancient limits, it passed over several buildings and flooded S. Paulo quarter (. . .)" (Moreira de Mendonça 1758), "(. . .) and flood in parts with its flow and reflux the side of the waters that came out of its river bed and flooded the custom-house, the Terreiro square and the Vedoria building (. . .)". According to Baptista *et al.* (1998) downtown was flooded, being the distance of penetration of 250 m, while the "fernandine" wall (rebuilt by King Filipe I) acted as a strong barrier to the passing waters. The area between the ancient "Ribeira das Naus", the "Terreiro do Paço" and the "Jardim do Tabaco" – squares in the river banks – became totally flooded".

Another reference indicates that "the Castle of Bugio was almost covered with water in such a way that the soldiers shooted asking for help and had to withdraw to the highest part of the tower".

It is important to know the tide level by the time of the tsunami wave arrival, to take this effect into account in the progression of the waters entering Lisbon harbour. It is difficult to analyse this subject with precision because of the error introduced in the extrapolation of tide times into the past (two centuries before). However, according to the US Naval Observatory Astronomical Applications Department, from the phases of the moon, the 1st of November 1755 was two and a half days before New Moon, far away from high tides. So, the low tide was probably around noon and the high tide around 17h:45 (Azevedo 2004, personal communication). On the other hand, according to historical source, the low tide in Benavente was at noon. Based in this information, the tsunami would have arrived to the cowl of the Tagus when the waters were in strong low tide, which turns the rising of the rivers more difficult. Andrade (1992) confirms that the first wave of the tsunami reached the coast in Algarve during low tide. This information is, however, in contradiction to witnesses in Cadiz, which claim that the tsunami reached there at high tide (Campos-Romero 1989).

The tsunami was felt not only in the Portuguese coast (the harbour of Setúbal was submerged by an enormous wave; in the Algarve, the waves reached great heights) but also in the Southeast of Spain, North of Africa, Great Britain and The

Netherlands. The passage time between the "possible"[1] seismic source and Cape São Vicente is esteemed in 6–7 min and in 1 h in relation to Cadiz. In Lagos, the tsunami arrived about 15 min after the mainshock onset, and the waters first run-down, then went up 13 feet, causing great destruction mainly in the walls protecting the city. In Portimão, the waters rising 6 "braças" (fathom) drowned too many people. As referred, the biggest impact of the tsunami in the Algarve was in the bay of Lagos which could no longer accommodate big boats (greater than 45 tones) due to sediment transport and therefore the Harbour Administration has moved from Lagos to Tavira. Also the Ria de Faro suffered great changes in its coast line (Faro Beach) with significant sandy movements altering the deposition (Andrade 1992).

In Madeira and Azores Islands, the tsunami was also felt and caused great damages in the islands of Terceira (cities of Angra do Heroísmo and Praia da Vitória) and Faial (city of Horta) (Andrade *et al.* 2006).

In Creston Ferry, near Plymouth, England, the waters raised around 16h:00. Two boats that were in dry land, one and a half meters from the water were "drowned in mud" after the tsunami. It took around 8 min for the waters to get back to normal and for the boats to float again. The tsunami was also felt in the coast of America: in Antigua, 6,000 km away from Lisbon, the first wave of the tsunami arrived at 19h:30 (Lisbon time). Here, the variations of the water level were felt during two and a half hours, with the highest wave of about 3.5 m. It was also felt in Recife (Brazil) where the waves destroyed the fisherman huts.

Pararas-Carayannis (1997) mentions for tsunami heights different values and different consequences: Lisbon – run-up with 6 m height entering inland 20 m, Cascais – destruction of many boats, Peniche – many people killed, Setúbal – the water reached the 1st floor of buildings, Algarve – run-up of 30 m and many fortresses in the western portion destroyed, Lagos – the waves went over the top of City-walls (11 m) and entered the river to a distance of more than half mile carrying vessels to a great distance, Faro – not affected because of the sandy banks that protected the town, Guadalquibir – the waters reached Seville, Gibraltar – the waves reach 2 m high, Agadir – waves passed over the fortified walls of the town killing many people, Martinique – waves rose 1 m.

In summary, run-up was observed first in Gibraltar, Ceuta and Madeira; and run-down was observed first in Lisbon, Lagos (20 fathom) and Cadiz. This allows the definition of a source zone running EW to the south of Cadiz with uplifting in the northern wall.

In distances larger than 1,000 km, the seismic waves caused floods originated by seiches, the movement of the waters of the lakes, rivers and harbours, in a rhythmic way. This was observed in Switzerland, England, Scotland, Finland and Sweden. In Scotland, 2,000 km away, the waters of Lake Lamond oscillated with amplitudes of more than 60 cm during more than one and half hours. In the Dal river, north of Stockholm, 3,000 km away, these oscillations were also felt. No other earthquake in

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[1] The location of seismic source in this case is simply $\sim$100 km to the west and is mentioned just as a reference.

the history caused rhythmic perturbations in the water at such large distances in a certain predominant direction of propagation (to the north). It is important to refer that only very large magnitude events, such as the Alaska 1964 Mw9.2, have caused phenomena of the same type denoting important energy at very short frequencies (<0.02 Hz).

Besides the damages caused in the area of Lisbon, which will be object of a detailed study, the earthquake was strongly felt in the south of the country. Faro was totally destroyed with a high number of death people. The same happened in other villages in the Algarve, mainly in the western part, like Lagos, Portimão, etc. The south of Spain also suffered damages but not so catastrophic.

To the North of Lisbon, the intensity was quickly attenuated; Alenquer, Torres Vedras and Óbidos were the most damaged places. Coimbra did not feel great damage[2]. However, in Corunha (Spain), 800 km away from the epicentre, some high chimneys felt down, although the population did not feel the movement. In Barcelona, 1,200 km away from the epicentral region, there are records of oscillation of lamps hanging from the ceilings of the churches. This information is extremely important in order to characterize the frequency of the vibrations at such large distances. A simple calculation shows that the seismic movement at the ground level at these sites may have reached a few centimetres for frequencies of 0.1–0.2 Hz.

The earthquake was slightly felt in the Azores Islands and curiously one of the few earthquakes felt in the islands of Flores and Corvo. This information confirms the idea that the 1755 earthquake had a radius of perceptibility of the movement of about 2,500 km.

Let's see other quotations of phenomena that should be referred:

- "On the ground, cracks were opened from where sulphuric gases came out, some closed almost immediately, others remain",
- "Light effects were seen like rays coming out of the ground".

The phenomena of leakage of sulphuric gases, accounted for in different locations, are difficult to associate to the opening of cracks caused by the passage of seismic waves on locations where geothermal springs ("Hot Baths of São Paulo" in Lisbon) already existed due to the large distances separating them from the seismic source. However, we understand that the passage of waves may somehow have instabilized a few areas already prone to these effects.

3.1 Isoseismals of the Earthquake

The way that the earthquake was felt in all the Iberian Peninsula and north of Africa has been the theme of many works published during the XXth century, among which

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[2] In a document recently discovered, Calvário (1755–1764) confirms most of the information in Table 2 and adds a group of earthquakes felt in Coimbra such as 6/03/1756–6h; 11/03/1756–22–23h; 25/03/1756–2h).

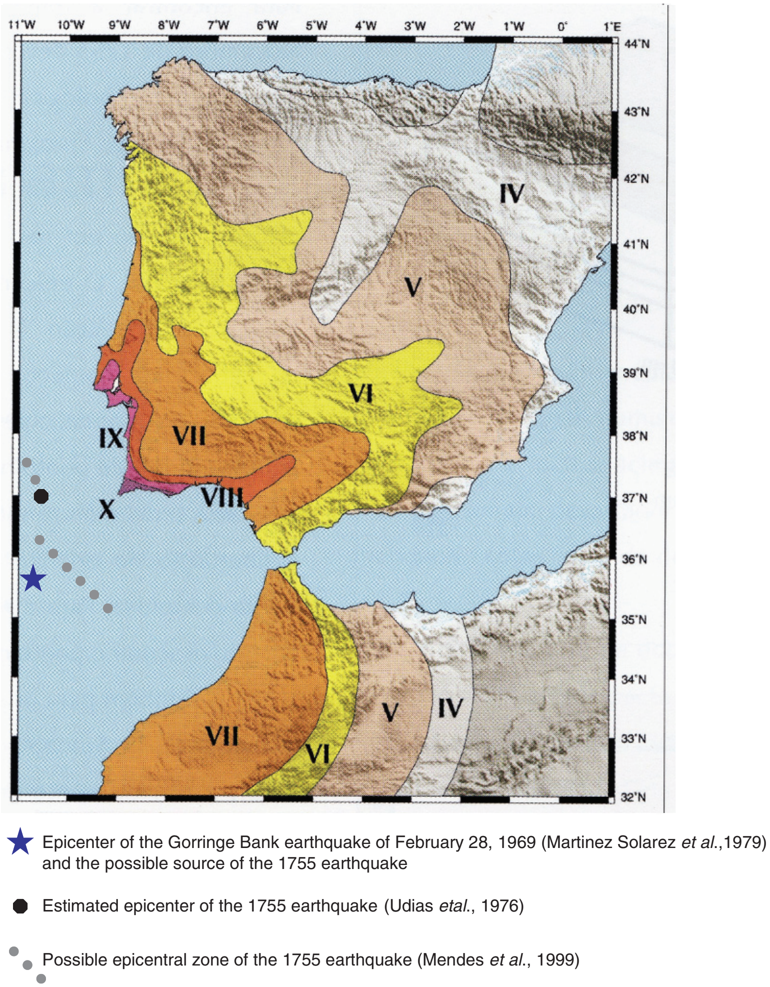
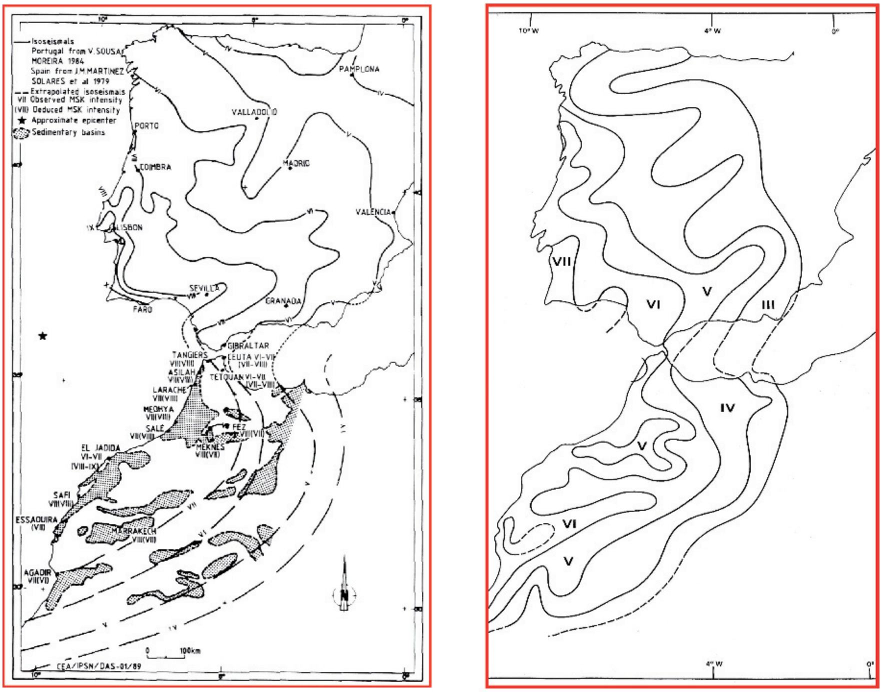


Fig. 1 Map of isoseismals (MSK Intensities) from the earthquake of November 1st 1755, with some possible localizations of the seismic source (based on Martinez Solares *et al.* (1979); Levret (1991); Moreira (1984) and Mendes *et al.* (1999)

we should mention Choffat (1904), Reid (1914), Pereira de Sousa (1919–1932), Moreira (1984) and Martinez-Solares (1979). Figures 1 and 2 summarize some of those studies, presenting the isoseismals and the possible localizations of epicentres of 1755 and of February/28/1969 event, which, until a few years ago, was considered as belonging to the same geo-morphological fault system.

The analysis of the isoseismals in Fig. 2, which joins large consensus among specialists, shows clearly that the vibrations were more intense in the south of the Mainland and in the area of Lisbon, attenuating rapidly from coastal line of the country both in the west and south. The geometric pattern of the attenuation is clearly away from the typical patterns of other earthquakes where the attenuation



(a) (b)

Fig. 2 Isoseismals of two large intra-plate events: a) 1755 (Levret 1991) and b) 1969 (Moreira, 1984). Note the similarities (the Guadalquibir valley) and dissimilarities (the southwestern Iberia) in the propagation of these two events

is more regular and concentric, emphasizing the possible role of the source mechanism, the wave attenuation anisotropy and the site effects. This latter effect is remarkably well illustrated in the positive irregularity (higher values than we could expect) in the Guadalquibir valley, showing an effect of amplification due to the presence of thick alluvial layers in that region.

In Spain, Martinez Solares (2000) was able to classify the damages occurred, distinguishing the damages in buildings of high frequency (small buildings) from the damages of buildings of lower frequency (monumental buildings), clearly prevailing the energies associated to lower frequency in areas very far from the seismic source.

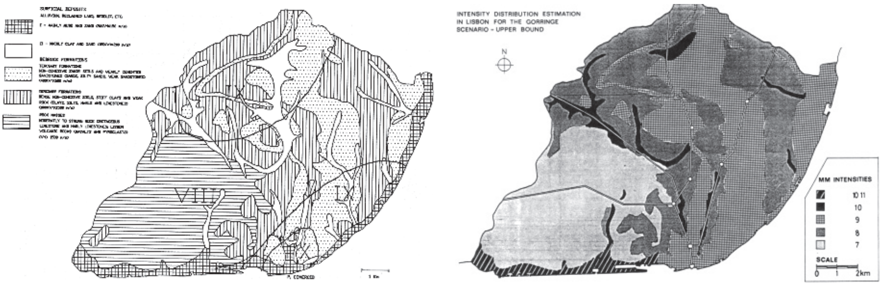
Pereira de Sousa (1919–1932) draws also the isoseismals from 1755 taking as basis of his work the geological map by assuming that the intensities should correlate well with surface geology. And he was not particularly mistaken, because that analogy exists, although it is not only the lithology of the superficial formations that contributes to the amplification of seismic waves. It is well known, and this earthquake is a clear example of that, besides the source mechanism and the wave propagation phenomenon, the type, geometry and mechanical properties of local geological strata are of most importance to characterize seismic action at a site.

Fig. 3 Main localities of Continental Portugal and Lisbon Region cited in this paper

Figure 2 was used as basis to define the outline of the seismic areas established in the Construction Regulation (RSCS 1958) promoted after the meeting of 1955 (Symposium about the action of the earthquakes 1955).

From general patterns to details for the city of Lisbon (in Fig. 3 we present the main localities mentioned throughout this paper), we find in Figs. 4 and 5 different aspects of the distribution of the damages in the interior of the city. The first Figure outlines the isoseismals according to Pereira de Sousa (1929) for the area corresponding to the entire district, overlapping once more the type of superficial geology, higher intensities being shown in the area of downtown and in the northern part of the district. Figure 5 presents in detail the most damaged areas (intensity X) corresponding to the outline of the city by that time, as well as the area of the impact of the fire (França 1978). As we can see, there is a big overlap in the outlines of the most damaged areas by shaking and by the fire, being hard to distinguish the main causes from the damages suffered. Also we can not forget the effect of the tsunami, responsible by the damages from flooding along the river.

It is important to remark that a study done in the years of 1990 (Mendes-Victor *et al.* 1994) for a scenery corresponding to the earthquake of 1755, using a simplified model to represent the effect of the surface geological layers, proposed variations of intensity (MMI) of 5 degrees, with a geographical distribution very different from the one referred by Pereira de Sousa (1929), Fig. 4(b). More recent models (Oliveira 2004), although based in more sophisticated developments than those used



(a) (b)

Fig. 4 a) Isoseismals of 1755 in the current district of Lisbon over the geological map, according to Pereira de Sousa (1929); b) Chart of intensity (Mercally Modified), done from a possible similar scenery to 1755 (scenery of Gorringe) (Mendes-Victor *et al.* 1994)

in the work of 1994, are still away from reproducing satisfactorily the damages observed. For example, the population of Belém and Pedrouços, western areas of Lisbon, reported just a small shaking, being later amazed when confronted with what had happened in Lisbon.

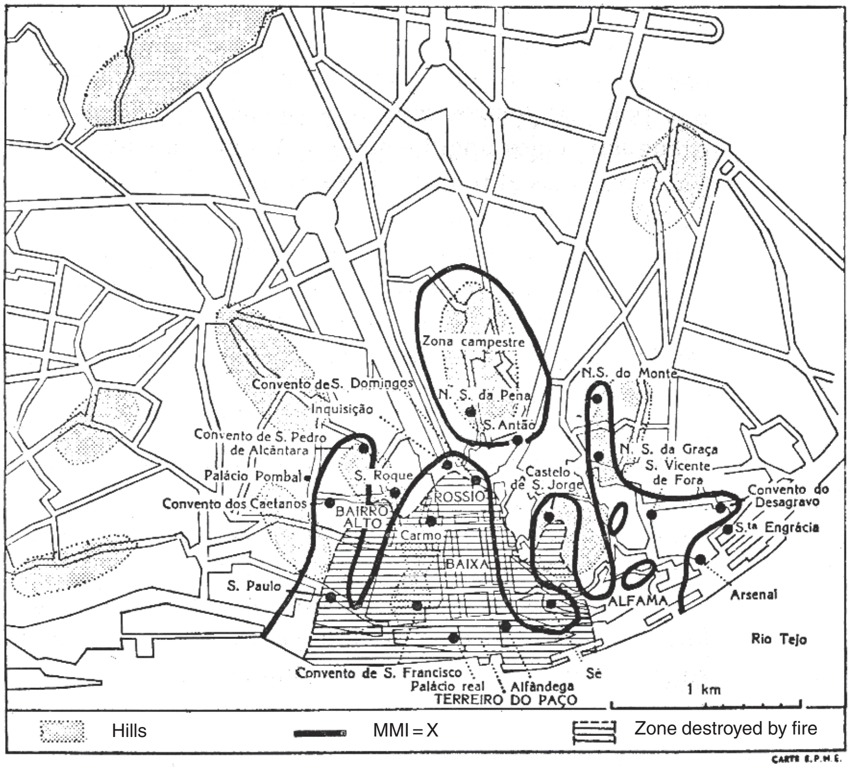


Fig. 5 Detail of the damages in the downtown Lisbon due to the vibration and fire (according to França, 1978)

The influence of the topography, of the morphology of the geological layers, the influence of three-dimensional deep geology, of the effect of important discontinuities inside the geological structures, of the three-dimensional aspects of the wave propagation, etc, are some other very important aspects that have been relegated to a second level until now. Only recently, new projects are addressing topics related to these aspects.

This theme, which is very important to determine with accuracy the effects of future earthquakes in the city of Lisbon, needs a conjugation of efforts of different areas of knowledge, including geology, seismology, geotechnical and earthquake engineering, along with the effort of analytic modulation and calibration through a careful monitoring as complete as possible. Oliveira (2004) makes the confrontation of the developed models for the city of Lisbon, using different scales of work and concluding that, although the general results are similar, the differences can be really large when seen in detail.

3.2 General Characteristics of the Earthquake

3.2.1 The Seismic Source

Based on the similarity of isoseismals and on the connection done during a long time between this earthquake and the one of February 28, 1969, the epicentral location of 1755 was placed in the region of the epicentre of 1969. Former studies placed the epicentre in different places of the Atlantic, more or less near Lisbon. Although the much research done in the last 10 years supported by studies which will be referred ahead, mainly the tsunami, the information about the crust properties, and the engineered behaviour of different structures, several source mechanisms are still disputing the origins of the 1755 earthquake (Fig. 6):

- A wide geological fault structure split in two large lengthy areas that develop in parallel to the west coast and south of Mainland Portugal (Ribeiro 2002, Zitellini *et al.* 1999).
- A phenomenon build up by two main episodes, one originated in one of the sources already described, and another located somewhere in the region of the inferior Tagus Valley (Vilanova *et al.* 2003).
- A phenomenon originated by the interaction of the Alboran Plate with the Euro-Asian Plate in a region of incipient subduction (Gutscher 2004).
- A simple model of rupture at deeper location at a “sub-horizontal” dislocation area.

These models require the use of more complex wave propagation schemes, introducing fault directivity, anisotropy elastic medium and three-dimensional (lateral heterogeneous) modelling.

The arguments put forward by the different teams working in this theme are several, and they do not take enough evidence to allow us to choose one among the

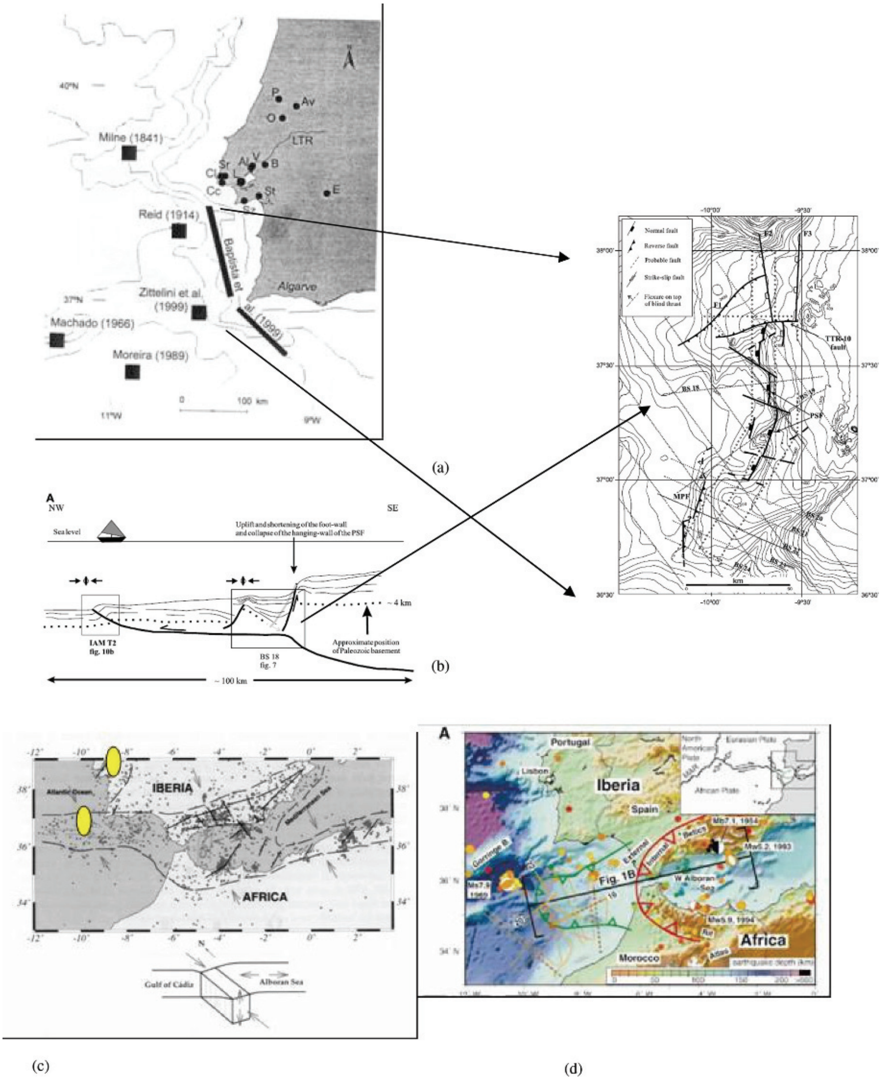


Fig. 6 Geodynamic models in contact with the Euro-Asian, African and of Alborn plates, to explain the seismic source that generated the 1755 earthquake: a) epicentres defined by several authors, along the XXth century (Zitellini *et al.*, 1999 and 2000); b) western area of the portuguese coast controled by the phenomenon of compression between the plates (Terrinha *et al.*, 2003); c) model of multiple rupture Southwest of Cape São Vicente and in the Lower Tagus Valley (Vilanova *et al.*, 2003); d) interaction of the mini Plate of Alboran with two other plates, as a possible trigger to initiate the rupture (Gutscher, 2004)

others. Even having gone forward in the information collected about such complex tectonic situation, we need more elements to clarify the models given.

In any case, the following aspects seem already irrefutable:

- The earthquake was originated in a collision area between plates, that approach each other at a low rate (5 mm/year).
- Areas of more crustal compression in the Iberian Peninsula and its surroundings are already known (Fig. 7).
- With the present information on the relative shallow depth of focal locations, the fault rupture associated to the earthquake ($Mw > 8.7$) must extend several hundred kilometres. So, the various geological structures already identified are too small, even if they rupture in "cascade" by sympathy, to explain the amount of energy released, unless the source is deeper than presently thought or of sub-horizontal nature as Terrinha *et al.* (2003) propose. In this case, an horizontal zone involving all structural systems of Fig. 6(a) between 9° 30′–10° W and 36°–38° N, would rupture.
- The mechanism is different from the 1969 earthquake.
- The recent seismicity and even the one from the final of the XXth century, much more rigorous in the localization of the epicentres and in the definition of the source mechanisms, they do not define clearly a pattern of activity allowing a good acknowledgement of the geo-dynamic at SW of the Iberian Peninsula

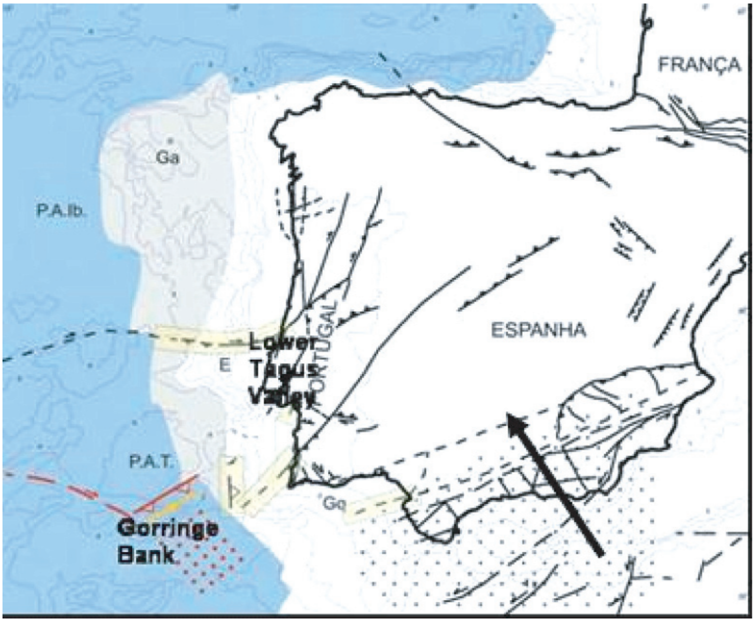


Fig. 7 Contact between the two Euro-Asian and African Plates and the main geological structures (Cabral, 1993) – the arrow indicates the predominant movement of the African Plate in relation to the Euro-Asiatic Plate

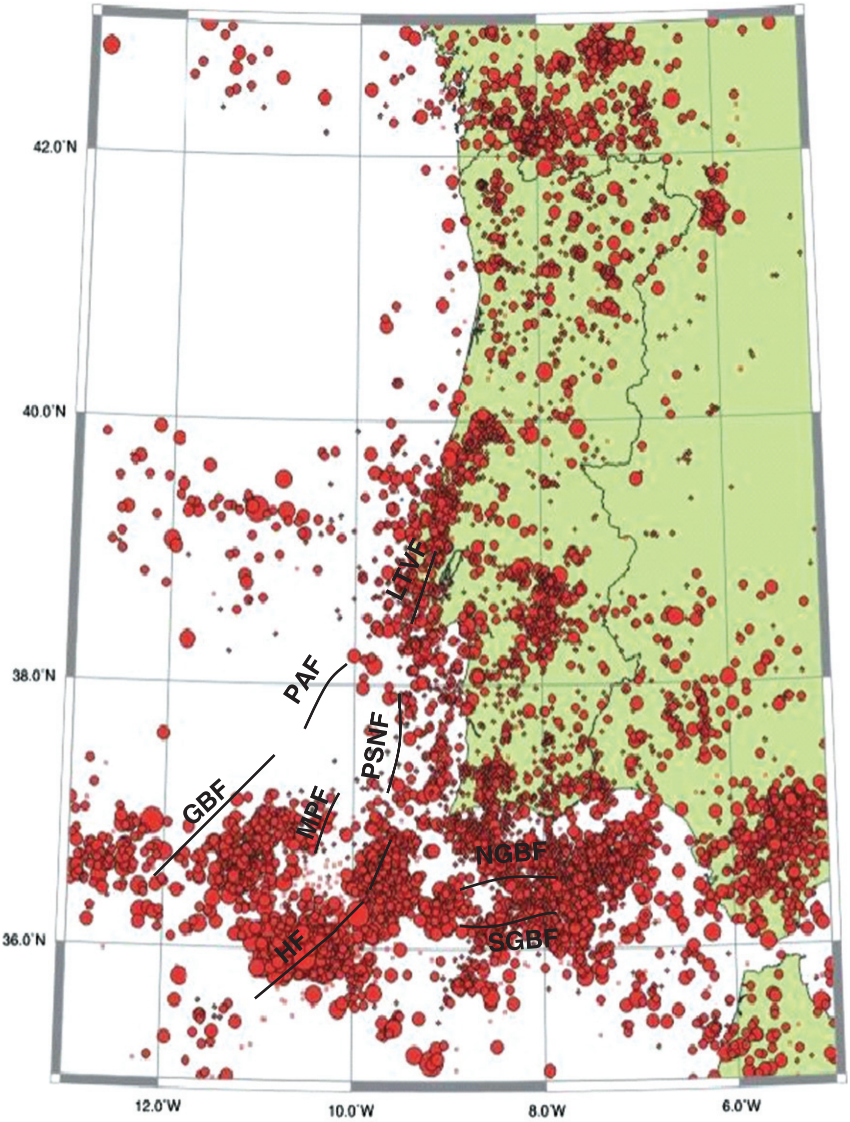


Fig. 8 Epicenters during the period of 1960-2003 (IM, 2007 and Carrilho *et al.*, 2004). MPF – Marquês de Pombal Fault System; PSNF – Pereira de Sousa Normal Fault System; GBF - Gorringe Bank Fault; PAF – Principes de Avis Fault; HF – Horseshoe Fault; NGBF – Northern Guadalquivir Bank Fault; Southern Guadalquivir Bank Fault; LTVF – Lower Tagus Valley Fault

(Fig. 8). However, we can say, for the first time, that epicentral alignments (1960–2003) in that area are becoming apparent, showing some “plausible sources” where large magnitude events may take place. Only the years to come will or will not confirm these patterns, and relate them to the 1755 seismic source.

3.2.2 The Magnitude

If it is difficult to identify a seismic source for 1755, it is no less difficult to attribute it a magnitude. Nowadays, the magnitude parameter is obtained from instrumentation which became available only a long time after the 1755 earthquake. Thus the difficulty in establishing the magnitude of historical earthquakes, for which the most accurate data is the distribution of damages or the knowledge of any simple structure that functioned as a seismograph. In this case, we should appeal to all available information of different origins, to essay an evaluation. Besides the geographical distribution of the damages, other elements of great importance are: the duration, the area of perception of the vibrations, the effects on long distances, and, finally, the comparison to other events of recent times occurred in seismo-tectonic environment similar to those of the contact of the Euro-Asian and African (Nubia) plates (Figs. 6 and 7).

The large magnitude of the 1755 earthquake is seen by the large radius of perception of its waves and the devastating effect in some regions of the coast in Portugal, Spain and Morocco. A magnitude of $Mw = 8.5–8.75$ has been attributed to this earthquake, presenting a rupture mechanism in the south-west region of Cape São Vicente, but it is not clear what really happened. To reach such a high magnitude in an area of collision of the plates, as referred in Section 3.2.1, it is necessary that the rupture in the plan of the fault has been rather extended, that the phenomenon has been composed by more than one single rupture, or the fault depth has been much larger than presently thought. The duration of the event was extremely long. It is hardly believed that the different phases of the vibration can correspond to the arrival of the P, S waves and the surface waves, because the time differences are too large and rupture may have been long. It seems more reasonable to think that they correspond to initial and stop phases in the rupture process. Data coming from Spanish sources confirm the great duration of felt motion, between 4 and 15 min. In Lisbon, the duration, quoted by several sources, was 6–9 min, as referred above. In Lagos, the duration did not surpass 4 or 5 min. A sound contribution to this topic can only be made after analytical simulation of different ruptures and seismic sources, to understand the effect of rupture direction, onset of the event, etc. Carvalho (2007) is presently doing a large set of experiments to analyse these effects not only in duration but also in attenuation, and the findings may contribute to clarify these mechanisms.

Based on Spanish data (Martinez-Solares 2000, Fig. 9), the correlation of duration with epicentral distance[3] is very poor: the larger durations were observed in places with epicentral distances between 300 and 500 km, decreasing for larger distances. For shorter distances the duration was smaller, as the cases of Lagos and Lisbon.

Comparing with what has happened with the earthquake of December 26th, 2004, in Sumatra Island, it is possible to review the above magnitude estimations

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[3] The concept of epicentral distance in this case should be viewed under a great uncertainty, due to lack of knowledge of source mechanism.

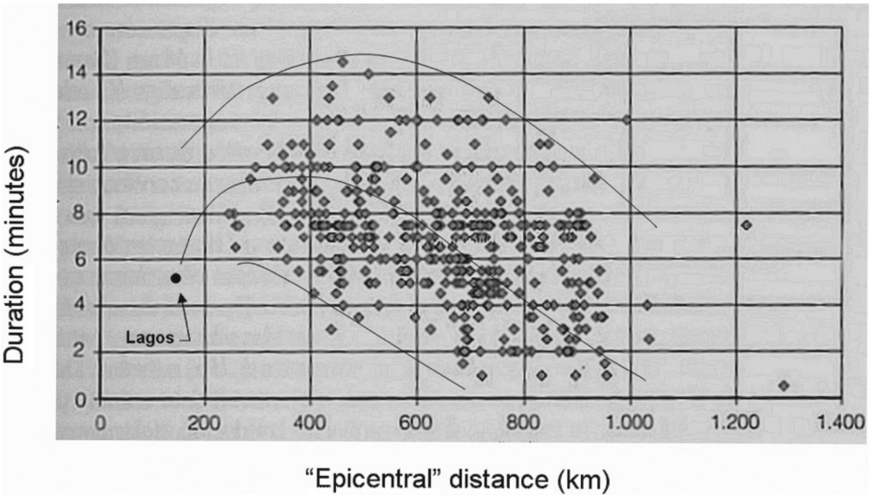


Fig. 9 Duration of vibrations as function of distance (composed after Martinez-Solares, 2000)

to higher values, in the order of Mw9 or larger. These large magnitudes have not been observed in tectonic environments of collision such as the one under study, but essentially in subduction zones. This is an important issue to be resolved in the future.

The spectrum of the vibration is different depending on the phase that is being analysed. In the first phase, the vibrations, essentially vertical and with a predominant North-South component, are of the highest frequency. The second phase and mainly the third phase are of much lower frequency.

As referred above, the seism was felt in great distances exhibiting a pattern of attenuation somewhat strange, departing significantly from the normal circular symmetry.

3.2.3 Attenuation of the Seismic Waves

The phenomenon of attenuation of the seismic waves was based on the EMS-98 intensities observations (821 points) throughout the Iberian Peninsula (Fig. 10). These points correspond to the isoseismals map of Fig. 2. The first comment is the large dispersion in existing data, due to the non-radial wave propagation pattern, as referred in Fig. 2, masked by several problems already mentioned: radiation pattern, rupture mechanism, three-dimensional propagation effects, large alluvial basins, etc. Several authors have tried to fit attenuation curves (in Teves-Costa *et al.* 2002), but the dispersion problem persists, unless those aspects are filtered out before the fitting.

The geometry of the transition ocean crust – continental crust, as well as the alluvial geological setting in large areas of the coastal and lower river estuary regions, seem to be the two most important factors in these anisotropies. Other factors

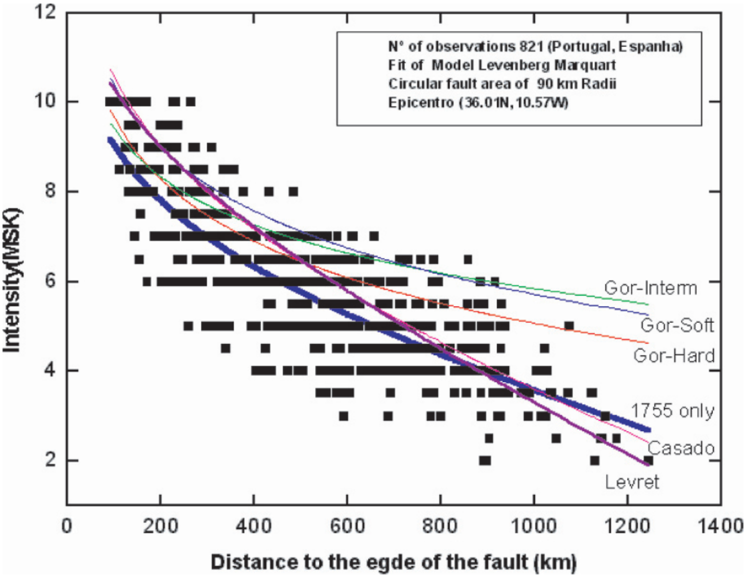


Fig. 10 Models of attenuation of the intensities seen during the seism of 1755 (Baptista *et al.*, 2001)

that might be important are the existence of “propagation channels”, “orogenic barriers”, etc. which were never looked upon.

Once again, we make a comparison with another earthquake, now to emphasize the existence of large dispersions (Fig. 11) for the attenuation of intensities in the 1950 earthquake of Assam, India, one of the biggest occurred in the boarder India–China (Arunachal Pradesh) (http://asc-india.org/gq/19500815_indochina.htm). Although the seismo-tectonic situations between the 1755 and this earthquake are different in several aspects, it can be noticed, by comparison of Figs. 10 and 11, that there are similarities in the general pattern of attenuation and in the dispersion of the results, with the difference that for the earthquake of Assam the closest distances to the epicentre are nearer than those in 1755. The average values for 1755 are slightly above those of the Assam earthquake, which shows a magnitude larger than Mw8.6, as referred above. The fact that the seism of Assam has a radius of perception around 1,800 km (against 2,500 km in 1755) and duration of the vibrations between 4 and 8 min (against 5–15 min in 1755) just proves this statement. Concerning the interpretation of the dispersion observed in Fig. 11, the lower line intends to represent the cases of “stiff” soils, while the upper line is a limit related with the phenomenon of soil amplification. Dispersions of this order of magnitude are observed in other earthquakes of the Portuguese catalogues (Sousa *et al.* 1992, Paula *et al.* 1996), and therefore can correspond to phenomena of amplification inherent to the complex processes of propagation and of local effects in Mainland Portugal.

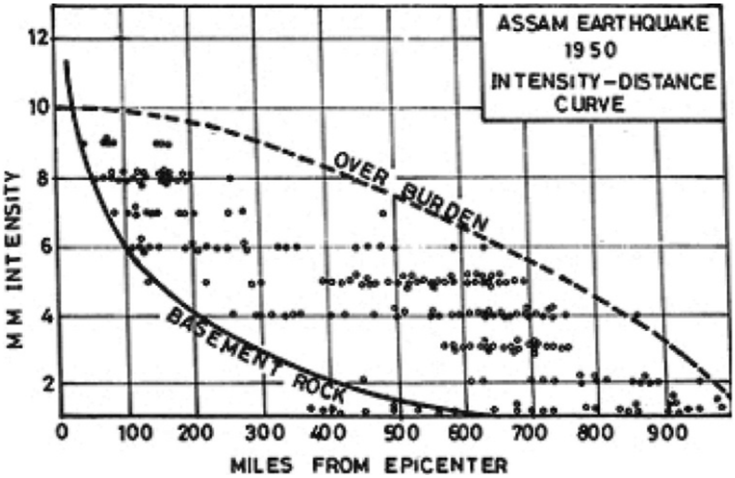


Fig. 11 The dispersion of the results is well referred in the data of the seism of 1950 in India (Mw 8.6; distance in miles)

Up to now only in subduction zones large Mw>9.0 events have been generated. However, even though occurring in a collision zone, the 1755 earthquake presents many characteristics that suggest a magnitude of that value. Certainly, due to the non existence of a single geological structure large enough to release such amount of energy, a multiple event involving more than one structure (for instance, parallel structures, rupturing in cascade) might be a possibility. Figure 8 shows alignments and gaps in the seismicity of last 50 years that fit this hypothesis.

4 Description of the City of Lisbon and Quantification of Damage

The city of Lisbon, around re-occupation (1147) fulfilled essentially the interior of the Mourish Wall with a population of about 15,000 inhabitants, organized in only seven parishes, with its main hills, roman monuments and the arm of the Tagus river spread to Rossio (Castilho 1893).

The city develops differently along the times with its own rhythms. For instance the evolution during the second half of the XIIIth century and the first half of the XIVth century was rather quick.

The urban network (Fig. 12) was composed by the open squares near the river and Rossio and the hills that surrounded downtown. More than 140 important buildings were identified in the XIIth century, and by the time of the earthquake several new buildings, some of great grandeur like the Opera House were present.

In 1755, Lisbon was organized in 43 parishes, from which the first 39 were the city itself and the other 4 correspond to the parishes of the farms that, today, belong to the City Council of Lisbon.

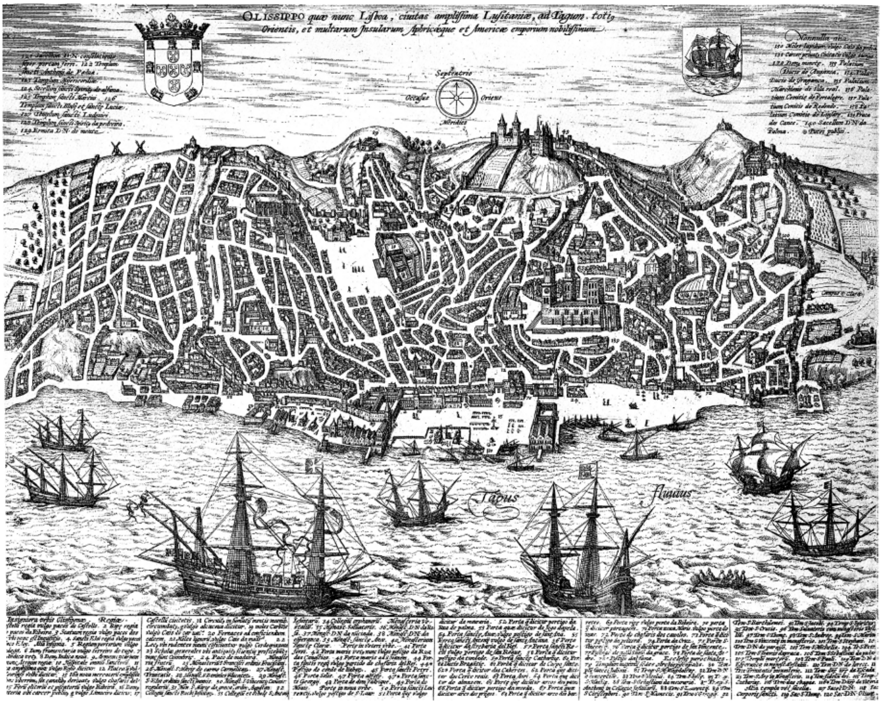


Fig. 12 Engraving Lisbon plan view at the XVIth century (G.Braunio)

4.1 Structural Characteristics of the Building Stock and Monumental Structures

Palaces and monumental structures, for its own characteristics, were classified separately from the building stock. In general, all these constructions have vertical resisting elements made of stone masonry of better or worst quality, with wooden elements forming the floors and the roof. The walls were very thick, with thickness slightly decreasing towards the higher floors. Spans between walls were rather small as well as doors and openings. Monumental constructions, usually made of good quality masonry walls, showed stone arches to sustain larger spans, especially in the ground floor, like the archways in Rossio, with 25–35 arches, constituting the advanced wing of the Hospital “Todos os Santos”, which was badly damaged during the earthquake. The larger churches showed peripheral walls extremely high forming “boxes” that sustained the roof in stone vaults. Depending on the dimension, the interior could present medium columns to support arches and vaults, as the construction tradition at those times would dictate. The chapels, on the other hand, were small and not so slender.

From the structural point of view the monumental buildings were classified into the following categories:

- Churches – structures of big dimensions with large open spaces and developed predominantly along one single direction – typically of rectangular shape with supporting walls on the sides and vaults with arches to sustain the ceilings and roofs. The walls are made of well-cut stone masonry in the exterior with widths that could reach 4–6 m at the base. The structure that sustains the roof can be in stone forming vaults or bay arches, etc., or wooden structures. To strengthen the walls, metallic ties were used in the XVIIIth century and they transmit horizontal loads from one wall to the other. All churches have bell towers of 20–30 m high, also in stone masonry, some times being part of its front, others placed sidelong.
- Convents and monasteries (cloisters) – structures with 2 or 3 floors, disposed in square, having in general, the first floor laid on abutments forming archways. The walls are on well-cut stone masonry in the exterior, preferably making the corners, with 1–2 m width, floors over wooden grounds supported in 10–15 cm over the walls. The abutments of the ground floor are built of one only stone, in slender structures, or by the overlap of several stones interconnected, in the cases of larger dimensions. The abutments of one only stone are connected in their crests by metallic ties.
- Palaces – structures for the home of noble people and/or public buildings with big with large spaces, several floors, extremely high interiors, walls on stone masonry more or less well cut, with a width of 1–2 m, with big windows and wooden floors.
- Hospitals, Hospices and Schools – buildings of quality inferior to that of palaces and with a structure mixed between a palace and a convent.
- Chapels – small churches with walls in stone masonry with no windows. They are strong and rigid structures with walls of 1 or 2 m of thickness.
- Other structures – in this category we include specific cases that present different behaviours from those referred above: (a) Military garrisons – very heavy structures, partially buried, with very thick walls. They formed the defence system of the coast of Lisbon. (b) Towers – beautiful high structures. (c) Bridges – roman type. (d) Aqueduct – bridge of big dimensions across a large valley. (e) Walls – San Jorge Castle of and Almada, and Walls "Cercas" of the City. (f) Fountains and pendulum structures.

The building stock, where most people lived, was composed by houses organized in city blocks, with 3 or 4 floors. The houses built in inclined areas could present 1 or 2 more floors at the downhill side, making 5–7 floors. The urban tissue was rather chaotic, with very narrow and winding streets, reflecting the merging of Arab culture. We can still see, today, some very well preserved samples in the district of Alfama, around the San Jorge Castle and near the river west to the "Terreiro do Paço" square. These houses have small rooms and small interstory heights, thick walls and small openings, wooden floors and stairs of one only flight. Very often they present a ground floor in stone arch supporting the walls. Façades with wooden frame in cantilever to the exterior forming a "bump" are also common. Roofs with 2 or 4 attics complete the structure.

Fig. 13 Constructive typologies used before the earthquake: a) house of narrow front with an external wall forming a "bump"; b) house of narrow front with a roof of "four attics"

Figure 13 shows two examples of the typologies of the houses above described, presenting photos, elevations of the buildings and schematic cross-sections (Santos *et al.* 1993).

4.2 Quantification of Damage

Great uncertainties still do exist on the performance of building structures and monuments, extremely devastated by the earthquake, as well as on the number of victims caused by the earthquake throughout Portugal.

In relation to monuments it was possible to identify 419 in the area of the present City of Lisbon, classifying them according to the classes referred in Section 4.1. The damage inflicted by the earthquake was differentiated into 5 levels, from no damage to total collapse. Figure 14 shows the geographical distribution of those monuments in the central area of Lisbon, and Fig. 15 the damage statistics.

From Fig. 15 one can see that structures of larger dimensions suffered larger damages than small structures. This behaviour can be explained by the proximity of the frequencies of the incoming waves with the frequencies of the structures which cause a resonance phenomenon. As larger structures exhibit lower natural frequencies, the above referred behaviour supports the idea that the incoming seismic waves were with energy predominantly in the longer periods originated by sources away from Lisbon.

New studies are being made compiling all the available information on the type geometry and dimensions of the monuments, damage level sustained, and the type of soil profile underneath. The use of GIS technology is being applied to more easily establish correlations with the different parameters intervening. In this study we try to separate damage caused by the shaking from damage due to fire or even due to

Fig. 14 Damage distribution in monuments in the City of Lisbon: a) work by Oliveira (1986); b) work by San-Payo *et al.* (2005)

the tsunami, even though, in many instances, this is quite difficult to achieve. We use engravings such as the one in Fig. 16, representing a construction having very slender walls standing alone, to analyse the cause of damage. It seems that, for this case, the fire may have destructed the roof and the shaking was not responsible for the inflicted damage.

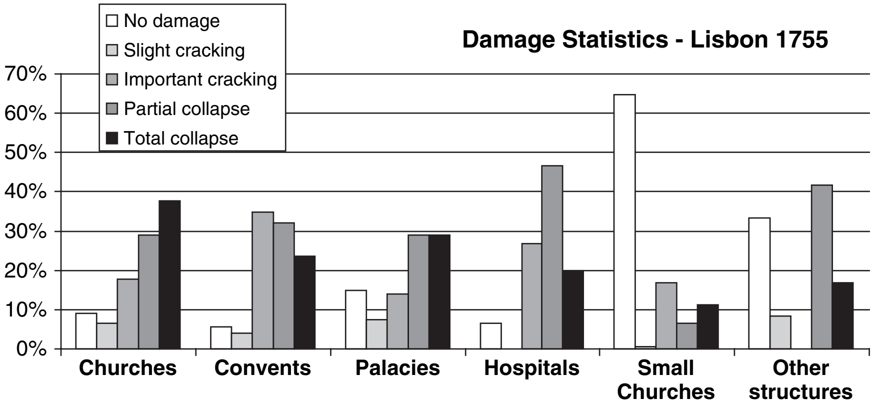


Fig. 15 Damage statistics in monuments

In relation to the housing stock, the situation is much more difficult to analyse, due to the different estimates presented by various authors. According to Pereira de Sousa (1929), confirmed in "Memórias Paroquiais", the population of Lisbon at the time was around 150,000 inhabitants with age above 7 years. The Census in 1758 indicates 34,000 apartments and 20,000 houses. Only 10–20% were in safety conditions of habitability, 60% exhibit important damage and were inhabitable, and 10–20% collapsed.

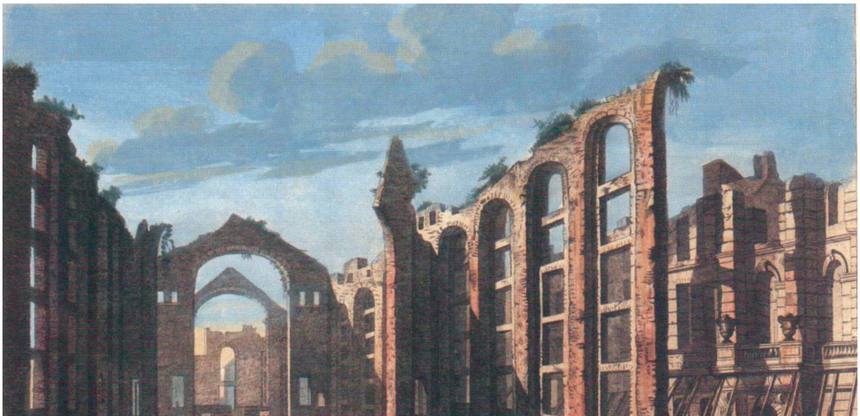


Fig. 16 Structure with slender walls without falling (Opera House or Real Theater) denoting damage caused essentially by the fire

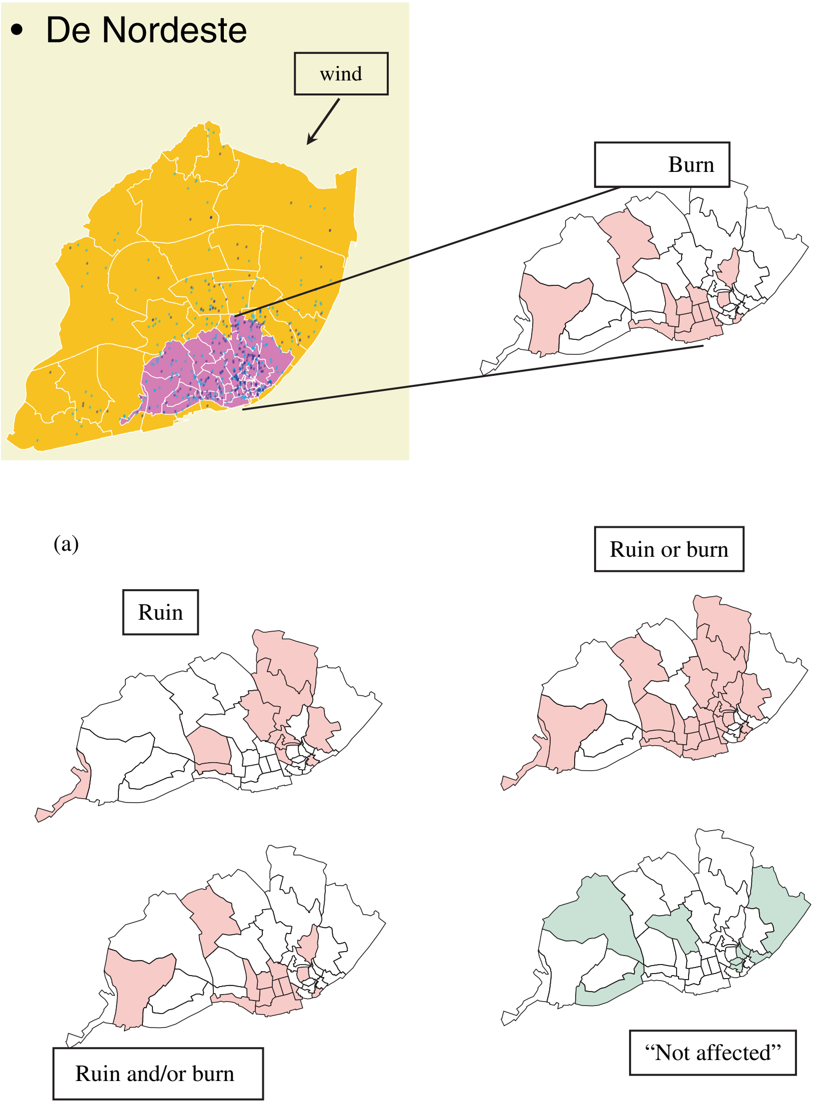


Fig. 17 Lisbon parishes more affected by shaking or fire

The fire seems to be responsible for destroying one third of the housing stock, mainly the one localized in the centre where the concentration of houses was higher. Figure 17 presents the parishes that were most affected by shaking or fire.

The estimative on the number of victims is even more uncertain. The official numbers right after the event were in the order of 5,000, a lower bound, but other sources indicate an upper bound of 30,000 death. According to the judgement of many individuals living outside the country and quoting Francisco Xavier de Oliveira (1756), the number of 30,000 victims in Lisbon seems a reasonable estimate.

However, information obtained from the population movements after the event, point to different values according to the sources. Pereira de Sousa (1914), after studying the balance of population before and after the event by parish, proposes the upper value of 8,000 deaths which correspond to around 5% of the entire population. However, he lacks information in many parishes. Pereira (2005) uses partially Pereira de Sousa data filling up many of the existing gaps supported on a more thorough research and he gets to values of the order of 30,000 deaths. This seems in better agreement if we look at the part of the housing stock damaged, from where the percent of victims should be higher, unless the collapsed houses did not kill all the population inside.

Ourselves, comparing both studies, we arrived to the following numbers:

- Prior to earthquake: Population (age < 7 years) – 147,556; Dwellings – 33,633.
- Disappeared after the earthquake: Population (age <7 years) – 31,344; Dwellings – 13,526.

These numbers need further confirmation due to the change in the administrative setting of parishes but also due to population movements to outside the Greater Area of Lisbon.

Statistics for other areas besides Lisbon are also difficult to obtain, either in Portugal, Morocco and Algeria. On the other hand, in Spain, the number of victims are of 1,200, the great majority caused by the tsunami impact in the southern coast. Only 60 were caught by the collapse of structures or fall of ornaments. 10 deaths in the Azores were due to the tsunami run-up.

To attest the tremendous work we need to perform before reducing the uncertainty bounds in this matter, the following recent findings constitute a good example of what new information can provide. Recently, in the Convent of Jesus in Lisbon, presently the Academy of Sciences, many corpses were found during excavations for maintenance procedures. It is thought that more than 1,000–2,000 victims might be there (Telles Antunes and Cardoso, 2007, personal communication). Among these victims, these investigators found corpses with signs of earthquake traumas, corpses burned by the fire that followed the earthquake, but also corpses with signs of violence practiced after the event.

This Convent was greatly damaged by the earthquake. However, the Palace of São Bento (present Assembleia da República) which is within 0.5 km and seating in the same geological setting, did not suffer much.

Detailing a little more the situation in Portugal outside Lisbon (Fig. 3, for toponym), statistics in the epoch show that in Setúbal, a village to the south of Lisbon, greatly shaken by the seismic waves with many collapsed monumental structures and suffering from the violence of the tsunami, more than 1,000 victims may have occurred and a few houses got on fire. In Santarém, to the north, very much affected with many collapses of churches and sulphur smell was spread all over the village (Pereira de Sousa 1919–1932). On the other hand, in Lagos, the village most exposed to the earthquake threat, suffering extensive damage and tsunami impact, from a population of 4,000 people housed in 900 households, only 200 died immediately and another approximately 200 were seriously injured and did not survive.

This means that the first 5% of victims were increased to 10% due to the injuries. In Lagos many large and small churches were destroyed by the strong shaking. Only one (São Sebastião) out of 5 or 6 large churches had minor damage. Also, the town walls facing the ocean and fortresses in the beach were greatly damaged.

In Oporto, 300 km to the north of Lisbon, very little damage was observed (Rosas da Silva 1939).

In Madeira Island the tower of the Cathedral (Sé) fall off to the south over the "Capela-Mor". In the Northern coast the tsunami caused first a run-down of 100 m. Then, the run-up flooded the villages of San Vicente, Ponta Delgada and Porto Moniz. There still exist some speculation on the formation of the Fajã, a place where many people may have died (Baptista, personal communication, UAveiro 2004).

Claudio da Conceição (1829) presented some complementary data worth mention. Around the so-called Greater Area of Lisbon there has been quite severe damage in locations like Sintra, Cascais, Ericeira, etc. The great Convent in Mafra did not suffer much, neither Alcobaça, even though in this one water feeding the monastery disappeared during a few days. To the north of the country the shaking was less felt. In Coimbra there were several ornamental objects that fall from their top walls. Also, the bells sound in the University tower and the river waters became very agitated. In Madrid the duration was about 8 min. The shaking was felt and in two situations the fall of the front wall in churches took place.

To the above numbers we should add the tremendous economic impact caused by the earthquake, which is also a matter of great uncertainty. Values vary from as low as 40% of the Portuguese GDP to values that can add up to 3–4 times. Twenty percentage were attributed to the losses from the collapse of the new buildings in "Terrreiro do Paço", another 20–30% to losses of stocked goods of high value, 20–30% to the housing stock, and 20% to the monumental structures in general. In a recent paper, Pereira (2005), after studying new archival and existing data concludes that direct losses from the earthquake were much lower, of the order of 40–60% of the Portuguese GDP, but the indirect consequences in the years that follow the event were major for the economical situation. "In the long-term, in spite of the terrible casualty toll and significant wealth losses, the 1755 earthquake was beneficial to the economy". In contrast, for Spain the total losses may represent as much as 20% GDP, 5% of which could be attributed to the tsunami damage (Martinez-Solares 2000).

5 Information from the Behaviour of Simple Structures: The Inverse Problem

To obtain more precise information to determine a few parameters of ground motion felt in various sites and to contribute to the establishment of the seismic source of this event in a more convincing way, we should use the most varied pieces of data. Besides the distribution of damage which is translated into the isoseismal map, the tsunami effects on the coastal areas and harbours, the behaviour of simple structures, the description of geological effects such as liquefaction, far-way effects, etc., are important points where we can gain additional information. Several of these topics were already addressed in detail. In this Section we will look into a few new topics of great importance to understand incoming ground motion, namely looking at

- The Aqueduct: "Aqueduto das Águas Livres";
- The Corner Building: "Torreão do Terreiro do Paço";
- The liquefaction distribution and the sinking of "Cais das Colunas";
- The return period associated to the event from paleoseismology related to the tsunami.

5.1 The "Aqueduto das Águas Livres"

The "Aqueduto das Águas Livres" in Lisbon, a magnificent masonry structure built a few years before the earthquake, is a long structure crossing the Alcântara Valley supported by tall pillars that transform into arches. It behaved quite well during the earthquake suffering only stone block displacement in three airing towers ("Torreões"). The damaged towers were the ones positioned along the deck where the heights in relation to the valley were larger.

Many analytical and experimental studies were performed to evaluate the seismic input that generated the minor damage observed. Mathematic models were developed after determination of the mechanical properties of the materials, and were calibrated through the values of frequencies of vibration obtained with *in-situ* measurements (Fig. 18), both with ambient noise vibration (Oliveira 1986) and from records obtained during recent earthquakes (Oliveira 2005). Results indicate that Peak Ground Accelerations (PGA) at the soil level that provoke the observed damage should not have surpassed 100–150 cm/s^2. Sincraian *et al.* (1998) developed complex 2-D and 3-D non-linear models to obtain ultimate seismic loading causing the collapse of the structure, and the PGA values obtained for the longitudinal direction are above 1 g. In the transverse direction, PGA values of 0.3–0.5 g are enough to provoke the collapse of the structure.

5.2 The Corner Building: "Torreão do Terreiro do Paço"

The "Torreão do Terreiro do Paço" was a magnificent structure built just prior to the 1755 earthquake. As today, it is a massive good masonry structure (Fig. 19) founded in a soft soil of a few tens of meters. The fundamental frequency of this structure measured nowadays is on the order of 4–5 Hz. Assuming that the original structure was similar to the present one, we can say that damage to the "Torreão" was not very important. It seems that the vertical crack observed in Fig. 19 was essentially due to settlement of the foundation soil, and the part at the lower section with diagonal pattern denotes the N–S movement of incoming waves. In the adjacent cloister type

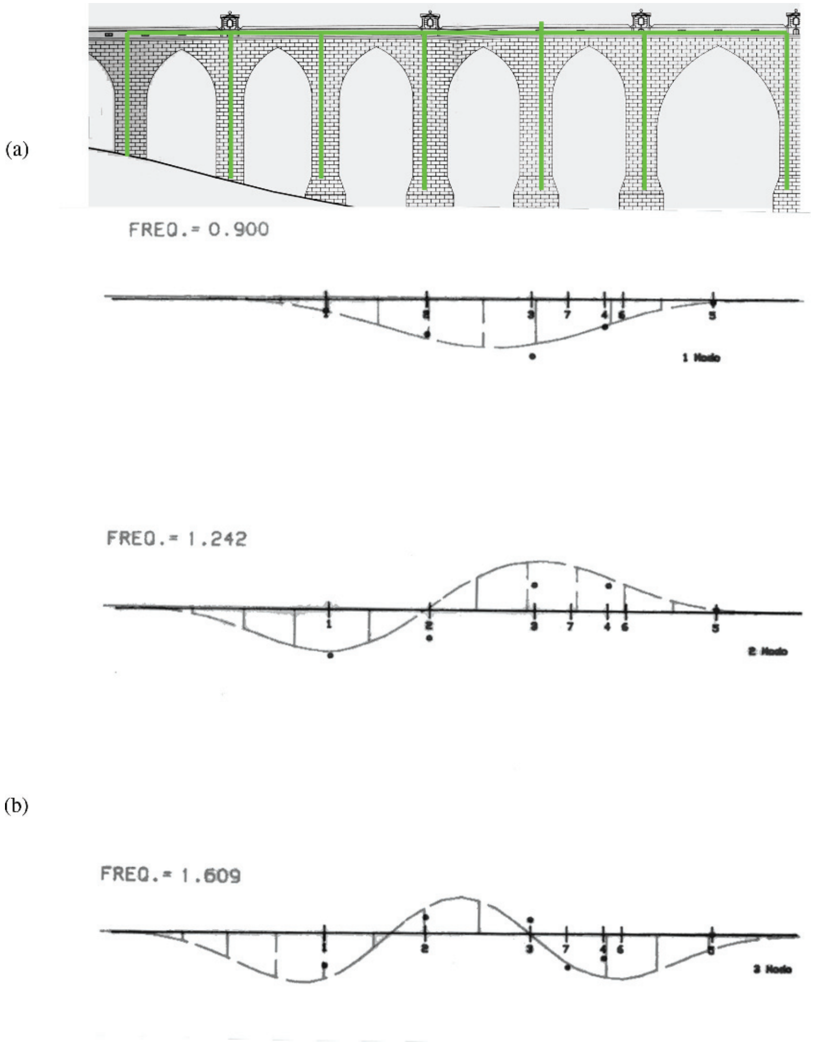


Fig. 18 Aqueduto das Águas Livres: a) 2-D model and b) *in-situ* testing to determine frequencies and modal shapes (Oliveira, 1986)

section, to the right, the soil layer is thinner, and the damage is observed at the upper floors and might be due to fire, and not so much due to shaking.

Complementary studies are being performed to clarify the behaviour of the "Torreão" by:

- Determining the structural alterations introduced in the present structure along the times in order to obtain the geometry when the earthquake occurred.
- Develop a non-linear finite element model to analyze damage and be able to foreseen what really has happened.

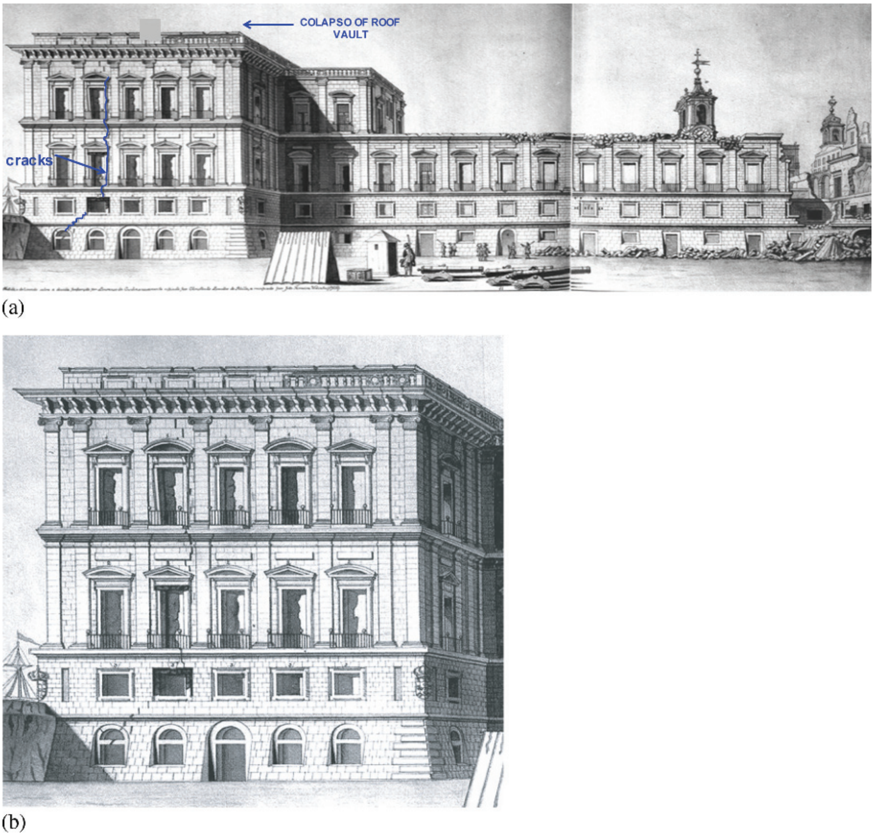


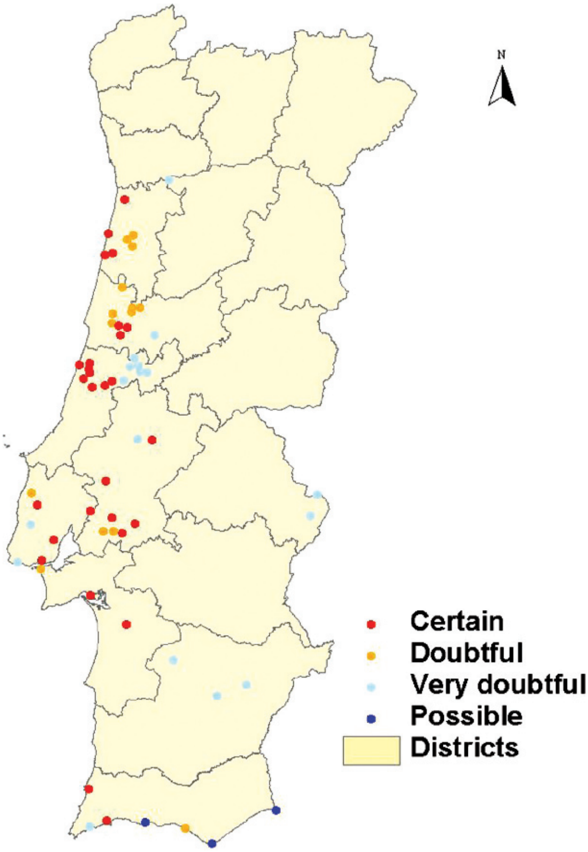
Fig. 19 Damage caused to the "Torreão do Terreiro do Paço" and West wing of "Terreiro do Paço": a) vertical cracking caused by strong motion and soil settlement (on the left hand side). Damage due to fire (on the right hand side). b) detail of "Torreão"

5.3 The Liquefaction Distribution and the Sinking of "Cais das Colunas"

Liquefaction observed throughout the country was another source of important information. Jorge (1994) showed locations of confirmed and probable liquefaction at sites near the coastal areas at large distances to the epicentre, denoting the large amplitude of the event, Fig. 20. According to Ambraseys (1988) only magnitudes above 9 would originate these phenomena at such large distances.

We should also add that a large number of people that run into the "Cais das Colunas", a pier built in front of the Tagus River just before the earthquake, were drowned due to its collapse. The collapse, previously attributed to tsunami waves, is now recognized as a liquefaction phenomenon with the sinking of the entire pier whose foundation was sitting on a muddy sand.

Fig. 20 Sites where liquefaction was observed (after Jorge, 1994)



5.4 The Return Period Associated to the Event from Paleoseismology Studies on Tsunamis

Paleoseismology applied to earlier tsunamis which occurred in the geological past is a new field of research which may help in identifying sites of ancient tsunami impacts and in dating the time of their occurrence. The 1755 tsunami has always called the interest of the few experts working in this topic.

Along this Section a recollection of studies is brought into discussion as the ultimate goal of estimating the return period of such an event as 1755.

Sedimentology and geomorphology evidence of the 1755 AD Lisbon tsunami includes sand, pebbles, and cobbles in the Scilly islands, UK, and in southern England (Banerjee *et al.* 2001), and on the Algarve coast in southern Portugal (Hindson *et al.* 1999, Dawson *et al.* 1995). Andrade (1992) reported the transformation of barrier islands on the Algarve coast, e.g. overwash and channels, generated by the 1755 AD tsunami. Kortekaasa and Dawson (2007) also found evidence of 1755 tsunami in other sandy beach in Algarve, Martinhal, separating the sedimentology of tsunami events from strong storm surges. 1755 Lisbon tsunami deposits have been also reported in Cadiz province, Spain (Luque *et al.* 1999).

Whelan and Kelletat (2005) observed large littoral debris and accompanying geomorphic features and they speculate about their relationship to a tsunami event at Cape of Trafalgar, located on the southern Spanish Atlantic coast, 500 km east of Gorringe Bank. Relative dating of weathering features as well as minor bioconstructive forms in the littoral zone, suggest the Lisbon tsunami of 1755 AD as the event responsible for the large deposits described. They consider that tsunami run-up or wave heights for the Cape of Trafalgar boulders of 14–16 m are conservative values.

Banerjee *et al.* (2001) also found elements for another tsunami 1,000 years ago. According to Luque *et al.* (2002) the presence of washover fan deposits on the inland margin of the Valdelagrana Spit bar, Cadiz, indicates the occurrence of a high energy marine event around 2300 cal. year BC. Historical, geomorphological, sedimentological, palaeontological and geochronological data suggest that a tsunami could have affected the area during Roman times.

In a recent study on the Aveiro lagoon, to the north of Portugal, Sarmento and Cardoso (2006) realized that the salty water flooding occurred in the Spring of 1756 may have been originated by the accumulation of water that entered the lagoon during the tsunami of 1755, together with the occlusion of the lagoon caused by the anomalous tsunami sedimentary process in the sandbank (Memórias Paroquiais, Aveiro).

New investigations on boulder deposits (>1 ton) found several west of Lisbon, and signatures of run-up to 50 m asl in vegetation scars with datings of about 200–300 years ago. This is another indication for the presence of a tsunami associated to the 1755 event. But it also gives indications of the occurrence of older tsunami, about 2400 BC and 6000 BC(?), see Scheffers and Kelletat (2005).

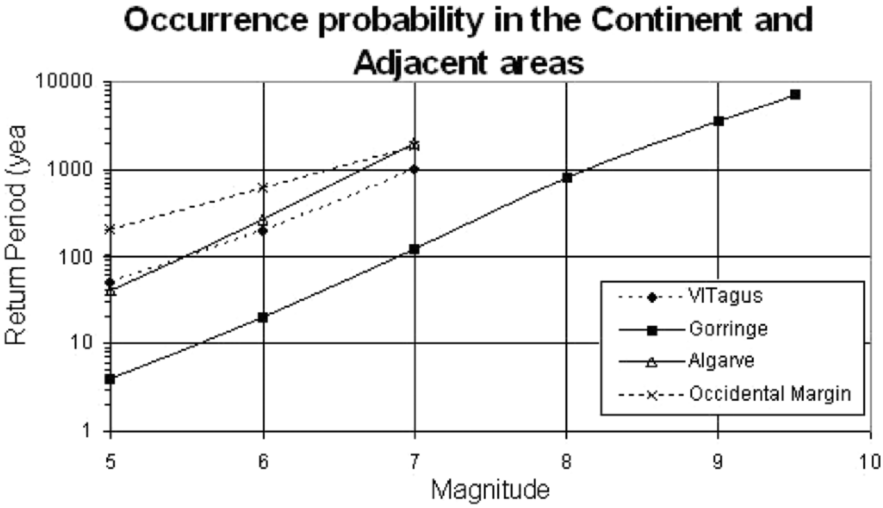


Fig. 21 Reccurrence rate for events in the most important seismic sources of Portuguese region (adapted from Rio, 1996)

All this information, together with instrumental and historical data for the Gorringe area led to the hypothesis that the Mw9 1755 earthquake may occur every 2,000–5,000 years. Figure 21 gathers all the recurrence rates for events in the most important seismic sources in the Portuguese region, including that of 1755. The above mentioned return periods seems to be in agreement with the 5 mm rate of collision between Plates and the Mw>9.

6 A Final Word

Many things have been learned in recent years using the most advanced technological tools for a better understanding of the various unknowns related to the seismic source, wave propagation, site effects, duration of ground motion, predominance of lower frequencies, etc. The damage distribution in monuments is very well known, but in the stock of housing it is still very uncertain. Much more work should be done to better clarify these aspects. This is the only way we can proceed to minimize the effects of future events of this kind. Even though this event belongs to a class of rare events with a low probability of occurrence, it may come at any time. The better we understand the better we are prepared to face it.

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Part IV

Quantifying Historical Earthquakes: Effects, Intensity, Magnitude, Seismograms

Earthquake Effects on Nature and Macroseismic Intensity Scales

J. Vogt†

Foreword Earthquake effects on nature are very important macroseismic phenomena, which can be of relevant use for assessing the level of shaking. For that reason, they have been traditionally incorporated into intensity scales, despite the fact that such effects are not homogeneous with the ones commonly used for assessing intensity degrees, such as effects on humans and buildings (damage). Problems arise for five main reasons; (i) these effects are not peculiar to one degree, but can take place at strengths of shaking that the intensity scales relate to a wide number of degrees; (ii) they often happen in a few instances (in many cases just single ones), while modern intensity scales have a statistical "philosophy"; (iii) the effects are often highly dependant on pre-existing vulnerability states that are usually unknown; (iv) some effects are not strictly related to strength of shaking at all, and only appear to be correlated with intensity for indirect reasons; (v) they mostly take place outside the localities where intensity is assessed on the base of damage and effects on humans, and often the corresponding shaking is referred, wrongly, to the nearest locality. EMS-98 tackled this problem by assigning to geological effects a side role. Geological effects have been related to intensity degrees through a table, where it is clear that they are not correlated one to one. Most of the preparatory work was performed by Jean Vogt, who retrieved a lot of data from his personal and partly still unexploited archive. It must be said he was never fully happy with the final table, a hard-to-reach compromise, the development of which can be traced through a number of letters.

After the publication of the EM-92 intensity scale, which later became EMS-98, the table was published with some comments by Vogt et al., 1994. At the same time Jean Vogt prepared a draft of this paper which was completed in the present shape in 1993 and then waited for an opportunity to be published.

We present the paper mostly as it stands, in spite of the fact that some parts are still draft, because we do not want to change the original flavour. Most references have been tracked by P. Albini, A.A. Gomez Capera and P. Migliavacca; a few are still lacking.

R.M.W. Musson and M. Stucchi

J. Vogt
Strasbourg, France

J. Fréchet et al. (eds.), *Historical Seismology*,

1 Introduction

A first draft on geological effects has been prepared for the 1991 meeting of the ESC WG on macroseismic scales, held in Munich. Later I received one contribution from T. Zsiros and a paper by L. Serva written in 1990 in another context, but serving our purpose (Serva, 1994); then I prepared a second draft at the last minute, in a haste.

I was in the unhappy situation of using mainly my own files and experience and submitting mainly personal opinions. Nevertheless I tried:

- to develop a more thorough and logical discussion, repeating myself to some extent;
- to give more examples of methodological interest, among a wealth of cases;
- to formulate some guidelines, here and there.

This paper stems from the material prepared for that purpose.

2 Problems with Seismogeological Effects of Earthquakes

It is commonplace to state that the geological effects of earthquakes are often more important than the direct ones. Such a statement was made, for instance, by Solonenko (1976), at the 25th International Geological Congress: "… sometimes during earthquakes most of the damage (up to 80–90%) is not due to the earthquake itself, but to accompanying seismogravitational phenomena". Such effects, are dealt with by a wealth of papers, by seismologists, engineers, geologists, geomorphologists and even historians, usually without, at my knowledge, any considered methodological and interdisciplinary discussion. Although they are sometimes a main feature of the interpretations of major events, geological effects are far from being mastered by classical intensity scales, with criteria seemingly formulated by seismologists in a kind of "splendid isolation", while interdisciplinary discussion is needed even more than for other criteria. Such a situation is rather paradoxical.

Of course, such remarks led to some misunderstandings in the past. Criticism by people with geological backgrounds has sometimes been interpreted by seismologists as a wish to discard geological effects from intensity scales. Doing so, geologists would dig a pit for themselves. It would have been better, while discussing their use by scales, to emphasise geological effects and consider them more systematically.

At this point, a discussion of the geological criteria used by the original MSK (Medvedev-Sponheuer-Kárník) scale is useful. Some logical flaws can be pointed out. In a general way, these criteria show a sharp contrast of major discontinuities and utter precision given for one or another degree. Sometimes conditions are given (one case of waterlogged soil, some cases of lithology, several cases of relief, etc.), sometimes not. So river-banks, particularly sensitive, appear only with degree 9 in a specific way. While the possibility of landslides in mountains is considered in a general way for degree 6 (which good), only small slides under peculiar conditions are used as criteria (along with others, of course) for degree 7 and even 8. Rockfalls appear only with degree 8 (not good), are not considered explicitly for degree 10, but then are once more emphasized for higher degrees. Rivers are dammed with degrees 8, 10 and 12, but not explicitly for degrees 9 and 11. On the other hand, crevices of different width, centimetres, several centimetres, 10 cm. and more, 1 m, are used as criteria for degree 6, 8, 9, 10, sometimes under peculiar conditions. On the whole, degree 7 is neglected. Liquefaction does not appear clearly (see degree 9).

Of course, these remarks are formal. Enlightened users would adapt criteria to different cases with their specific backgrounds and extrapolate or interpolate when necessary, but others, proceeding mechanically, uncritically, would make huge mistakes, with a lot of consequences (in the appraisal of seismic hazard, etc.) that we cannot afford. Some cases can be given.

Rockfalls, frequent, and landslides, less frequent, are considered together with a large extent, for two reasons. There are not always easily discriminated in old sources, and give rise to similar methodological problems. While liquefaction may be an important factor in landslides, it will be considered separately in the narrow sense of liquefaction occurring in plains, clearly described by a wealth of sources.

For rockfalls and landslides let's consider some pitfalls.

First it should be stressed that most classical catalogues actually list as earthquakes some rockfalls and landslides that were not at all triggered by quakes. Such confusion can result from:

- the indiscriminate use of the word "earthquake" (or terraemotus) itself, by many sources, ancient and modern;
- an uncritical handling of such sources;
- an inability to master the geological background of an event.

While classical catalogues allow a discrimination of more or less genuine effects of earthquakes, sometimes at the price of painful retrieval of sources, misleading statements resulting from hasty listing are not easily detected. Part of these problems have been discussed by Albini and Vogt (1992).

A few significant examples are the following:

From France: since Perrey (1845) the otherwise well-known Pardines rockfall (1733) is listed as an earthquake, latterly with an epicentre located by Rothé (1946).

From Spain: the 1885 Boltaña landslide (1885) is wonderfully described by a local newspaper (Diario de Huesca, 1885), which unfortunately uses in its title the misleading word "Terremoto", the reason why this event is listed as a quake in the Ibero-Maghrebian catalogue (Mezcua and Martínez Solares, 1983).

From Morocco: it seems that a rockfall or a landslide in the northern Riff, where they are common (Vogt, 1984), is responsible for a 1909 "earthquake" listed with intensity 9 (!) by the same catalogue and 6 by Cherkaoui's (1988) Moroccan catalogue. *(Note: this has become, in modern databases, an earthquake of magnitude 6.1, the maximum event for the sensitive area around any projected crossing of the Straits of Gibraltar).*

In these cases (among many others) the fact that only one piece of information is available, and from one location only, should have been a sufficient reason (besides others) for some critical thinking *(Note: how should such a strong earthquake in 1909 not been felt more widely*?) Let's turn to more complex cases.

Some are linked with chronological problems. Rockfalls and landslides, sometimes in distant places, are easily attributed by old sources to earthquakes occurring more or less at the same time, maybe within weeks or months. The lack of chronological precision makes any interpretation a difficult task, for instance for various phenomena reported here and there at the time of the famous Basel earthquake of 1356. Such amalgams (in areas of high intensity) and accretions (at a distance) crept into catalogues, easily escaping even critical minds.

While a more or less precise chronology is of help, numerous problems of diagnostics nevertheless arise. Consider as an example the southern Tunisian sequence of 1881. On one hand we have rather precise information (chronology, damage) from the Gabès area. On the other a rockfall is reported vaguely to the west, in a uninhabited area. While an intensity is easily assessed in the first case, it is practically unassessable in the second with the available meagre information. As a consequence, estimating the location of an epicentre would be hazardous. Special attention is required by complex sequences of earthquakes as well as of rockfalls and/or landslides. So a thorough discussion of the famous Yvorne events of 1584 (Vogt, 1981), would be welcome to ascertain if the geological effects are the best argument for the location of the epicentre (Alexander, 1983).

Even with the best possible knowledge of the chronology, the discussion of delayed geological effects is arduous. So De Quervain (1925) was tortured by major rockfalls occurring on the shores of Walensee 34 h after the earthquake of 7 November 1924, with an epicentral intensity of V–VI. Disagreeing to some extent with geologists, quoting a similar example from Central Alps in 1917, considering theoretical accelerations, he insists on the earthquake as the main triggering factor, despite the rather low intensity.

Actually, many seemingly clear cases are not clear at all unless the background is known.

Among whereabouts, ground acceleration is of course fundamental with a wealth of theoretical discussions, during the last years. Meteorological conditions are also critical. At the time of the 1716 Algerian earthquake, a landslide occurred in the Chelif basin, South of Algiers, after a period of heavy rains. This may be essential for the understanding of the earthquake, but its interrelation is not an easy task (Ambraseys and Vogt, 1988). A major rockfall in Southern Jura, 1791, is considered by Riboud (1817) a consequence of both rains and earthquake, the shaking being actually slight. We would easily misinterpret geological effects of the 1887 Ligurian earthquake if we did not know that rain brought down rocks loosened by the earthquake in the hinterland of Menton.

Backgrounds should be considered in the widest sense of the word. In many cases they are not discussed at all or in a very unsatisfactory way even if information is available.

In most cases, geological maps are hardly usable for such purposes for reasons either of scale or of mapping doctrine. Many maps do not provide reasonable information on surface formations, weathering, joints. Specific maps (maps of surface formations, geotechnical maps) are seldom available. So field-work, possibly with specialists, is needed in many cases to identify and weigh factors, a condition *sine qua non* for the assessment of intensities from such data.

Several peculiar cases, easily leading to exaggerated intensities, should be mentioned. First, let's consider coastal cliffs, with very different backgrounds. While a small cape fell into the sea near Vostizza during the strong 1817 earthquake (Pouqueville, 1820), two huge rocks fell from the cliffs of Yeu Island in 1808, yet no damage to buildings was reported (Le Moniteur Universel, 1808; Journal de l'Empire, 1808). Alluvial banks are most sensitive and prone to failure even with low intensities. Sinkholes (*karst collapse*) occurring during quakes must be considered with the utmost care.

Mastering whereabouts and background and, of course, common sense are needed to solve many cases of more or less discordant evidence obtained at some distance from geological effects. While damage in the town of Carpentras in 1738 (Daleman, 1740) suggests a degree $\leq$ 7 MSK, deep and large crevices in the countryside would mean, strictly, an intensity of 9 MSK, clearly incompatible. Similar problems arise in 1763 in Provence, with rockfalls in the Luberon mountains (Anonymous, 18th cent.; Vogt, 1991) and in 1765 in the Pyrenees, with rocks rolling in the valley of Couserans (Vogt, 1987). Such apparent discordances may remain controversial for long years, a fine example, being the 1564 Nissart (hinterland of Nice) sequence (Vogt, 1992; Moroni and Stucchi, 1993), with widely different interpretations of rockfalls and landslides by catastrophist and anti-catastrophist minds raising even a sort of political strife.

In a more general way, inquiries about the relative decrease of geological effects with distance can be rewarding. Consider, for instance, the major 25 January 1946 Valais earthquake. While huge rockfalls occurred the epicentral area, minor ones were reported from Savoie, for instance, of rocks of several m^3 on the banks of the Rhone. Further away, on the shores of Lake Evian, fishermen's nets were buried by sliding masses of mud, with intensity 5 (Lambert and Vogt, n.d.). Such a discussion for the 1755 Lisbon quake would doubtless be enlightening, for instance about the case of rockfall at Gibraltar.

Looking for coherence of intensities from geological effects and from other criteria, investigators should also consider to what extent the same effects could also occur with lower intensities, an important step for a sound assessment of risks at a regional scale.

Such remarks could be developed at great length. While it is often suggested that ground effects are particularly important for establishing the highest intensity degrees, at the top of the intensity scale where damage effects on buildings have probably reached saturation, these effects really have to be studied in the context of the whole range of intensities.

It should be emphasised once more that rockfalls and landslides on the whole occur within a wide range of intensities. A world-wide sample of forty events (named "landslides" but including rockfalls) of twelve types has been discussed by Keefer (1984), mostly from literature but, in the cases from the USA, from macroseismic enquiries. Looking for "the smallest earthquake that causes landslides", Keefer (1984) correlates his sample with magnitude (in a rather abstract way) and intensities. We learn that "few landslides are caused by events smaller than ML 4.0" and, for given types, the predominant minimum intensity was 6 MM, or in some cases, 4 MM.

While everybody should agree with these general conclusions, despite formal problems met by Keefer's investigation, it seems that an European undertaking of this kind, with its specific statistical repartition of earthquakes; with its wealth of information over centuries, with the possibility of a detailed knowledge of backgrounds, could lead to better founded and more differentiated conclusions, specially for processes associated with low intensities. Such an enquiry combining the wealth of available earthquake and other information with field-work, would be useful in the Alps and the Pyrenees and their foreland, for instance.

One of the main aims of future research in this area should be the often difficult distinction between fundamentally different earthquake-linked processes, two extremes of which are outlined.

On the one hand, effects of different types (geotechnically speaking) and scales, often clearly disproportionate with the seismic factor, are triggered in more or less sensitive sites. Such effects have sometimes been named "purges", the "cleaning" of slopes, cliffs of vulnerable blocks. In any post-seismic enquiry, the following questions should be a first step: could such rockfalls and landslides also occur without triggering by earthquakes? Did such normal processes occur in the past? The scale of events should be considered.

Of course, local processes in most sensitive sites should be easily understandable. The 1959 Ubaye (French Alps) earthquake triggered numerous falls of stones in an area clearly affected by rain and snow melting (Lettre, 1959). At another scale the 1855 Valais earthquake was considered responsible for the revival and enlargement of a 38 year-old crevice in a moving mass in Glarus (Volger, 1858). Problems are more complex with "normal" processes at a "geological scale", occurring in the Alps, the Caucasus, etc. perhaps only at the interval of every 100 years or so and. Sometimes these phenomena are too easily explained by some earthquake. So consideration of time is also essential, with a more developed question: could "normal" processes, without triggering, occur tomorrow, in a month, in a year, in a century?

On the other hand, genuine earthquake-linked geological effects mostly at a "geological scale" should be defined, with an acontrario question: was no "normal" factor of some importance capable of producing such effects? While rocks simply drop during a "purge", the may be thrown from a cliff by an earthquake with a high acceleration. The clearest case is of course faulting, possibly inducing other minor secondary geological effects. More complex are once more delayed effects, described by Solonenko (1976) from Devochan (Stanovoy): "The recurrence of collapse common to Devochan is conditioned by a higly stressed state of the rock masses in the body of the seismogenetic structure: therefore, large collpses often occur without visible cause, even on seemingly stable slopes. During the Khait earthquake, some new fractures systems appeared in the zone of collapse. These systems predetermined the subsequent large collapse." At such a geological scale arise of course tricky problems of convergence of a mainly seismic factor or mainly "normal" factors.

Even without a discussion of complex intermediate cases, between plain "purge" and genuine seismogenetic effects *sensu stricto*, not in Solonenko's wide sense, it is clear that such problems requiere a high interdisciplinary expertise, a sense of scales of events, and a large regional knowledge, first of all of past events, seismological and geological. We are far from a standard implementing of an intensity scale's criteria.

Appraisal of liquefaction features in alluvial plains, etc. is considered apart. In most cases, even in the past, liquefaction is clearly identified by descriptions of hollows, mounds and, above all, projection of water, sand, etc. Outstanding inventories have been prepared over centuries, for instance for Italy (Berardi et al., 1991), with deep-dipping correlations with magnitudes, etc. On the other hand, unlike other geological effects, liquefaction has been discussed in a systematic way from a geotechnical point of view (Wang Zhong-qi et al., 1983), with a high theoretical level. So, at a first glance, no peculiar problem should arise with the use of liquefaction in an intensity scale.

However it should be emphasized that sources, inventories and geotechnical discussions mostly deal with impressive cases, either by their scale or their effects. To some extent correlations and appraisals could be biased. Further the interpretation of many not so well described "crevices" is not easy. Considering their setting, part of them could possibly be linked with liquefaction. While not one doubtless example of liquefaction is known from France, vague descriptions of several "crevices" do not exclude such a possibility.

Whatsoever, the MSK scale considers liquefaction with degree 9 and, in an implicit way, with higher ones, discussing, although in a more general way, including other effects, it seems, the width of crevices. Indeed, most inventories agree, on the whole, with this threshold.

However such a wide agreement should not lead to an indiscriminate use of this appraisal. Once more careful confrontation with other evidence is needed in each case. For the 1856 Algerian earthquake, damage to buildings is known only from Djidjelli, while liquefaction features (as well as rockfalls) are described from the countryside, rising an arduous problem of location of the epicentre, depending on the very way liquefaction is interpreted (Gaultier de Claubry, 1856).

Besides acceleration, local conditions should be carefully considered without giving too much weight to abstract discussions of a more general kind. These conditions are:

- seasonal, with the evolution of the water-table, a most important factor;
- permanent lithology and geometry, with emphasis on contrasting behaviour of layers and complex channel systems. Such essential information is not often provided by geological maps, for reasons either of scale or of doctrine, with "wholesale" mapping surficial formations, considered a hindrance. While some preventive research is devoted to potential of liquefaction, background information is often gathered after an earthquake.

Careful work shows fine examples of liquefaction with degree lower than 9. During the 1989 earthquakes of coastal Venezuela, such processes occurred with degree 7 (De Santis et al., 1990). During the 1946 British Columbia earthquake, liquefaction was observed in sensitive settings even with degree 6 (Rogers, 1980). So the range of degree is the same as for rockfalls and landslides, more or less.

Special cases should of course be considered. Discussing landslides triggered by earthquakes, Solonenko draws attentions, in a more general way to the role of ice. During main earthquakes in the Selenga area (Baikal region) it confers peculiar features to liquefaction, for instance in 1862 (Über Erdbeben, 1865).

The example leads us, besides, to problems of convergence. Actually liquefaction features often look like periglacial ones with indeed, similar pressure dynamics. During discussions of the origin of the "mounds" of Gulf Plain their similarity with features of the New Madrid 1811–1812 (Central USA) quakes have been underlined (Thomassy, 1860; Hobbs, 1907). Such convergence actually could be a basic problem during palaeoseismological interpretation and subsequent appraisal of intensities.

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What is the Lowest Magnitude Threshold at Which an Earthquake can be Felt or Heard, or Objects Thrown into the Air?

F. Thouvenot and M. Bouchon

Foreword This article is a reflection on effects produced by earthquakes at both ends of intensity scales: II ('Scarcely felt') and XII ('Completely devastating').

Now that most seismic regions—at least in developed countries—are monitored by seismic networks with magnitude thresholds close to magnitude 1, less attention is paid to reports of abnormal phenomena such as vibrations or noises. The alleged reason is that, if the event has not been detected by monitoring networks, there was no event at all. This point of view is discussed in the light of recent examples in South-East France, where tectonic earthquakes with a very shallow focus (sometimes only 300-m deep) can be heard and felt, whereas the nearby (less than 20 km) seismic stations could not record the events. Our study concludes that events with a magnitude smaller than 1, and even negative magnitudes, can be felt, thus making the human being an instrument eventually much more sensitive than monitoring networks.

Another type of remarkable observation which has been reported during earthquakes is the upthrow of objects into the air. Such observations are evidence of ground acceleration exceeding gravity. Although this type of observation is associated with an intensity of XII on the modified Mercalli intensity scale, we show that earthquakes of magnitude as low as 6 can produce such effects.

1 Introduction

The question of the lowest magnitude threshold at which an earthquake can be felt or heard is of particular importance when small historical events are used for delineating active zones in moderately seismic areas. The answer provided by most encyclopaedias and earth-science primers is that earthquakes are usually felt for shocks with magnitudes 3 and above. Actually, most authors of seismology textbooks are reluctant to tackle the question. Although Richter (1958)

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clearly states that ‘the smallest shocks reported felt by persons are near magnitude 2’, he does not expatiate on key parameters such as focal depth or population density.

Samuel Johnson (Boswell 1791) had a poor opinion on the accuracy and usefulness of popular reactions after an earthquake. Upon Boswell’s reporting him a small earthquake which had just happened in Staffordshire (England), he replied: ‘Sir, it will be much exaggerated in popular talk: for, in the first place, the common people do not accurately adapt their thoughts to the objects; nor, secondly, do they accurately adapt their words to their thoughts: they do not mean to lie; but, taking no pains to be exact, they give you very false accounts. A great part of their language is proverbial. If any thing rocks at all, they say *it rocks like a cradle*; and in this way they go on.’ This peremptory, extreme, although clever statement is an early (14 Sept. 1777) critical analysis of earthquake descriptions by lay persons. Fortunately, seismologists have long since reconsidered this viewpoint and, using appropriate precautions, now value such accounts.

Browsing Web pages can supply a wealth of information on felt earthquakes as shown for instance by the Community Internet Intensity Map developed by Wald (2007) at USGS, but low-magnitude events are rarely included in such lists because persons experiencing a faint rattle seldom bother to report it. If they ever do, the information is often judged insignificant and not deserving publication. However, out of the many Web sites providing information on felt earthquakes, the Australian Seismology Research Centre (http://www.seis.com.au) is one of the few to list carefully small events felt in Australia. Over the last seven years, the smallest magnitude value they report is an M_L (Richter local magnitude) 1.3 earthquake felt in 2000 in the suburbs of Melbourne.

There are good reasons to believe that this magnitude threshold can be still lower. Feeling small-magnitude shocks is perhaps not that unusual, the main problem being only how to collect this kind of information. Small earthquakes which occur in mines when the upper soil layers are depleted are often reported heard because they emit acoustic energy in the 200–1,000-Hz frequency range. Audible acoustic waves in the 50–70-Hz range have also been reported for many tectonic earthquakes (e.g. Hill et al. 1976; Tosi et al. 2000). Sylvander and Mogos (2005) analysed a macroseismic regional database which contains detailed reports of sounds heard for $M_L < 4$ earthquakes. They demonstrate that, in the Pyrenees, ‘events with M_L as low as 1.0 (and perhaps even smaller) may be perceived under very favourable conditions’.

We will not discuss here the now-recognized audibility of small shocks, but rather address the question of repetitive occurrence of earthquakes, another factor which increases the sensitivity of the population. Long aftershock series or swarm earthquakes often further a flow of information, even though the phenomena are faintly felt or heard. We present two cases of low-energy, unusually-shallow seismic activity reported felt in 2002–3 and 2006 in South-East France. Records obtained at temporary stations only tens of metres from epicentres demonstrate that, under particular circumstances, even negative magnitude values can be associated with felt events.

At the other end of the gamut of effects produced by earthquakes, the upthrow of objects was thought for a long time to be an exceptional event encountered in great earthquakes only. The first such documented account was made by Oldham from field observations following the great Assam earthquake of 1897. Oldham reported that in some areas stones had been tossed in the air 'like peas on a drum' (Oldham 1899; Bolt and Hansen 1977).

The magnitude of the great Assam earthquake is estimated to have been close to 8.1 (Ambraseys and Bilham 2003). Reflecting the view that the upthrow of objects in earthquakes is exceptional, 'Objects thrown in the air' are listed as evidence of intensity XII on the modified Mercalli intensity scale. In this article, we will discuss observations of upthrown rocks and boulders produced by earthquakes with magnitudes much smaller than 8.

2 In Quest of Small Felt Events in South-East France

Since the Sismalp monitoring network run by the Grenoble Observatory was set up in the 1980s (Thouvenot et al. 1990; Thouvenot and Fréchet 2006), the original procedure proposed by Richter (1935) has been used to compute the local magnitude M_L of earthquakes: the velocity seismogram is first integrated; the magnification value of the Mark Product L4C or L4C-3D 1-Hz sensors and the field recording gain are then taken into account to compare the displacement seismogram to the signal that would have been recorded by a Wood–Anderson torsion pendulum (Fréchet and Thouvenot 2000). In this stage, we use the 2,800 magnification value given for the Wood–Anderson. Uhrhammer and Collins (1990) found out that this value had been calculated on the basis of wrong assumptions on the suspension geometry, and a more correct value would be 2,080. We might therefore underestimate the size of events by 0.13 (Bormann et al. 2002), but we have not introduced this correction in the present study. We use the same attenuation law as that used by Richter although this law has been established for California. However Kradolfer and Mayer-Rosa (1988) analysed a set of earthquakes in and around Switzerland, and concluded that Richter's law was also suitable for the western Alps. Magnitudes computed by Sismalp and the Swiss Seismological Service usually differ by less than 0.2.

A Gutenberg-Richter (1956) analysis of the 11,777 earthquakes located by Sismalp in the western Alps between 1989 and 2005 shows that events with a magnitude larger than ~ 1.3 can be confidently located (Marsan et al. 2008). Out of those 11,777 events, 725 (43 per year) have a magnitude larger than 2. If we follow Richter in his vague 1958 assumption, these events could be felt. We have checked this since 1996 by directly appealing to testimonies for most $M_L > 2$ earthquakes that occurred in the French Alps, instead of letting information reach us. This was done mainly through telephone calls to gendarmeries, municipal services, and hotels. In recent years, Internet accounts spontaneously sent to us made this quest dispensable. Out of the 128 $M_L > 2$ earthquakes we checked, 123 (96%) were felt. The five events that were not reported felt had magnitudes between 2.0 and 2.3; they either occurred in remote mountainous areas or had a focus deeper than $\sim$ 10 km. Although common farther east in Italy, such 'deep' earthquakes seldom occur in the French Alps, where the seismogenic zone is mostly restricted to the first 10 km of the crust (Thouvenot and Fréchet 2006).

There is also fair evidence that protracted aftershock series favour the perception of still smaller magnitudes. We have in mind two recent destructive earthquakes, viz. the $M_L = 5.3$ 1996 Annecy earthquake, and the $M_L = 3.5$ 1999 Laffrey earthquake (Fig. 1). The Annecy earthquake (maximum MSK intensity VII–VIII) had its epicentre in the NW suburbs of the prefecture town of Haute-Savoie. Its focus was shallow ($\sim$ 2 km), within the Mesozoic sedimentary cover. The densely-inhabited epicentral zone was formerly a marsh area whose loose sediments amplified ground acceleration by a factor close to 10 in the 1–10-Hz frequency range (Thouvenot et al. 1998). The strike-slip mainshock generated aftershocks for more than 3 years, a much longer span than what could be anticipated for a 5.3 magnitude. Many aftershocks were locally felt that were recorded only by a temporary station maintained

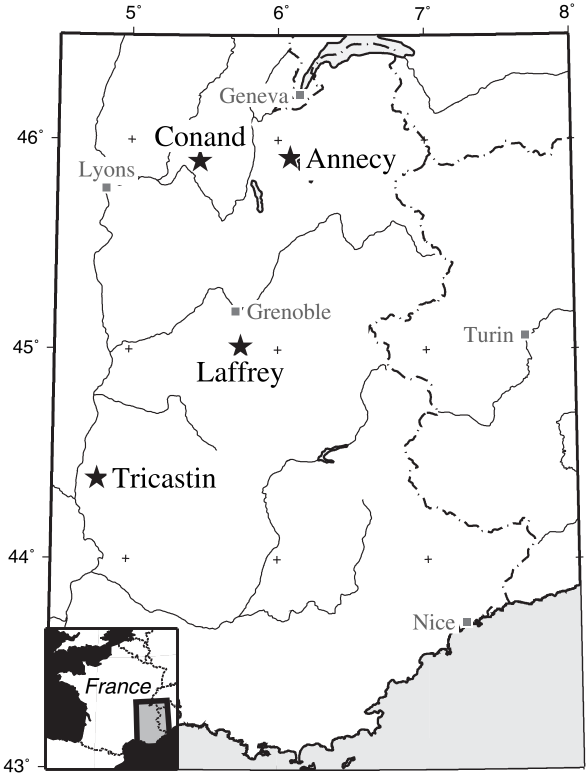

Fig. 1 Map of South-East France, with the 4 earthquakes discussed in the text: Annecy (15 Jul. 1996, $M_L = 5.3$), Laffrey (11 Jan. 1999, $M_L = 3.5$), Tricastin earthquake swarm (Dec. 2002–Mar. 2003), and Conand (11 Jan. 2006, $M_L = 3.5$)

in operation at the epicentre. Since our Gutenberg-Richter analysis shows that all $M_L > 1.3$ events can be located, we conclude that those aftershocks recorded at a single station probably have a magnitude smaller than 1.3.

A second example is the Laffrey earthquake (maximum EMS intensity V–VI), 15 km south of Grenoble (Isère). Besides the fact that its focus was similarly shallow ($\sim$ 3 km) although here located in the pre-Triassic micaschist basement, it should be also pointed out that: (i) it also involved strike slip; (ii) glacial deposits along the Drac river also produced site effects; (iii) it also generated a long series of aftershocks over more than 15 months (Thouvenot et al. 2003), again an unusual span for a 3.5 magnitude. Many of these aftershocks were locally felt, although the information that reached us by e-mail (no on-line questionnaire was then available) is necessarily biased. The smallest aftershock that could be located and was also reported felt occurred 3 days after the mainshock. For this event, we compute a magnitude of 1.1 only, whereas we estimate a maximum intensity of IV from the fragmented received testimonies.

At short epicentral distance, the routine computation of the M_L magnitude can be questioned: Richter (1935) dealt with earthquakes assumed to be sited at a depth of 15 km, and his flat attenuation curve for the first 5 km of epicentral distance expresses this assumption. In the case of the aforementioned event, 4 Sismalp stations at distances of 10, 35, 58, and 100 km were available for M_L computation, which yielded the respective values of 0.86, 1.29, 1.00, and 1.11 (mean value: 1.07 ± 0.18). Although the 0.86 value obtained at a distance of 10 km is the lowest of the series, it does not deviate significantly from the mean value if we take the standard deviation into account. However at still shorter epicentral distance we can expect problems: what would be the meaning of an M_L-magnitude computation for a station sited just above a 300-m-deep focus? The question seems academic, but such instances are encountered when small, ultra-shallow earthquakes are felt or heard.

3 The 2002–3 Tricastin Earthquake Swarm and the 2006 Conand Aftershocks

3.1 The 2002–3 Tricastin Earthquake Swarm

The first instance of such small, ultra-shallow earthquakes is provided by the earthquake swarm that occurred in 2002–3 in Tricastin (France) close to Saint-Paul-Trois-Châteaux (Drôme). This area of the middle ‘Sillon Rhôdanien’ (Fig. 1), between the French Massif Central to the west and the Alps to the east, has been known for centuries as the seat of long-lasting earthquake swarms. In 1772–3 such a swarm visited the village of Clansayes where the church tower was knocked down by the strongest event of the sequence (maximum intensity: VII–VIII); in 1933–6 another swarm visited several villages close to La Garde-Adhémar, which suffered slight damage (maximum intensity: VII) during the 1934 climax (Rothé 1936).

The 2002–3 earthquake swarm initiated at the beginning of December 2002 by shocks perceived as explosions by the inhabitants of a ∼ 20-house hamlet close to Clansayes. These abnormal sounds were not at once identified as earthquakes by the inhabitants because local earthquakes are inexistent in the inter-swarm quiescence periods, and—to our knowledge—the latter felt swarm dates back to 1933–6. A temporary velocimetric station was installed in the basement of one of the houses at the end of December 2002; thirteen more stations were installed later in January after we identified the phenomenon as seismic.

Several scores of events could be located over a few weeks monitoring. Although activity was maximum right beneath the hamlet, other shocks were detected along a north–south-trending, ∼ 7-km-long zone. Available geological maps identify no corresponding fault. On several seismograms recorded by the station installed in the hamlet, we observed an S – P interval of only 45 ms (Fig. 2). The massive coral-limestone formation that outcrops in the vicinity can be assigned a velocity of 5,000 m s^{-1}. Consequently the corresponding focal depth for those ultra-shallow earthquakes is 300 m at most (Jenatton et al. 2004).

Because of their small magnitude, most of these swarm earthquakes could not be located by the *permanent* monitoring networks, although the Clansayes permanent station could detect some of them. Only two events could be located (14 Dec. 2002, M_L = 1.5 and 1 Jan. 2003, M_L = 1.7), whereas in December explosions were

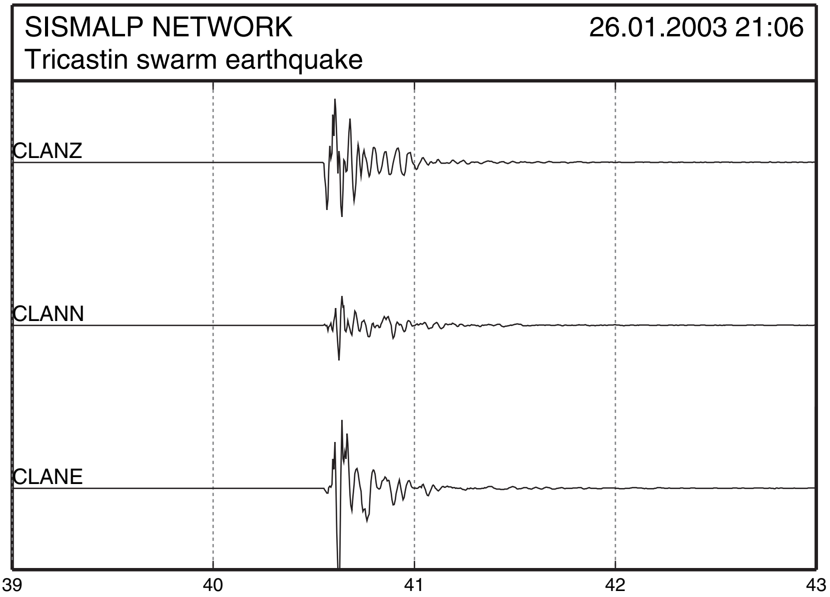

Fig. 2 Example of ultra-shallow swarm earthquake recorded in Tricastin by a temporary station (vertical, N–S, and E–W components of a 2-Hz velocimeter; 200-Hz sampling rate). This 4-s window shows P- and S-wave arrivals only 45 ms apart (S waves better observed on the E–W component). Focal depth is about 300 m. Amplitude window for each component is ± 300 μm s^{-1}

reported heard sometimes as frequently as several times a day. The same observation was made in 1934 (Rothé 1936) when earwitnesses described 'véritables canonnades' and 'tirs de barrage'.

3.2 The 2006 Conand Aftershocks

The $M_L = 3.5$ earthquake that occurred on the south-western flank of the French Jura on 11 Jan. 2006 at 11.32 local time is one of the many events that—just like the Annecy or Laffrey earthquakes—regularly strike the external domain of the Alps (Fig. 1). The epicentral zone is sited amidst NW–SE-trending ranges where Dogger (Middle Jurassic) limestone outcrops. The earthquake was felt up to a distance of ~ 20 km, but reached EMS intensity IV in 5 villages only. A maximum intensity of VI was assigned to Conand (Ain), where more than half of the startled 72 inhabitants left their dwellings. A chimney was knocked down. The church pavement was cracked on both sides of the aisle, and rock flour was expelled from the fissures. Drinking water was turbid for 2 days, and a falling in of stones blocked a small road (Bureau Central Sismologique Français 2006).

These effects, unusual for a 3.5 magnitude, were followed by vibrations and explosions in the next days. Such phenomena were of course reported by the residents to the prefectoral services, which then addressed the seismological networks. As the magnitude of the corresponding shocks was much below any detection level, the obvious answer was that no seismic activity had been observed, hence leaving the Conand inhabitants in perplexity. It actually took 10 days before we realized that something unusual was happening. A temporary velocimetric station installed in the village soon recorded aftershocks which proved very shallow: with $S - P = 0.12$ s, and by assuming a 5,000 m s^{-1} velocity for P waves in Dogger limestone, we compute a hypocentral distance of 900 m. From the P-wave amplitude recorded on the vertical and horizontal components, we estimate the station to be sited at ~ 50 m from the epicentre, while the focal depth is ~ 900 m.

The largest recorded aftershock occurred on 10 Feb. 2006, 1 month after the mainshock. This event was heard as a loud explosion. Vibrations were also reported. It was not recorded by the surrounding monitoring networks although the closest permanent Sismalp station is only 15 km away. This station, installed in a mushroom cave bored in Dogger limestone, has a low noise level; however it is only triggered by an STA/LTA algorithm (no continuous recording).

If we use the seismograms obtained at the Conand local station (Fig. 3) for computing the M_L magnitude of the 10-Feb. earthquake, our routine processing infers a value of 2.3. This is obviously overestimated because Richter's assumption of a 15-km focal depth does not apply here with a station at the epicentre and a shallow focus. To ascertain the seismic moment of this earthquake, we theoretically modelled the S-wave pulse which has a frequency close to 20 Hz and an amplitude of 280 μm s^{-1}. We assumed a 900-m-deep source with a focal mechanism similar to that of the mainshock (pure normal faulting, N135°E-trending horizontal tension axis). We adopted P- and S-wave velocities of 5,000 and 2,900 m s^{-1}, and a density

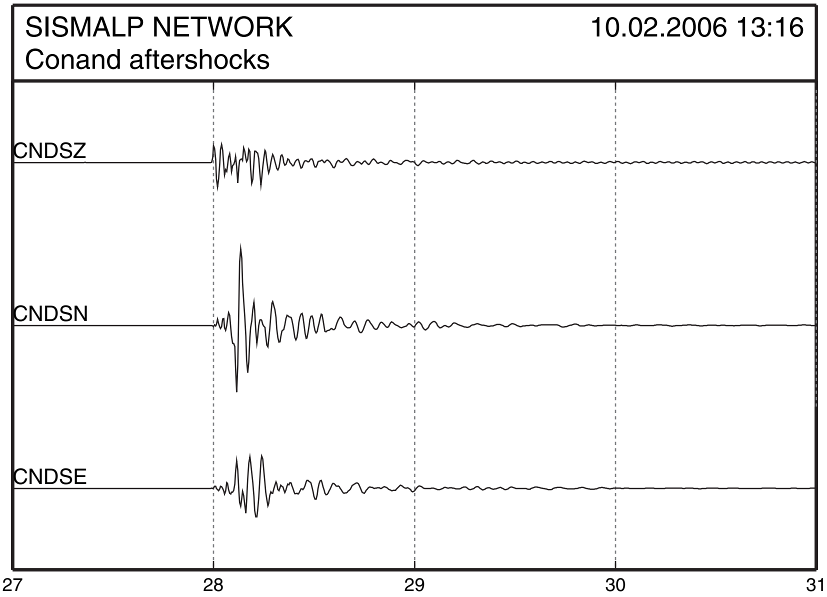

Fig. 3 Felt Conand aftershock (200-Hz sampling rate) used for computing seismic moment and corresponding M_L-0.75 magnitude (4-s window). S – P = 120 ms; focal depth is about 900 m. Amplitude window for each component is ± 300 μm s^{-1} (same amplification as Fig. 2)

of 2,500 kg m^{-3} for Dogger limestone. We found that a 55°-dipping, 40 m × 50 m source where a 2-mm slip propagated at 2,000 m s^{-1} with a rise time of 12 ms fitted reasonably well the observed S-wave pulse. The seismic moment M_0, obtained by multiplying the rigidy, the fault surface, and the slip, is 8.4 10^{10} N m. To convert it to local magnitude, we use the relation advocated by Bakun (1984) for $M_L < 3$ earthquakes:

$$\log_{10} M_0 = 1.2M_L + 10.$$

Hence, under the assumed conditions, M_L is found equal to 0.75.

In February and March 2006, a total of 16 events were recorded by the Conand station. On 28 Mar. 2006 at 07.34 in the morning, two late aftershocks were felt. They were described as two explosions separated by 10 s, the first louder than the second. This doublet was recorded by the local station (Fig. 4). The S – P intervals (0.135 and 0.140 s) are slightly larger than for the 10-Feb. earthquake (0.120 s), but we will assume that the difference in focal depth is not significant. By scaling the maximum displacement amplitudes with that of the 10-Feb. shock, we find that the corresponding magnitudes for these two felt events were −0.2 and −0.7.

The large discrepancy between the magnitude value computed by routine Richter's technique (2.3) and that computed through the evaluation of the seismic moment M_0 (0.75) demonstrates—if ever it were necessary—that Richter's technique cannot be safely used for shallow ($z < \sim 15$ km) events observed at short ($D < \sim 15$ km) epicentral distance.

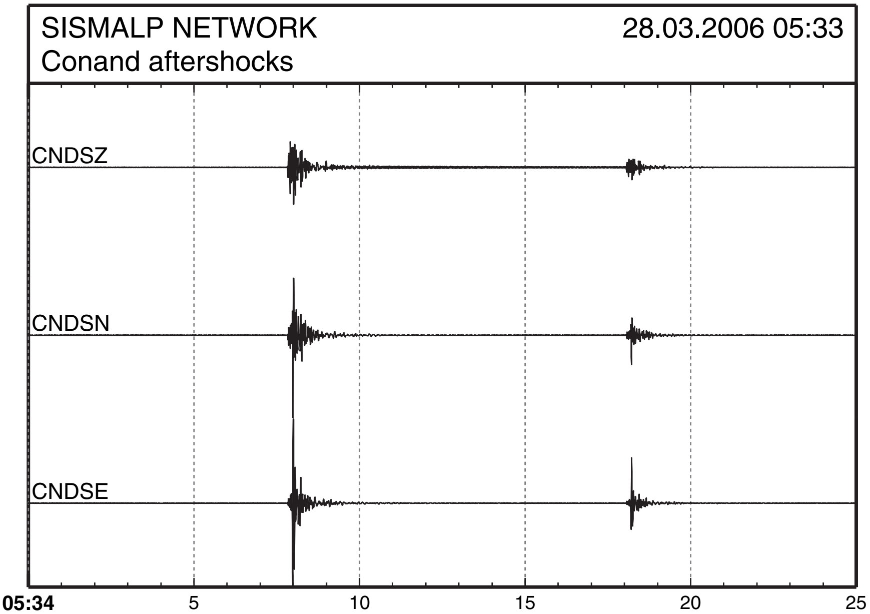

Fig. 4 Aftershock doublet felt at Conand (M_L = – 0.2 and – 0.7), 25-s time window, 200-Hz sampling rate. Amplitude window for each component is ± 30 μm s^{-1}. Note that the maximum amplitude is here reached on the E–W component, whereas it is observed on the N–S component for Fig. 3. It indicates either a slight difference in the position of the epicentre or a difference in source mechanism

However, a very large uncertainty on magnitude values computed here is brought by the conversion from M_0 to M_L. Kanamori's (1977) relation does not apply here because it addresses great earthquakes and involves the so-called moment magnitude. (Were it applied, it would provide a 1.3 value for the magnitude of the 10-Feb. event.) Other empirical relations similar to Bakun's have been proposed, for instance by Hainzl and Fischer (2002) in their study of an earthquake swarm with magnitudes between −0.5 and 3.2:

$$\log_{10} M_0 = 1.05 M_L + 11.3.$$

This relation would provide an M_L = – 0.35 value for the 10-Feb. event, still smaller than the 0.75 value computed with Bakun's relation. This conversion problem set aside, it seems anyway rather clear that the two 28-Mar. events had very small, most probably negative magnitudes.

4 The Upthrow of Rocks

Documented observations of upthrown rocks and boulders are relatively scarce. They include the $M = 6.9$ 1984 Western Nagano, Japan, earthquake (Umeda et al. 1987), the M = 7.8 1990 Philippine earthquake (Umeda 1992), the M = 6.0 1997

Colfiorito, Italy, earthquake (Bouchon et al. 2000), the $M = 6.6$ 2003 Bam, Iran, earthquake (Jackson et al. 2006). One of the interests of these observations is that they provide direct evidence that vertical ground acceleration locally exceeded gravity during these earthquakes. Reports of the upthrow of man-made objects are somewhat more common but, as shown by Newmark (1973) and Bolt and Hansen (1977), they do not necessarily entail vertical ground acceleration greater than gravity.

Recordings of vertical ground accelerations in excess of 1 g during earthquakes are still sparse and uncommon. To date, only half a dozen such records have been documented (Anderson 2006). Remarkably, the best recorded large earthquake to date, the $M = 7.6$ 1999 Chi-Chi earthquake, although it produced surface breaks locally exceeding 7 m in height, generated vertical ground accelerations well below 1 g at all the near-fault accelerometric stations (Lee et al. 2001). Furthermore, although much field work was done following this earthquake, no observation of upthrown rocks was reported.

The smallest-magnitude event for which the upthrow of rocks is well documented is the $M = 6.0$ 1997 Colfiorito, Italy, earthquake. This earthquake has been the largest shock of a series of earthquakes that shook central Italy for several weeks in the autumn of 1997. After this earthquake, it was observed that thousands of stones and rocks, which are numerous in this region of smooth hills and scattered limestone outcrops, had been freshly fractured and broken. Some of the broken stones were lying isolated on soft detritic soil (Fig. 5) while others had been piled up together,

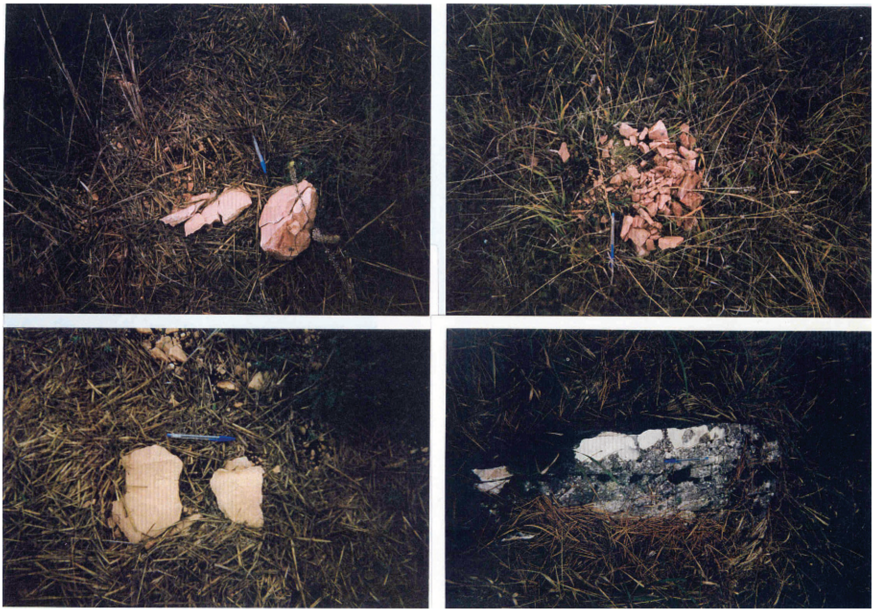

Fig. 5 Typical pictures of isolated stones (fragile marly limestone) found throughout a 1-km^2 zone following the $M = 6.0$ Colfiorito earthquake. The two original stones on the left were broken into several pieces while the one on the *upper right* was completely shattered. The rock on the *lower right* had its top partly scaled (the white areas), likely at impact. (After Bouchon et al. 2000.)

Fig. 6 General typical view of a rock pile (*upper left*) and three detail views near the heavily-damaged village of Annifo following the Colfiorito earthquake. Most of the stones in the piles (fragile marly limestone) were freshly fractured or broken (After Bouchon et al. 2000)

probably a long time ago to clear the land for farming (Fig. 6). Broken rocks and stones were found everywhere throughout a zone which covers an area of about 1 km by 1 km, and is located near the heavily damaged village of Annifo, where the maximum shaking intensity (IX) of the earthquake was registered (Camassi et al. 1997). Freshness of cuts and fractures, visible in Figs. 5 and 6, and the consistency of the observations for thousands of rocks and stones indicate that these rocks were tossed into the air during the earthquake, with breakage occurring at the time of impact. In several places, the old imprint of the stone in the soil was still visible. A similar phenomenon, although not as extensive, occurred in a second area, located about 4 km away from the first zone, near the village of Colle-Croce, which was also heavily damaged.

This earthquake, like most of the shocks in this sequence, had a normal-fault mechanism typical of the extension regime that characterizes the present-day tectonics of this region. The hypocentre was located at a depth of about 7 km near the bottom of the aftershock zone that delineates the fault plane (Amato et al. 1998). The fault dip was about 40° (Amato et al. 1998). The lack of surface ruptures clearly associated with the earthquake fault plane (Cinti et al. 1999) and the near-disappearance of seismicity at depths shallower than 2 km (Amato et al. 1998) suggest that significant slip during the earthquake was confined to depths larger than 2 km. Satellite radar interferometry data of the area and local GPS measurements (Stramondo et al. 1999) combined with the modelling of the rupture show that the zones of upthrown rocks were located in the area where the largest vertical ground displacement occurred. Vertical displacement inferred in the zones of upthrown rocks is about 30 cm. The relatively moderate size of this event suggests that the upthrow of rocks during earthquakes is a much more common phenomenon than is usually thought.

5 Conclusions

Our study concludes that earthquakes much smaller than those commonly assumed, and even with negative magnitudes, can be felt in the case of ultra-shallow earthquakes (those with a focus less than 1 km deep). It means that magnitudes for these events should not be overestimated in historical-seismicity studies whenever such testimonies are used. On the other side, we believe that reports of such phenomena—whether in the past or at present time—should not be neglected. They pinpoint the activity of local faults much more precisely than studies of large earthquakes with complicated isoseismal curves. Felt events with negative magnitudes, usually below the detection threshold of seismometers, finally demonstrate that the human being is an instrument eventually much more sensitive—and perhaps cheaper to maintain—than dense monitoring networks. Awfully, this fact reduces to populated areas the places where the occurrence of such earthquakes can be asserted.

At the other end of remarkable effects, we showed that earthquakes of relatively moderate size ($M = 6.0$) associated with near-fault ground displacement of a few tens of centimetres and no surface break can produce vertical ground accelerations exceeding gravity, and toss objects and rocks into the air. Conversely, some great earthquakes, such as the $M = 7.6$ Chi-Chi event which generated vertical ground displacements more than 10 times higher and a 100-km-long surface break, do not produce vertical ground accelerations exceeding gravity. Both sets of observations are difficult to conciliate. They provide a formidable challenge to seismologists and earthquake engineers for the years to come.

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Attenuation of Intensity for the Zemmouri Earthquake of 21 May 2003 (Mw 6.8): Insights for the Seismic Hazard and Historical Earthquake Sources in Northern Algeria

S. Maouche, A. Harbi and M. Meghraoui

Foreword On the basis of the detailed macroseismic study of the 21 May, 2003 Zemmouri earthquake (Mw = 6.8), we measured the epicentral distance to about 600 intensity-observation localities and analysed the resulting dataset by regression procedures. The earthquake that is the most destructive event in Algeria since 1980 caused 2,280 casualties and the collapse and serious damage of more than 30,000 buildings. The coastal epicentre location makes the earthquake an important case study useful for a better understanding of the seismic hazard of the Algiers region. Different regression curves are calculated using various directions and the resulting attenuation distribution shows diverse behaviours related to the specific geological structures. Significant variations of intensity are related to the sedimentary versus basement and rocky areas. These results extend our knowledge on the interaction between the damage distribution and the local soil conditions. Moreover, the comparison of the Zemmouri earthquake with historical offshore and coastal seismic events, the 1856 Djidjelli earthquake to the east and the 1891 Villebourg earthquake to the west, allows us to infer new conclusions on the seismogenic sources along the Algerian coastal area.

1 Introduction

The Tell Atlas of Northern Algeria has been the site of several destructive earthquakes during the last seven centuries that cover the historical catalogue (Rothé 1950, Mokrane et al. 1994, Benouar 1994; Table 1, Fig. 1). This high rate of earthquake activity is due to the Tell Atlas location along the convergent domain at the plate boundary between Africa and Eurasia. The most recent Zemmouri earthquake of 21 May 2003 (Mw 6.8) allowed us to characterize a newly identified active zone

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Table 1 The most damaging earthquakes in Algeria with estimated intensities (see also Fig. 1)

No	Earthquake	Damage and casualties	Intensity	References
1	Algiers 3.1.1365	Large number of dead; collapse of houses and palaces.	X EMS	Harbi et al. 2007a
2	Algiers 3.2.1716	Strong damage to buildings, half of them destroyed; 20,000 victims	IX EMS	Harbi et al. 2007a
3	Djidjelli 22.8.1856	Heavy damage to several traditional, dwellings, colonial houses and public buildings in at least 27 sites. The total of the damage had been estimated at about 443,000 FF.	VIII MSK	Harbi et al. 2003
4	Biskra 16.11.1869	30 dead and several injured. More than 245 housing units destroyed and several seriously damaged	VIII MSK	Harbi et al. 2003
5	M’sila 3.12.1885	33 dead, 17 injured; 75% of the village of M’sila destroyed and many others seriously damaged in the epicentral area	IX MSK	Harbi et al. 2003
6	Mansourah 8.1.1887	Destruction of 60 traditional houses and severe damage to many others	VIII MSK	Harbi et al. 2003
7	Villebourg 15.1.1891	39 dead, destruction of almost all the houses of Villebourg, destruction and serious damage at Gouraya	IX EMS	This study
8	Constantine 4.8.1908	Many deadly accidents; destruction of old houses; heavy damage to public buildings	VIII MSK	Benouar 1994
9	Aumale 24.6.1910	At least 81 dead and several injured; destruction or heavy damage to many traditional houses; colonial and public buildings	VIII MSK	Benouar 1994
10	Cavaignac 25.8.1922	At least 4 dead and several injured; destruction of about 80% of houses in Cavaignac and heavy damage to others in the epicentral area	VIII–IX MSK	Benouar 1994
11	Mac-Mahon 16.3.1924	At least 4 dead and several injured; destruction or heavy damage to many traditional houses; colonial and public buildings	VIII MSK	Benouar 1994
12	Douéra 5.11.1924	At least 4 dead and several injured, destruction or heavy damage to several housing units and colonial farms	VIII MSK	Benouar 1994
13	Inkerman 24.8.1928	At least 4 dead; destruction or heavy damage to many traditional houses and serious cracks to well built colonial constructions	VIII MSK	Benouar 1994
14	Guelma 10.2.1937	2 dead and at least 16 injured; destruction or heavy damage to several housing units and public buildings	VIII MSK	Benouar 1994
14	Guelma 10.2.1937	2 dead and at least 16 injured; destruction or heavy damage to several housing units and public buildings	VIII MSK	Benouar 1994

Table 1 (continued)

No	Earthquake	Damage and casualties	Intensity	References
15	Berhoum 12.2.1946	277 dead, 118 injured and 7,500 homeless; destruction or heavy damage to 1,000 housing units	VIII MSK	Benouar 1994
16	Orléansville 9.9.1954	1,409 dead, 5,000 injured and 50,000 homeless; destruction of more than 33,000 buildings	X MSK	Benouar 1994
17	Béni Rached 5.6.1955	No casualties but destruction of colonial and traditional houses	VIII MSK	Benouar 1994
18	Bou Medfaa 7.11.1959	2 injured and at least 500 homeless; destruction or heavy damage to 80% of the houses, farms and buildings	VIII MSK	Benouar 1994
19	Melouza 21.2.1960	47 dead, 129 injured and 4,900 homeless; destruction of about 600 housing units	VIII MSK	Benouar 1994
20	Bir Hadada 4.9.1963	1 dead and ∼ 100 injured; collapse of more than 50% of the traditional housing units of the city	VIII–IX EMS	Harbi 2006
21	M’sila 1.1.1965	5 dead, 25 injured and 25,000 homeless; destruction or serious damage to 3,145 housing units	VIII MSK	Benouar 1994
22	Mansourah 24.11.1973	4 dead, 43 injured, 14,922 homeless; Serious damage and destruction of∼ 2,000 housing units	VIII–IX EMS	Harbi 2006
23	Ouled Aissa 31.1.1979	15 dwellings seriously damaged without casualties	VII–VIII EMS	Harbi 2006
24	El Asnam 10.10.1980	3,000 dead, 8,500 injured and 400,000 homeless, destruction or serious damage to 60,000 housing units	X MSK	Benouar 1994
25	Ain Fekroun 5.10.1984	123 traditional houses seriously damaged with 13 shattered	VII–VIII EMS	Harbi 2006
26	Constantine 27.10.1985	10 dead, 300 injured; severe damage or destruction to old houses and farms	VIII MSK	Benouar 1994
27	Chenoua 29.10.1989	35 dead, more than 700 injured and 50,000 homeless; severe damage or destruction to 8,000 housing units and 500 public buildings	VIII MSK	Benouar 1994
28	Mascara 18.8.1994	171 dead, 654 injured, 12,500 homeless; serious damage or destruction to 2,000 housing units, farms and about 10 schools	VIII MSK	Benouar 1994
29	Ain Temouchent 1999	25 dead, 25,000 homeless; Serious damage to housing units and public buildings	VII MSK	Yelles et al. 2004
30	Zemmouri 21.5.2003	2,278 dead, 1,1450 injured and 250,000 homeless; destruction or serious damage to 6,000 buildings and 20,800 housing units	X MSK	Harbi et al. 2007b

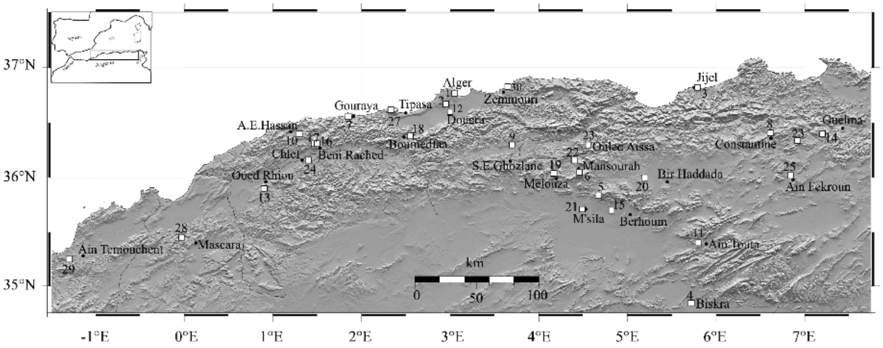


Fig. 1 The most damaging earthquakes in Algeria with estimated intensities (as cited in Table 1). *Circle*: city, *square*: seismic event

east of Algiers (Ayadi et al. 2003, Bounif et al. 2004). Therefore, it offers an opportunity to study in detail the spatial variation of damage distribution and evaluate the related attenuation of intensity necessary for the earthquake engineering and seismic hazard assessment near the capital city of Algeria. The macroseismic survey was carried out a few days after the 2003 mainshock by means of a thorough field investigation using a detailed questionnaire and official reports in the damaged area (Harbi et al. 2007b). The detailed macroseismic study has provided us with the most complete intensity dataset ever obtained from field investigations of previous earthquakes. For comparison, we revisited two destructive historical offshore seismic events, namely the Djidjelli earthquake of 22 August 1856 (Jijel, Io VIII MKS; Ambraseys 1982) and the Villebourg earthquake of 15 January 1891 (Larhat, Io X MM; Rothé 1950).

The crustal attenuation in northern Algeria has been poorly studied due to the lack of strong motion records. The damage distribution of moderate and large earthquakes along the Tell Atlas provides, however, a wealth of macroseismic information. The intensity distribution has been the subject of several studies that allowed determining an attenuation law in Europe (Ambraseys 1995). The decay of body waves may have a direct relationship with the source dimension as represented by the seismic moment and fault rupture size (Frankel 1991). The tsunamigenic 1856 Djidjelli earthquake was studied by Ambraseys and Vogt (1988) who prepared an isoseismals map, and by Harbi et al. (1999, 2003b) who discussed the possible seismic source from the interpretation of seismic profiles. The 1891 Villebourg earthquake presents favourable conditions for a comparison with the 2003 Zemmouri earthquake. Indeed, the coastal location between the seismogenic Cheliff and the Mitidja Plio-Quaternary basins confers to this seismic event and causative source a great interest for the understanding of the earthquake hazard in northern Algeria. These results, in connection with the soil conditions and the building vulnerability suggest that the coastal area, which extends along 1,200 km in the E–W direction, is exposed to a relatively high seismic risk sometimes caused by tsunamigenic sources.

This paper is two-fold: (1) Using the dataset of the isoseismal map produced by Harbi et al. (2007b) and taking into account previous field investigations and macroseismic distribution in the Algiers-Zemmouri region, we estimate the attenuation of intensity with distance from assigned European Macroseismic Scale intensity value to 600 localities; and (2) we compare the results to those obtained for the 1856 (Djidjelli) and 1891 (Villebourg) coastal earthquakes and show similarities from the damage distribution, seismological effects and geological structures viewpoints.

2 The 21 May 2003 Earthquake

The Mw 6.8 coastal mainshock generated strong and damaging effects within 150 km radius as well as significant ground deformation with uplifted marine terraces, liquefaction, minor landslides, rockfalls, ground fissures and anomalies in the flow of springs (Harbi et al. 2007b). The most impressive phenomenon induced by the earthquake corresponds to the large coastal uplift of marine terraces which implied an important continental deformation related to a SE dipping and 55-km-long thrust fault (Meghraoui et al. 2004). The seismic event has been a subject of several studies. Using a simple double difference method, Bounif et al. (2004) relocated the mainshock epicentre on the coastline (36.83°N, 3.65°E, Fig. 1) with 8–10 km hypocentral depth and analysed the distribution of the aftershocks sequence which shows a $\sim 40^\circ$–50° south dipping fault plane and two distinct clusters of seismic events along strike. From the inversion of the teleseismic body waves, joined with GPS and uplift data, Delouis et al. (2004) calculated the effective 12s rupture duration, the 2.86×10^{19} N-m seismic moment and pointed up that the Zemmouri earthquake involved a bilateral rupture propagation from the hypocentre: the south-westward slip with 11–2 km depth range, and the north-eastward slip zone that extends from 6 km depth to the surface. Meghraoui et al. (2004) measured coseismic shoreline changes of emerged algae jointly with kinematic GPS and conventional levelling lines. The obtained dataset allowed them to model the surface deformation along about 60 km coastline and suggest two rupture patches along a 50°SE dipping planar reverse fault geometry located between 5 and 10 km offshore. Using modelling GPS data from 5 stations located west of the epicentral area, Yelles et al. (2004) infer a uniform model on a plane dipping 42° to the south. Semmane et al. (2005) combined geodetic data and accelerograms to model the fault location at 15–22 km offshore and showed two large slip zones on the fault with the largest located west of the hypocenter. Alasset et al. (2006) modelled the initiation and propagation of the tsunami wave triggered by the earthquake and compared synthetic results with the 2 m high waves of tide gauge records of the Balearic Islands, whereas no similar effect was reported along the Algerian coast. Their analysis and modelling lead to the conclusion that an earthquake larger than $\mathrm{Mw} = 7$ followed by tsunami could produce a possible run-up along the Algerian coast (the Zemmouri earthquake did not) and large wave-amplitudes (more than 3 m) could reach the Balearic Islands. Laouami et al. (2004) reconsidered the epicentre location and magnitude using the accelerograms and the accelerometric records, respectively, with the empirical formula of Betbeder-Matibet (1995); they also give details on the recorded acceleration at 12 stations. Harbi et al. (2007b) provided the results of the macroseismic survey conducted immediately after the earthquake and produced maps of damage and intensity of the Zemmouri earthquake. The NE–SW elongation of isoseismals well correlates with the fault direction identified from seismotectonic studies (Ayadi et al. 2003).

3 Soil Conditions

The geological and tectonic setting of the Mitidja basin was presented and discussed at length in previous works (Meghraoui 1988, 1991, Harbi et al. 2004, Maouche et al. 2004). In the 2003 earthquake area, the local geology shows that, the basement outcrops east of Boumerdes, North Thenia and west in the Blida Mountain. It is mainly composed of bedrock formed by schist, micaschist, gneiss and the Mesozoic calcareous units which constitute the eastern mountain chain of Djurdjura. To the west, the basement outcrops at Cap Matifou and Bouzareah (Algiers). The epicentral zone is covered essentially by Plio-Quaternary deposits. The recent Quaternary includes the alluvial deposits made of clay, silt and gravel within the basin area and marine terraces along the coast (Fig. 2). From Boumerdes to Algiers, crossing the Mitidja basin, the local geology is made of soft sediment such as sandy dunes with alluvial and marine deposits, mixed sandstone and clay (fill) and the

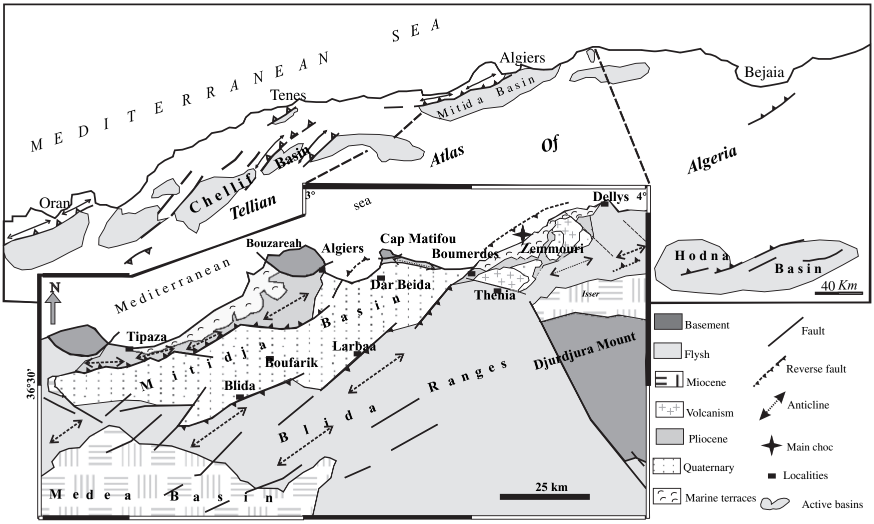


Fig. 2 Structural geological map of the Algiers region including the area affected by the 21 May 2003 Zemmouri earthquake

marshy deposits which extend over the most recent suburbs such as Bab Ezzouar and Dar El Beida in the Algiers province. The early Quaternary (Villafranchian) alluvial deposit made of sand or sand with other components (silt, clay, gravel, sandstone) and the recent landfill, represented by sandy, silty or argillous deposits, cover the area from Boumerdes to Zemmouri and Cap Djinet. To the south of the earthquake area, the Isser, Si Mustapha and Bordj Menaiel cities have the same soil conditions.

4 Damage Assessment and Interpretation

The detailed damage description and other ground effects as well as the intensity assessment are presented in a previous work by Harbi et al. (2007b). The results of the macroseismic study of the Zemmouri earthquake, conducted at about 600 locations, allowed drawing with good constraint the spatial distribution of damage in the form of an isoseismal map (Fig. 3). The NE-SW elongated isoseismals are accentuated along the Mitidja basin mainly because of the lithological and structural framework. It is worthwhile to note that the general shape of intensity distribution appears to be primarily controlled by this sedimentary basin and the isoseismals seems to be compressed in the SE direction. In some localities such as at Bordj Menaiel, Baghlia and Bouira the intensities are influenced by smaller scale basins

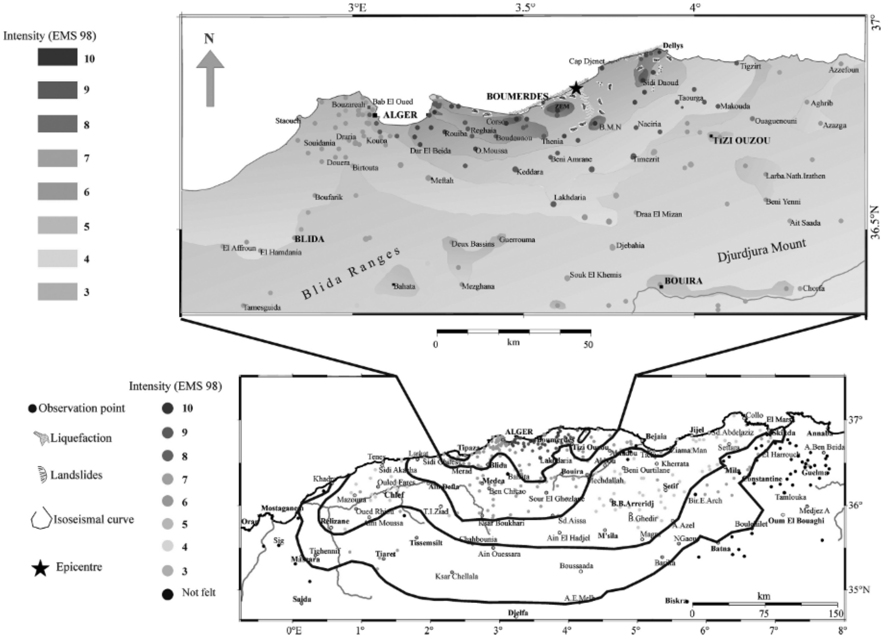


Fig. 3 Isoseismal map of the Zemmouri earthquake of 21 May 2003 (Mw 6.8, I_0 X EMS), modified from Harbi et al. (2007b) (Zem: Zemmouri, Z. Bah: Zemmouri Bahri, B. Kfane: Bordj El Kiffane, BMN: Bordj Menaïel)

containing soft sediments and related local lithological and topographic conditions. However, geology is not the only factor which explains the observed elongation of the intensity patterns. Directivity effects played an important role in the damage amplification particularly for intensities 8, 9 and 10. This is attested by the PGA records which show higher values for the E–W components than the N–S ones, independently from station azimuth, epicentral distance and site conditions (Laouami et al. 2006).

As the first step of analysis, we compared the damage distribution with the population density inside the provinces where the event was felt (Appendix 1). The 2003 epicentral area that includes a large section of the eastern suburb of Algiers city and related large population within the Mitidja basin is crossed by at least 3 macroseismic curves. The macroseismic field investigations also indicate that damage distribution is strongly conditioned by soil conditions and building vulnerability. In some zones, the separation of the isoseismals X and IX could not be achieved because of the large variation of the local geology and likely related site effects. The isoseismals are clearly asymmetric and elongated in the NE–SW direction which represents the fault rupture strike.

5 Attenuation

The assessment of seismic hazard at a given site requires an attenuation law for the peak ground acceleration (PGA). The intensity-attenuation relationship is obtained by deriving empirical correlations between intensity and epicentral distance for earthquakes for which isoseismal maps are available. Many authors developed attenuation relationships worldwide. Douglas (2001) presents a valuable summary of 121 published attenuation relations for PGA. Examples include the attenuation laws developed by Idriss (1978), Joyner and Boore (1981), Campbell (1985), Boore and Joyner (1982), Joyner and Boore (1988), Sadigh et al. (1993), Ambraseys and Boomer (1991) and Ambraseys (1995). In Algeria, generally when assessing the seismic hazard at a given site, authors (Benouar 1996, Naili and Benouar 2000, Laouami et al. 2004) adopt the PGA attenuation laws developed by Ambraseys and Boomer (1991) (Equation (1)) and Ambraseys (1995) (Equation (2)). The former has been derived from 529 accelerograms recorded mainly on soft rock or soil from 219 shallow seismic events (≤ 25 km) mainly in the Mediterranean region, which includes Algerian data, and the second is based after data correction on 1,260 accelerograms generated from 619 shallow seismic events of which 3% are Algerian data.

$$\log_{10}(a_h) = -0.87 + 0.217(Ms) - \log_{10}(r) - 0.00117(r) \pm 0.26P \tag{1}$$

$$\log_{10}(a_h) = -1.43 + 0.245(Ms) - 0.786\log_{10}(r) - 0.0010(r) \pm 0.24P \tag{2}$$

Where $r^2 = (d^2 + h^2)$, h is the focal depth (taken at an optimum value of $h = 2.7$ km), d is the epicentral distance in km, Ms is the surface-wave magnitude, and a_h is the predicted peak horizontal ground acceleration. The values 0.26 and 0.24 in Equations (1) and (2) are the respective standard deviation. The parameter P takes a value of zero for 50% probability that the predicted parameter a (ground acceleration) will exceed the real (observed) value and a value of 1 for 84% probability.

Recently, Laouami et al. (2006) published for northern Algeria a new attenuation law (Equation (3)) derived from the strong motion dataset of four moderate Algerian earthquakes (Constantine, 1985; Mont Chenoua, 1989; Mascara, 1994 and Ain Benian, 1996).

$$a(m/s^2) = 0.38778\exp(0.32927M_s)\left[D^{0.29202} + 1.557574\right]^{-1.537231-0.27024R} + 0.03 \tag{3}$$

Where $D = \sqrt{R^2 + d^2}$ is the hypocentral distance, the constants are obtained by fitting the experimental maximum acceleration of the three components at each distance the least square technique (Laouami et al. 2006).

The 2003 Zemmouri earthquake occurred in an area for which no other reliable and complete isoseismal maps exist for previous seismic events. It is important, therefore, to analyse the attenuation for this single event by taking into consideration the local lithological characteristics. Based on the analysis of the attenuation of intensities during an earthquake, the variation of the intensity is assumed to be primarily related to the surface wave propagation, which is controlled by the change of soil conditions. The Zemmouri earthquake represents a good example for assessing the intensity attenuation with distance in several ways. The approach we followed here consists in performing a regression analysis using an equation of the form:

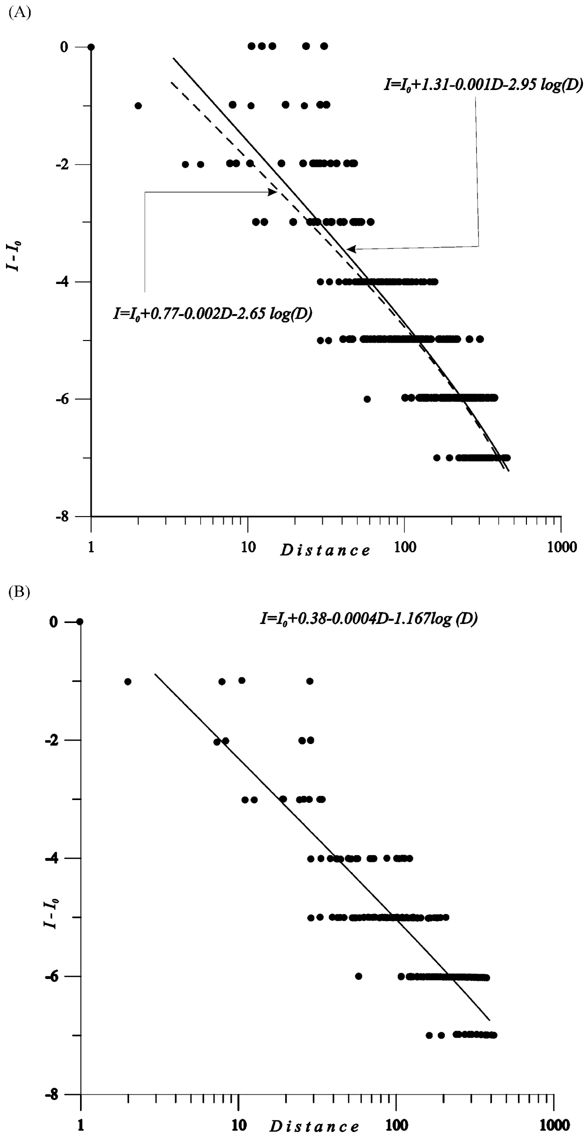
$$\mathrm{I} = \mathrm{I}_0 + \mathrm{a} + \mathrm{b}^*\mathrm{D} + \mathrm{c}^*\log(\mathrm{D}) \tag{4}$$

for all the data set (Douglas 2001). For all computations I_0 is 10, D is the macroseismic epicentral distance in km and the coefficients a, b and c are given in Table 2 for various cases. For practical reasons and since the instrumental epicentre is coastal and the activated fault emerged at about 8 km offshore, we used in our computations the macroseismic epicentre estimated at the city of Zemmouri. From the isoseismal map, the intensity decreases gradually until 3 within a radius of ~ 500 km to the SE as well as in the NE–SW direction parallel to the fault rupture strike. The intensity-distance relationship for all the combined data is shown on Fig. 4a. We calculate this attenuation using two directions: to the SE (perpendicularly to the fault azimuth) and to the SW (parallel to the fault azimuth) (Fig. 4b and 4c). The regression is performed using average values of D (from isoseismals) and also all data in the two directions with respect to the macroseismic epicentre (Fig. 4d). For soil classification, Fig. 4e shows that the intensity decreases clearly at the rock soil

Table 2 Regression coefficients for the used equation

Parameters	All data	Fault azimuth (FA)	FA+ 90°	Isoseismals	
				FA	FA+90°
A	1.31	0.137	0.38	1.22	0.159
B	−0.001	−0.0032	−0.0004	−0.01	−0.0004
C	−2.95	−1.193	−1.167	−1.820	−2.325

Fig. 4 Intensity attenuation curves. (**a**) all data, (**b**) perpendicular to the fault azimuth, (**c**) fault azimuth, (**d**) based on isoseismals, (**e**) combined with the geological cross-section, (**f**) PGA distance attenuation, (**g**) PGA-Intensity correlation



level. In this case we use subjectively four categories of site classification which are related to the lithofacies as shown in the used geological cross section. One may consider that attributing an amplification value to broad areas such as at the Blida Mountains is useless.

To determine the contribution of the source of the 2003 earthquake to the seismic hazard, it is essential to estimate how the seismic parameters such as the peak acceleration or EMS intensity decrease with distance. Our attempt is to use previous works on the elaboration of an empirical attenuation law for northern Algeria and

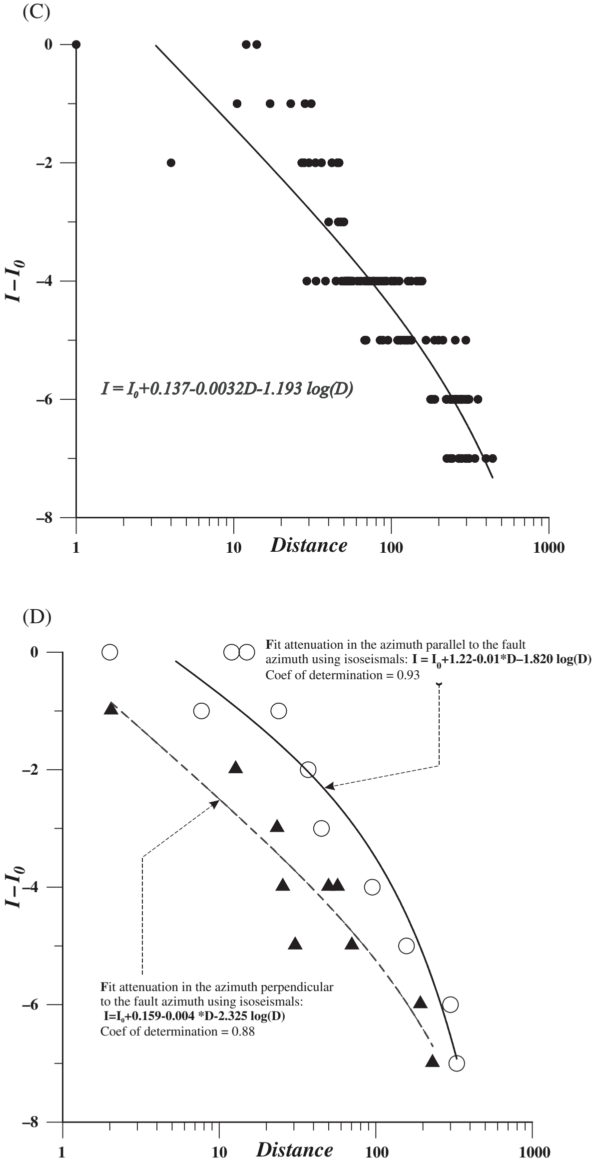


Fig. 4 (continued)

horizontal peak acceleration decays as a function of distance (Laouami et al. 2004) and provide a comparison with the attenuation of intensities for the Algiers region. Only the PGA values at sites for which the intensity is available are considered and we obtain a good correlation between the distance and PGA parameters (Fig. 4f). All observed PGA values show a better fit than the average values predicted by

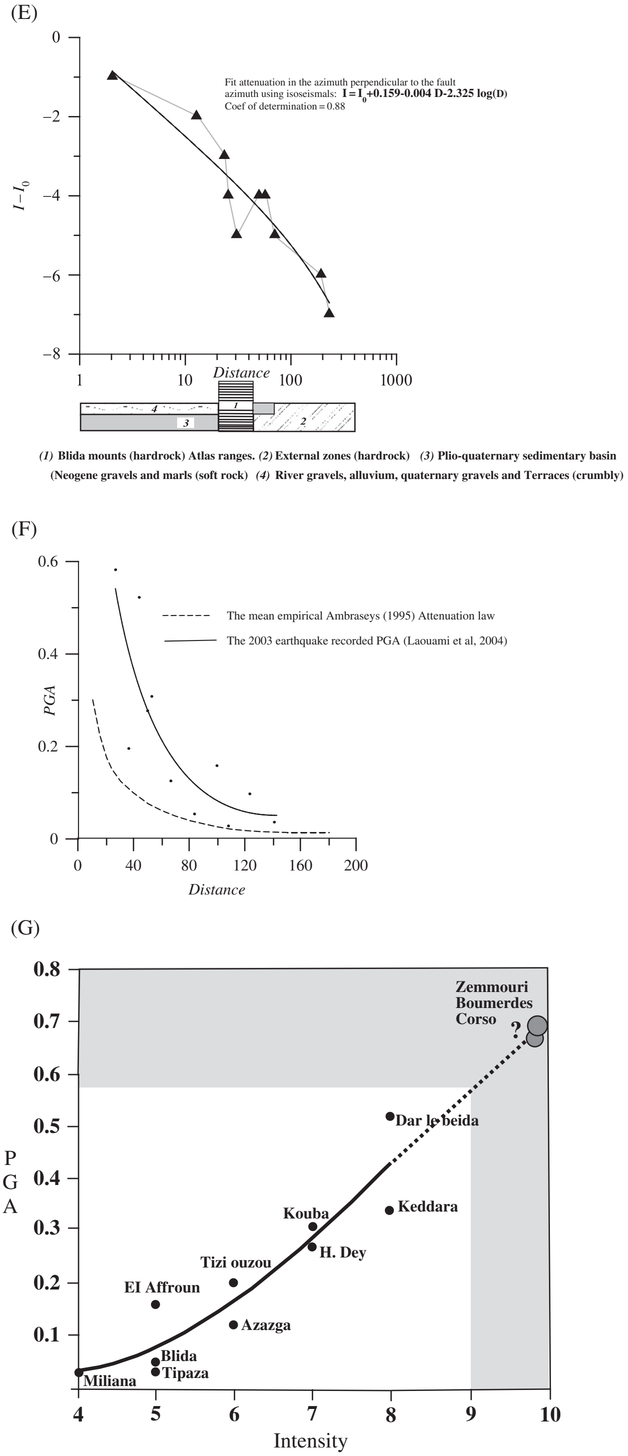


Fig. 4 (continued)

Ambraseys (1995) which clearly underestimates the recorded accelerations for all distances less than 50 km. This significant variation up to 50 km can be interpreted as due to the amplification effects but it requires further field investigations. The site amplification, however, is clearly highlighted by Laouami et al. (2004) at Kaddara site in which a significant PGA variation is observed between two stations of 150 m distance (0.34 g and 0.58 g) suggesting site effect phenomena. Unfortunately, there are no ground acceleration records in the epicentral zone of intensity IX and X in which the ground motion was certainly strong. The plot on Fig. 4f suggests that the peak ground horizontal acceleration at the macroseismic intensity IX and X locations is probably more than 0.70 g. On the basis of the strong-motion and intensity databases ($I \geq 4$) of the 2003 Zemmouri earthquake (Laouami et al. 2004, Harbi et al. 2007b, respectively), we investigated the correlation between the available strong ground-motion and earthquake damage through a regression analysis. The peak ground acceleration (PGA) well correlates with the earthquake damage. The empirical relationship between PGA and the intensity (I) is determined in this study as follow:

$$(\mathrm{PGA}) = 0.403 + 0.292(\mathrm{I}) - 2.554\ \mathrm{Log}(\mathrm{I}) \tag{5}$$

This PGA-intensity correlation is particularly useful in real-time applications for damage prediction and assessment. This empirical relationship shows (Fig. 4g) that the PGA value could be higher for $I > 8$ particularly in the zones (the grey area on Fig. 4g) close to the epicentre (Zemmouri ($I = 10$) and at Boumerdes ($I = 10$) for which PGA records are not available.

6 Comparison with Historical Damaging Events

The Djidjelli earthquake of 22 August 1856 and its foreshock and aftershocks as well as the Villebourg earthquake of 15 January 1891 and its following seismic sequence caused the largest catastrophes affecting respectively the eastern and the central Algeria coastal area before the 2003 Zemmouri earthquake. They are also considered as among the most well documented historical seismic events. The detailed re-appraisal of the damage and surface effects of these historical events allowed us to obtain a complete isoseismals map for each one of them. The comparison with the recent Zemmouri earthquake is thus pertinent since these earthquakes, being the largest that occurred along the coastal area, contributes considerably to the reduction of seismic risk in northern Algeria.

6.1 *The Djidjelli Earthquake*

The 1856 Djidjelli earthquake produced damage effects in a large area along the Algerian coast and was felt at several points of the northern Mediterranean coast

(Fig. 5a). A first study of the Djidjelli earthquake has been accomplished by Ambraseys (1982) who published the corresponding isoseismals map (VI^+ and VII^+) and assigned intensity VIII MSK to the city of Djidjelli (now Jijel). Recently, Harbi et al. (2003a) re-assessed the extent of the damage and the people reaction by making a comprehensive research using contemporary accounts relative to this event and confronting all the available reports, press accounts and published papers (Aucapitaine 1856, Gaultier de Claubry 1856, De Senarmont 1857, Rothé 1950, Ambraseys 1982; contemporary press: *Akhbar, Le Moniteur Algérien, L'illustration, La Seybousse, Le Courrier mercantile, La Gazette de Lyon, 1856*). The analysis shows macroseismic data with a relatively good description of the impact of the earthquake on humans, man-made buildings and ground movements. Although the maximum damage is reported in a rather small area (Fig. 5b), the mainshock caused the loss of at least five lives and triggered a sea wave of 2–3 m high that flooded the Djidjelli coast a number of times.

6.2 The Villebourg Earthquake

The earthquake of 15 January 1891 of Villebourg (now Larhat) is considered among the largest event after the 2003 Zemmouri earthquake that occurred in the coastal area of north-central Algeria. Due to the location of maximum damage, one may question the inland epicentre location as previously suggested by Rothé (1950) at 36.5°N, 1.80°E and Ambraseys and Vogt (1988) at 36.50°N, 1.90°E. Therefore, it became important to reassess the macroseismic data in light of the new information retrieved mainly from the local press reports. The most extensive accounts are given in "La Dépêche Algérienne" and the contemporary document of Pomel (1891). All the macroseismic information (Appendix 2) retrieved from the available sources at 20 sites, were carefully analysed and used in the reassessment of the ground shaking with reference to EMS intensity scale. As a result of the analysis of the reconstructed macroseismic field, an isoseismal map has been drawn (Fig. 6) and accordingly a macroseismic epicentre was located on the coast, between Villebourg (Larhat nowadays) and Gouraya, at 36°56N, 1°85E.

All sources describe surface effects such as rock falls and landslides triggered by the Villebourg earthquake. The retrospective study and related construction of the macroseismic field of this earthquake coupled with a morphological analysis has allowed a better understanding of the seismotectonic framework of the study area. We present an aerial photo which shows the landslide (Fig. 7) on which the city of Larhat (ex Villebourg) is constructed today. This landslide was certainly reactivated during the earthquake (see Appendix 2) and is characterized by the presence of marine terraces showing multiple scarps displaying gliding planes inclined northwards. The recent tectonics of the epicentral area is highlighted by a set of uplifted terraces incised by the Damous River running parallel to the NE-SW trending active geological structure.

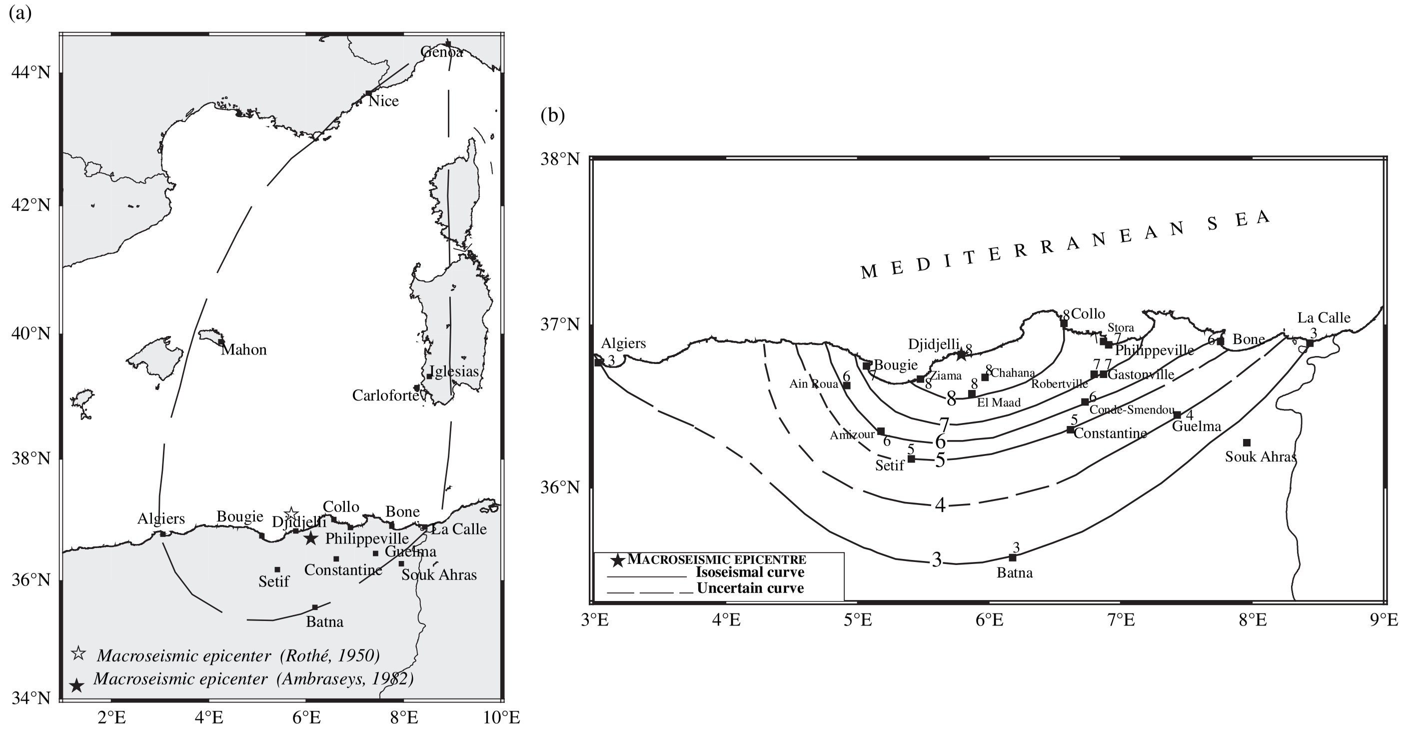


Fig. 5 (**a**) Area of perceptibility of the Djidjelli earthquake of 22 August 1856 (after Harbi et al. 2003a modified from Ambraseys, 1982). (**b**) Isoseismal map of the Djidjelli earthquake (Ms 6.0, I_0 VIII EMS), modified from Harbi et al. (2003a)

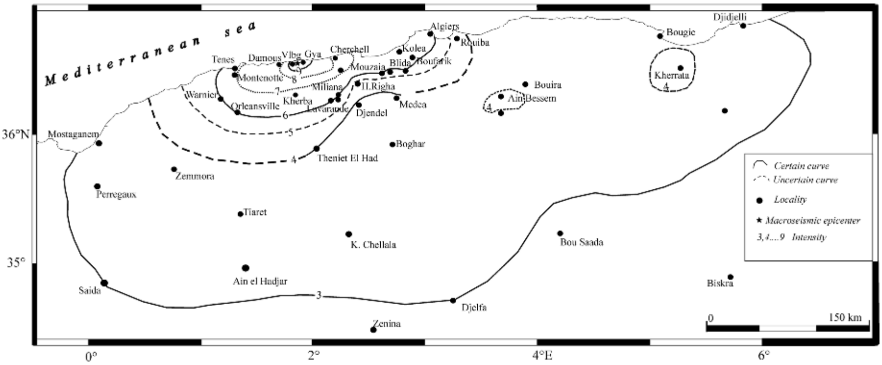


Fig. 6 Isoseismal map of the Villebourg earthquake of 15 January 1891 (Ms 6.0, I_0 IX EMS) (Vlb: Villebourg, Gya: Gouraya)

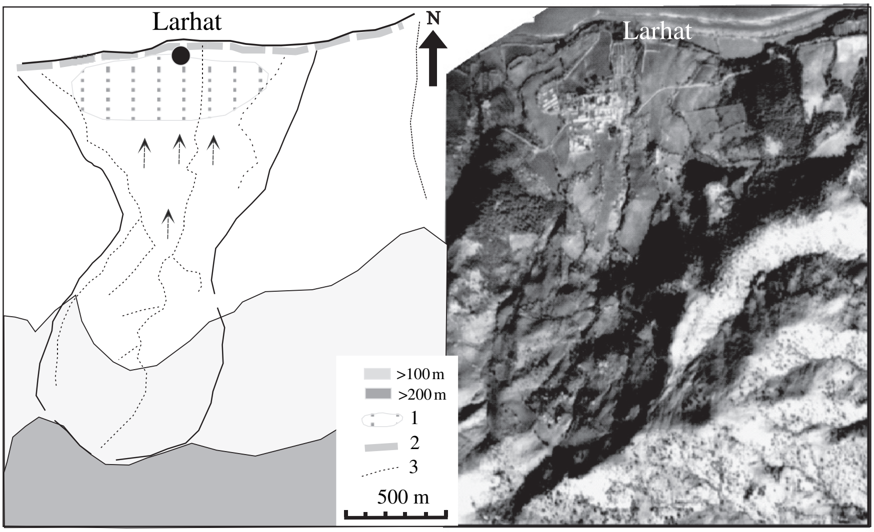


Fig. 7 The landslide reactivated by the Villebourg earthquake of 15 January 1891 (1: compressive pad, 2: zone uplifted during the earthquake, 3: hydrographic network)

7 Discussion and Conclusion

The 2003 Zemmouri earthquake induced a large number of fatalities and serious damage along the Algerian coast. The results of the detailed macroseismic survey indicate the spatial distribution of the related effects in terms of an isoseismals map and related intensity attenuation. A maximum intensity of X (EMS) has been assessed inside numerous isolated areas separated by others with a lower intensity

(VIII and IX). The decrease of intensity with the epicentral distance is not homogeneous and depends strongly on the azimuth at a regional scale. The area with intensity greater than or equal to VI is elongated in the NE-SW direction with a length of 160 km and a width of 50 km. A regression analysis performed in two different azimuths conduced to eliminate the effect of the fault itself and the low attenuation around the faulted area. The results obtained, using the average radii of isoseismals, show a clear difference between the fault azimuth and its perpendicular direction. This difference is related to the geological conditions which are marked by the thrust-and-fold Atlas belt and the Mitidja intermountain basins.

As shown in diverse attenuation curves related to the Zemmouri mainshock, this study suggest a low attenuation in the affected area. The intensity attenuation is clearly stronger along the NW-SE direction with an abrupt decrease to the South at the Blida Atlas Ranges. This highly fractured E-W zone could have played the role of a screen for the seismic waves propagating to the South. The occurrence of an earthquake with epicentre further to the west part along the tectonically active zone, at Blida for example, will have a strong impact on the Algiers capital city. The different attenuation relationships deduced for the Zemmouri earthquake can be inferred to calculate the probability of damage due to a future earthquake occurring in the same area including Algiers and its surroundings (Table 3).

The Djidjelli 1856 and Villebourg 1891 earthquakes are smaller than the Zemmouri event which produced significant surface effects and deformation. However, the three earthquakes are almost comparable in the extent of the affected area as well as in some of their characteristics (Table 4). As we know, the magnitude of historical events may be assessed roughly from the area of perceptibility. By using the relationships derived by Benouar (1994) for Algeria: $\mathrm{Ms} = -0.04 + 2.56\log(r_3)$ (where r_3 corresponds to the mean epicentral distance of an area within which the shaking was felt with intensity III (MSK or EMS)), we calculated the surface-wave magnitude of both historical events (Table 4). It is worthwhile noting that the Djidjelli and Villebourg earthquakes were also felt far from the shore by sailors of the *Aviso Tartare* located at 15 mi at North 7° of Djidjelli and the ship *Porro* located at 6 mi of Cherchell, respectively. The maximum intensities VIII+ and IX EMS have been estimated, respectively, for the 1856 and 1891 historical events. For both of them, the intensity could easily exceed these estimations in the case of an epicentre closer to the coast. In the same way, the respective surface-wave magnitude may differ from those calculated (Table 4). Regarding the Djidjelli earthquake if we consider an area of perceptibility including the localities of the north-Mediterranean coast

Table 3 The different attenuation relationships deduced for the Zemmouri earthquake

	Attenuation relationship
All data	$I = I_0 + 1.31 - 0.001D - 2.95\log(D)$
Perpendicular to the fault azimuth	$I = I_0 + 0.38 - 0.0004D - 1.167\log(D)$
Parallel to the fault azimuth	$I = I_0 + 0.137 - 0.0032D - 1.193\log(D)$
Parallel to the fault azimuth using isoseismals	$I = I_0 + 1.22 - 0.01D - 1.820\log(D)$
Perpendicular to the fault azimuth using isoseismals	$I = I_0 + 0.159 - 0.004D - 2.325\log(D)$

Table 4 Similarities of the characteristics of three destructive coastal earthquakes

	Zemmouri 2003	Djidjelli 1856	Villebourg 1891
Type of location	Coastal	Offshore*	Coastal
Magnitude	Mw 6.8	Ms $\geq$ 6.0	Ms $\geq$ 6.0
Intensity I_0	X (EMS)	VIII$^+$ MSK	IX EMS
Source	Offshore	Offshore	Offshore
Mean radius of I = VIII	40 km	$\sim$ 40 km	15 km
Mean radius of I = III	$\sim$ 350 km	$\sim$ 230 km	$\sim$ 260 km
Direction of the isoseismals	NE-SW	NE–SW	NE–SW to E–W
Other parameters	– Faulted area: 50 km – Coastal uplift: 50 cm – The sea retreated and flooded the *Balearic* coasts – Tsunami	– The sea retreated by $\sim$ 35 m and a sea-wave of $\sim$ 3 m flooded the *Algerian* coast a number of times. – Tsunami – No evidence of coastal uplift	– Coastal uplift of 30 cm – The sea retreated by $\sim$ 30 m and flooded the *Algerian* coast. – No strong evidence of tsunami

* Even if the macroseismic epicenter is coastal, we think that the instrumental one could be offshore.

where the shock was felt (Fig. 5a), we obtain Ms = 6.6 when Ms is equal to 6.0 if only the Algerian part is taken into account (r_3 on Fig. 5b). On the other hand, the lack of intensity points offshore determines the shift of the epicentre onshore. We assume that the strongest earthquake, which hit Djidjelli in the past, may be due to an offshore causative fault (Harbi et al. 2003b). The comparison of the isoseismal maps of the three earthquakes presented in this work show quite similar attenuation laws with a slight shift for the 2003 Zemmouri event. This difference is due to the size of shock (Mw = 6.8, greater than the magnitude of the two others events). In order to develop a curve that predicts the intensity for the Algerian offshore events, we used the equation in the form of:

$$I = a + b^{*}D + c^{*} \log(D) \tag{6}$$

Where $D^2 = (r^2 + h^2)$, h is the focal depth (taken at an optimum value of h = 8 km), r is the epicentral distance in km. The results of the fitting are presented in Fig. 8 from which, we can see that the relation fit the used data with a certain degree of reliability and thus, they can be used in seismic hazard analysis for Algerian offshore events.

Destructive earthquakes occur very infrequently along the Algerian coastline but the Zemmouri 2003 event (Mw 6.8) warns us against possible strong events

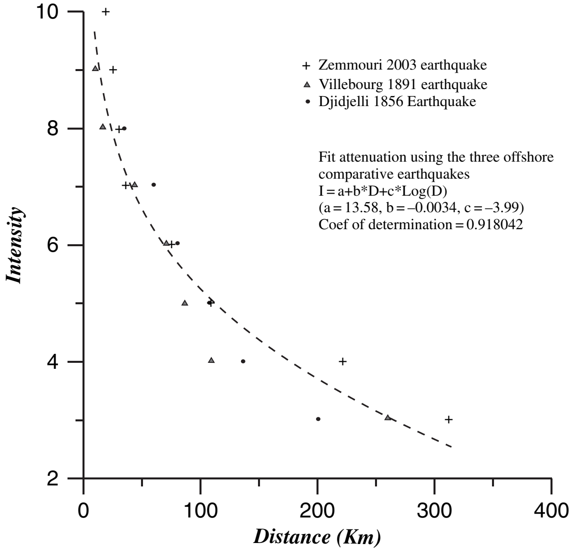


Fig. 8 Attenuation regression curve computed for the Djidjelli, Villebourg and Zemmouri earthquakes, using isoseismals

which should be expected in the future, accompanied by geodetic effects and tsunamis. The comparison between the three reviewed earthquakes shows the potential for destructive seismic events and the presence of seismogenic sources along the coastline.

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Appendix 1

Table A.1 Rate of the population (*) living in the earthquake area and corresponding intensity

Wilaya (district)	Population	Number of persons living in the earthquake area	Number of victims	Intensity
Boumerdes	742,466	∼ 4 millions	1,382	I = X, IX and VIII
Algiers	3,335,142		883	
Tizi ouzou	1,115,352	∼ 4.5 millions	7	I = VII, VI and V
Tipaza	686,660		–	
Bouira	773,118		2	
Blida	1,116,292	∼ 4 millions	2	I = V and IV
Médéa	860,592		–	
Béjaia	838,484		2	
Relizane	668,828		–	
Bordj Bou Arréridj	633,514		–	
Djelfa	750,126		–	
Mostaganem	752,380	∼ 4 millions	–	I = III
M'sila	866,198		–	
Mascara	818,612		–	
Oran	1,666,218		–	
Constantine	1,036,518		–	
Tissemssilt	281,498		–	
Batna	1,034,422		–	
Skikda	956,994		–	
Guelma	590,746		–	
Total	*24,232,152*	*Downwards: 17%, 19%, 16%, 32%nd 16%*		

*From official reports.

Appendix 2

This appendix summarizes the macroseismic effects of the Villebourg-Gouraya earthquake as reported in the original and contemporaneous sources cited in the text.

On 15 January 1891, at 3 h 55 min, a destructive earthquake struck the locality of Gouraya and its surroundings villages. The epicentral area, which is centred between Gouraya and Villebourg (Larhat nowadays, a village of the Gouraya commune), is located at 110 km west of the capital Algiers. Two shocks were felt in the time span of 10 min and the earthquake was strong enough to awake people and caused great panic in the coastal zone of Tenes-Algiers. The whole population of Gouraya, was evacuated and camped in the streets. Many people of Algiers fled their homes and as reported 500 crowded to the Government square. Two Europeans and 37 native persons were killed, buried under the ruins of their traditional houses, in the commune of Gouraya and many people were injured. It is said that about hundred people were killed in farms near Gouraya due to bad local traditional housing units called "gourbis". The cost of damage was estimated, by the administration, at 47,000 French Francs. The earthquake was felt over an area of 300 km; in Djelfa, 240 km south of Gouraya, where the shock was noticed by very few persons.

The earthquake caused widespread damage in the epicentral area mainly associated with the high vulnerability of the traditional housing units. All the sources of information concentrate on the destruction and serious damage in the localities of Gouraya and Villebourg and their close farms. Gouraya was almost razed, 53 European houses collapsed as the country police barracks and the telegraph house were heavily damaged beyond repair. Several traditional houses and even concrete structures in villages crashed down. At Villebourg, 22 houses out of 24 were almost totally demolished; the remaining sections of walls are disconnected, the foundations unusable and the factory of Oued Mellah is described as an accumulation of ruins. The Bonefoy farm located between Gouraya and Villebourg was completely destroyed. Several houses were shattered at Marceau (Menaceur nowadays) and Blida but more precise details are lacking. At Montenotte (Oued Allalah near Tenes) some buildings sustained damage and several ceilings collapsed and at El Affroun several houses cracked. At Koléa, an individual house collapsed and the losses were severe. At Orléansville, a report mentions some cracks and damaged ceilings as well as broken glasses and many overturned objects. No serious damage nor casualty are reported at Tenes where only few houses cracked and the communications disrupted between Tenes, Cavaignac and the Trois Palmiers because of the breaking of the footbridge. In the capital Algiers, damage consisted of the partial collapse of a terrace of one house located at Bab El Oued; several houses cracked in this locality and furniture moved and dishes rolled on the ground; at Mustapha, the mayor evacuated the inhabitants of one building threatening collapse; at Mustapha Supérieur, one villa cracked and in the Casbah a section of a wall fell down and some houses cracked; in general broken glass and overturned furniture are reported in various places of the city.

It is reported in the press and contemporary accounts that in Kherba and Lavarande the water sources dried up. The direction of the shock was vertical. The earthquake was associated with long and deep cracks with one of 40 cm wide running through the village of Villebourg. It was reported that "... it is to be feared that the ground will come down in the sea". In fact, the mausoleum of Sidi Braham was projected into the sea. The inhabitants and local authorities wondered whether they could rebuild at the same place. We found no reports of sign of liquefaction but rockfalls and landslides, as a result of the shake, were considered as the most spectacular phenomena at that time. Rockfalls were observed at Beni Hendel and landslides cut the road Mouzaïa-Algiers. Moreover, the landslide on which the Village of Villebourg has been built, was re-activated by the earthquake. After the earthquake, a coastal uplift of 30 cm, attested by the uplift of algae levels of the coastline and the change of the depth of the sea level, was observed. It was also said that as a result of the shock the sea retreated 30 m from the shore and returned flooding the coast. A comparable phenomenon was observed during the 2003 Zemmouri earthquake.

The Gouraya earthquake occurred without any premonitory sign but was followed by a series of aftershocks with the two most important strong events (that occurred the same day) showed no further damage or casualties. According to Ambraseys and Vogt (1988), the aftershocks continued to the beginning of the following month. However, Hée (1950) reports some shocks which hit the Cherchell region on June, July and September 1891.

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Large 19th Century Earthquakes in Eastern/Central North America: A Comparative Analysis

S. E. Hough

Foreword For the understanding of seismogenesis as well as seismic hazard assessment in the North American mid-continent, two historical events are of paramount importance: the 1811–1812 New Madrid, central U.S,. sequence and the 1886 Charleston, South Carolina earthquake. Published estimates of magnitudes of the four principal New Madrid earthquakes have ranged from M$\sim$7–8.75. In contrast, published estimates of the magnitude of the Charleston earthquake have almost all been within a range of Mw6.8–7.3. Upon cursory inspection, the macroseismic effects of the New Madrid mainshocks appear to be more severe at regional distances than those of the Charleston mainshock. I compare the intensity distributions more carefully, focusing on key indicators rather than the poorly constrained overall distribution of intensities. I conclude that the primary difference between the intensity distributions of the Charleston and New Madrid earthquakes is that the former has much better sampling, in particular of the low intensity field. These results suggest that the largest New Madrid mainshocks were not substantially larger than the Charleston earthquake.

1 Introduction

The earthquake sequence that struck the New Madrid region of the North American mid-continent in 1811–1812 had remarkably far-reaching effects. By some accounts the principal events in this sequence are among the largest—if not the largest—earthquakes to have ever occurred in a so-called Stable Continental Region (SCR, Johnston, 1996). Ground motions from the three principal events were felt by individuals as far away as Canada, New England, and at a number of locations along the Atlantic coast (Mitchill, 1815; Bradbury, 1819; Fuller, 1912; Nuttli, 1973; Penick, 1981; Street, 1984; Johnston, 1996). Contemporary accounts document three principal mainshocks: approximately 0215 local time (LT) on 16 December

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1811; around 0900 LT on 23 January, 1812, and approximately 0345 LT on 7 February 1812 (henceforth NM1, NM2, and NM3, respectively). All three events were felt throughout much of the central and eastern United States. Additionally, a large aftershock to NM1 (NM1-A) occurred near dawn on 16 December 1811. Available accounts also document substantial aftershock activity following all three mainshocks (Drake, 1815; McMurtrie, 1819; Fuller, 1912; Penick, 1981).

The Charleston earthquake of 1 September 1886—9:50 p.m. LT on 31 August 1886—was the primary event in a more conventional earthquake sequence: a single large mainshock preceded by a small number of foreshocks and followed by a conventional, if perhaps widespread, aftershock sequence (Dutton, 1889; Seeber and Armbruster, 1987).

Paleoseismic investigations suggest a repeat time of the order of 400–500 years for both the New Madrid sequence and the Charleston earthquake (Talwani and Schaeffer, 2001; Tuttle et al., 2002); they also suggest that the New Madrid seismic zone tends to produce prolonged sequences with multiple, distinct mainshocks, the magnitudes of which are comparable to those of the 1811–1812 events (e.g., Tuttle and Schweig, 1996; Tuttle et al., 2002). Thus, the magnitudes of these earthquakes are a critical issue for the quantification of regional hazard in central North America. A repeat of the 1811–1812 sequence would clearly have a tremendous impact. Because of low regional attenuation, the New Madrid seismic zone (NMSZ) contributes a nontrival component of seismic hazard in relatively distant, large midwestern U.S. cities such as St. Louis, Missouri (Frankel et al., 1996). The Charleston seismic zone also contributes significantly to regional as well as local hazard.

A second impetus to investigate the 1811–1812 sequence stems from its implications for general issues related to intraplate earthquake processes. The NMSZ is among the best-understood intraplate source zones in the world, largely because it has been so active throughout the historic and recent prehistoric past. This relative abundance of data affords the opportunity to explore critical unanswered scientific questions regarding large SCR earthquakes, most notably the questions of why such events occur in certain regions but (apparently) not in others, why and to what extent large earthquakes are clustered, and the nature (i.e., scaling) of large intraplate earthquakes.

In a sense, the importance of the New Madrid earthquakes—both scientifically and for hazard–correlates with their magnitudes, yet these values remain grossly uncertain. Considerable effort has been invested in gleaning quantitative information from the limited available data. Available data include (1) paleoliquefaction features preserved by the sediments within the Mississippi embayment (e.g., Tuttle and Schweig, 1996); (2) the present-day distribution of seismicity in the NMSZ, which is generally assumed to be a long-lived aftershock sequence that illuminates the principal fault zones (e.g., Gomberg, 1993; Johnston, 1996; Mueller et al., 2004); (3) first-hand reports ("felt reports") of the shaking and/or damage caused by the events over the central/eastern United States (e.g., Nuttli, 1973; Street, 1984).

While the size of both inferred mainshock ruptures and liquefaction features provides some constraint on magnitude, such estimates are invariably less well-constrained than those based on macroseismic effects. Determination of magnitudes for the 1811–1812 mainshocks thus hinges on the felt reports and their interpretation for modified Mercalli intensity (MMI) values. In a seminal investigation, Nuttli (1973) drew isoseismal contours based on his compilation and interpretation of approximately 40 archival accounts. He determined body-wave magnitude, m_b, values of 7.2, 7.1, and 7.4 for NM1, NM2, and NM3, respectively, based on a relationship between ground motion and intensities from smaller and more recent instrumentally recorded earthquakes in the central United States. With an exhaustive archival search, Street (1984) greatly expanded the number of reports (to approximately 100 for NM1) and assigned his own intensity values. Street (1982, 1984) used these new data and the same method used by Nuttli, (1973) to obtain m_b of 7.1 and 7.3 for NM2 and NM3 and 7.0 for the 0715 LT aftershock of December 16, 1811. Street (1982) determined these values by assuming the m_b value for NM1 determined by Nuttli (1973) and comparing the relative isoseismal areas of the other events.

Following the introduction of the moment-magnitude scale in 1979 (Hanks and Kanamori, 1979), attempts were made to convert earlier m_b values to moment-magnitude, M_w. It was at this time that the magnitude estimates grew to very large values, with estimates as high as 8.75 (Nuttli, 1979). Even as these estimates were made, it was recognized that they were based on extrapolations of data from smaller earthquakes and thus were highly uncertain. The lack of true calibration events from central/eastern North America led Johnston (1996) to undertake a comparison between intensity distributions and moment magnitudes M_w for large earthquakes in stable continental regions worldwide. He compared areas within isoseismals of discrete intensities with instrumentally measured moment magnitudes. On the basis of this calibration, he assigned Mw values of 8.1+−0.31, 7.8+/−0.33, and 8.0+/−0.33 for NM1, NM2, and NM3, respectively.

Hough et al. (2000) reinterpreted the accounts compiled by Nuttli (1973) and Street (1984), identifying a small number of outright transcription errors in the study of Nuttli (1973) and a larger number of inappropriately high intensity values that had apparently been assigned based on subjective perceptions of shaking. This study also addressed the bias due to early American settlement patterns, namely the fact that observers of the earthquakes were concentrated along major river valleys where substantial sediment-induced amplification is expected (e.g., Singh et al., 1988), and was in fact documented (e.g., Drake, 1815).

Hough et al. (2000) did not correct MMI values for site-response. Rather, the MMI values were assigned based on a careful consideration of the overall macroseismic effects as described by available archival accounts. In their interpretation, Hough et al. (2000) considered site response biases, in effect not allowing biased values to inappropriately control inferred isoseismal areas. Using the method of Johnston (1996), Hough et al. estimated Mw values of 7.2–7.3, 7.1, and 7.4–7.5 for NM1, NM2, and NM3, respectively.

The method of Johnston (1996) was developed using MMI values for a set of instrumentally recorded calibration earthquakes in so-called Stable Continental Regions (SCR) world-wide. If there are biases in the MMI values for the calibration earthquakes, or if other SCR regions are not perfect analogs for central/eastern North America, then the application of the Johnston (1996) method will introduce biases that are difficult to quantify. For this reason, the comparison between the New Madrid earthquake magnitudes and the magnitude of the Charleston earthquake is especially illuminating. That is, while analysis of the New Madrid intensity values alone might be fraught with uncertainty, a direct comparison with intensity values for the Charleston earthquake can help constrain the relative sizes of the events.

More recently, Bakun and Hopper (2004) estimated magnitude values for the New Madrid mainshocks using a new method, one in which intensity versus distance observations are used together with attenuation relationships developed from instrumentally recorded earthquakes in central/eastern North America (Bakun et al., 2003). His preferred estimates are 7.6, 7.5, and 7.8 for NM1, NM2, and NM3, respectively. These estimates are described as M-I, indicating that they are derived from intensity data. Because the attenuation relationships are derived using Mw values, it is generally assumed that M-I represents Mw. The approach of Bakun et al. (2003) does not require isoseismal contours and is thus less subjective than the method of Johnston (1996). However, Bakun's method reintroduces the problem that Johnston (1996) attempted to solve with his SCR compilation—namely, the lack of true calibration events for the largest historical earthquakes. This re-introduces the need for extrapolation, and its attendant uncertainties. For example, Bakun and Hopper (2004) consider two different extrapolation techniques, the one that leads to the preferred values and a second technique that yields values about 0.3 units smaller. A further potential difficulty is that Bakun et al. (2003) use the 1929 Mw7.3 Grand Banks earthquake (Bent, 1995) to develop their attenuation relationship—the only Mw>7 earthquake in their dataset. However, this event was located offshore from Newfoundland, Canada, arguably in a very different tectonic setting than the New Madrid events. Also, because the event occurred several hundred kilometers off-shore, its macroseismic effects are not well documented.

Investigation of the Charleston earthquake dates back to the immediate post-earthquake investigations led by Clarence Dutton, an Army officer detailed to the U.S. Geological Survey. This effort culminated in the publication of one of the earliest comprehensive, scientific reports of a large earthquake (Dutton, 1889). The so-called "Dutton Report" includes thorough and consistent compilations of near-field geological effects of the earthquake and far-field macroseismic effects. Whereas about 100 or fewer intensity values are available for each of the New Madrid mainshocks, the Dutton Report provides the basis for assignment of over 1000 intensity values. In a comprehensive interpretation of these accounts, Bollinger (1977) assigned almost 800 intensity values based on the 1337 intensity reports tallied by Dutton (1889). Bollinger (1977) estimated an m_b value of 6.8–7.1 using the same techniques that Nuttli (1973) used to estimate magnitudes for the New Madrid earthquakes.

Whereas an initial review of earlier intensity assignments for the New Madrid earthquakes suggested immediate biases (and a small handful of outright mistakes) that led to the reinterpretation by Hough et al. (2000), a initial review of the intensity assignments by Bollinger (1977) reveals the values to have been assigned carefully and in keeping with modern conventions. Each of the accounts were evaluated independently by three individuals and any discrepancies in assignment were evaluated and reconciled.

The intensity values determined by Bollinger (1977) have provided the basis for later investigation using increasingly modern methodology. Johnston (1996) estimated Mw 7.3+/−0.26 for the Charleston earthquake. Bakun and Hopper (2004) report a preferred Mw value of 6.9.

Published Mw values for the Charleston earthquake have thus been relatively consistent: the U.S. National Hazards Mapping project currently assumes a range between 6.8 and 7.5, with highest weight given to a value of 7.3 (Frankel et al., 2002). In contrast, Mw values for the New Madrid mainshocks have varied from 7.2 to 8.75, and the National Hazard Mapping project currently uses a range of 7.3–8.0, with highest weight assigned to 7.7 (Frankel et al., 2002). Considering the long-term strain-accrual rate, Newman et al. (1999) suggested an even lower value (Mw7.0), although Kenner and Segall (2000) showed that the long-term strain accrual rate provides at best only a weak constraint on the short-term rate of earthquakes generated by a local stress perturbation.

The enormous range of Mw values for the New Madrid events reflects the fundamental difficulty in interpreting sparse macroseismic effects for an earthquake for which no modern calibration event exists. With estimates varying by over a full magnitude unit, the task of reducing the uncertainties is clearly daunting. Yet it is important to not lose sight of the original, documented macroseismic effects of the earthquakes. In the following section I consider these in detail, including a comparison with the better documented effects of the Charleston earthquake. I focus on the first New Madrid mainshock, NM1, because the largest number of intensity values are available for this event.

2 Macroseismic Effects

Figures 1 and 2 present ShakeMap representations of intensities from the 16 December 1811 mainshock and the 1 September 1886 Charleston earthquake. These figures are generated using intensity data from Hough et al. (2000) and Hough (2004) and, for the Charleston earthquake, from Bollinger (1977). Obviously any comparison of intensities for the two events will depend critically on which intensity data one uses for NM1. Using the earlier intensity values of Nuttli (1973), Street (1982, 1984), or those in the official NOAA database (http://www.ngdc.noaa.gov/seg/hazard/int_srch.shtml), a comparison would look quite different. The arguments in favor of the reinterpreted values are discussed at length in Hough et al. (2000) and Hough (2004). Figures 1 and 2 are generated with identical color palettes and interpolation schemes; the greater sampling for the Charleston earthquake is manifest in both the number of sample points and the resolution of small-scale details in the intensity field.

Converting the intensity values to MMI (r) assuming epicentral locations of 35.8N and −90.1 W for NM1 and 32.4 N, −79.5 W for Charleston, one obtains

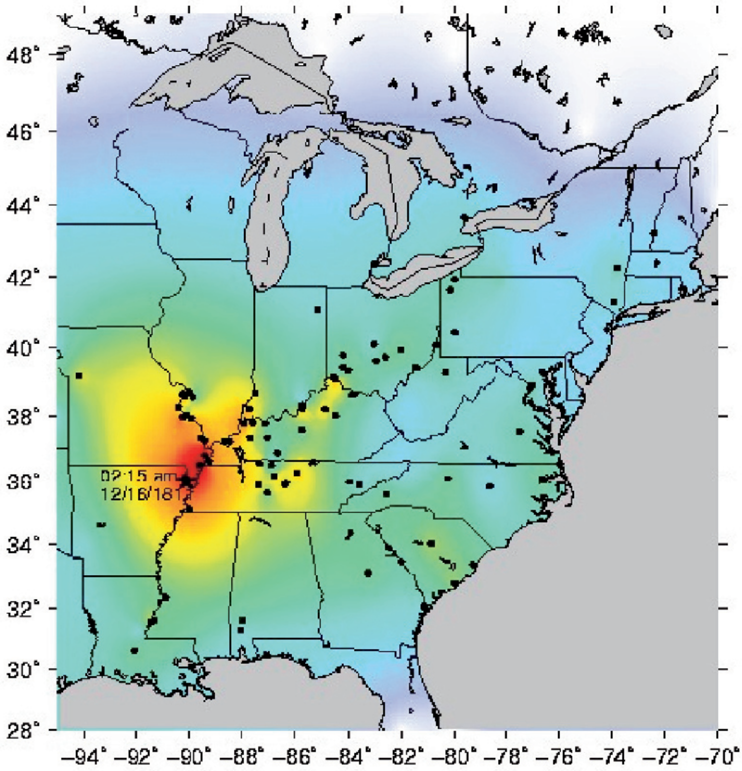

Fig. 1 Intensity map for the 16 December 1811 New Madrid mainshock constrained by intensity values determined by Hough et al. (2000) and Hough (2004). Intensity values are constrained for locations indicated by solid circles; between these locations intensity values are interpolated. The decay of the far-field intensity pattern is artificially imposed

the values shown in Fig. 3b. Figure 3b also shows the average distance at which each intensity level is observed for both earthquakes. Intensity values, I, for a given earthquake can typically be fit by

$$I = \mathrm{A} - \mathrm{B}(r) - \mathrm{C}\log(r) \qquad (1)$$

Where A, B, and C are constants and r is epicentral distance. Fitting this equation to the intensity values for Charleston and NM1 yields the curves shown in Fig. 3a. These curves suggest that, on average, New Madrid intensity values are systematically about 1 unit larger than Charleston values any given distance. However, focusing on the average values within distance bins (black and gray stars), it is clear that average values of moderate intensities (V–VIII) are very similar. The overall amplitude of the NM1 curve is strongly controlled by, first, a couple of high intensity values at ~100 km, and, second, high values at distances around 1000 km. The former are very poorly constrained given the paucity of well-built structures within

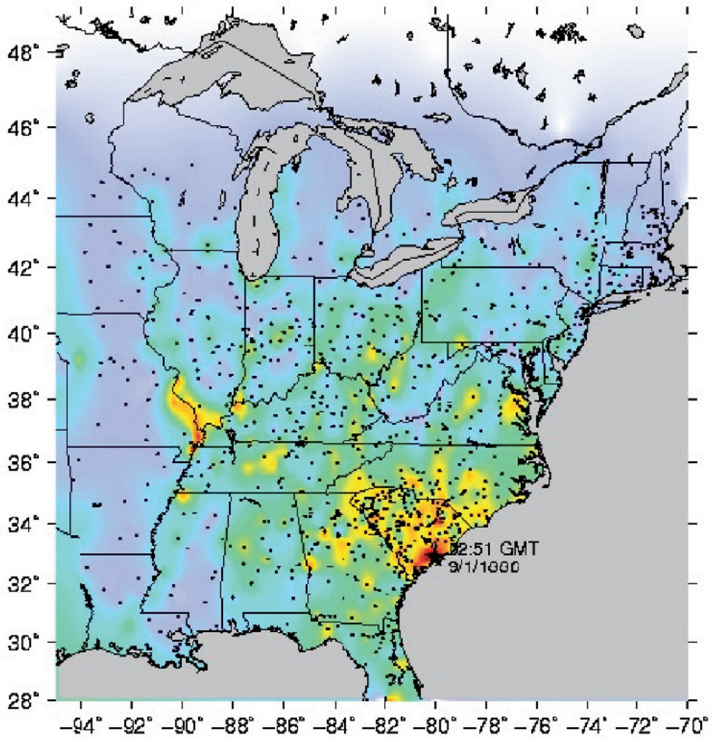

Fig. 2 Intensity map for the 1886 Charleston mainshock constrained by intensity values determined by Bollinger (1977) using accounts compiled by Dutton (1889). Intensity values are constrained for locations indicated by solid circles; between these locations intensity values are interpolated. The decay of the far-field intensity pattern is artificially imposed

100 km of NM1; the latter are also poorly constrained, as I discuss below. Focusing on average values for moderate MMI levels, Fig. 3b reveals that the two intensity distributions are quite similar for distances < 600 km, but that at greater distances higher intensities are suggested for the New Madrid event.

However, the low intensity values (II–IV) assigned for NM1 require careful consideration. A key distinction between the Charleston earthquake and NM1 is that the former struck at 9:50 p.m. LT whereas the latter occurred around 2:15 a.m. LT. Bollinger (1977) assigned values of II and III at locations where the shaking was described as felt by only those at rest and generally felt by those indoors, respectively. Assuming that NM1 was felt only by those who were awakened by the shaking, Hough et al. (2000) assigned MMI values of IV to accounts that described the shaking in any detail, making the conservative assumption that witnesses were asleep and were awakened by the shaking. Values of III were assigned to those locations where it was only noted that the shaking was felt. Values of II–IV are thus clearly difficult to distinguish for NM1.

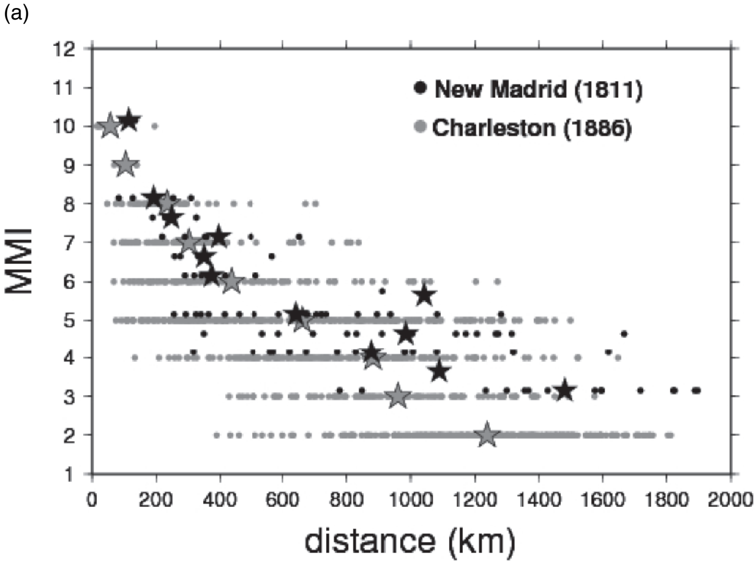

Fig. 3a Intensity versus distance for the 16 December 1811 New Madrid mainshock (*black circles*) and the 1 September 1886 Charleston mainshock (*gray circles.*) New Madrid values are shifted slightly up for clarity. Stars indicate average distance at which each intensity level is observed

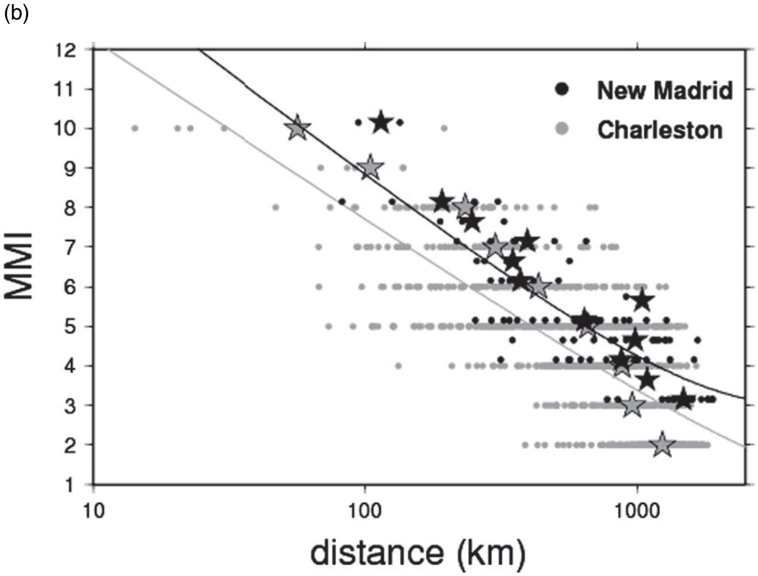

Fig. 3b Black and gray lines indicate regression curves fit to NM1 and Charleston intensity values, respectively. Intensity values for New Madrid (*black circles*) are shifted up by 0.1 units for clarity

To explore this issue further, one can hypothesize that the values of III and IV assigned by Hough (2000) in fact represent a mix of values between II and IV. One can then consider the distribution of distances at which this these values were observed for both of the earthquakes (Fig. 4). The distributions are similar. NM1 was weakly felt at *relatively* more locations at distances of 1800+ km. This may, however, reflect a relative concentration of population centers along the Altantic seaboard at the time of the New Madrid earthquakes. To test this one can consider the population distributions as revealed by the 1820 and 1880 US censuses. Assigning each state population to the average latitude and longitude for that state, one can examine state population as a function of distance from the Charleston and New Madrid earthquakes, respectively (Fig. 5a). The relative number of potential eyewitnesses to the New Madrid earthquake was indeed higher at distances greater than 1000 km than at smaller distances (Fig. 5b.) Thus the apparently large relative number of intensity values (i.e., felt reports) for NM1 at large distances may in fact be due to the low number of potential witnesses at closer distances.

It is clearly impossible to interpret the macroseismic effects of the New Madrid earthquakes without an appreciation for historical context, including settlement

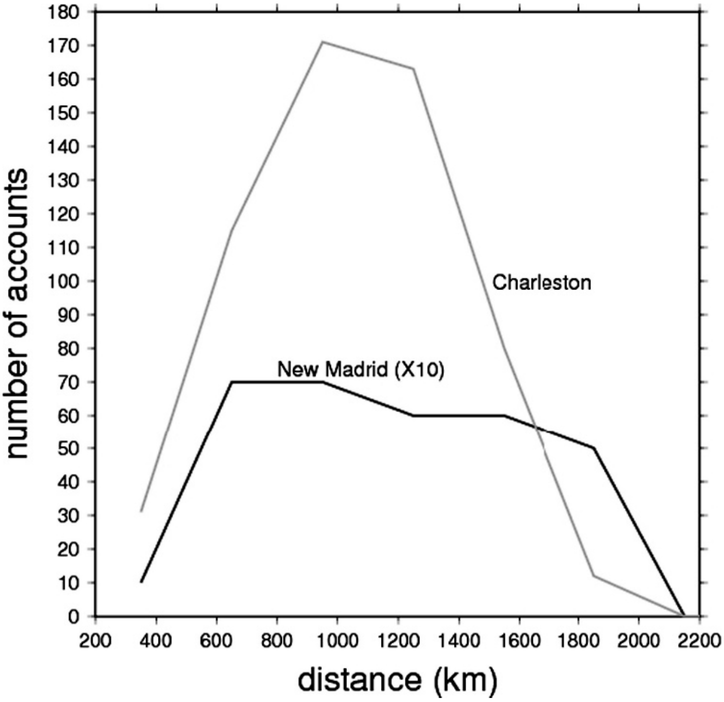

Fig. 4 Distance distribution showing the number of available accounts of weak shaking during the Charleston earthquake (*gray line*) and 16 December 1811 New Madrid mainshock (*black line*) as a function of epicentral distance. Values for the New Madrid event are amplified by a factor of 10; only about 100 total values are available for this event

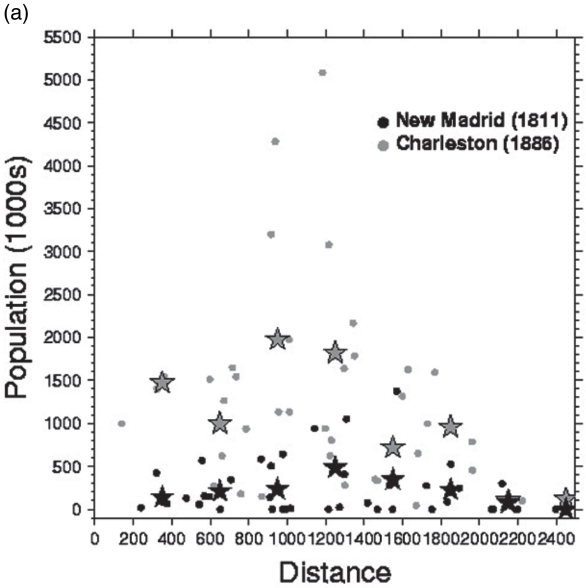

Fig. 5a Population (in 1000s) as a function of distance from the Charleston earthquake (*gray circles*) and NM1 (*black circles*), from the 1880 and 1820 census, respectively. Stars indicate average values within distance bins

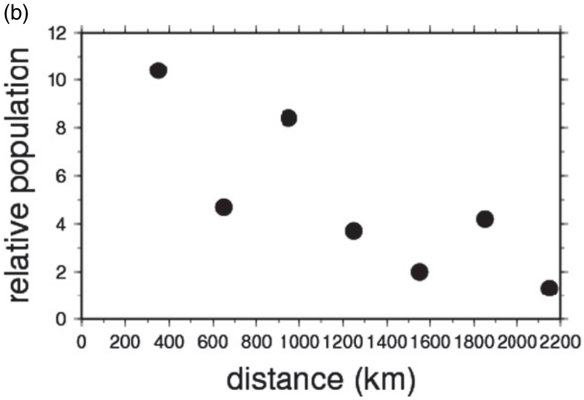

Fig. 5b The distribution of populations shown in Fig. 5a. are used to generate the relative population distribution of the Charleston earthquake and the 16 December 1811 New Madrid mainshock. Values shown here represent the ratio of the gray versus the black stars in Fig. 5a, and illustrate that, while roughly comparable populations experienced the 16 December 1811 New Madrid and Charleston mainshocks at distances of 2000 km, about a factor of 10 more people were living close to the latter event compared to those who were around to experience the former

patterns as well as overall population figures. The population of the United States was approximately 7,000,000 in 1811, with sizable numbers in the states of Tennessee, Kentucky, and the region including the present-day states of Missouri and Louisiana. The 1810 Census gives the population for several districts for which felt reports are considered, including the District of St. Louis (population 5667), Cincinnati (2540), New Orleans (24,552), Louisville (1357), and New Madrid (2103). By 1811 some towns had grown beyond simple frontier villages, with solidly constructed houses appearing by the turn of the century. The oldest brick building west of the Mississippi was built in the town of Ste. Genevieve in 1804; this town is along the Mississippi River valley north of New Madrid. This house and approximately 50 others that predate the New Madrid sequence, are still standing today.

Although the New Madrid earthquakes were likely felt by hundreds of thousands of people, spatial sampling of the intensity field was far from uniform. Especially throughout the mid-continent, early American settlements clustered in proximity to major river valleys. Significant amplification of shaking is expected at such sites, and was in fact explicitly documented by several eye-witnesses to the New Madrid earthquakes. As discussed at length by Hough et al. (2000), while every macroseismic data set will include some effects that reflect sediment-induced amplification effects, special care is necessary when interpreting 1811–1812 intensities because of the especially biased nature of the data set.

In contrast, by 1880 the population of the United States had grown to over 50 million, and settlement patterns had changed dramatically, largely due to the development of the U.S. railroad system. Railroad construction began in the U.S. in the late 1820s and the first commercial lines began in the early 1830s. In 1838 the railroads were designated as "post roads" by the U.S. Post Office; from this time onward the railroads were used to move U.S. mail. This provided further impetus for development of the rail system to the mid-continent and the West. As a consequence of these developments, as well as the growing overall population, settlement became more uniform throughout the former frontier regions. By the 1920s, early settlers had also begun to recognize the pitfalls associated with life on the immediate river banks, which included poor drainage, floods, and disease. The very earliest settlements of the late 1700s and very early 1800s often were on fluvial sites, immediately adjacent to rivers. New Madrid was built so close to the river bank that even before the earthquakes, parts of the town regularly gave way under the continued assault of river currents (Penick, 1981). By the time the Charleston earthquake occurred, settlements had migrated inland, away from waterways.

Given the disparate size and distribution of the populations in 1811–1812 versus 1886, it is appropriate to consider the intensity distributions in more detail. As a simple experiment, I winnow the 1886 intensity distribution down to only those locations that are within 10 km of a point location for which an intensity is available for NM1 (Figs. 6 and 7). Although one would ideally like use only the precise set of locations for which an intensity value is available for NM1, in fact the locations of early intensity observations are rarely precisely known. Using a buffer of 10 km, the list of winnowed values for Charleston is about the same size as the number available for NM1. In effect, this provides an indication of what the Charleston

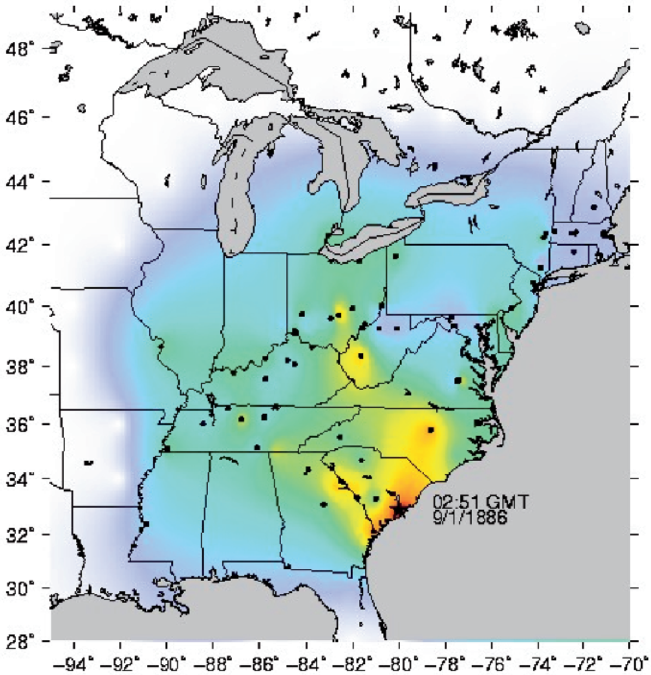

Fig. 6 The intensity distribution shown in Fig. 2, calculated using only those locations that are within 10 km of a location for which there is an account of NM1. This illustrates what the Charleston intensity distribution would have looked like, had the earthquake occurred in 1811 rather than 1886

intensity distribution might have looked like if the earthquake had occurred in 1811. One still finds higher intensity values for NM1 at distances greater than 800 km, but the winnowed values at closer distances are generally lower than the intensity values for NM1.

One can further consider key indicators of the intensity field for NM1 versus that for the Charleston earthquake: the maximum distance at which light damage occurred, and the nature of shaking at hard rocks sites. The latter comparison is difficult because so few observations are available from locations that are known to be hard-rock sites. However, a few reliable observations are available. In Cincinnati, Ohio, physician Daniel Drake described light damage in town along the river valley, but noted that on the elevated ridges away from the river, many families slept through the shock. (Drake went on to attribute this discrepancy to the fact that strata in the river valley were “loose” compared to the nearby limestone hills, one of the earliest observations of, and explanations for, site response (Drake, 1815)). This indicates a MMI no higher than IV for hard rock sites, as V is the level at which sleepers are generally awakened.

Another key hard-rock observation is available from Sainte Genevieve, Missouri, which had been moved to higher ground approximately a mile from the river after a

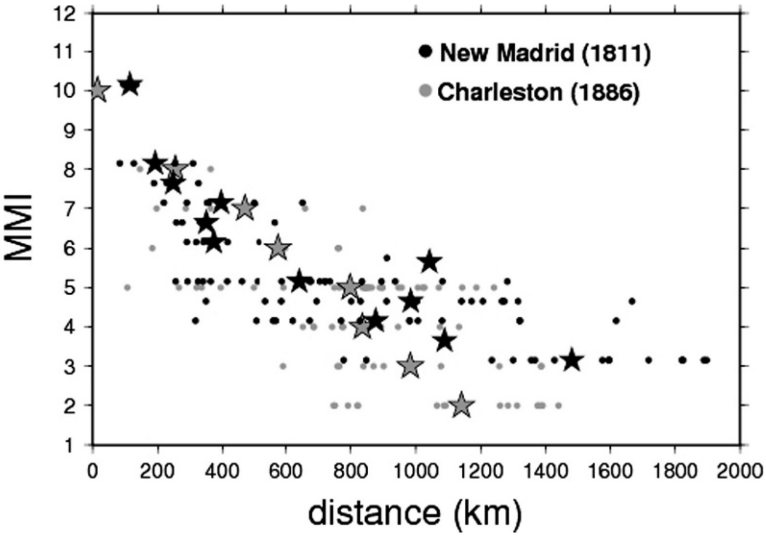

Fig. 7 Same as Fig. 3, but generated using only the winnowed Charleston data set shown in Fig. 6. Intensity values for New Madrid earthquake are shifted upwards by 0.1 units for clarity

flood in the late 1700s resulted in substantial erosion of the river bank upon which the town had originally been built (Brackenridge, 1817). According to a historian whose father lived in Ste. Genevieve at the time of the earthquakes, many shocks were felt in the town but they caused no damage (Rozier, 1890). This indicates MMI values no higher than V for any of the events. Ste. Genevieve provides a further illustration of the biases that can be associated with early archival records: the fact that dramatic effects are more likely to be documented than less dramatic effects. No account of the earthquakes from Ste. Genevieve is included in the compilation of Street (1984). The brief account in Rozier (1890) was discovered by the author following a focused archival search (Hough, 2004).

The accounts from Ste. Genevieve and Cincinnati thus suggest maximum credible MMI values of V and IV for hard-rock sites at distances of 160 and 560 km, respectively. Considering the distribution of MMI values estimated by Bollinger (1977), presumably at a given distance range, the low values provide an indication of intensities at hard-rock sites (Fig. 8). At a distance range of 100–199 km, MMI values range from a high of IX to a low of V, with just a single assignment of IV. At a distance range of 500–599 km, values range from VIII to II-III, with just 7 values of II-III versus 19 for MMI IV. I thus suggest that V represents an estimate of intensities at hard-rock sites at distances of 100–200 km, and an intensity of III–IV for distances of 500–600 km. In both cases the estimated hard-rock intensities are comparable to those available for the New Madrid events.

One can also consider the maximum distance at which NM1 and the Charleston earthquake caused damage. As discussed by Bollinger (1977), the Charleston earthquake caused plaster to fall from walls in Chicago, Illinois, and Valparaiso, Indiana,

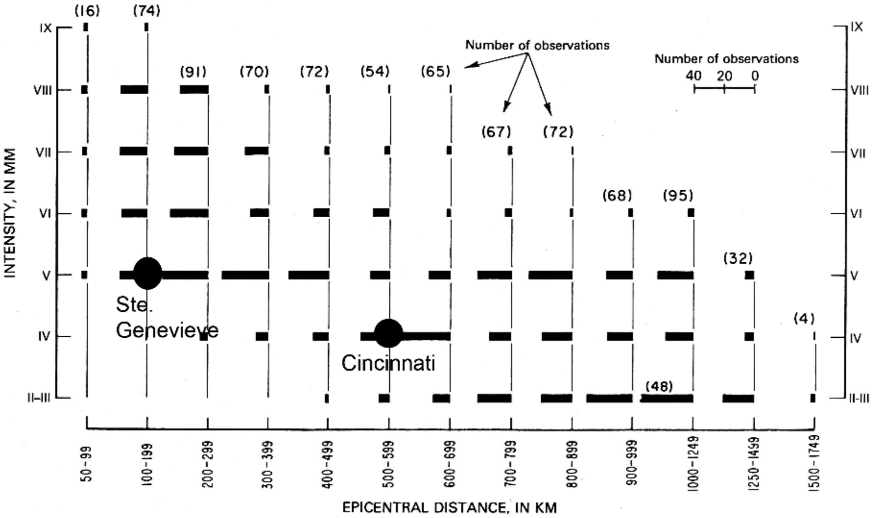

Fig. 8 Original figure from Bollinger (1977) shows the distribution of intensity values as a function of epicentral distance for the Charleston earthquake. Black circles indicate inferred hard-rock intensity values for NM1 based on especially reliable accounts from Ste. Genevieve, Missouri, and Cincinnati, Ohio

both at a distance of approximately 1200 km. In Terra Haute, Indiana, at a distance of ~1000 km, plaster fell from walls of the Opera House. Following NM1, plaster fell from walls in Columbia, South Carolina, and a church bell rang at Charleston, South Carolina, at distances of ~830 and ~960 km, respectively. The Charleston intensities might have been associated with swaying of tall buildings: plaster fell in one building in Chicago, Illinois, only above the fourth floor. However, the dramatic effects following NM1 occurred in a college dormitory building in Columbia, South Carolina, and in a church steeple in Charleston, South Carolina, also two especially tall and large structures. Again, the observations for NM1 appear to be comparable to those for the Charleston earthquake.

3 Conclusions

Although there has always been good agreement regarding the magnitude of the 1886 Charleston earthquake, there has been considerable disagreement about the magnitudes of the principle 1811–1812 New Madrid events; there has also been a prevailing conventional wisdom that the latter events were much larger than the former. Part of this impression might be rooted in the especially dramatic effects that the largest New Madrid events produced along riverbanks, in particular along the Mississippi River. The Charleston earthquake, in contrast, caused widespread liquefaction and ground failure, but did not have the same impact on a major river. Nonetheless, considering carefully the intensity distributions of NM1 versus the Charleston mainshock, one concludes that the former was not significantly larger than the latter. Available evidence in fact suggests the two to have been comparable in size—or at least to have produced comparable intensity fields.

I have focused on NM1 because more complete intensity data set is available for this event compared to the other large earthquakes in the sequence. The magnitude of NM2 is especially uncertain because some evidence suggests a location outside of the New Madrid Seismic Zone (Mueller et al., 2004; Hough et al., 2005). If the event did occur in the northern NMSZ, previous studies suggest a magnitude 0.1–0.2 units smaller than NM1. However, using the method of Bakun et al. (2003) and the intensities of Hough et al. (2000), one obtains a preferred value of 6.8 for the location suggested by Mueller et al. (2004).

In contrast, the location of NM3 is the best constrained of any of the New Madrid events: the earthquake created uplift across the Mississippi River and therefore can be associated with confidence with the Reelfoot thrust fault (e.g., Russ, 1982; Odum et al., 1998). Hough et al. (2000) and Bakun et al. (2003) both conclude that NM3 was approximately 0.2 magnitudes larger than NM1. Thus, while the magnitude of NM2 remains especially uncertain, one can estimate magnitudes of NM1 and NM3 relative to the magnitude of the Charleston earthquake. The latter value is, of course, itself uncertain; but magnitude estimates have been much more consistent for this event than for the principal New Madrid earthquakes. The most recent iteration of the U.S. National Hazard Mapping project assigned a maximum weight to a value of 7.3 for the Charleston earthquake; this implies values of 7.3 and 7.5 for NM1 and NM3, respectively. If the Charleston event was smaller than M7.3, the values for NM1 and NM3 would drop by a corresponding amount.

M_W values of 7.3 and 7.5 for NM1 and NM3 are consistent with the estimates obtained by Hough et al. (2000). These are in turn consistent with other lines of evidence, including rupture area as inferred from geomorphology, aftershock distribution, and stress-transfer theory, assuming standard scaling relations (Mueller et al., 2004). In particular, given the inferred dimensions of the rupture areas of NM1 and NM3, one need not postulate especially high stress drop values.

The M_W estimate of NM3 is slightly smaller than the instrumentally determined magnitude of the 2001 Bhuj, India earthquake: Mw7.6 (Antolik and Dreger, 2003). While this event is generally regarded as the best modern calibration event for the largest New Madrid mainshocks, Bakun and McGarr (2002) conclude that both intensity and weak motion data reveal lower attenuation in central/eastern North America than in other SCR regions around the world, including India. For this reason, while Hough et al. (2002) show that Bhuj mainshock and the largest New Madrid events produced comparable intensity distributions, they conclude that the magnitude of the Bhuj earthquake represents a credible upper bound for the largest New Madrid mainshocks. This conclusion is, again, consistent with the results of this study.

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Magnitude of Historical Earthquakes, from Macroseismic Data to Seismic Waveform Modelling: Application to the Pyrenees and a 1905 Earthquake in the Alps

M. Cara, P.-J. Alasset and C. Sira

Foreword Magnitudes of pre-instrumental moderate-size earthquakes ($M \sim 5.5$) strongly rely on the way macroseismic data are interpreted. In the first part of this paper, after recalling how macroseismic intensity is linearly related to magnitude, we apply a method based on the comparison between historical and recent earthquakes to estimate the moment magnitudes M_W of three earthquakes in the French Pyrenees (Bagneres-de-Bigorre (1660); Juncalas (1750); Arette (1967) and one earthquake in the Alps (Chamonix (1905)). In the second part of the paper we discuss these results in the light of two waveform modelling experiments related to the 1905 Chamonix earthquake, an event well recorded by a Wiechert instrument in Göttingen, and the more recent Arette (1967) earthquake by using WWSSN records. Our instrumental estimate for the Arette (1967) earthquake is 5.1 M_W while we find 5.0 M_W from the macroseismic data. This confirms the rather low magnitude of this most destructive earthquake in continental France since 1909. For the Chamonix (1905) earthquake we find 5.5 M_W, a value close to our macroseismic estimate 5.6 M_W. This good agreement between our macroseismic and instrumental M_W is encouraging for future application of the differential macroseismic method to historical earthquakes, such as the application presented here for the Bigorre (1960) and the Juncalas (1750) Pyrenean earthquakes.

1 Introduction

Macroseismic observations are the only information available for estimating the magnitude of pre-instrumental earthquakes when no fault rupture is observable at the surface, as it is the case for most moderate-size earthquakes in Europe (magnitude ∼5.5). Macroseismic scales currently in use are twelve-degree scales that were formerly based on the Mercalli Cancani Sieberg scale (MCS) (Sieberg 1932). It is important to recall that the suggestion to extend the former ten-degree European scales to twelve degrees is due to Cancani who suggested a quantitative approach

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based on ground acceleration measurements. In the proceedings of a meeting held in Strasbourg in 1903, he wrote (Cancani 1904): *collecting these data* [on macroseismic intensity]*, and performing some interpolations, I think I have found, with enough accuracy, the accelerations corresponding to the ten degrees of the Forel-Mercalli scale. These accelerations increase following a geometrical rule with a common ratio of two. According to the seismologist's judgment, the tenth degree of the Forel-Mercalli scale corresponds to an acceleration which is not larger than 2 500 mm* (sic), *while there are some earthquakes in Japan or South America (...) where acceleration reaches 10 000 mm per second* (sic)*; this is why it was necessary to add two degrees to the above scale.* Because this 1903s note linking degree XII to 10 m/s^2 is not easily accessible, we reproduce it in its original French language in the appendix. One can find in (Sieberg 1912) a detailed description of the twelve-degree scale of what became later on the MCS scale.

The Cancani 1903s factor 2 in ground acceleration between two degrees of intensity may be compared with the factor 2.15 that can be inferred from a relationship published by Richter (1958). It is not far either from the factor which can be expected from the study of Alkinson and Sonley (2000) who established a more sophisticated relationship taking implicitly into account the shift in frequency with epicentral distance. Alkinson and Sonley's formula is established for 29 California earthquakes in the moment magnitude range 4.9–7.4. It links intensity I, peak ground acceleration Y, epicentral distance D, and magnitude M through the relationship:

$$\mathrm{I} = -9.32 + 6.08(\log \mathrm{Y} + 0.46\mathrm{D} - 0.03\mathrm{M}). \tag{1}$$

The correction by the factor 0.03 M being negligible, one can infer from (1) that one degree of intensity at a fixed epicentral distance D roughly corresponds to a multiplicative factor 1.5 in peak ground acceleration.

The logarithmic relationship between ground acceleration and macroseismic intensity has been thus known for more than a century. As the Richter magnitude M is defined from the logarithm of the output of the short period Wood Anderson seismometer with a flat response to acceleration up to 1.25 Hz (Richter 1935), it corresponds to frequencies which are relevant for macroseismic effects and M may be linearly related to intensity I. This is what many empirical relationships show, such as the following general equation adapted from Musson and Cecic (2002):

$$\mathrm{I} = \mathrm{a} + \mathrm{b\,M} + \mathrm{c} \log \mathrm{R} + \mathrm{d\,R}, \tag{2}$$

where "a" and "b" are constants, R is the hypocentral distance, and c and d depend on geometrical spreading and anelastic attenuation, respectively.

Most estimations of magnitude of historical earthquake rely on (2). Focal depth h and magnitude M of small and moderate-size earthquakes are commonly estimated from I versus D observations, taking in mind that $\mathrm{R}^2 = \mathrm{D}^2 + \mathrm{h}^2$. Most often, a magnitude is estimated directly from the epicentral intensity I_0 after correction is made from the focal depth h. By doing so, site effect at the epicentre and/or error in the focal depth may strongly bias an estimation of magnitude made from macroseismic observations as we will see for the 1967 Arette earthquake in the French Pyrenees. Furthermore, I_0 may differ from the maximum intensity I_{max} when the epicentre is outside a zone of observation, making I_0 estimate difficult. The situation is not much better when using the whole set of macroseismic areas A(I) due to the strong dependence of the macroseismic attenuation law on the focal depth.

To avoid the uncertainties due to the attenuation law, site effects, or shift in frequency with epicentral distance, Cara et al. (2005) have proposed to compare directly the intensities of a recent instrumentally-known earthquake with the historical-earthquake intensities at large distances from the epicentre. Looking at (2), it is clear that for two earthquakes located at the same hypocentral distance R, the difference of intensity ΔI is proportional to the difference of their magnitude ΔM:

$$\Delta I = b\Delta M, \tag{3}$$

where the constant factor "b" is determined experimentally in the region of interest. For two earthquakes located at the same epicentral distance, R may be confounded with D far from the observation point. As a rule of thumb, we propose to work at distances D larger than three times the standard 10–15 km focal depths of crustal earthquakes in continents, a difference between D and R of a few kilometres being negligible for a macroseismic investigation.

Using the isoseismal areas A(I) to estimate D(I), as in Cara et al. (2005), furthermore acts as a smoothing filter on the azimuthal radiation pattern at the source and on the possible site effects. The investigated zone may then be broad enough to cover densely-populated regions, making the average intensity observations more robust and reliable than the epicentral intensity I_0 for estimating an earthquake magnitude.

The main source of uncertainty comes from the parameter "b" of relationship (3). As the linearity of this relationship probably fails when it is applied to a too broad magnitude range, it is safe to estimate "b" from a set of events with magnitudes not too far from those under study. In France, Levret et al. (1994) found $b = 2.27$ for a large set of data based on a homogeneous set of local magnitudes (4–5.8 M_L) issued by the Laboratoire de Détection Géophysique (LDG) of the French commission of atomic energy, while Souriau (2006) found $b = 2.17$ from a smaller set of recent earthquakes and magnitudes issued by the Réseau National de Surveillance Sismique (ReNaSS) (3.0–5.4 M_L). Accordingly, a value $b = 2.2$ will be used in the present paper for application to France in the moderate-size magnitude range 4.5–6 M_w. The fact that we use a factor "b" determined from M_L catalogues to compute M_w should not be a problem if we refer to Braunmiller et al. (2005). These authors have shown that the slope of the M_w versus M_L relationship is close to 1 for the different European catalogues they have investigated in the neighbouring countries of Switzerland. Only the intercept differs, M_w being smaller than M_L. The difference reaches 0.2 for both the Swiss Seismological Service (SED) and the Karlsruhe catalogues and 0.6 for the LDG catalogue. Note also that in the differential macroseismic method proposed here, an error on "b" will only affect the difference of magnitude ΔM. Taking a difference of macroseismic intensity $\Delta I = 2.2$, a typical value in the application made in this paper, an error of 0.1 on "b" would for example cause an error of 0.05 on ΔM. In addition to the error on "b", the uncertainty of the magnitude of a historical earthquake computed from (3) also depends on the errors on ΔI and on the magnitude of the reference event.

2 Application to Historical Earthquakes in the Pyrenees

The Pyrenees is one of the most active seismic zones of France (Souriau et al. 2001). In the present paper, we focus our attention on the western part of the mountain range. Since the Lambesc (1909) earthquake in the South of France ($M_w = 5.7$–6.1 (Baroux et al. 2003)), this region of the Pyrenees has been visited by the most damaging French earthquake, with a maximum intensity of VIII near the locality of Arette. This is also where two large historical earthquakes occurred (Bigorre (1660) I_{max} = VIII–IX, Juncalas (1750) I_{max} = VIII). In order to apply the differential technique described above, we choose two events as reference earthquakes, one located near Lourdes (Argelès-Gazost (2006) $M_L = 4.9$ ReNaSS, $m_b = 4.6$ NEIC, $M_w = 4.5$ from several independent sources) and another one near Arudy (Arudy (1980) $m_b = 5.1$ (Gagnepain-Beyneix et al. 1982)). The epicentre of the Arudy earthquake is located about 35 km from both the macroseismic epicentres of the Arette (1967) and Bigorre (1660) earthquakes (Fig. 1). The epicentre of the Argelès-Gazost earthquake is located around 10 km from the Bigorre (1660) macroseismic epicentre.

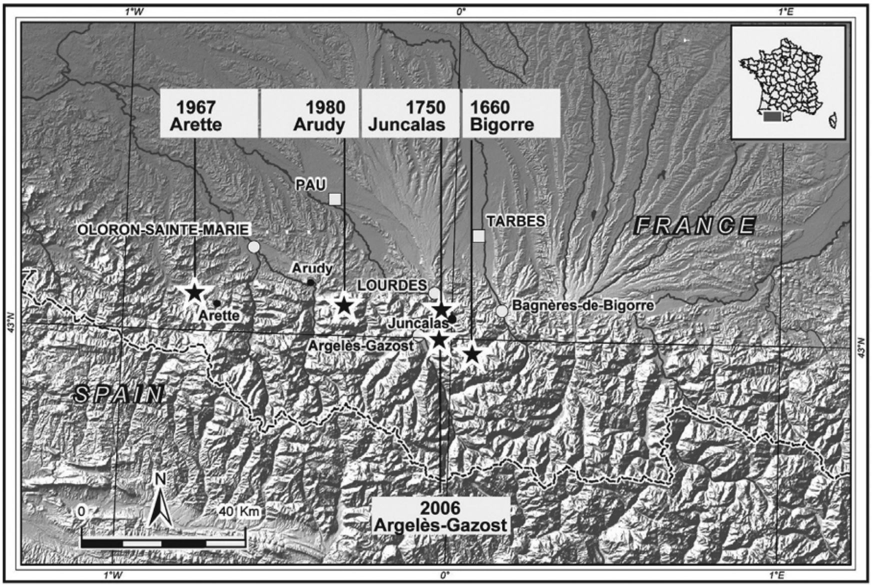


Fig. 1 Epicentres of the Pyrenean earthquakes investigated in this paper

To guarantee a similar spatial sampling for the pairs of historical and recent events, we have clustered the recent localities inside circles of 10 km radius around each historical site, and took the average intensity within each circle. For example, intensities of the Argelès-Gazost (2006) earthquake is known in several localities around the city of Bordeaux while we have only one value of intensity in Bordeaux for the Bigorre (1660) earthquake. With this procedure we can draw the isoseismals of the recent and historical earthquakes from the same geographical sampling. Historical intensities (MSK scale) are taken from the SisFrance data base (www.sisfrance.net). The MSK scale (Medvedev et al. 1964), which was in use in France until 2000, is now replaced by the EMS-98 (Grünthal 1998). The differences between MCS, MSK and EMS are negligible at degrees smaller than or equal to V, and are less than half a degree for larger degrees of intensity (Molin 1995). Working with small intensities, we may thus confound the two scales. Figure 2 shows the isoseismals drawn for the pair of events Argelès-Gazost (2006) – Bigorre (1660). When the isoseismals are not complete, such as those cutting the Atlantic coast or the Franco-Spanish border, we have linearly extrapolated each isoseismal area to a full 360° azimuthal range.

Once the macroseismic areas A(I) are known within each isoseismal, we convert them into distance-intensity curves $D(I) = \sqrt{A(I)/\pi}$ for both the reference and the historical earthquakes, such as in Fig. 3. For the Argelès-Gazost (2006) earthquake, we have completed the D(I) curve down to intensity II by setting its macroseismic

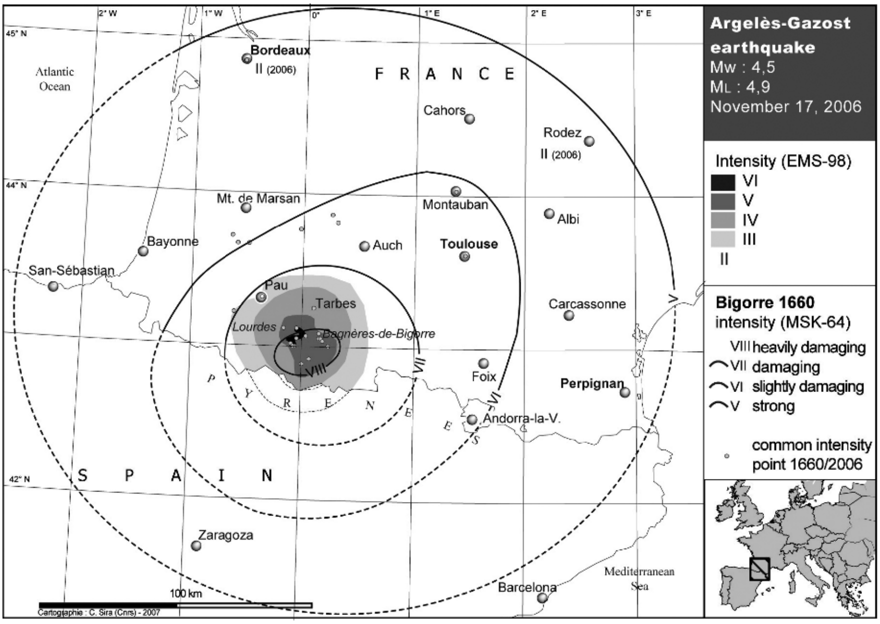


Fig. 2 Isoseismals and macroseismic areas for the Bigorre (1660, MSK-64) and Argelès-Gazost (2006, EMS-98) earthquakes

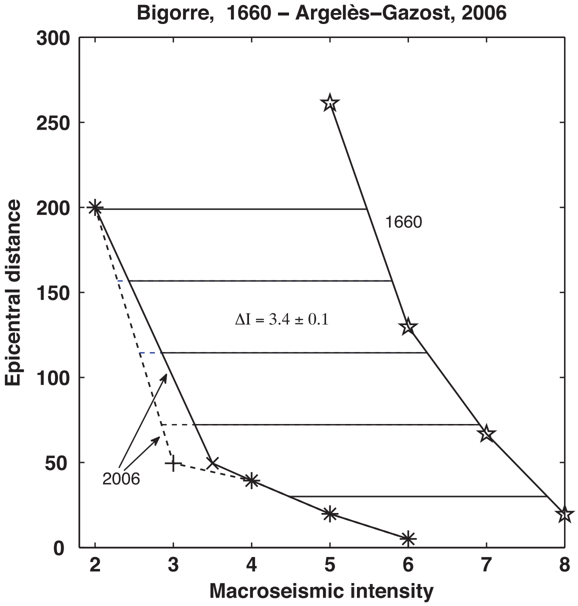


Fig. 3 Epicentral distance D versus intensity I inferred from Fig. 2 for the pair of earthquakes Bigorre (1660) – Argelès-Gazost (2006). Dotted line for the uncorrected intensity

radius to D = 200 km according to the farthest unambiguous macroseismic observations in France (Rodez, D = 255 km; Bordeaux and its vicinity, D = 200 km).

As explained in the previous section, at a fixed epicentral distance D, we expect that the differences of intensities depend on the differences of magnitudes ΔM only. The curves D(I) should thus be parallel. From this respect, the recent Argelès-Gazost curve is abnormal at intensity III. Unreliable answers to the macroseismic questionnaires received at BCSF for distances between 50 and 100 km is the most likely reason for this anomaly. Within this distance range, the answer "not felt" is often quoted by local city officers while reliable reports of intensity II (felt) are sent by individuals. This lack of information from local city officers could explain the abnormally too small area of intensity III in Fig. 2. In order to check the effect of this possible underestimation of intensity III area we test below what is the consequence of increasing the intensity by half a degree at a distance of 50 km from the epicentre.

The average difference of intensity between the pair of earthquakes Argelès-Gazost (2006) – Bigorre (1660) is estimated to $\Delta I = 3.59 \pm 0.29$ from a set of five epicentral distances D in the range 30–200 km (Fig. 3). From the relationship (3) we found that the difference between their magnitudes is $\Delta M = 1.63 \pm 0.13$ (rms deviation). Starting from the 4.5 M_W Argelès-Gazost (2006) earthquake, we thus find a magnitude $M_W = 6.13 \pm 0.13$ (rms deviation) for the Bigorre (1660) earthquake. Following the same procedure with the corrected intensity III $^1/_2$ we get $\Delta M = 1.56 \pm 0.06$ and $M_W = 6.06 \pm 0.06$. Within an rms deviation around 0.1, one can thus conclude with a quite good confidence that a magnitude 6.1 M_w is expected for the Bigorre (1660) earthquake. If one adds an uncertainty around 0.1 for both the reference magnitude and "b", the total error on the macroseismic M_w may be estimated to ±0.2.

The same differential technique can be applied to the pair of earthquakes Arudy (1980) – Bigorre (1660). An average difference of intensity $\Delta I = 1.9 \pm 0.2$ is observed in the distance range 30–200 km (Fig. 4). It corresponds to $\Delta M = 0.86 \pm 0.09$. As no M_W is available for the Arudy (1980) event, we start from the teleseismic body wave magnitude $m_b = 5.1$ (Gagnepain-Beyneix et al. 1982) and we get $m_b = 5.96 \pm 0.09$ for the Bigorre (1660) earthquake, a value close to the 6.1 M_W estimated from the Argelès-Gazost (1980) reference event.

When comparing the Juncalas (1750) to the Arudy (1980) earthquakes in the distance range 30–200 km, we find $\Delta I = 1.3 \pm 0.3$ and $\Delta M = 0.60 \pm 0.12$. Starting again from $m_b = 5.1$ we get a magnitude $m_b = 5.7 \pm 0.1$ for this second largest historical earthquake of the region ($M_W = 5.8$ based on the 4.5 M_W Argelès-Gazost (2006) earthquake). Table 1 gives the different magnitudes reported here and our final preferred solution for M_w.

Similarly, we can compute a magnitude for the Arette (1967) earthquake from the Arudy (1980) event. We get $m_b = 4.9 \pm 0.1$ from $\Delta I = -0.4 \pm 0.2$ and $\Delta M = -0.17 \pm 0.10$. Starting from the magnitude $m_b = 4.6$ ($M_w = 4.5$) of the Argelès-Gazost (2006) event, we get the slightly larger value $m_b = 5.1$ ($M_w = 5.0$). The Arette (1967) earthquake thus has m_b and M_w magnitudes close to 5. Such a magnitude is much smaller than the macroseismic magnitude MM = 5.8 found by Rothé (1972) from macroseismic data (I_0 = VIII, h = 15 km). It is closer to the value MM = 5.2 proposed by Levret et al. (1994). Following the procedure used by Rothé (1972), it is easy to fit both I_0 = VIII and MM = 5 by changing the focal depth to 2.5 km, a depth also shallower than that found by Levret et al. (1994) (h = 5 km). It is thus likely that the hypocentre of the second largest damaging

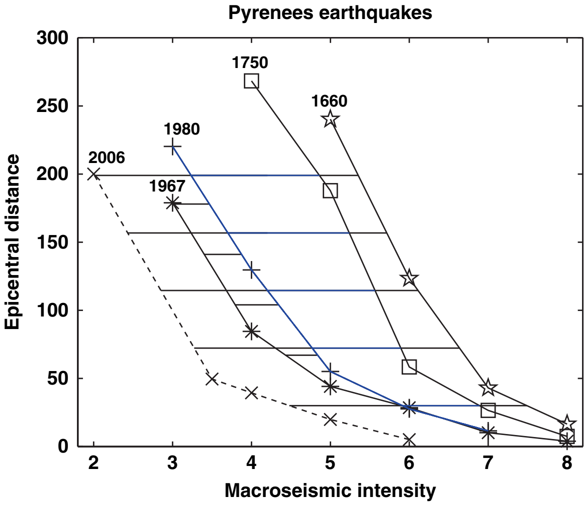


Fig. 4 The same as Fig. 3, but for the Bigorre (1660), Juncalas (1750), Arudy (1980), Arette (1967) and Argelès-Gazost (2006) earthquakes

Table 1 Summary of the different magnitudes investigated in this study

Event	date	m_b	Instrumental M_w	Macroseismic M_w	Proposed M_W
Argelès-Gazost	17-11-2006	*4.6*(a)	*4.5*(1)	–	*4.5*
Arudy	29-02-1980	*5.1*(b)	–	**5.2**(1)	**5.2**
Arette	13-08-1967	**5.1**(a), **4.9**(b)	*5.1*(2)	**5.0**(1)	**5.0**
Juncalas	24-05-1750	**5.9**(a), **5.7**(b)	–	**5.8**(1)	**5.8**
Bigorre	21-06-1660	**6.2**(a), **6.0**(b)	–	**6.1**(1)	**6.1**
Vallorcine	08-09-2005	–	*4.5*(3)	–	*4.5*
Epagny	15-07-1996	*4.5*(c)	*4.6*(4)	**4.9**(3)	**4.8**
Grand-Bornand	14-12-1994	–	*4.3*(5)	**4.4**(3)	**4.4**
Chamonix	29-04-1905	–	*5.5*(2)	**5.7**(3), **5.6**(4), **5.5**(5)	**5.6**

– *italic*: instrumental magnitudes m_b and M_w from different agencies and authors ((a) and (c) USGS's PED catalogue; (b) Gagnepain-Beyneix et al. (1982); (1) INGV and Géoscience Azur, (2) this study; (3) SED, Géoscience Azur and INGV; (4) and (5) Braunmiller et al. 2005).
– **bold**: macroseismic magnitude computed from the reference event magnitude (n).
Right column: final M_w proposed in this study. The cumulative errors in ΔI, Δb and the reference-event M_w cause an uncertainty on the macroseismic M_w is estimated to ±0.2.

earthquake that occurred in France in the XX century is much shallower than what was previously thought.

There is another conclusion we can draw from Fig. 4 by comparing the two recent Arudy (1980) and Argelès-Gazost (2006) earthquakes. Our macroseismic investigation favoured a rather large magnitude difference $\Delta M = 0.7$ between the two earthquakes, similar to the difference between their teleseismic body wave magnitude ($\Delta m_b = 0.5$), while the French catalogues published by BCSF show similar values (4.9 M_L for Argelès-Gazost (2006) according to ReNaSS and 5.0 M_L for Arudy (1980) according to Schlich and Hoang Trong (1987)). In addition to the well known systematic discrepancy between M_L and M_w when looking at the catalogues of several agencies in Europe (Braunmiller et al. 2005), this example shows that there is no simple rule to convert M_L into M_w when using the BCSF catalogues covering the last 25 years.

3 Application to the Chamonix April 29th, 1905 Earthquake in the Alps

The northwestern part of the Alps is another seismically active region of France (e.g. Thouvenot et al. 1998) where we can test the differential macroseismic method. The Chamonix earthquake of April 29th, 1905 is one of the poorly known earthquakes of this region. Located near the triple border between France, Italy and Switzerland, it is close to several $M \sim 6$ earthquakes of the Swiss Alps. The catalogue issued by the Swiss Seismological Service ECOS (Fäh et al. 2003) contains four historical $M_w > 6$ events at distances less than 60 km from the city of Chamonix. On September 8, 2005, an earthquake of magnitude 4.9 M_L (4.5 Mw) occurred at proximity of the macroseismic epicentre of the 1905 Chamonix event, near the locality of

Vallorcine. As this later earthquake has been well investigated from both local and regional broad-band seismic networks, it provides an excellent opportunity to apply our differential technique.

Intensities of the 1905 earthquake are taken in three catalogues: BCIS (Bureau Central International de Sismologie (Christensen and Ziemendorff (1909)), BSSI (Bollettino della Societa Sismologica Italiana (Palazzo 1907)), and ECOS. Intensities issued by BCIS and BSSI are given in the Rossi-Forel scale (De Rossi 1883), while ECOS intensities are converted into the EMS-98. We have checked the description of the macroseismic effects published by BCIS with both the Rossi-Forel scale and the EMS-98. Doing so, we conclude that for this event, intensities V of the Rossi-Forel scale was intermediate between IV and V of the EMS-98, while VI and VII are equivalent to V and VI of the EMS-98, respectively. Figure 5 shows the isoseismals of the 1905 Chamonix earthquake where intensities are converted into the EMS-98 with two possible interpretations for intensity V. Superimposed on the 1905 map, we have drawn the isoseismals of the Vallorcine (2005) earthquake by using, as previously, the same spatial grid for both the historical and the recent events.

Figure 6 displays the distance-intensity curves D(I) for the pair of earthquakes 1905-2005, together with the curves corresponding to two recent magnitude $M_L \sim 5$ earthquakes located at distances less than 80 km from Chamonix. The moment magnitude of the Vallorcine (2005) earthquake is well constrained to 4.5 from three independent sources (SED in Zurich, INGV in Rome, and Géosciences Azur in

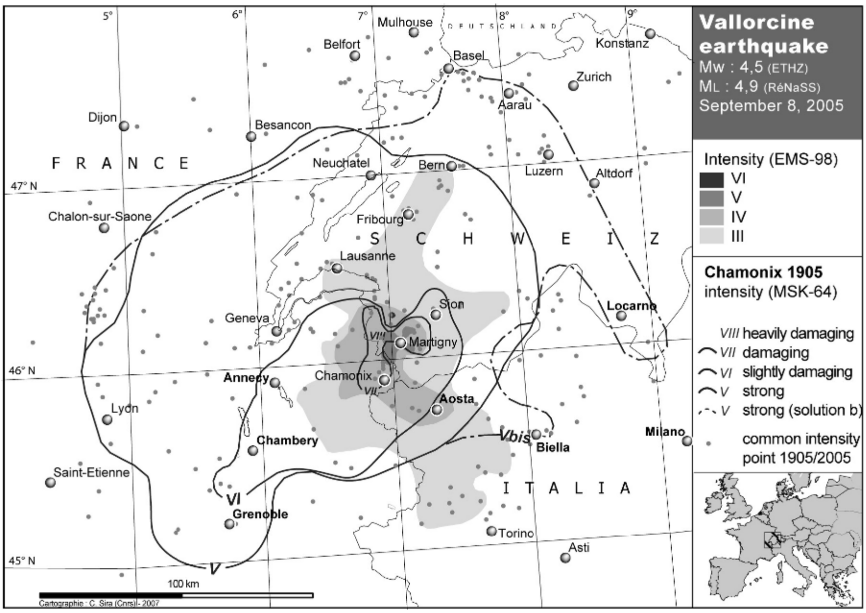
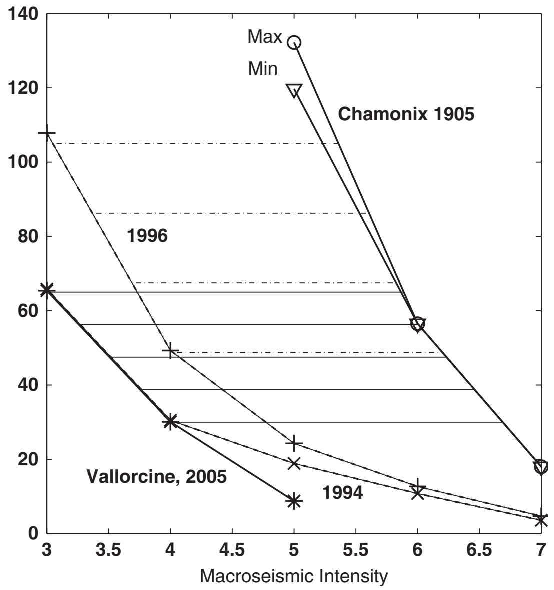


Fig. 5 Isoseismals and macroseismic areas for the Vallorcine (2005) and Chamonix (1905) earthquakes (EMS-98 converted)

Fig. 6 The same as Fig. 3 but for the Chamonix (1905), Epagny (1996), Grand-Bornand (1994), and Vallorcine (2005) earthquakes



Nice). For the Epagny (1996) event near Annecy and the Grand-Bornand (1994) event, at mid path between Annecy and Chamonix, we use the values M_w computed from several broad-band stations by Braunmiller et al. (2005): 4.6 and 4.3 M_w, respectively. Note that the local magnitude M_L issued by ReNaSS for these three reference events are higher by 0.4–0.6 units (4.9, 5.2 and 4.7, respectively). Using as previously ΔI for the reference earthquakes at a set of five epicentral distances, we obtain an average magnitude $M_w = 5.6 \pm 0.1$ for the Chamonix (1905) earthquake while it would be 6.1 M_L if we start from the short period ReNaSS magnitudes. It is also interesting to note that the macroseismic magnitude MM $= 5.7$ given by Karnik (1969) for the main shock of the April 29th 1905 Chamonix earthquake is in better agreement with our 5.6 M_w macroseismic estimate than what is excepted from the ReNaSS M_L.

4 Instrumental Magnitude and Discussion

The above magnitude estimates can be compared with the instrumental seismic moment magnitudes M_w for both the Arette (1967) and Chamonix (1905) events, although very few reliable records are available for the latter.

In 1967, the WWSSN stations provide many long-period records so that a reliable measurement of the seismic moment can be performed from the surface-wave records. Fitting by trials and errors the observed Rayleigh waves in the distance range 463–2656 km, we find that the best fit is obtained with the following source parameters: strike of the fault $= 100°$, dip $= 75°$, rake $= -160°$ and $M_W = 5.1$ (Alasset 2005). The instrumental magnitude $M_W = 5.1$ we find from the long period WWSSN records is very close to that computed from the reference events with macroseismic data ($M_w = 5.0$ or $m_b = 4.9$–5.1). Note also that teleseismic m_b of $M \sim 5$ earthquakes provide a good reference for computing the seismic moment magnitude of this moderate-size Arette (1967) earthquake, while starting from local magnitudes we find a significantly larger value $M_L = 5.4$.

Classical estimates of both the surface-wave magnitude M_{SZ} and duration magnitude M_D can also be made for the Arette (1967) earthquake. By using the long-period WWSSN records and a short-period record from a Mainka seismometer in Bagnères-de-Bigorre, we find $M_{sz} = 5.1 \pm 0.3$ and $M_D = 5.2$ (Alasset 2005). This confirms the rather small magnitude we find above for the Arette earthquake. One can thus conclude from these very different approaches that a magnitude 5.1 (M_w, m_b, M_{sz}) is a quite well constrained value for the most damaging earthquake that occurred in metropolitan France since the Lambesc (1909) earthquake. This also confirms that the hypocentre of this earthquake should have been closer to the surface than proposed by Rothé (1972) from his interpretation of macroseismic data.

Estimating an instrumental magnitude for the Chamonix (1905) is much more difficult. Quite many short period instruments recorded this earthquake in Europe but very few long-period instruments were functioning at that time. Three horizontal 1-ton Wiechert seismometers recorded the April 29, 1905 earthquake (Strasbourg, Göttingen and Uppsala). The records in Strasbourg have been lost and those in Uppsala are of very small amplitude and clearly distorted by the solid friction of the pen on the smoke paper drum. The two horizontal records made in Göttingen are of high quality and the amplitudes of the seismograms are large enough so that comparison with synthetics can be made. Another record is available from a Rebeur-Ehlert long-period instrument in Uccle, Belgium, but the drum speed was so small that no signal can be extracted from the record.

The only records we can rely on for the Chamonix (1905) are thus the two horizontal Wiechert records from Goettingen observatory. Taking several plausible focal mechanisms for this event based on tectonics hypotheses, we find a seismic moment magnitude around 5.5 M_w when modelling both the Love and Rayleigh waves signals (Fig. 7). This result is in very good agreement with the magnitude

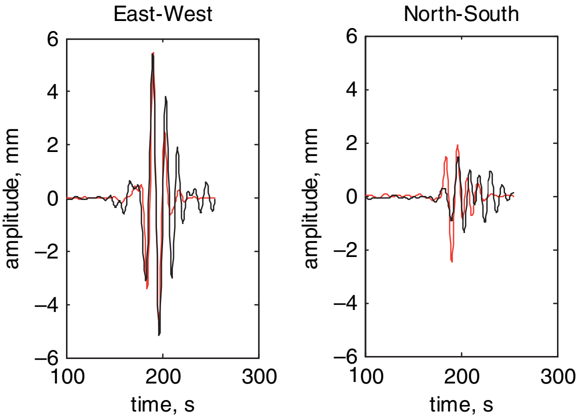


Fig. 7 Fit of the two horizontal component of the Chamonix (1905) records made in Goettingen with synthetics. The observed signals (*black line*) and synthetics (*red line*) are low pass-filtered (cut-off frequency 0.03 Hz). The focal mechanisms used for computing the synthetics corresponds to a normal left-lateral fault (strike 20°, dip 70°, rake –70°, Alasset 2005)

Table 2 Instrumental and macroseismic moment magnitudes computed in this paper (bold characters) or reported from publications (normal characters). MM are published macroseismic magnitudes

		MM	Instrumental M_W	Macroseismic M_W
Arudy	29-02-1980	5.3(1)	–	5.2
Arette	13-08-1967	5.2(1)	5.1	5.0
Juncalas	24-05-1750	–	–	5.8
Bigorre	21-06-1660	–	–	6.1
Epagny	15-07-1996	–	4.6(3)	4.9
Grand-Bornand	14-12-1994	–	4.3(3)	4.4
Chamonix	29-04-1905	5.7(2)	5.5	5.6

References: [1]Levret et al. (1994), [2]Karnik (1969), [3]Braunmiller et al. (2005).

5.6 M_w obtained in this paper by applying our differential macroseismic method to three recent earthquakes. Table 2 gives a summary of the M_w inferred from both macroseismic and instrumental data together with published macroseismic magnitudes MM.

5 Conclusion

The two XX century damaging earthquakes studied in this paper, Arette (1967) in the Pyrenees and Chamonix (1905) in the Alps, show that the magnitudes M_w of moderate-size earthquakes inferred from our differential macroseismic method are in reasonable agreement with those directly computed from the low-frequency instrumental observations. They are also in close agreement with the macroseismic magnitudes MM published for these two events by Levret et al. (1994) and Karnik (1969), respectively. For the Arette (1967) earthquake, we find a macroseismic value $M_w = 5.0$, while our instrumental estimate is 5.1. For the Chamonix (1905) earthquake, the macroseismic value $M_w = 5.6$ is close to our instrumental estimate 5.5 M_w. The macroseismic magnitude MM = 5.8 issued by Rothé (1972) for the Arette (1967) event is much larger than the value 5.0 M_w reported here. As a consequence the focal depth of this $I_0 =$ VIII latter earthquake must have been much shallower than previously thought.

Present-day macroseismic investigations performed on earthquakes of magnitude $\sim$4.5 M_w thus appear to be extremely useful for calibrating moderate size historical earthquakes when working in the low intensity range [II–V] at some distances from the epicentre. As an application, we have computed seismic moment magnitude of two historical earthquakes in the Pyrenees (Bigorre (1660) 6.1 M_w, and Juncalas (1750) 5.8 M_w). The accuracy of these latter magnitudes is estimated around ±0.2.

Appendix

Sur l’emploi d’une double échelle sismique des intensités, empirique et absolue. *On the use of a double seismic intensity scale, empirical and absolute* (Cancani, 1904)

Les avantages que présente l’emploi d’une échelle sismique des intensités sont bien connus et c’est pourquoi je n’entretiens pas la Conférence sur cet argument.

Je me permets au contraire d’appeler son attention sur l’utilité que retirerait la sismologie de la diffusion universelle d’une échelle unique, qui servirait également bien à évaluer empiriquement le degré d’intensité comme à l’évaluer rationnellement et mathématiquement.

Pour l’évaluation empirique, presque tous les sismologues, en Italie et à l’étranger, ont accepté l’échelle De Rossi-Forel qui a été sensiblement améliorée par M. le prof. Mercalli.

L’échelle Mercalli, aussi bien pour la valeur des degrés que pour les critériums qui président à leur définition nous offre une différence remarquable par rapport à celle qui, sous le nom De Rossi-Forel, a été adoptée, particulièrement en Italie, depuis 1883 jusqu’à 1899, mais elle ressemble au contraire beaucoup à l’échelle proposée par M. le prof. Forel en 1881. Voilà pourquoi, selon le désir que m’a manifesté tout dernièrement M. Mercalli, nous donnerons dès à présent à la nouvelle échelle le nom de Forel-Mercalli.

Elle apporte une utilité incontestée dans la formation des catalogues sismiques, comme j’ai pu moi-même le constater par l’expérience de l’application que j’en ai faite depuis quatre ans.

L’emploi d’une bonne échelle sismique est aussi nécessaire à donner une valeur conventionnelle, mais précise et invariable aux adjectifs léger, médiocre etc. qu’on a introduits dans la sismologie.

Cependant, tandis que l’échelle susdite est bien appropriée à une classification des effets de la secousse dans une description détaillée d’un tremblement de terre, ou dans une monographie de caractère narratif, certainement elle ne se prête pas bien à une étude mécanique à une recherche de caractère scientifique sur le même tremblement de terre.

Dans ce dernier cas il est évident qu’on doit nécessairement adopter une échelle absolue, c’est à dire une échelle dans laquelle les degrés représentent un élément mécanique bien défini de la secousse, par exemple, l’accélération du mouvement.

Toutefois, au lieu de généraliser et recommander l’emploi d’une échelle absolue des intensités, isolée, qui réponde par elle seule aux exigences de la science, il me semble plus rationnel, et de facile réalisation, réunir (sic) aux degrés de la susdite échelle Forel-Mercalli, les valeurs absolues correspondantes.

MM. les professeurs Omori et Milne et d’autres sismologues illustres, ont pu exécuter en plusieurs occasions, des mesures absolues d’intensité nous fournissant ainsi du matériel qui contribue largement à trouver les accélérations correspondantes aux différents degrés de l’échelle empirique.

En recueillant çà et là ce matériel, et en faisant les nécessaires interpolations, je crois avoir réussi à trouver, avec une exactitude suffisante, les accélérations correspondantes aux dix degrés de l'échelle Forel-Mercalli. Ces accélérations augmentent suivant une progression géométrique qui a pour raison deux.

Selon le jugement très concordant des sismologues déjà nommés, le dixième degré de l'échelle Forel-Mercalli correspond à une accélération qui n'est pas supérieure à 2500 mm (sic), tandis qu'il y a des tremblements de terre, qui ont lieu bien des fois au Japon, dans l'Amérique du Sud, et en d'autres pays terriblement éprouvés par ce fléau, dans lesquels l'accélération arrive jusqu'à 10 000 mm par seconde (sic); c'est pour cela qu'il était nécessaire d'ajouter deux degrés à l'échelle susdite.

Les professeurs Forel et Mercalli convaincus de cette nécessité ont bien voulu m'autoriser à prolonger leur échelle par les deux degrés XI et XII, et former ainsi une échelle sismique qui puisse être adoptée non seulement en Italie mais dans tous les pays du monde.

J'ai donc l'honneur de présenter à la Conférence l'échelle sismique Forel-Mercalli, avec les deux degrés ajoutés et avec les accélérations qui correspondent à chaque degré.

Je prie la Conférence de procéder à la nomination d'une Commission chargée de discuter la double échelle que j'ai l'honneur de présenter avec la faculté de la modifier, si elle le juge nécessaire, et d'en proposer ensuite l'emploi universel.

A. Cancani

Echelle sismique Forel-Mercalli, empirique et absolue

Degrés	Dénominations	Accélérations correspondantes (mm. par seconde)*
I	Secousse instrumentale	<2,5
II	Bien légère	2,5–5,0
III	Légère	5–10
IV	Sensible ou médiocre	10–25
V	Assez forte 1)	25–50
VI	Forte	50–100
VII	Très forte	100–250
VIII	Ruineuse	250–500
IX	Désastreuse	500–1000
X	Très désastreuse	1000–2500
XI	Catastrophe	2500–5000
XII	Grande catastrophe	5000–10000

1)Les dénominations Assez forte et forte en correspondance aux degrés V et VI, sont préférables, selon l'opinion de M. Mercalli, aux dénominations forte et beaucoup forte, déjà introduites.

*mm/s^2, the original error is corrected in the different publications of Sieberg (1932, 2005 (translation of a 1943 publication)).

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Quantitative Analysis of Early Seismograph Recordings

J. Batlló, D. Stich and R. Macià

Foreword Seismograms are the most comprehensive and quantitative documents of ground motion produced by earthquakes. First preserved records account for more than 100 years of instrumental seismology already, outperforming the time-span covered by modern broad-band seismic networks. But their uniqueness, as a document, prior to the generalization of massive methods of copy and distribution, limits the usability and availability of the earliest seismograms for research purposes. Contemporaneous analysis of old seismograms predated fundamental developments in quantitative seismology, as well as the digital revolution, suggesting the reanalysis of these unique and valuable records with modern seismological tools for the direct calculation of earthquake source parameters, at least for the most relevant events.

However, this is not straightforward: Early seismograms have been recorded at instruments with low dynamic range and narrow frequency band. Many times the complementary information required to process the records and to recover ground displacement, like instrument calibration and time accuracy, has been lost or is doubtful. In fact, procedures to make old seismograms useful for quantitative analysis are, in many aspects, similar to those needed to process and to use old macroseismic information. The present contribution reviews the main topics and methodologies leading to a proper use of old seismograms and related documents, including the location and distribution of the original seismograms and recording system information, as well as the sequence from the original paper seismogram to digital ground displacement, involving digitization, trace correction and deconvolution of the instrument response. We discuss the potential and the limitations of such treatments, and review some applications of recovered records in retrieving earthquake source parameters through full waveform analysis.

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1 Introduction

Seismograms can be regarded as the most comprehensive and quantitative documents of the ground motion produced by earthquakes, and are the basis of the large majority of earthquake studies. Only the availability and constant improvement of quantitative data made possible the development of seismology as a quantitative science. Modern seismology has produced a huge variety of methodologies and tools, many of which have become standard, to investigate earthquake source characteristics, seismic wave propagation and earth structure from waveforms recorded in digital form. Many of such calculations are performed on a routine basis by different agencies on global and regional scale.

But seismograms much older predate these relatively recent developments. First preserved records date from the end of the XIX century, accounting already for more than 100 years of instrumental seismology. Those old records were not obtained, evidently, in digital form: they are analogue records. Many times we call them historical seismograms or, simply, old seismograms, for all records before the 1960s, when standardizing efforts like the WWSSN deployment and the related system of microfilming and distribution, and other parallel initiatives around the world, made seismograms more easily available for researchers. Early records are unique documents preserved mainly on paper. Up to now, and mainly for technological reasons, it has not been easy the archiving, copying and distribution of these seismograms, but many of the original recordings are still preserved today. Actually, also WWSSN microfilms and analogue tape recordings fall within the scope of this article, in the sense that they require digitization and dedicated pre-processing.

But, are these records important to present seismology? The answer is definitely yes. But it is a conditional one, with many similarities to the importance of old macroseismic data to modern seismology. The main interest to use old records arises from the uniqueness of each earthquake. Earthquakes nucleate at some place and time, and rupture propagates according to instantaneous conditions along a fault. Among them, the largest earthquakes – either in a regional or global context- are particularly interesting because they are the most exceptional ones over the long-term earthquake cycle and often absent over the only two decades for which we dispose of modern-standard broad-band recordings, while on the other hand they are the most relevant to characterize seismic hazard and strain release. Kanamori (1988) proposed an exhaustive list of general research topics for which we apparently depend on the evaluation of old seismograms: (1) Global seismicity and (2) subduction zone seismotectonics, (3) Rupture process of large earthquakes, (4) Study of seismic gaps, (5) Regional seismotectonics, (6) Seismic moment release, (7) Strong motion seismology, (8) Tsunami earthquakes and (9) Unusual events in general.

The interest and willingness to preserve the quantitative documents of the Earth's physical activity and processes comes from far, even it was often an oscillating consciousness. One of the important results of the International Geophysical Year (IGY) of 1956–57 was the creation of the "International Data Centers", envisaged as depositories of the large amount of data necessary to study the Earth. Similar initiatives took off in other fields. Of our interest, for its global character, is the organization and management of the WWSSN data centre, in charge of the centralization and distribution of the recorded seismograms over the world. Also, in the 80s, following the resolutions approved by the IASPEI and the task of the IASPEI/UNESCO Working Group on Historical Seismograms, the World Data Centre A (WDC-A) started collecting, microfilming and archiving of seismograms recorded before 1963 (Glover and Meyers 1982, 1988 and references therein). More recently, applying the modern digital facilities, other efforts to store copies of the old seismograms as images in digital format have been undertaken. Among them, we may point to the SISMOS and the EUROSEISMOS projects at European scale (Michelini et al. 2005). Also Lee impulses a project to digitize part of the microfilm chips of the WWSSN (see Lee and Benson, this volume).

If we are interested to study an old earthquake, we face the necessity to use old records. At a first glance, it looks like it involves only the digitization of the relevant portions of the waveforms in the old recordings, and to process those time series with the available tools. But, at this point, problems arise. Among them, it can be mentioned that old seismograms have been recorded with narrow-band, low-range instruments, now technologically surpassed and let behind. Many times the complementary information (metadata) required to process the records and to recover ground displacement, like instrument calibration and time accuracy, has been lost or is doubtful. Even, sometimes, the physical support of the record, the paper itself, is in poor conditions and physical restoration of the document is needed (Ferrari and Roversi Monaco 2005). In few words, the use of historical waveforms is not straightforward. In fact, procedures to make old seismograms useful for earthquake analysis (restoration, metadata, study of the context) are, in many aspects, similar to those needed to process and to use old macroseismic information.

In the next sections we report some of our own experience in processing and evaluating this particularly challenging kind of data, and summarize other efforts within the seismological community to use early waveforms for the quantitative analysis of seismic sources. The present contribution reviews the main topics and methodologies leading to a proper use of old seismograms and related documents, including the location and distribution of the original seismograms and recording system information, as well as the sequence from the original paper seismogram to digital ground displacement, involving digitization, trace correction and deconvolution of the instrument response. We discuss the potential and the limitations of such treatments, and show the performance of recovered records of ground displacement in analyzing earthquake source parameters.

2 Early Seismic Sensors and Recording Systems

The beginning of quantitative recording of earthquake ground motion is more related to the solution of technical problems that of scientific ones. Even though the nature of earthquakes sources and shaking was not well understood, it was known from old times that a suspended mass (a pendulum) oscillates with earthquakes.

Also, a propagating nature of earthquake disturbances was crudely assumed since the second half of the XVIII century (see, for example, Agnew 2002, for a short sketch of the history of seismology). Problems arise when we try to keep a record of the motion of the suspended mass. As ground motions are often small, it will be also necessary some kind of amplification and the whole system should be very sensitive and stable at the same time. These problems impeded the recording of ground motion generated by earthquakes prior to the second half of the XIX century, when technical solutions became available and first recording tests took place. Italian Filippo Cecchi's instrument of 1875, with separate record of the two horizontal components, can be considered the first modern seismograph. Milne, Ewing and others were recording earthquakes in Japan already in 1881 (Dewey and Byerly 1969). After these firsts records of near earthquakes have been obtained, Ernst von Rebeur-Paschwitz (1889) discovered the possibility to record major earthquakes also at teleseismic distances. As early as 1895, J. Milne, under the auspices of the British Association for the Advancement of Sciences, deployed the first world seismographic network. But, unfortunately, the seismograms of these Milne pendulums, recorded on photographic paper at too slow speed (1–4 mm/min), are useless for waveform studies, because consecutive wiggles are drawn one onto another and only the seismogram envelope is preserved.

At the beginning of the XX century, a number of new seismological observatories began recording earthquakes, forming an early, however sparse and heterogeneous seismic network. Instrument design includes purely mechanical sensors, transferring pendulum motion continuously onto smoked papers, as the Bosch-Omori seismographs (Batlló et al. 2004) or the Wiechert instruments (Wiechert 1904). The last ones became soon a de-facto standard and the most widely distributed instruments, at least for the purpose of recording relatively long period motion, up to the IGY. A second group of widely used instruments couple the pendulum with a galvanometer, record ground motion electromagnetically via induced currents, and keep a photographic record (Galitzin 1914). In fact, electromagnetic instruments are more sensitive than mechanical ones but, again, technical problems (like the demagnetization of transducer magnets and the difficulties to manage photographic records) delayed its generalization until the 50s. Figure 1 shows the world distribution of seismic stations around 1909–10. To collect old waveforms for an individual earthquake, we may consider database facilities like EUROSEISMOS, a request – or the inspection of seismogram archives- at seismic observatories or their successor organizations, and sometimes even high-quality reproductions of seismograms in the contemporaneous scientific literature.

An important feature of early seismographs, severely complicating the analysis of old recordings, is the diversity of instruments. Existing networks were instrumented very heterogeneously, and even a same type of instrument was operated under different settings from one observatory to another. This diversity arises mainly from two reasons. First one is that the basic principles of earthquake recording were not definitely established and many "trial and error" experiments were going on. Second one is due to the limited bandwidth and range of the instruments, as discussed later. No recording configuration was able to record all signals of interest,

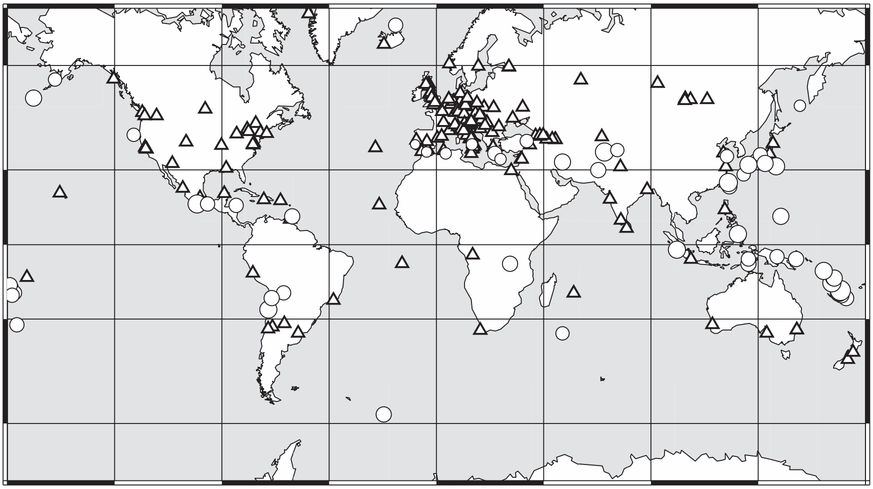

Fig. 1 Worldwide distribution of seismic stations (*triangles*) from Schweitzer and Lee (2003) complemented with data from Merlin and Somville (1910) and magnitude 6+ earthquakes (*circles*, from Gutenberg and Richter 1954), for the years 1909–1910. Around 150 seismological stations were operative at that time, but, on a first sight, only for approximately fifty of them seismograms are available (IASPEI Working Group 2006)

and different purposes resulted in different recording parameters. Therefore, the study of an event recorded in old seismograms implies to deal with many different kinds of records, with different dimensions, diverse recording speeds, and different instrument transfer functions. Consequently, the recovering and consideration of related metadata, describing the mode of operation of the recording system, is an issue as important as the recovering of the seismogram itself. Of main importance are the free period, the damping, the magnification and the orientation and polarity of the recording system. Often, these instrument characteristics may be recovered from contemporaneous bulletins and station books, or from daily calibration pulses included on many old seismograms. This kind of signals, the recording of an electromagnetic or mechanical kick to the oscillating mass, permit to obtain directly damping from the decay of the calibration pulse, as well as the free period in case of undercritical damping of the system.

3 Conservation, Digitization and Restitution of Analog Recordings

The reanalysis of arrival times, polarities and amplitudes contained in old station bulletins is fundamental to our knowledge on old earthquakes (e.g. Abe 1981, Dineva et al. 2002), and the qualitative assessment of waveform similarity and a trivial comparison of the raw amplitudes can even lead to a quite robust estimation of the relative size of nearby earthquakes recorded at the same (or nearby) stations (e.g. Kanamori et al. 2006). Here, however, we centre our interest in the investigation of full waveforms preserved on old seismograms, which can, in general, give us a more complete picture of the earthquakes process. Consequently, the objective is to convert our analogue record, supported on paper, to a digital time series of seismic ground motion, ready to use for any of our waveform analysis tools. The first step of such a procedure, just like for the purpose of conservation and digital storage of old records, is the scanning of the seismogram as a raster image.

The first key decision is the dpi density the raster image should be acquired to preserve the resolution of the original seismogram. The answer is tied to the dimensions of the trace to be extracted: It is unlikely to find traces thinner than 0.1 mm on smoked paper. To have a good definition of the trace on a digitalized image, we should have at least 3 pixels covering the thickness of the trace (i.e. 762 dpi). Such a resolution allows to properly defining the centre of the trace. In the case of photographic paper records, line width is much larger, and just half this estimate is enough. SISMOS and EUROSEISMOS projects adopted a basic scanning density of 1,016 dpi, this is, 4 pixels in 0.1 mm, for all records.

As seismograms are always monochrome records (black on white for photographic records, white on black on smoked papers, a unique color on white in the case of ink paper records) grayscale scanned images are enough to keep the information about the trace without any loss of resolution. For the case of film scanning, dpi density should be adjusted to the scale of the filmed seismogram to maintain the resolution of the original image. Such parameters (1,016 dpi, grayscale) impose the record dimensions: For the example of a WWSSN record (900 × 300 mm) the scanned image size will be ~440 MB. The efficiency of file compression algorithms depends on the image characteristics, and is usually good only for photographic or ink recordings. Only recently, image processing with standard PC's, and the management of databases containing thousands of these files at large facilities has become functional. Finally, prior to trace extraction, it is useful to optimize the characteristics of the raster image enhancing the contrast, brightness and other parameters adjustable within standard image processing software.

Following, the waveform of the seismic trace of interest (usually just a fragment of the section contained in the image) must be extracted and pre-processed for further seismic analysis. This involves the digitization itself and several steps of trace correction. On early studies involving the use of digitized old seismograms, the digitization of the trace was performed from the original records, or enlarged copies obtained with photographic techniques, with digitizing tables (ex.: Adams and Allen 1961, Howell 1966, Wickens and Kollar 1967, Batlló et al. 1997). Even, some studies used digitized points obtained directly on the seismograms measuring with a rule (Samardjieva et al. 1997). Actual procedures typically avoid the use of special hardware and involve the use of computer software to extract the traces from the scanned images. Several commercial or freeware programs, not specially designed for seismological purposes, are available for this step. Most of them involve the manual picking of points. Whichever will be the program, control on the original scale of the record, i.e., accurate control of the exact coordinates of the picked digitization points, must be carefully maintained.

Also, some specific programs have been developed for this purpose (among others: Teves-Costa et al. 1999, Baskoutas et al. 2000, Liu et al. 2001). The most comprehensive and "up to date" are SeisDig (Bromirski and Chuang 2003) and TESEO (Pintore et al. 2005). Both are intended for general distribution. In most cases, totally automatic digitization of the seismograms has shown, up to now, extremely problematic. Main problems are interruptions on the trace lines, the variation of the contrast of the image from one part to another and the continuous crossover of lines. The use of a semiautomatic digitization scheme, where the user has the possibility to feed back with the algorithm, allowing the redrawing of wrong sectors of the acquired trace or editing of points, is currently the best option when image quality is quite good. Otherwise, a purely manual digitization is not more time consuming than any semiautomatic procedure. Figure 2 shows a scanned and processed seismogram. As it can be seen, small dimensions and frequency contents are important handicaps for its digitization.

After a series of points on the seismic trace has been extracted, several corrections are necessary to convert it into a ready to process description of ground motion. They depend on the type of seismograph and on some specific technical problems of each one, and can be grouped into geometrical corrections, timing corrections and instrument corrections.

Arm length correction and skew correction as geometrical corrections depend on the geometrical characteristic of the recording seismograph and are implemented analytically, point by point. They should be applied only to records on mechanical seismographs. The correction for arm length arises from the conversion of the motion of the inertial mass of the mechanical seismographs into a rotational motion through the use of levelers. The recording arm, with the stylus attached to it, moves on an arc of circumference over the recording drum. If the longitude of the arm and its angle from the vector of angular velocity on the drum are known, the curvature of the record can be immediately corrected, point by point (Cadek 1987, Samardjieva et al. 1997). Schlupp (1996) refines this correction taking into account the dimensions of the drum where the record was wrapped.

Record skew correction, also known as the detrending of the zero-line, are necessary when the equilibrium point of the inertial mass is such that the recording arm does not stand parallel to the vector of angular velocity (Crouse and Matuschka 1983). Figure 2 shows an example of arm length and skew correction. Problems may arise when the equilibrium point of the inertial mass changes during the event recording, as shown by Inoue and Matsumoto (1988) in the case of strong motion records. In this case, a particular analysis and correction is needed, though sometimes high-pass filtering may reduce the impact of those instabilities. Figure 3 shows an example of this problem. It is possible, but uncommon, to find skew in photographic records. It is due to misalignments between the recording drum and the light spot projection system.

Corrections of time marks present more difficult problems. They haven't direct analytical solution and some hypotheses should be made to process the record. Time marks are present in almost all old seismograms. They are introduced in the record in three ways:

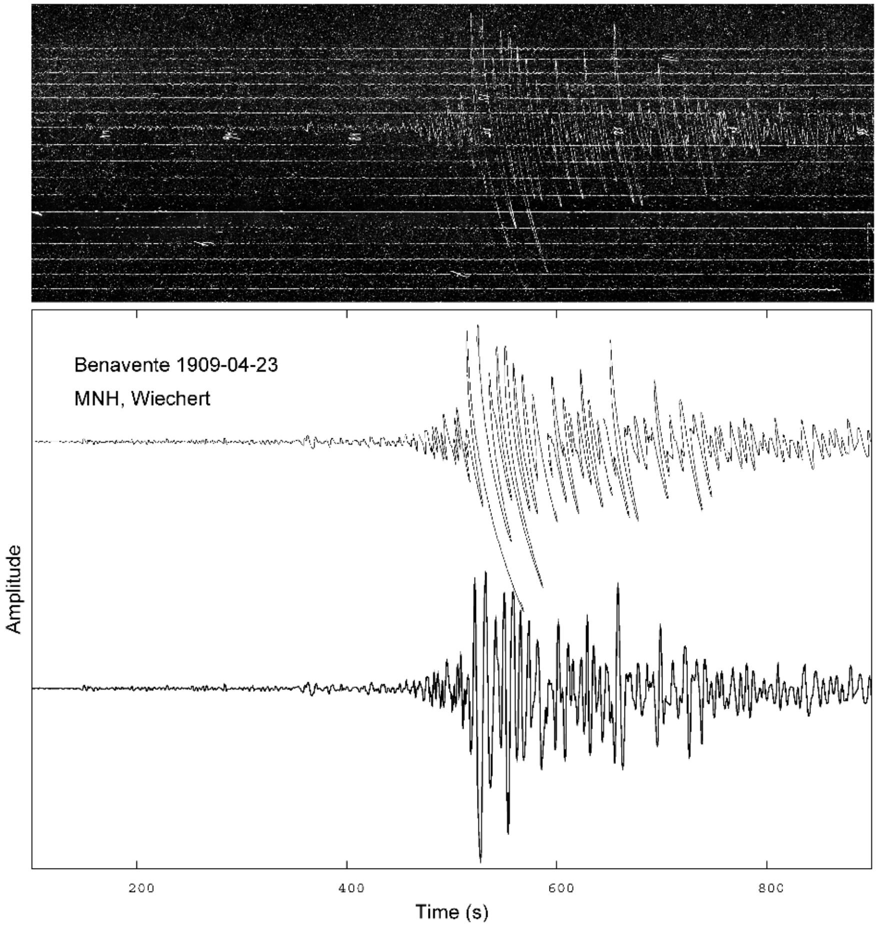

Fig. 2 *Top*: Scanned image of the record of the N–S component of the Wiechert seismograph at Munich seismic station for the 23 April 1909 Benavente earthquake, near Lisbon. *Upper trace*: Raw digitized record. *Lower trace*: The same record corrected for arm length curvature and skew. Note how the time mark (minute 50 in the seismogram image), clearly visible in the raw digitized record at about 530 s, in this case remains almost invisible after geometrical correction

- With an additional stylus, external to the recording stylus. They do not introduce distortion on the record, but absolute timing problems may arise due to parallax.
- Directly on the record: an electromagnet shakes the stylus or interrupts the record. In both cases, part of the record is lost. In some cases (low frequency motion) it is possible to ignore them. Schlupp (1996) introduced and tested linear predictive filter to successfully reconstruct part of the missing signal after interpolation.
- Finally, an electromagnet displaces the record line. The displaced fragment should be reintegrated to the "unaltered" trace.

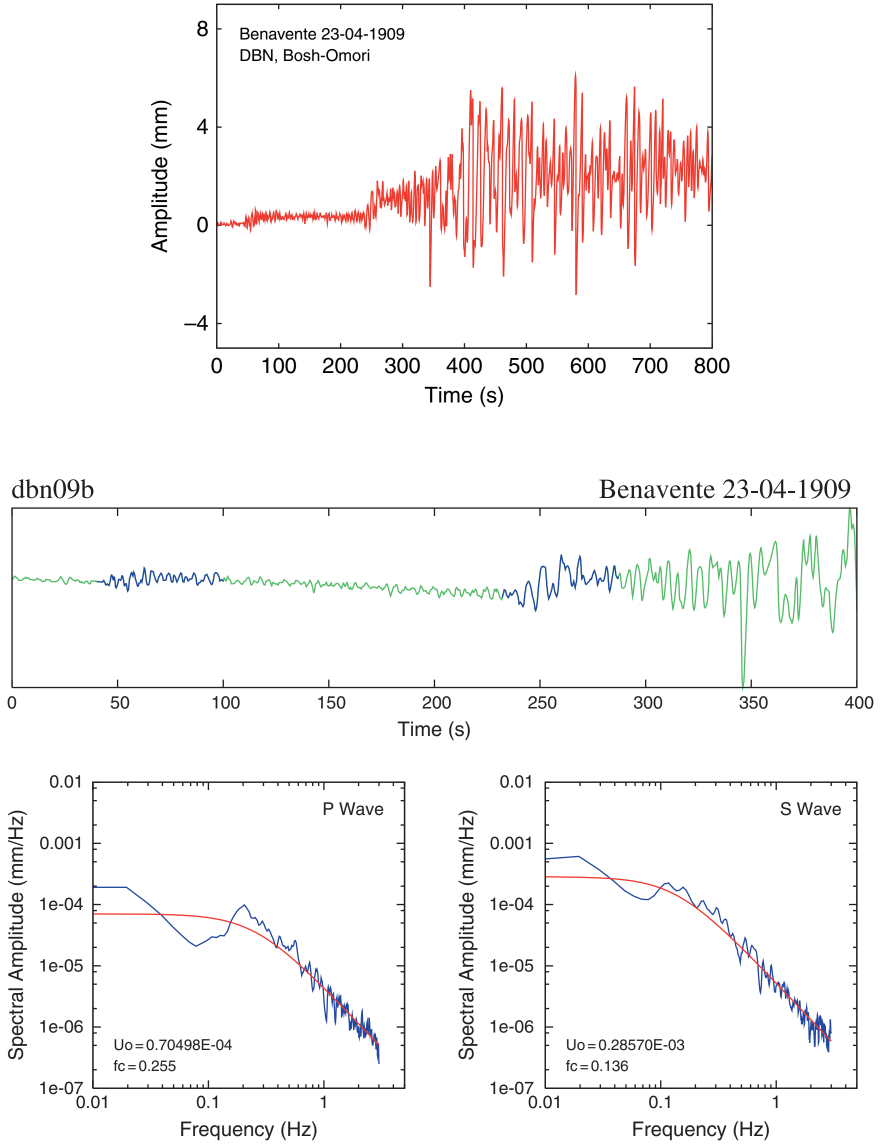

Fig. 3 (**a**) Digitized record of the Bosch-Omori seismograph at De Bilt seismic station for the 23 April 1909 Benavente earthquake, near Lisbon. It is clearly seen how a displacement of the equilibrium centre of the recording mass occurs during the P and S wave arrivals. Note also the whole dimension of the record, peak to peak maximum amplitude is just 15 mm. In the horizontal scale 100s are equivalent to 25 mm. (**b**) Even though mass displacement is noteworthy, after HP filtering (Butterworth filter at half the free period of the instrument) the P and S wave spectra give reasonable results

While bothersome for the retrieval of waveforms, time marks are essential to control the record speed and convert distance on the seismograms to differences in time. Especially for uneven recording speed or for distorted raster images of seismogram sections (e.g. due to the process of photographic reproduction), time marks are key to recover the time series. Between time marks, fluctuations of the recording drum angular velocity may distort the apparent frequency contents of the record. As the real instantaneous velocity of the drum is unknown, Herrmann (1987) suggested interpolating linearly between time marks. After these corrections are applied, the records can be interpolated to a constant sampling rate.

After such preprocessing, the signal amplitude is still given in counts, and we need to deconvolve the proper instrument response to restitute actual ground displacement. The instrument transfer functions are defined by design characteristics as are the damping and the magnification of the system, the free period of the pendulum, and the free period of the coupled galvanometer in case of electromagnetic recording systems. Above the free period of the instruments, the magnification drops rapidly, following a ω^{-2} slope for purely mechanical sensors, and a ω^{-3} slope for electromagnetic sensors (e.g. Kanamori 1988, Batlló 2004). Below the free period, nominal sensor sensitivity is nearly flat for purely mechanical sensors and drops proportional to ω for electromagnetic sensors. Near the free period, the response curve is conditioned by the damping of the pendulum motion. Some of the earliest instruments are essentially undamped except of friction effects, making a stable restitution of ground motion problematic. The removal of the instrument response through deconvolution is a task performed by many standard seismic processing tools. Though most of them do not contemplate the responses of old mechanical and electromagnetic instruments directly, it is possible to introduce the response as a series of poles and zeroes (Scherbaum 1996, Batlló and Bormann 2000, Batlló 2004).

For mechanical instruments a further problem arises. The inscription system (leveler contacts and stylus) presents a non negligible amount of dry friction. Dry friction is a dissipative force and introduces a loss of signal energy. It is a problem that, even early acknowledged (Reid 1925), still needs further studies to properly characterize its importance. Also, sometimes, mainly for some mechanical instruments, the transfer function may not be exactly linear (Herak et al. 1997, Ritter 2002). To complete our description of possible pitfalls, we recall that even idealized instrument transfer functions may be inappropriately estimated, since instrumental parameters are sometimes insufficiently documented (if at all) in contemporaneous sources, and furthermore may be subject to temporal drifts and fluctuations. Especially damping on mechanical seismographs may depend on the daily variations of room temperature. This type of uncertainties is particularly critical for the restitution of intermediate period waveforms (e.g. Rodgers 1968, Stich et al. 2005). Given the uncertainties of estimated transfer functions and the potential instabilities of deconvolution, a more stable alternative for waveform modeling may be applying the convolution of the corresponding instrument response to the synthetic Green functions instead (e.g. Kikuchi et al. 2003, Ichinose et al. 2003), or – in case we want to compare two real seismograms recorded with different instrument response- the re-convolution of the records with the interchanged instrument responses (Rivera et al., 2002). In both cases the resulting traces are directly comparable since they correspond both to the same transfer function.

4 Inversion of Source Parameters from Historical Seismograms

Digitized and corrected time series from old seismogram recordings can –in principle – be used in any state-of-the-art digital inversion procedure to derive point source seismic source parameters or the distribution of rupture parameters over a finite fault. However, there are evident differences between modern recordings of the seismic wavefield at dense networks of modern-standard accelerometers or very broadband velocity sensors with force feedback technology and 24 bit digitizing systems (Wielandt 2002), and sparse early XX century recordings. Beneath station coverage, the main limitation is due to the small dynamic range and bandwidth of early instruments. The dynamic range is nominally limited between the most tiny amplitude differences we can resolve and digitize on analogue recordings, about 0.2–0.3 mm under most favourable conditions, and the full width of the recording medium, which does not exceed 30 cm. This corresponds to about 60 dB. To translate this into the language of the digital seismologist: The double amplitude of digitized waveforms is intrinsically limited to 1,000 meaningful counts, which would be equivalent to the performance of a 10 bit digitizer. Considering the enormous amplitude range of seismic ground motion in nature, only for small subsets of earthquake magnitudes and epicentral distances the input signal could be recorded appropriately at those instruments. In practice, the dynamic range will be even smaller due to background noise at the low end, or due to nonlinearity and imaging issues at the high end of the recording range.

The frequency bandwidth of early instruments is conditioned by the free period of the pendulum, as well as the free period of the coupled galvanometer where applicable. By early XX century standards, long period recording meant free periods for either seismometer or galvanometer to be 10–25 s at horizontal components, and less for vertical sensors (e.g. Kanamori 1988, Batlló 2004). For longer periods, the decrease of instrument magnification is proportional to ω^{-2} for mechanical sensors, and ω^{-3} for electromagnetic sensors, usually corresponding to just the same decay of dynamic range for the longer period component of recorded ground motion (12 dB/octave and 18 dB/octave, respectively). At the high frequency end, bandwidth is practically limited at about 1–4 Hz by an instrument-specific ratio between the effective pen width and the velocity of the recording media: high frequency wiggles in quick succession may be drawn onto one another and cannot be distinguished readily anymore. In this case, aliasing effects may be introduced into the digitized waveforms (c.f. Scherbaum 1996), and recordings with too low drum speed are not suitable for digital waveform analysis.

Teleseismic recordings of early XX century recordings are a comparably reliable source of information. Teleseismic body waves with periods of a few seconds carry a lot of information on the source process and are recorded with low distortion in the flat part of the instrument response. Teleseismic body wave arrivals for large events can be picked rather accurately, overcoming the notorious timing inaccuracies of early seismographs, and permitting a consistency check between the assumed component polarities and the direction of the incident ray. Consequently, many studies focused on modelling or inverting teleseismic body waves to constrain the orientation of faulting, scalar seismic moment, and source time histories (e.g. Singh et al. 1984, Stein et al. 1988, Doser 1992, Doser et al. 1999, Alvarado and Beck 2006). A combination of teleseismic data and either geodetic leveling data or observed surface faulting was used to obtain finite slip distributions for several large earthquakes (e.g. the 1906 San Francisco earthquake by Wald et al. 1993; the 1923 Kanto earthquake by Wald and Somerville 1995; the 1905 Mongolian earthquakes at Tsetserleg and Bolnay by Schlupp and Cisternas 2007, and the 1944 Tonankai earthquake by Ichinose et al. 2003). Many of those results are highly relevant for science and society, such as the fault dimensions of early XX century subduction earthquakes in Japan or Mexico.

When historical teleseismic waveforms are on scale and well resolved, the long period component may be input into routine schemes for global source parameter retrieval, as shown by Okal and Reymond (2003), who use long period (100–200 s) mantle Love and Rayleigh waves to invert for the seismic moment tensor of the 1938, Mw 8.5 Banda Sea earthquake from the azimuthal pattern of spectral amplitudes, or Huang et al. (1998), who systematically applied the Harvard centroid moment tensor technique (Dziewonski et al. 1981) to a global set of 35 pre-WWSSN deep earthquakes (depth 330–670 km, Mw 6.3–7.9), benefiting from the comparably even resolution of moment tensor elements and simple excitation kernels for deep focus events.

For local and regional distance recordings, the small range, bandwidth, and station sparseness may introduce more severe complications in the analysis of historical waveforms. Strong ground motion is off scale, except for few purpose-built low gain instruments that may have recorded near-regional P waves of large earthquakes (Kikuchi et al. 2003, Ichinose et al. 2003). The limited frequency bandwidth affects the reliability of restituted long period ground motion, and source analysis must be often based on shorter period components that do not account for the entire source process and, furthermore, are severely influenced by small-scale heterogeneity affecting regional wave propagation. Two strategies to stabilize source retrieval suggest the use of as unaltered historical recordings as possible, that is substituting the deconvolution of the instrument response from the target waveforms by the corresponding convolutions (see previous section and Rivera et al. 2002, Kikuchi et al. 2003, Ichinose et al. 2003), or the direct processing of individual un-rotated horizontal component seismograms instead of the usual radial and transverse waveforms (Stich et al. 2005), to avoid distortions introduced by rotation of pairs of horizontal historical seismograms with incorrect alignment, uneven drum speed, and imprecise instrumental correction.

Comparably stable approaches for analysing regional historical data include the retrieval of scalar seismic moment from displacement amplitude spectra (e.g. Teves-Costa et al. 1999, Pino et al. 2000), or seismic moment rate from empirical

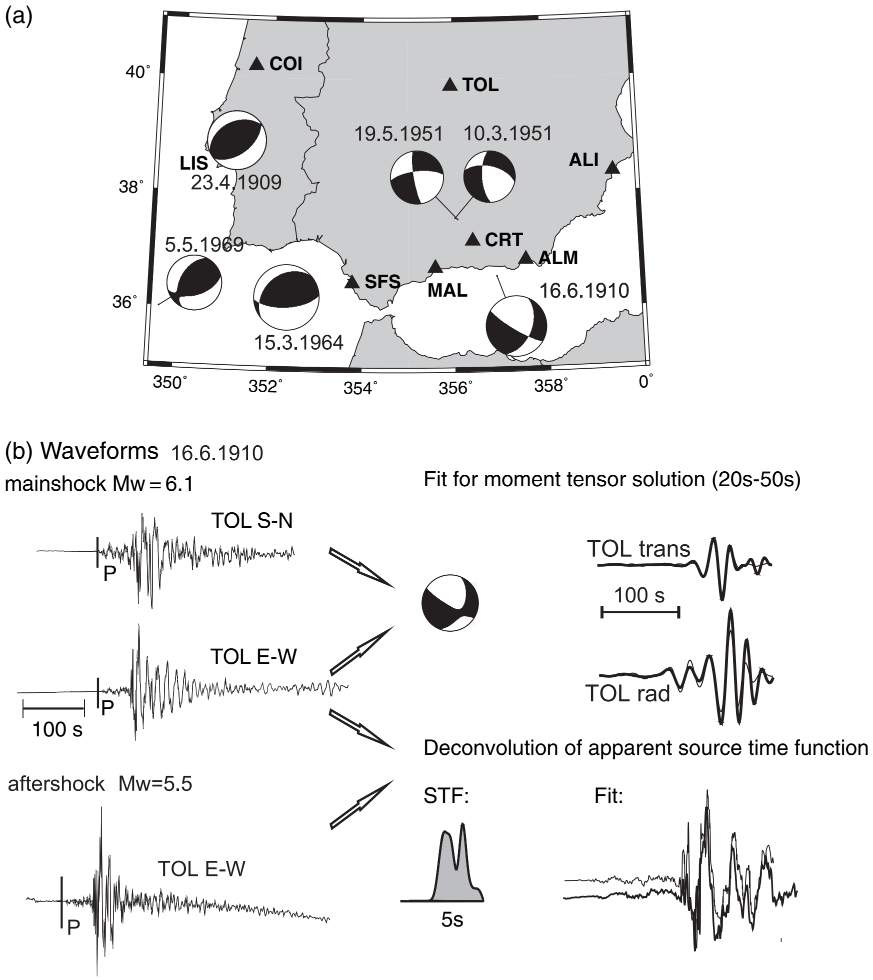

Fig. 4 (**a**) Map showing early seismic observatories (*triangles*) and regional moment tensor estimates from digitized analogue data for the south of the Iberian Peninsula (Pondrelli et al. 1999, Stich et al. 2003, 2005, Batlló et al. 2008), showing a NE–SW orientation of P-axes and a change in faulting style from east to west consistent with source estimates from modern broad band data (Stich et al. 2006). (**b**) Waveform examples for the 16 June 1910 Adra earthquake recorded at station TOL, showing original seismograms after geometrical corrections (*left*), moment tensor fits to intermediate period waveform (*upper right*, the inversion is based on 5 stations altogether, Stich et al. 2003), and waveform fits and apparent source time functions from aftershock deconvolution (*lower right*)

Green functions analysis based on aftershock waveforms (Stich et al. 2003, Batlló et al. 2008, Fig. 4). Forward modeling of sparse regional waveforms can provide valuable insight into focal mechanisms (Baroux et al. 2003), and slip distribution in the case of large events like the Mw 7.1, 1908 Messina Strait earthquake (Pino et al. 2000). Time domain moment tensor inversion of regional historical intermediate period waveforms led to useful source approximations for the largest instrumentally recorded shallow earthquakes that hit Portugal, Spain and France, respectively (Mw 5.5–6.1, Stich et al. 2003, 2005, Fig. 4), showing good consistency with modern seismotectonic studies. For later decades, technical advances including the densification of networks and the deployment of electrodynamic instruments in addition to existing mechanical systems, permitted moment tensor inversion for smaller earthquakes in areas of comparably dense station coverage, e.g. the case of a Mw 5.2 and 5.3 earthquake doublet in 1951 in southern Spain (Batlló et al. 2008, Fig. 4), or small to moderate (Mw 4.5–5.6) aftershocks of the 1952 Kern County earthquake in California (Dreger and Savage 1999).

5 Conclusions

In the early XX century, fundamental concepts of seismic source physics, such as the double couple model for the equivalent body forces of a shear dislocation, were yet to be discovered, as well as the benefits of computer technology and digital signal processing. Fundamental advances of scientific theory and methodology should lead themselves to a reprocessing and reinterpretation of previously obtained data, which is especially true for analog seismograph recordings. To date, most of the instrumental era in seismology predates the invention of digital recording systems and processing schemes, containing the larger share of all moderate and large earthquakes for which waveform information may be available. Large earthquakes, either in a regional or global context, are the rarest events within the seismic cycle, and may be of particular interest, although sometimes their analysis from historic recordings may be hampered by the small dynamic range (causing nonlinearity or clipping of the signal) or the narrow bandwidth (with the instruments being not sufficiently sensitive to long period signals, leading to an underestimation of the total source duration and seismic moment). The characterization of source properties from recorded waveforms of early XX century earthquakes may provide key information for very diverse topics such as regional tectonics and strain accumulation, the identification and kinematics of individual seismogenic faults, earthquake recurrence and seismic hazard, tsunami generation, or the benchmarking of contemporaneous magnitude estimates or earthquake parameters derived from macroseismic observations.

Pointed reasons strongly sustain the need to reanalyze the seismograms of past conspicuous events. The use of such records for seismic research may expand considerably the instrumental period of earthquake seismology. But such reanalysis is not straightforward. Especially dedicated procedures should be taken into account, from restoration of the physical support to the search and recovery of the metadata accompanying the old seismograms to be processed. It is necessary to recover, at least, the information concerning the transfer function, orientation, and polarity of the recording instrument from seismic bulletins, photography and other contemporaneous documents. In the previous sections the acquisition of analogue records obtained from old seismograms, its special characteristics and processing and some possibilities they offer for actual research have been reviewed. Special attention has been paid to the processing procedures, from the scanning of the record image to the generation of a digital seismogram useful for modern seismic analysis tools. Often, the older the seismogram, the more critical is the accurate control of issues like image resolution and adequate instrument performance, complicating the whole procedure. All these factors point to the conclusion that image acquisition and the consecutive digitization and restitution of ground displacement is, in general, a time consuming process. This limits the scope of the different campaigns developed at several institutions to recover and make available those records. Despite those difficulties, the reprocessing of old seismograms for inversion of source parameters can – and did- yield results highly relevant for science and society.

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Making Non-Digitally-Recorded Seismograms Accessible Online for Studying Earthquakes

W. H. K. Lee and R. B. Benson

Foreword Instrumental observations of earthquakes using the available technology at different times have been carried out over the past 120 years at either single seismic stations or networks of various sizes, from local to global scales. Before the 1980s, almost all seismograms were recorded on paper or photographic medium. Due to wars or neglects, many of these analog (or non-digitally recorded) seismograms had been lost, or are deteriorating and disappearing in a rapid rate.

This article is intended to summarize the authors' efforts to rescue and preserve seismograms, and to post non-digitally recorded seismograms and related research materials online for free access by anyone, anywhere. We also included some background information about observational seismology and constructions of online archives of old seismograms by others.

1 Introduction

Seismology became a quantitative scientific discipline after instruments were developed to record seismic waves in the late 19th century (Dewey and Byerly 1969; Agnew 2002). Earthquake seismology is essentially based on field observations. The great progress made in the past several decades has been primarily due to increasingly plentiful, high-quality digital data that have been archived in open and readily accessible archives designed exclusively for this purpose (see e.g., Ahern 2003). Our ability to collect, process, and analyze earthquake data has been accelerated by advances in electronics, communication, computers, and software, and is no longer limited by communication and technical difficulties that hampered scientists in the early years of seismology.

Historically, instrumental observations of earthquakes using the available technology at different times have been carried out over the past 120 years at either single seismic stations or networks of various sizes, from local to global scales (see e.g., Lee 2002). The observed data have been used, for example, (1) to compute

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the source parameters of earthquakes, (2) to determine the physical properties of the Earth's interior, (3) to test the theory of plate tectonics, (4) to map active faults, (5) to infer the nature of damaging ground shaking, and (6) to carry out seismic hazard analysis. Constructing a satisfactory theory of the earthquake process has not yet been achieved within the context of physical laws. Good progress, however, has been made in building a physical foundation of the earthquake source process, partly as a result of research directed toward earthquake prediction. All of this effort has been hinged on reliable data access.

However, the instrumental record of earthquakes collected over the past 120 years is too short for reliable seismic hazard assessments and therefore, non-instrumental observations of earthquakes in the past must be utilized as much as possible. For example, Jean Vogt (1979) led an in-depth research program for revising French earthquake catalogs to better understand the seismicity near nuclear power plants in France, as required by the French government for safety considerations. The importance of historical records about earthquakes is well-recognized as shown in many articles of this volume. Semi-quantitative analysis of earthquake intensity data has been practiced for many decades in preparing seismic hazard maps (see, e.g., Frankel et al. 2000; Musson and Cecic 2002; Giardini et al. 2003). In addition, extending our knowledge about earthquakes by means of archaeological and paleoseismogical methods and techniques have been pursued by many scientists as summarized, for example, by Nur (2002) and by Grant (2002), respectively.

This article is intended to summarize the authors' efforts (in the past three decades) to rescue and preserve seismograms, and in particular, to post non-digitally recorded seismograms and related research materials online for free access by anyone, anywhere. We also included some background information about observational seismology and constructions of online archives of old seismograms by others.

2 Seismographs for Monitoring Earthquakes

Besides geodetic data (see, e.g., Feigl 2002), the primary instrumental data for the quantitative study of earthquakes are seismograms, records of the ground motion caused by the propagation of seismic waves generated by earthquakes. Seismograms are written by seismographs, instruments that detect and record ground motion with timing information. A seismograph usually consists of three components: (1) a seismometer that responds to ground motion and produces a signal proportional to acceleration, velocity, or displacement over a range of input motions in amplitude and in frequency; (2) a timing device; and (3) a recording device that writes seismograms (ground motion plus time marks) on papers or on electronic storage media. An accelerograph is a seismograph designed to record the time history of acceleration of strong ground motion on scale. Most modern seismographs are velocigraphs recording the time history of ground velocity (see e.g., Wielandt 2002 for a discussion of seismometry). A seismic network (or array if sensors are in close proximity to one another) is a group of seismographs that are "linked" to a central headquarters. The link is by mail or telegrams in the early days or simply by manual collecting of the records, and by various methods of telemetry since about 1950s. When we speak of a seismic station, it may be an observatory with multiple instruments in special vaults, or a small instrument package buried in a remote unmanned site.

2.1 *Early Years*

In the beginning of instrumental seismology, observatories with various types of seismographs operated independently. The observatories were linked by mail, which could take months. Many seismological studies require seismograms or their readings from multiple stations. For example, arrival times of seismic waves from at least four well-distributed stations are needed to locate an earthquake satisfactorily. Even after one managed to get a few seismograms, it was difficult to work with records from different instruments with poorly synchronized time until after about 1930.

In the late 19th century the need for standardization and for data exchange was recognized by G. Gerland, J. Milne, and E. von Rebeur-Paschwitz. With the support of the British Association for the Advancement of Science, over 30 Milne seismographs were placed at locations throughout the British Empire beginning in the late 1890s, and seismogram readings were reported to Milne's observatory at Shide on the Isle of Wight, England. A global earthquake summary with seismogram readings was issued by John Milne beginning in 1899, as shown in Fig. 1 by Milne (1900). These summaries are now known as the "Shide

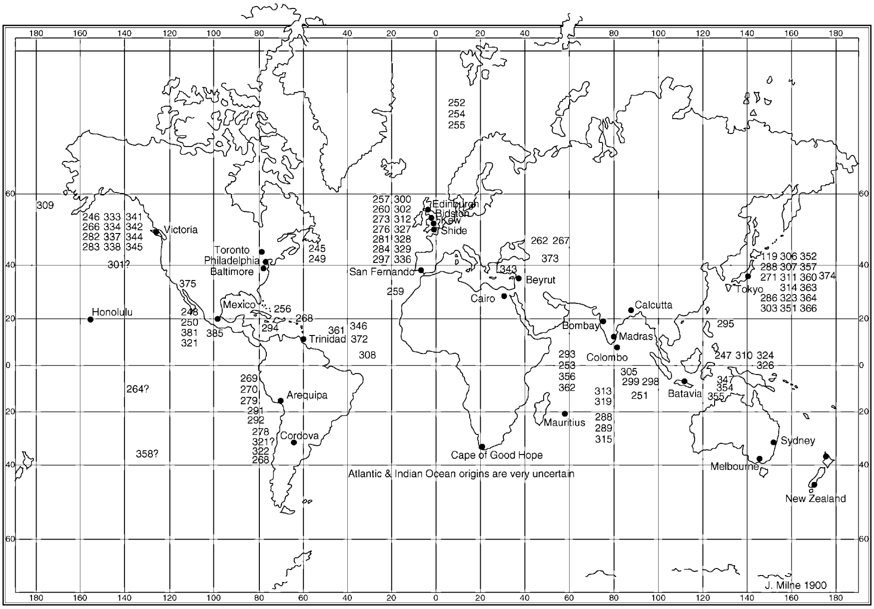


Fig. 1 Global earthquakes and seismograph stations in 1899, as published in Milne (1900). Numbers refer to earthquakes listed in Milne's catalogue and show approximate positions

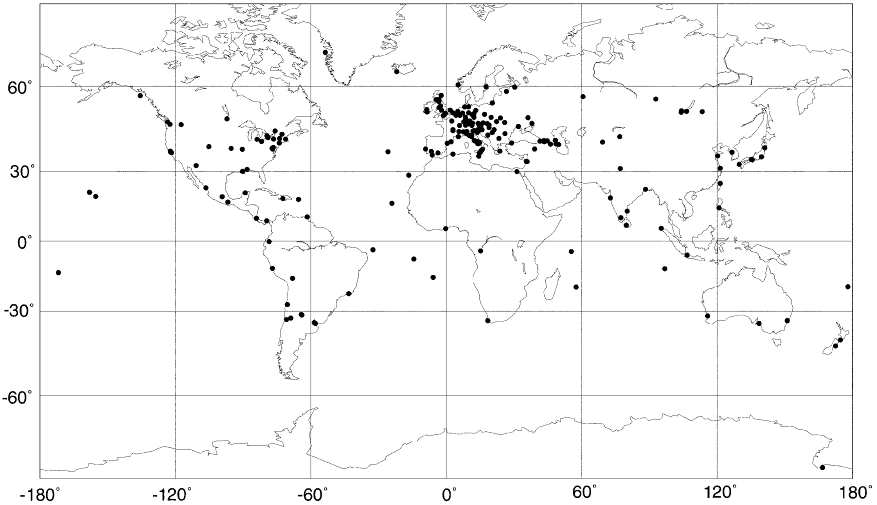


Fig. 2 A map showing all seismographic stations for which we could locate seismic bulletin materials with earthquake observations from before 1921 (from Schweitzer and Lee 2003)

Circulars" (Schweitzer and Lee 2003). Milne seismographs were soon superseded by more advanced instruments, and the Headquarters of the International Association of Seismology was established in Strassburg im Elsass (now, Strasbourg, France) by 1904 (Adams 2002).

Seismographs for recording teleseisms were installed at many observatories, especially meteorological and astronomical observatories. By 1920, about 250 seismic stations were established (although some operated only briefly), as shown in Fig. 2. The early enthusiasts included academic professors, Jesuits, and gentleman scientists. Revolutions and wars, however, frequently disrupted progress, especially in collecting and distributing earthquake information, during the first half of the 20th century.

2.2 WWSSN and ESSN

In the late 1950s, attempts to negotiate a comprehensive test ban treaty failed, in part because of perceptions that seismic methods were inadequate for monitoring the underground environment for nuclear testing (Richards 2002). The influential Berkner report of 1959 advocated major support for seismology (Kisslinger and Howell 2003). As a result, the World-Wide Standardized Seismograph Network (WWSSN) was created with about 120 continuously recording stations, located over much of the world (except China and USSR) in the early 1960s (Oliver and Murphy 1971), as shown in Fig. 3. Each WWSSN station was equipped with identical sets of short-period and long-period three-component seismographs and accurate chronometers. Seismograms were sent to the United States to be photographed

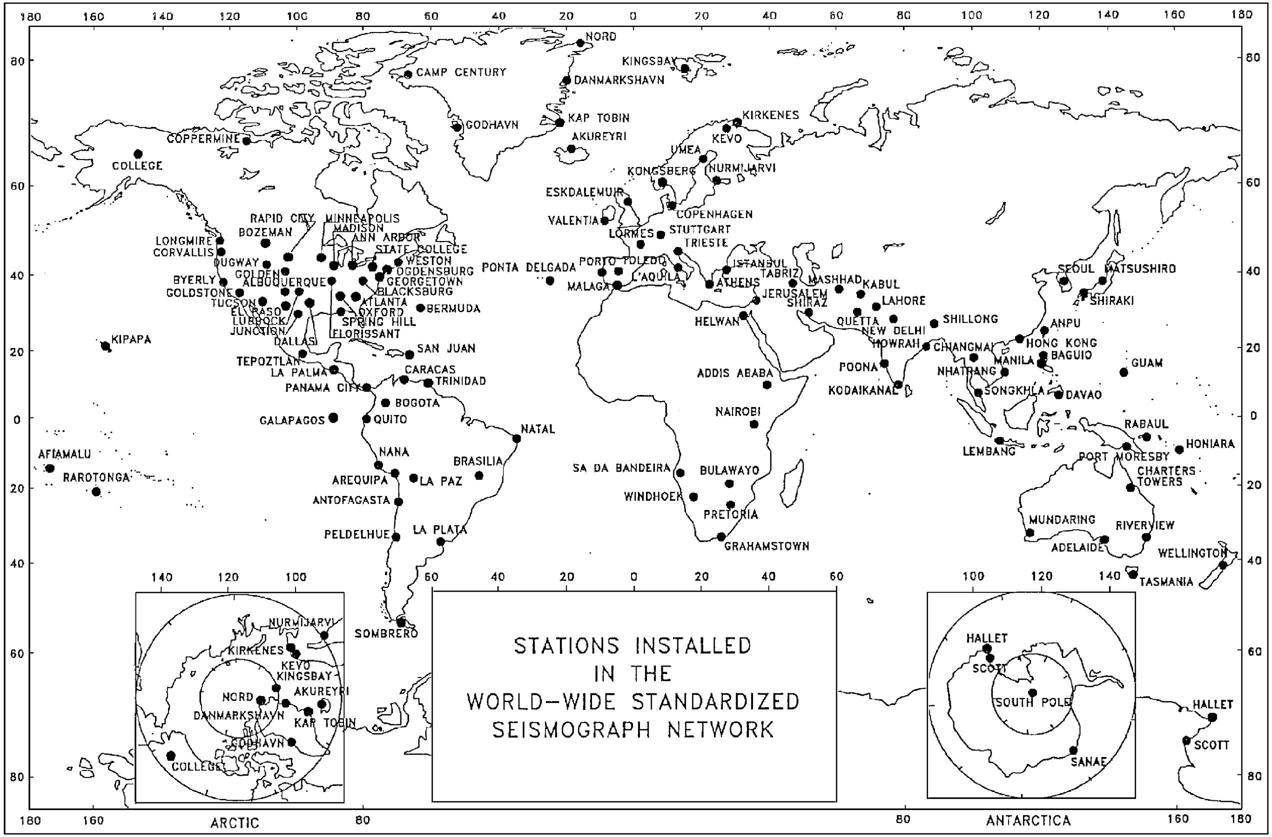


Fig. 3 Stations installed in the World-Wide Standardized Seismograph Network (WWSSN) in the 1960s

onto 70-mm film chips for distribution (about $1 per chip). This network is credited with making possible rapid progress in global seismology and with aiding the plate-tectonic revolution in the earth sciences in the late 1960s (Sykes 2003).

At about the same time, the Unified System of Seismic Observations (ESSN) of the former USSR and its allied countries was established for monitoring earthquakes, consisting of almost 100 stations equipped with Kirnos short-period, broadband (1–20 s displacement sensing), and long-period seismographs, as shown in Fig. 4 (Shishkevish 1974).

Despite its great success, the WWSSN declined after the mid-1970s. By then it had produced about 4 million seismograms, far more than seismologists could efficiently process and analyze. After about 10 years of operation, funding for the WWSSN began to disappear. The initial cost was funded by the U.S. Defense Advanced Research Projects Agency (DARPA), which emphasized research and not long-term operation. Funding for continuing the WWSSN was then left to the National Oceanic and Atmospheric Administration (NOAA) and subsequently to the U.S. Geological Survey (USGS). Because of statutory restriction, the USGS could not support global stations outside the United States. Although the U.S. National Science Foundation (NSF) did pick up the funding for supporting foreign stations for some time, NSF also wanted to avoid funding any ongoing seismic networks. In addition, the emphasis in seismology at the USGS was shifting to earthquake prediction, then considered a new and promising venture. Earthquake prediction, however, turned out to be far more difficult than anticipated (e.g., Kanamori 2003).

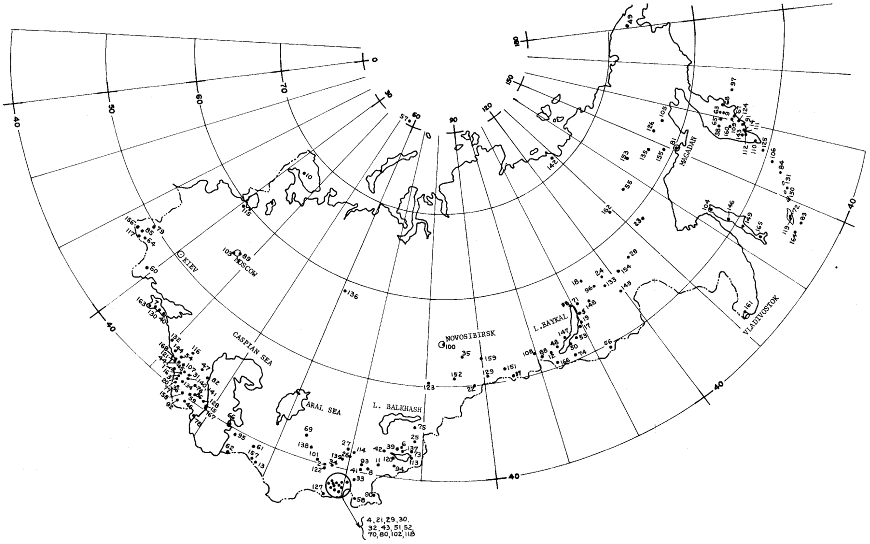


Fig. 4 Location of seismographic stations in the USSR (from Shishkevish 1974). Station names corresponding to the numbers shown can be found in Shishkevish 1974 (p. 10)

2.3 The Digital Revolution and the GDSN

Because analog (i.e., non-digitally recorded) seismograms have a low dynamic range (about 3 orders or less in amplitude) and must be digitized for computer processing, some seismologists recognized that "digital" instrumentation should be developed to achieve a much higher dynamic range, and for ease of computer processing. Many scientists and engineers in other disciplines had already been making great advances in that direction because of the emerging digital technology in the 1970s. Seismologists had long recognized that the tandem use of short-period and long-period instruments was needed to avoid the natural seismic noise (see Webb 2002). They realized that a new global seismic network should be built with (1) broadband, high-dynamic range seismographs, (2) digital electronics, (3) communication by telemetry or a mass storage medium, and (4) processing by computers.

The introduction of electronic force feedback to sealed inertial seismometers (Melton 1976; Wielandt and Streckeisen 1982) together with the application of high-resolution analog-to-digital converters made it possible to construct broadband, large dynamic-range seismograph systems. Many of the WWSSN stations were replaced by broadband digital systems starting in the 1980s (Hutt et al. 2002). A global digital seismic network has emerged since the 1980s under the guidance of two effective organizations: the international Federation of Digital Broadband Seismographic Networks (FDSN), and the Incorporated Research Institutions for Seismology (IRIS). Digital seismograms recorded by stations worldwide are now readily available via the Internet from the IRIS Data Management Center (DMC) within tens of minutes of a $M \approx 5.7$ (all depths, or $\mathrm{M} = 5.5$ for events $> 100\,\mathrm{km}$ depth) or larger earthquake occurring anywhere in the world (Ahern 2003), as well as, for example, through the European ORFEUS center at De Bilt, the Netherlands, the GEOFON center at the GeoForschungsZentrum, Potsdam, Germany, the Programme GEOSCOPE at the Institut de Physique du globe de Paris, France. Large strides have been made in networking these data centers, as well, so that data can be accessed transparently through web or imbedded interfaces, eliminating the need to know the specific location of waveform data in these distributed archives.

3 Microfilming Historical Seismograms of the World

Before the digital era (prior to 1980), seismograms were usually recorded locally on paper (a common size is about 30 cm by 90 cm) every day. There are usually 6 seismograms at a given station: east-west, north-south and vertical components for both long-period and short-period seismometers. Because of their size and fine resolution, seismograms were not easily reproducible until the 1960s. Consequently, seismologists must spend large amounts of time and effort to collect seismograms for their studies of earthquakes that occurred before the WWSSN era (i.e., before

1963). Many seismograms have been lost because of two World Wars and numerous political disturbances, and also because of poor storage conditions for preservation.

As noted by Kanamori (1988), "… old seismograms, if properly interpreted, provide invaluable information on earthquakes in the past, and every effort should be made to save them, …" Because modern digital seismograms cover only about the last 25 years, the analog seismograms collected during the first 100 years of observational seismology are very valuable for seismological research, especially in characterizing seismicity for seismic zonation, probabilistic seismic hazard analysis, and earthquake prediction research (Lee et al. 1988).

3.1 Preservation and Distribution of Historical Seismograms

In early 1977, W.H.K. Lee and J.F. Lander prepared a report, "A plan for establishing an international library of significant seismograms", and asked the International Association of Seismology and Physics of the Earth's Interior (IASPEI) to consider endorsing such a project. Lee and Lander's proposal was well received at the IASPEI General Assembly in August, 1977. Subsequently, IASPEI passed the following resolution:

> …it is essential that seismograms of significant earthquakes be systematically collected and preserved by making photographic copies at observatory sites, and be made available through the World Data Centres. IASPEI urges that seismological observatories around the world cooperate with a copying programme….

Following up on this resolution, the IASPEI Sub-Commission on Data Exchange established a working group for copying historical seismograms with Jorgen Hjelme as Chairman. In 1978, W.H.K. Lee obtained funding from the U.S. Geological Survey to begin the Historical Seismogram Filming Project in collaboration with the World Data Center A. These early efforts are summarized in Meyers and Lee (1979).

3.2 Working Group on Historical Seismograms

In July 22–24, 1981, the United Nations Educational, Scientific and Cultural Organization (UNESCO) sponsored a meeting of experts on historical seismograms during the IASPEI General Assembly in London, Ontario, Canada. A joint IASPEI/UNESCO Working Group on Historical Seismograms was established with W.H.K. Lee as its chairman. The proceedings of this meeting were summarized in a UNESCO report released in September, 1981, which was included in Lee et al. 1988 (pp. 6–10).

In December 20–22, 1982, the Working Group convened a regional workshop at the Earthquake Research Institute, University of Tokyo, Japan. The primary purposes of this Workshop were (1) to gain interest and cooperation from Asian seismological observatories, and (2) to evaluate the existing seismograms recorded by the Asian observatories. Six technical sessions were held with over 50 participants. The proceedings of this meeting were summarized in a report to UNESCO in March, 1983, which was included in Lee et al. 1988 (pp. 11–13).

In August 18–19, 1983, the Working Group convened a workshop in conjunction with the IASPEI General Assembly in Hamburg, Germany. This Workshop was organized to discuss the status of historical seismic data for Latin America and Europe. It was divided into six sessions with a total of 29 presentations from representatives of 19 countries and 4 international organizations. The proceedings of this meeting were summarized in a report to UNESCO in October, 1983, which was included in Lee et al. 1988 (pp. 13–15).

In addition to microfilming pre-1963 seismograms, the Working Group was actively engaged in organizing auxiliary earthquake information (such as station bulletins), and promoting research in studying instrumental and pre-instrumental earthquakes. Consequently, the name of the Working Group was changed to "Historical Seismograms and Earthquakes". The status of the Historical Seismogram Filming Project was presented by Glover and Meyers (1988) and appeared earlier in more detail in Glover et al. (1985). In brief, over 500,000 seismograms and station bulletins from 450 stations around the world were microfilmed. Countries that participated include China, Egypt, Germany, India, Japan, Philippines, Peru, USA, and USSR.

Unfortunately, the main source of funding to microfilm seismograms worldwide was terminated by the U.S. Geological Survey at the end of 1985, and no other funding source was found to replace it. The Working Group came to a halt and was disbanded after a book describing this effort was published (Lee et al., 1988).

4 Scanning WWSSN Seismograms

The World-Wide Standardized Seismograph Network (WWSSN) was fully operational in 1963 under the auspices of the U.S. Coast and Geodetic Survey (USCGS). Each WWSSN station consisted of 3 short-period (SP) and 3 long-period (LP) seismometers, recording apparatus, radio-synchronized crystal clock, and calibration controls (WWSSN 1964; Oliver and Murphy 1971). Typically, six 300 mm × 900 mm seismograms were produced each day (3 SP and 3 LP). Data were originally recorded on photographic paper mounted on rotating drums, and later (1980s) on heat sensitive paper. The rotation rate of the SP drums was one revolution every 15 min, resulting in a 60 mm/min chart speed (1 mm/s). The rotation rate of the LP drums was one revolution per hour, resulting in a 15 mm/min chart speed. Note that some of the LP records in the early 1960s were recorded at 30 mm/min. There are minute marks on the records (an offset in the traces of 2-s duration every minute). The time marks were recorded using the NIST WWVB broadcast signal, and typically have an accuracy of better than 100 milliseconds. Hours are marked with a 5-s offset, with no offset on the 0, 6, 12, and 18 h UTC.

The original photographic records were photographed using 70 mm film and stored by station and year on 70 × 120 mm film chips (one seismogram per film chip). Lamont-Doherty Earth Observatory and the USGS Albuquerque Seismological Laboratory (ASL) each hold a complete film chip set of the WWSSN seismograms. The slow degradation of these film chips, however, prompted a pilot scanning project.

4.1 First Rescue Attempt of WWSSN Seismograms

The idea of scanning the WWSSN film chips within the USGS came about in 1996 by Charles R. Hutt. A limited amount of USGS "data rescue" funding was used to perform some test film-chip scans. Direct scans of the 70 mm film chips were found possible if one used scanners having a resolution of at least 3200 dpi. One of the original ideas was to also digitize the waveforms on the scanned images, but this was judged to be too expensive. In late 1998, two high-resolution scanners were purchased to scan as many film chips as possible with the available funding. The main events of interest at the time were underground nuclear tests, along with some earthquakes. The event list was chosen in consultation with other government agencies and researchers interested in the project, resulting in scanning about 30,000 film chips of 156 nuclear events and 78 earthquakes.

The film chips are black and white and were scanned with a resolution of 3200 dpi. This is equivalent to scanning the original 300 × 900 mm seismogram at 394 dpi (the seismogram image on the film chip is approximately 8 times smaller than the original seismogram). The image has been cropped to exclude areas on the film chip which do not contain the image of the original record, but includes the record stamp containing station name, component, start and stop date and time of the record, and magnification. Because the primary selection was on U.S. nuclear explosion events, the 78 selected earthquakes were made for comparison purposes, and thus are not necessarily of primary interest to earthquake seismologists. In 2004, it was agreed that the IRIS Data Management Center would be the perpetual archive for these and other image files of non-digital recorded seismograms (see Section 5.1 for a description).

4.2 Second Rescue Attempt of WWSSN Seismograms

In fiscal year 2004, the International Council of Scientific Unions (ICSU) provided modest funding to the USGS to scan some WWSSN film chips. The USGS provided a similar amount of "in-kind" support (film-chip storage, work space, management oversight, etc.). A total of 10,548 film chips were scanned for 117 selected earthquakes on the basis of interest to earthquake seismologists. Due to funding limitations, seismograms from only 38 out of 123 WWSSN stations were selected.

The earthquake selection was made by W.H.K. Lee, starting with the Centennial Earthquake Catalog of Engdahl and Villasenor (2002) and selecting the largest earthquakes down to magnitude of 6.9 for the time period from 1962 to 1974. He then considered earthquakes that killed a lot of people from Utsu's deadly earthquakes list (Utsu 2002), and added some smaller events of seismological interests. Since this initial list had about 250 events, Lee sorted them by Flinn-Engdahl regions (FER) (Flinn et al. 1974) and chose at least one event (the largest if more than one is available) in each region.

Because the list contains 151 earthquakes, about 50% more than that could be scanned, Lee circulated the list to about 20 earthquake seismologists worldwide for comments and suggestions. Since no one proposed to delete any earthquakes on the list, Lee downsized the list by choosing fewer events after 1970. The final list of 117 earthquakes selected for the USGS/ICSU scanning project is given in Table 1. The station selection was made by C.R. Hutt so that stations are well-distributed globally, in addition to being either the current digital GSN stations or reasonably proximal to one (distance indicated in the table, if applicable), and a listing of the selected WWSSN stations is given in Table 2.

5 The SeismoArchives Project

In the past decade, modern information technology (including the World-Wide Web and the Internet) has made it possible to archive large volumes of data with back-end data storage for easy online search and access. Therefore, we take one step beyond scanning and preserving occasional analog seismograms. A new project termed the "SeismoArchives" utilizes these new technologies to make scanned seismograms and related materials readily accessible as online source material, suitable for research. The primary goal of the SeismoArchives project is to create online seismogram archives of significant earthquakes of the world. Unfortunately, because no funding is yet available for constructing these SeismoArchives, we depend on volunteers and donations of data files and/or financial support for scanning analog seismograms that date back as far as 1882.

These analog seismograms (about 50 millions pieces) have been disappearing at an alarming rate. We are now concentrating on preserving a small fraction of the seismograms recorded by the World-Wide Standardized Seismograph Network (Oliver and Murphy 1971) in the 1960s and 1970s (about 4 million seismograms on 70 mm film chips), and of the seismograms microfilmed by the Historical Seismogram Filming Project (Glover and Meyers 1988) in the 1980s (about 0.5 million seismograms on microfilms for earthquakes prior to 1963).

5.1 The IRIS Data Management Center

The Data Management Center (DMC) of IRIS is hosted by the University of Washington's Earth and Space Sciences Program in Seattle, Washington, USA. The IRIS DMC receives seismic data from nearly 100 networks worldwide. It archives more than 40 years of digital data, although almost most of them are from the past

Table 1 Selected earthquakes for the USGS/ICSU scanning project

Year	Mo	Dy	Hr:Mn	Lat	Long	Depth	Magnitude	FER	Deaths	Place/Name
1962	3	7	11:01	19.10	145.23	640	6.9 Mw	HRV	216	
1962	3	17	20:47	10.80	−43.30	15	7.0 mB	ABE1	403	
1962	4	12	0:52	38.07	142.74	24	7.2 Mw	P&S	228	
1962	5	11	14:11	17.18	−99.64	35	7.3 Mw	P&S	59	
1962	5	21	21:15	−20.00	−177.37	437	7.5 Mw	HRV	181	
1962	7	26	8:14	7.49	−82.78	23	7.2 Mw	P&S	83	
1962	8	3	8:56	−23.28	−68.01	113	7.2 mB	ABE1	123	
1962	9	1	19:20	35.56	49.81	19	6.9 Ms	ABE1	347	12225 Iran: Qazvin
1962	12	8	21:27	−25.81	−63.27	588	7.2 Mw	HRV	129	
1963	3	26	9:48	−30.11	−177.53	35	7.4 Mw	P&S	178	
1963	4	16	1:29	−1.13	128.00	34	7.2 Mw	P&S	267	
1963	4	19	7:35	35.63	96.96	15	6.9 Ms	ABE3	325	
1963	7	26	4:17	42.04	21.38	0	6.1 M	Utsu	383	1070 Macedonia: Skopje
1963	8	15	17:25	−13.71	−69.32	549	7.7 Mw	HRV	118	
1963	9	15	0:46	−10.47	165.76	35	7.5 Mw	P&S	184	
1963	9	17	19:20	−10.28	165.41	29	7.5 Mw	P&S	184	
1963	10	13	5:17	44.76	149.80	26	8.5 Mw	KANA	221	Kuril Is.
1963	10	20	0:53	44.76	150.56	27	7.9 Mw	P&S	222	
1963	11	4	1:17	−6.73	129.68	35	7.8 mB	ABE1	280	
1963	11	9	21:15	−8.98	−71.53	577	7.7 Mw	HRV	113	
1963	12	15	19:34	−4.76	108.05	666	7.1 Mw	HRV	275	
1963	12	18	0:30	−24.77	−176.51	35	7.7 Mw	P&S	171	
1964	2	6	13:07	55.64	−156.07	3	7.1 Mw	P&S	17	
1964	3	28	3:36	61.01	−147.62	6	9.2 Mw	KANA	2	131 Great Alaska EQ
1964	4	23	3:32	−5.42	133.93	5	7.1 Mw	P&S	204	
1964	4	24	5:56	−5.06	144.27	105	6.9 mB	ABE2	202	
1964	5	26	10:59	−56.24	−27.63	116	7.5 mB	ABE1	153	
1964	6	16	4:01	38.43	139.22	10	7.6 Mw	P&S	226	26 Japan: Niigata
1964	9	12	22:07	−49.07	164.39	27	6.9 Ms	ABE1	166	
1964	10	18	12:32	−7.18	123.80	581	7.0 Mw	HRV	280	

1964	11	17	8:15	−5.75	150.72	50	7.1 Mw	P&S	192	
1965	1	24	0:11	−2.45	125.96	28	8.2 Mw	P&S	270	71 Indonesia: CeramSea
1965	2	4	5:01	51.21	178.49	28	8.7 Mw	KANA	6	Aleutian Is.
1965	3	14	15:53	36.40	70.71	209	7.5 mB	ABE1	718	
1965	3	28	16:33	−32.49	−71.21	71	7.4 mB	ABE1	135	337 Chile: La Gigua
1965	4	29	15:28	47.31	−122.33	66	6.5 mb	ISC	29	USA: Puget Sound
1965	8	11	3:40	−15.47	166.98	17	7.2 Mw	P&S	186	
1965	8	11	22:31	−15.79	167.25	46	7.6 Mw	P&S	186	
1965	8	23	19:46	16.17	−95.84	10	7.4 Mw	P&S	60	
1965	9	12	22:02	−6.47	70.74	29	7.0 UK	BRK	426	
1965	11	13	4:33	43.84	87.75	51	7.0 UK	B&D	332	
1966	3	4	23:58	−38.70	178.00	33	6.2 M	NZ	160	NZ: Gisborne
1966	3	20	1:42	0.84	29.86	15	7.2 UK	B&D	567	200 Uganda/Zaire
1966	6	7	13:59	11.30	139.63	49	7.1 UK	B&D	209	
1966	6	15	1:32	−10.11	161.02	13	7.3 Mw	P&S	193	
1966	8	19	12:22	39.16	41.57	17	6.8 M	Utsu	366	2517 Turkey: Varto
1966	10	17	21:41	−10.79	−78.68	34	8.1 Mw	KANA	115	110 Peru: Lima
1966	10	19	8:01	−1.58	−15.39	19	7.0 UK	B&D	407	
1966	12	28	8:18	−25.50	−70.65	30	7.7 Mw	P&S	122	
1967	2	9	15:24	2.89	−74.80	41	7.2 Mw	P&S	103	98 Colombia
1967	2	15	16:11	−9.12	−71.32	600	7.0 Mw	HRV	112	
1967	3	13	16:06	−40.19	−74.84	23	7.3 UK	BRK	143	
1967	7	22	16:56	40.62	30.74	4	7.4 Mw	P&S	366	173 Turkey: Mudurnu
1967	7	30	0:00	10.55	−67.31	23	6.5 M	Utsu	97	240 Venezuela: Caracas
1967	11	23	8:35	14.44	51.98	12	7.0 UK	B&D	415	
1967	12	10	22:51	17.39	73.77	4	6.4 Ms	ISC	314	180 India: Koyna
1967	12	21	2:25	−21.86	−69.94	44	7.4 Mw	P&S	123	
1967	12	27	9:17	−21.21	−68.18	116	7.0 mB	ABE1	124	
1968	1	15	2:01	37.78	13.03	3	6.5 M	Utsu	398	231 Italy: ValdeBelice
1968	2	19	22:45	39.37	24.94	8	7.2 Mw	P&S	365	

Table 1 (continued)

Year	Mo	Dy	Hr:Mn	Lat	Long	Depth	Magnitude	FER	Deaths	Place/Name
1968	4	1	0:42	32.48	132.19	29	7.5 Mw	P&S	236	
1968	5	16	0:49	40.90	143.34	26	8.2 Mw	KANA	229	52 Japan: Tokachi-oki
1968	5	16	10:39	41.59	142.78	11	7.8 Mw	P&S	224	
1968	5	23	17:24	−41.74	172.12	46	7.2 Mw	P&S	162	NZ: Inangahua
1968	5	28	13:27	−2.92	139.40	63	7.2 mB	ABE1	197	
1968	6	19	8:13	−5.55	−77.15	17	6.9 Ms	ABE1	111	46 Peru: San Martin
1968	8	1	20:19	16.38	122.07	52	7.7 Mw	P&S	249	207 Philippines(Luzon)
1968	8	3	4:54	25.64	128.46	29	7.1 Mw	P&S	238	
1968	8	10	2:07	1.42	126.25	19	7.6 Mw	P&S	266	
1968	8	14	22:14	0.06	119.69	17	7.3 Mw	P&S	265	392 Indonesia(Celebes)
1968	8	18	18:38	−10.20	159.95	542	7.3 Mw	HRV	193	
1968	8	31	10:47	34.03	58.96	11	7.2 Mw	P&S	348	15000 Iran: Dasht-i Biyaz
1968	10	7	19:20	26.29	140.68	518	7.3 Mw	HRV	212	
1968	10	23	21:04	−3.37	143.31	9	7.1 Mw	P&S	200	
1969	1	30	10:29	4.76	127.43	73	7.1 mB	ABE1	263	
1969	2	11	22:08	41.42	79.23	13	7.1 UK	B&D	320	
1969	2	28	2:40	35.91	−10.57	21	7.8 Mw	P&S	739	
1969	3	29	9:16	11.91	41.21	35	6.3 M	Utsu	558	40 Ethiopia: Sardo
1969	7	18	5:24	38.41	119.45	10	7.2 Mw	P&S	658	
1969	8	11	21:27	43.47	147.81	45	8.2 Mw	KANA	221	Kuril Is.
1969	8	17	20:14	24.84	−109.68	32	7.2 UK	B&D	49	
1969	11	21	2:05	1.97	94.57	10	7.6 Mw	P&S	705	
1969	11	22	23:09	57.72	163.59	9	7.8 Mw	P&S	218	
1969	12	25	21:32	15.72	−59.64	11	7.2 Mw	P&S	92	
1970	1	8	17:12	−34.88	178.85	207	7.0 mB	ABE1	179	
1970	1	10	12:07	6.78	126.68	59	7.3 Ms	ABE1	259	
1970	3	28	21:02	39.17	29.54	24	7.4 UK	B&D	366	1086 Turkey: Gediz EQ
1970	4	7	5:34	15.77	121.65	29	7.2 Mw	P&S	249	Philippines: Luzon
1970	4	12	4:01	15.08	122.01	15	7.0 Ms	USCGS	248	
1970	4	29	14:01	14.45	−92.76	50	7.3 Mw	P&S	69	

1970	5	14	18:12	43.09	47.06	11	6.6 M	Utsu	337	many Russia: Dagestan
1970	5	31	20:23	−9.24	−78.84	73	7.9 Mw	KANA	109	66794 Peru: Peru EQ
1970	6	11	16:46	−59.41	159.22	15	7.3 Mw	P&S	167	
1970	6	15	11:14	−54.36	−64.11	3	7.0 Ms	USCGS	148	
1970	7	25	22:41	32.24	131.67	45	7.0 Mw	P&S	235	
1970	7	30	0:52	37.83	55.88	9	6.6 Ms	USCGS	341	220 Iran: Karnaveh
1970	7	31	17:08	−1.48	−72.55	644	7.5 mB	ABE1	103	
1970	8	30	17:46	52.34	151.61	649	7.3 Mw	HRV	663	
1970	12	10	4:34	−4.07	−80.66	19	7.1 Mw	P&S	110	81 Peru/Ecuador
1971	1	10	7:17	−3.23	139.74	55	7.7 Mw	P&S	201	
1971	2	09	14:01	34.40	−118.39	5	6.4 M	Utsu	43	58 USA: San Fernando
1971	5	22	16:43	38.86	40.53	4	7.0 M	Utsu	366	995 Turkey: Bingol
1971	7	14	6:11	−5.51	153.90	44	8.0 Mw	P&S	190	
1971	7	26	1:23	−4.88	153.18	37	8.1 Mw	P&S	190	
1971	12	15	8:29	56.02	163.17	21	7.8 Mw	P&S	218	
1972	1	25	2:06	22.55	122.32	10	7.5 Mw	P&S	243	
1972	2	29	9:23	33.37	140.88	58	7.5 Mw	P&S	211	
1972	4	10	2:06	28.41	52.78	5	6.9 Ms	NEIS	353	5010 Iran: Ghir EQ
1972	6	11	16:41	3.86	124.23	329	7.8 Mw	HRV	262	
1972	7	30	21:45	56.69	−136.09	7	7.6 Mw	P&S	20	
1972	12	23	6:29	12.35	−86.12	6	6.2 M	Utsu	75	6000 Nicaragua: Managua
1973	6	17	3:55	43.22	145.74	43	7.8 Mw	P&S	224	
1973	9	29	0:44	41.90	130.97	569	7.8 Mw	HRV	659	
1973	10	6	15:07	−60.95	−21.62	15	7.5 Ms	ISC	732	
1974	5	8	23:33	34.57	138.77	11	7.2 UK	B&D	230	30 Japan: Izuhanto−oki
1974	7	4	19:30	45.18	93.93	15	7.5 UK	B&D	334	
1974	12	28	12:11	35.02	72.90	13	6.2 M	Utsu	710	5300 Pakistan: Pattan

Table 2 Selected WWSSN stations for the USGS/ICSU scanning project

Number	Code	Latitude	Longitude	Location	Digital station
0011	ARE	−16.46	−71.49	Arequipa,	Peru NNA
0038	ESK	55.32	−3.21	Eskdalemuir,	Scotland ESK
0078	NNA	−11.99	−76.84	Nana,	Peru NNA
0001	AAE	9.03	38.77	Addis Ababa,	Ethiopia FURI
0005	AFI	−13.91	−171.78	Apia,	Western Samoa AFI
0112	ANP	25.18	121.52	Anpu,	Taiwan TATO
0009	ANT	−23.70	−70.42	Antofagasta,	Chile LVC
0021	BOG	4.62	−74.07	Bogota,	Columbia BOCO
0026	CHG	18.79	98.98	Chiengmai,	Thailand CHTO
0028	COL	64.90	−147.79	College,	Alaska COL,COLA
0030	COR	44.59	−123.30	Corvallis,	Oregon CSR
0031	CTA	−20.09	146.25	Charters Towers,	Australia CTAO
0033	DAV	7.09	125.57	Davao,	Philippines DAV
0042	GIE	−0.73	−90.30	Galapagos Islands,	Ecuador PAYS
0044	GUA	13.54	144.91	Guam,	Marianas Islands GUMO
0048	HNR	−9.43	159.95	Honiara,	Solomon Islands HNR
0070	KBS	78.92	11.92	Kingsbay,	Spitsbergen KBS
0052	KEV	67.76	27.01	Kevo,	Finland KEV
0053	KIP	21.42	158.02	Kipapa,	Hawaii KIP
0055	KON	59.65	9.63	Kongsberg,	Norway KONO
0064	MAT	36.54	138.21	Matsushiro,	Japan MAJO
0072	MUN	−31.98	116.21	Mundaring,	W. Australia NWAO (142 km)
0074	NAI	−1.27	36.80	Nairobi,	Kenya NAI, KMBO
0073	NAT	−5.12	−35.03	Natal,	Brazil RCBR (40 km)
0086	PMG	−9.41	147.15	Port Moresby,	New Guinea PMG
0093	QUI	−0.20	−78.50	Quito,	Ecuador OTAV (49 km)
0095	RAR	−21.22	−159.77	Rarotonga,	Cook Islands RAR
0099	SBA	−77.85	166.76	Scott Base,	Antarctica SBA
0102	SE0	37.57	126.97	Seoul,	Korea INCN (31 km)
0106	SJG	18.11	−66.15	San Juan,	Puerto Rico SJG
0108	SPA	−90.00	0.00	South Pole,	Antarctica SPA, QSPA
0113	TAU	−42.91	147.32	Hobart,	Tasmania TAU
0119	TUC	32.31	−110.78	Tucson,	Arizona TUC
0122	WEL	−41.29	174.77	Wellington,	New Zealand SNZO (6 km)
0123	WES	42.38	−71.32	Weston,	Massachusetts HRV (24 km)
0124	WIN	−22.57	17.10	Windhoek,	Namibia TSUM (375 km)
0096	RCD	44.08	103.21	Rapid City,	S. Dakota RSSD (67 km)
0101	SCP	40.80	−77.87	State College,	Pennsylvania SSPA (18 km)

25 years. It also includes the large temporary network archive of the IRIS PASSCAL Program data (http://www.iris.edu/about/PASSCAL/). It is responsible for the long-term (perpetual) archive and distribution of all IRIS generated data, and is the primary archive for the FDSN (http://www.fdsn.org/). The funding for IRIS comes from the National Science Foundation (through its Division of Earth Sciences), and acts in a leadership role to create a perpetually viable, openly accessible archive for seismic data. The DMC is the core component of the IRIS Data Management System (for more information, refer to http://www.iris.edu/).

The IRIS DMC mission is accomplished by creating a data management system suitable for archiving and processing of requests. This is enabled by providing the hardware and software infrastructure that includes a StorageTek Powerderhorn tape-based silo with a capacity of 1.2 petabytes, as well as currently keeping all data in an online RAID (redundant array of independent disks) filesystem to enable fast access. The policy employed is that 4 copies of the data are archived, including off-site copies, creating a redundant, fail-safe environment, and data are transcribed to new media every 4 years to keep technology current, and acts a read-back mechanism that provides a periodic verification of the holdings.

Since 1992 the quantity and diversity of data managed by the IRIS Data Management System continues to grow exponentially. The DMC currently (2007) manages data from 96 different permanent seismic networks, primarily in real-time, around the globe, and manages data from more than 165 temporary experiments. For the current, dynamic list of FDN approved network codes that shows current data availability at the DMC, refer to http://www.iris.edu/mda. Permanent networks includes the IRIS Global Seismographic Network (GSN), the International Federation of Digital Broad-Band Seismograph Networks (FDSN), and regional networks that contribute data to the IRIS archive or have open access to their data sets.

The primary function of the IRIS DMC is to archive and disseminate digital seismic data from modern instruments that began recording earthquakes after 1980 (Ahern 2003). In 2004, the IRIS DMC began hosting the SeismoArchives, which consist of scanned seismic data recorded by the older instruments from the 1880s to 1980, i.e., a period of about 110 years during which seismograms were recorded on papers and microfilms. This activity is in collaboration with the International Association of Seismology and Physics of the Earth's Interior (IASPEI) and the U.S. Geological Survey. Others are encouraged to collaborate as well.

5.2 Contents of the SeismoArchives Online

A stack of seismograms in the form of scanned raster-image files is not easy to use for research unless the seismograms can be quickly collated, viewed, and have some supporting documentation and metadata available. Technology has existed for the past decade to scan analog seismograms and related materials (e.g., maps, field notes, papers, and reports) into computer readable files, and the World-Wide Web provides easy access to these files online via the Internet. SeismoArchives at the IRIS DMC (http://www.iris.edu/seismo/) leverages modern information technology for archiving and disseminating historical seismograms and related materials. At present, there are 4 major sections: (1) Archives by Individual Earthquakes, (2) Archives by Stations, (3) Archives by Special Projects, and (4) Background Materials.

Each individual earthquake archive (http://www.iris.edu/seismo/quakes/) contains seismograms as well as supporting materials and links to appropriate files (if any) stored in the “Background Materials”. Some collections of seismograms created for certain specific projects are archived under “Archives by Special Projects”.

In 2007, W.H.K. Lee established seismograms archives for “Reference Stations of the World” at http://www.iris.edu/seismo/stations/. These Reference Stations are strategically located seismographic stations with relatively long duration of operation, and every effort is being made to scan the available seismograms and related materials (with the cooperation of the host stations). So far, Reference Stations include: (1) San Juan, Puerto Rico, (2) Honolulu/Kipapa, Hawaii, (3) College, Alaska, (4) Tucson, Arizona, (5) Albuquerque, New Mexico, (6) Weston Observatory, Massachusetts, and (7) Observatorio San Calixto, La Paz, Bolivia. We hope more seismographic stations will agree to become Reference Stations and make efforts to scan their seismograms and related materials.

In the section on “Background Information”, (http://www.iris.edu/seismo/info/), digital image-files of papers, books, reports, photos, and maps are archived in order to provide useful background information for the scanned seismograms. At present, this section is being developed and is far from being complete. It has (1) Historical Information: early developments in seismology, especially about instrumentation; (2) Seismographic Stations: catalogs of historical and WWSSN stations that contain detailed station information; and (3) Books and Reports: some valuable publications. Although most existing files are “borrowed” from the supplementary materials (on CD-ROMS) of the “International Handbook Earthquake and Engineering Seismology” (Lee et al. 2002; 2003), we plan to include additional materials over time, including the Handbook’s “errata and addenda”. We also encourage all seismologists to contribute their data files and related information that are relevant to the scanned seismograms.

The effort to preserve WWSSN and historical seismograms and related materials online is an immense task both in terms of human labor and computer resources, and the authors’ goal is to solicit contributions so that redundant search-and-discover operations are eliminated and the collection can grow and remain viable for generations to come.

At the time of writing this article, 30 earthquake archives are available online at various stages of construction, and about 100 more archives are in waiting. We realize that the scanned seismograms are just the first step. We hope users of these image files will convert them to digital data files, and make the digitized seismograms available through the SeismoArchives. Certainly a long-term goal is to be able to supply appropriate metadata, like gain information, etc., and information related to this would be very useful.

6 Other Projects for Archiving Seismograms

So far, we have described the efforts in archiving analog seismograms online taken by the authors and their USGS colleagues. Many other projects for archiving analog seismograms online have been and are being conducted by several institutions around the world. We will briefly describe three examples.

6.1 The SISMOS Project

The SISMOS Project started in 2001 at the Istituto Nazionale di Geofisica e Vulcanologia (INGV) of Italy. It involves scanning, archiving and distribution of historical seismograms, bulletins and other related material from the Italian observatories dating back to 1895 (Michelini et al. 2005). The scanned images of seismograms are available online at 200 dpi resolution for viewing, and are also available at 600 or 1024 dpi resolution upon request. This library contains over 3 terabytes of data volume currently, and growing. For more details, please visit their website at: http://sismos.rm.ingv.it/.

In addition, software for digitizing scanned seismogram images has been developed by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) of Italy (Pintore et al. 2005). It is called "Teseo" and is free available at: http://sismos.ingv.it/teseo/. The SISMOS scanning laboratory is one of the Trans-National Access facilities of the European Union's NERIES project. Under the NERIES project, funding is available for visitors to have historical seismograms scanned and to learn how to use the Teseo vectorization software.

6.2 The EuroSeismos Project

The EuroSeismos Project is being conducted by the Working Group on the History of Seismometry of the European Seismological Commission. It has been supported financially mainly by INGV and has relied on the SISMOS facility for scanning paper seismograms. As of early 2007, more than 25,000 historical seismograms recorded by observatories of 30 countries in the Europe-Mediterranean region are available online. For more details, please visit their website at: http://storing.ingv.it/es_web/.

6.3 The Caltech Scanning Project

The Seismological Laboratory of California Institute of Technology (Caltech), Pasadena, California, has scanned 12,223 pre-digital analog seismograms recorded in Southern California between 1963 and 1992. Scanned images of paper records for $M>3.5$ southern California earthquakes and several significant teleseisms are available for download at the Data Center of the Southern California Earthquake Center through a search tool at: http://www.data.scec.org/research/scans/. Additional information on this project is available online under the following headings: (1) List of local $M>3.5$ events (1963–1992), (2) File format and naming convention, and (3) A primer on how to read drum seismograms.

7 Some Sample Analog Seismograms

In this section, we present some sample seismograms that had been scanned to illustrate the progressive improvements of earthquake observations over the years. The

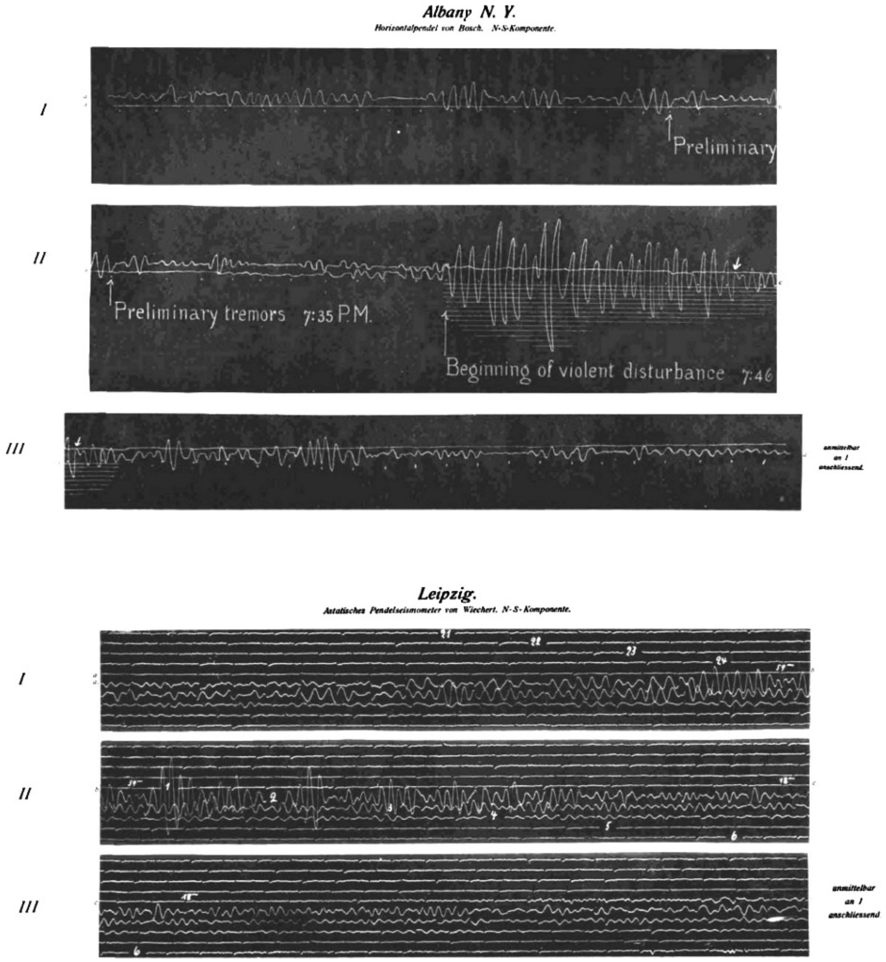
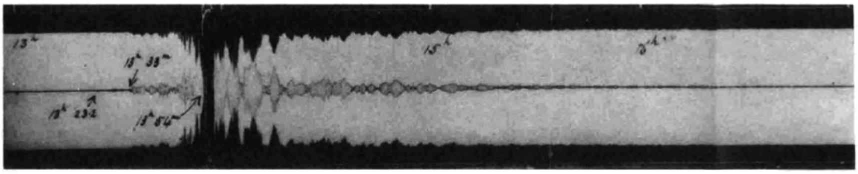


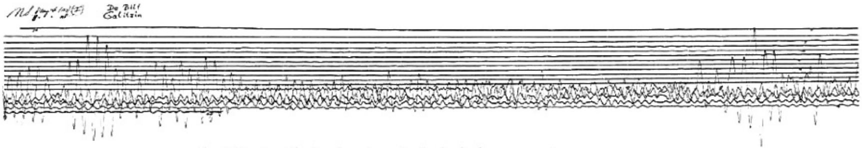
Fig. 5 Sample seismograms recorded on smoked paper. See text for explanation

first-generation seismographs are mechanical instruments with low magnifications of ground motions and recorded either on smoked paper or photographic paper. Figure 5 shows two seismograms of the 17 August, 1906 Valparaiso (Chile) earthquake. The first seismogram was recorded by the N–S component of a Bosch-Omori seismograph at Albany, N.Y., and the second seismogram, the N–S component of a Wiechert seismograph at Leipzig, Germany. Since these seismograms were too wide to fit the publication size of Rudolph and Tams (1907), each was cut into 3 sections. However, smoked paper seismograms are difficult to scan and most will be worse than these samples, as shown in: http://www.iris.edu/seismo/quakes/1906valparaiso/pdf/.

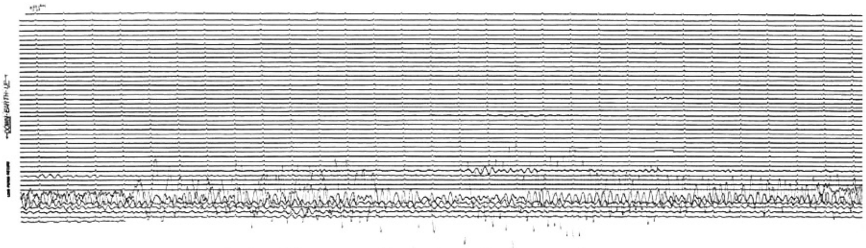
Figure 6 shows 4 seismograms that were recorded on photographic paper. The first seismogram was recorded by a Milne mechanical seismograph for the 18 April,



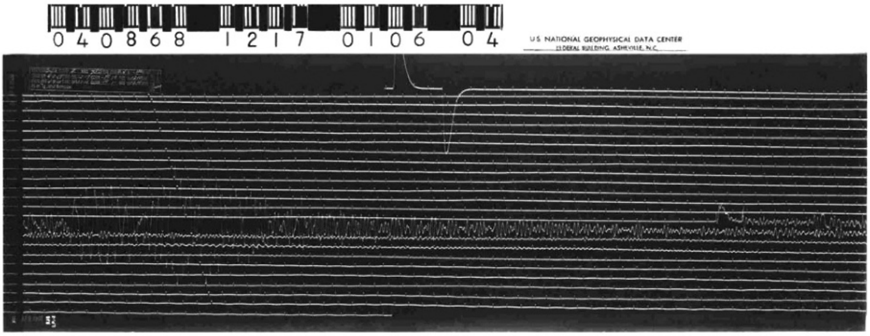
PAISLEY, SCOTLAND. Milne Seismograph. (*From photographic copy.*)



De Bilt, the Netherlands. Galitzin Seismograph.



Weston Observatory, USA. Benioff Seismograph.



San Juan, Puerto Rico. WWSSN Long-Period Seismograph.

Fig. 6 Sample seismograms recorded on photographic paper. See text for explanation

1906 San Francisco (California) earthquake at Paisley, Scotland. It is difficult to digitize from such an image because of the small time resolution, but most seismograms for the first decade of instrumental seismology were recorded by Milne seismographs. The second seismogram in Fig. 6 shows the 8 August, 1946 Mona Passage (Puerto Rico – Dominican Republic) earthquake recorded by the electromagnetic Galitzin seismograph at De Bilt, the Netherlands. The third seismogram in Fig. 6 shows the 28 June, 1944 Mexico-Guatemala earthquake recorded by the electromagnetic Benioff seismograph at the Weston Observatory, Massachusetts, USA. The fourth seismogram in Fig. 6 shows the 9 April, 1968 Borrego Mountain (California) earthquake recorded by a WWSSN electromagnetic seismograph at San Juan, Puerto Rico. All these electromagnetic seismographs belong to the second-generation of seismic instruments. After the 1960s, electronic seismographs were developed leading to digital, on-scale recordings of seismic waves. These electronic seismographs became the dominant seismic instruments for observing earthquakes starting in the 1980s.

Although seismic signals recorded by electromagnetic seismographs on photographic paper have a dynamic range of about 1000, they constitute the instrumental earthquake records we have from about 1910–1980. Although these analog seismograms are far inferior to the modern digital seismograms (with a dynamic range better than 1,000,000), we can still retrieve many useful information from them as shown by Kanamori (1988).

8 Discussion

The number of scanned images of the WWSSN and historical seismograms currently in the SeismoArchives is barely over 1%, numbering only approximately 50,000 out of a total of about 4 million available WWSSN film chips and about 0.5 million available on microfilms of historical seismograms. Nevertheless, it is a good first step toward preservation of these valuable seismograms. W.H.K. Lee volunteered to perform some quality assurance tasks and to prepare the prototype web pages of the current 30 "earthquake archives". The staff of the IRIS DMC provided the time necessary to post these earthquake archives online at the IRIS web site.

The hope is that institutions may be willing to fund scanning of analog seismograms that are of interest to them, and make the scanned image files available after their research interests are satisfied. So far, two institutions have provided modest funding for scanning specific sets of WWSSN seismograms: five Italian earthquakes by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) of Italy, and the 1964 Great Alaska earthquake by the URS Corporation of Pasadena, California.

At present, it costs about $2 US dollars to scan one WWSSN film chip and about $0.5 US dollars to scan one historical seismogram on microfilm roll. Projections suggest that it will cost a few million US dollars to scan a significant portion (e.g., 1 million) of the WWSSN and historical seismograms, and at least twice the amount of money (or equivalent volunteers' time) to perform quality assurance tasks and to prepare seismogram archives of earthquakes.

As we were preparing this manuscript in the fall of 2006, the USGS Albuquerque Seismological Laboratory began an 1-year project to scan and create images of about 60,000 WWSSN more seismograms in order to start constructing archives of "Earthquake Reference Stations": San Juan, Puerto Rico; and Honolulu/Kipapa, Hawaii (C.R. Hutt, personal communication, 2006). In addition, the National Earthquake Information Center (NEIC) of the USGS in Golden, CO scanned about

70,000 historical seismograms recorded at Tucson, Arizona (1926–1960); College, Alaska (1935–1956; 1959–1963), and San Juan, Puerto Rico (1946–1949; 1955–1963) (J.W. Dewey, personal communication, 2007). The USGS in Menlo Park began to scan about 15,000 historical seismograms recorded at San Juan, Puerto Rico (1926–1945; 1950–1954). As a result, we are expecting a significant increase in the number of scanned seismograms for SeismoArchives soon, and anyone can remain updated by referring to http://www.iris.edu/seismo/.

Acknowledgments We are indebted to C.R. "Bob" Hutt who provided the information for subsections 4.1 and 4.2. It was also Bob Hutt who kindly took over the WWSSN film chips collection from USGS Menlo Park in 1997 when the collection was to be discarded, and continuously makes efforts to scan the WWSSN seismograms. We thank Tim Knight of IRIS DMC for serving as webmaster for the SeismoArchives.

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