17-20
September 2023
Lixouri, Kefalonia Island

8th International Colloquium on Historical Earthquakes, Palaeo- Macroseismology and Seismotectonics

Past earthquakes and advances in seismology for informed risk decision-making.

BOOK OF ABSTRACTS

Bulletin of the Geological Society
Special Publication No. 11, 2023
Publisher:
Geological Society of Greece
ISBN: 978-618-86841-1-9
ISSN: 2945-1426

ΕΛΛΗΝΙΚΗ ΓΕΩΛΟΓΙΚΗ ΕΤΑΙΡΙΑ
1951

Organized by:

HELLENIC REPUBLIC
National and Kapodistrian
University of Athens

ΔΗΜΟΣ ΛΗΞΟΥΡΙΟΥ
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WELCOME LETTER

Dear colleagues,
We would like to invite you to the 8th International Colloquium on Historical Earthquakes, Palaeo- Macroseismology and Seismotectonics, to be held in Lixouri, Kefalonia Island, Greece, on 17-20 September, 2023.

Seventy (70) years have passed since the occurrence of the three earthquakes that destroyed Kefalonia and Zakynthos islands, which host the highest seismicity rates in Greece. In view of the recent devastating earthquakes in SE Turkey and Northern Syria, the detailed knowledge of seismotectonics in retrospect is considered now even more crucial. Past earthquakes lead us to estimate what will happen in the future; the study of their effects in historical times and their extrapolation in our time motivate awareness and influence our attitude towards protecting the built environment.

We cordially invite you to participate, as one of the main purposes of the colloquium is to give the opportunity to all colleagues to continue, or establish new, fruitful international collaborations in areas of mutual academic interest, exchange experience and handover to young scientists. We also believe that it will be a great chance for you to meet old friends and make new ones.

Within the 2-days sessions, we plan a special one dedicated to the recent catastrophic earthquakes in SE Turkey and Northern Syria. On the third day a field trip will be organized that will include visits to the ruins of the 1953 earthquakes, damages that occurred due to the 2014 earthquakes, expression of active tectonics and an overall experience of the morphology/landscape of the island, as a result of intense seismotectonic activity.
Apart from the scientific program, there will also be a lively social program, which will give you the opportunity to enjoy Kefalonia, its attractions and traditions.

The Colloquium abstracts will be published in the “Bulletin of the Geological Society of Greece”, Special Publication vol. 11, 2023.

The Colloquium Chairs
Prof. Vasiliki Kouskouna, National and Kapodistrian University of Athens
George Katsivelis, Mayor of Lixouri

PREFACE

Dear colleagues,

On behalf of the Local Organising Committee, I would like to welcome you to the 8 International Colloquium on Historical Earthquakes, Palaeo- Macroseismology and Seismotectonics, in Lixouri, Kefalonia.

The last International Colloquium on Historical Earthquakes & Paleoseismology Studies was held in Barcelona (Spain) between 4 and 6 November 2019. Since then, and with the advent of COVID-19, physical presence was lost or limited and all contact was made online.

In spite of this drawback, the colleagues who organized the previous Colloquiums would wish greatly to see them continue in not too distant future. With this in mind, and after the communication between us, we agreed on the necessity for organising the 8th Colloquium.

Thanks to the successful cooperation, initiated in 2021, between the National and Kapodistrian University of Athens, The National Observatory of Athens and the Municipality of Lixouri, Kefalonia, through three ongoing bilateral projects, this intention came to fruition in the island with the highest seismicity and seismic hazard in Europe. Furthermore, this year is the 70th anniversary of the 1953 great earthquakes. Delegates, including many early-career scientists, will have the opportunity to visit a dynamic seismological and tectonic laboratory and exchange experience in situ. Young scientists will have the chance of discussing all matters with elder, experienced colleagues and establish mutual collaborations.

During the two session-days of the colloquium, 7 invited speakers will lecture and 54 oral or poster communications will be presented in seven sessions on Palaeoseismology, Archaeoseismology, Historical Earthquakes, Macroseismology and Seismotectonics. On the third day, in the framework of the field trip, the participants will, among others, visit the uplifted coastline during the 1953 great earthquakes, the Atheras broadband seismological and GNSS stations and the Kouloumaki quarry site, crossed by an active fault.

It is the intention of the Organising Committee that all attendees have a lovely time in Lixouri, enjoy the hospitality of the locals and have a taste of the Kefalonian wines and local products. Looking forward to seeing you in Lixouri,

Professor Vasiliki Kouskouna
Chair of the Local Organising Committee
8th International Colloquium on Historical Earthquakes,
Palaeo- Macroseismology and Seismotectonics

ABSTRACTS

8th International Colloquium on Historical Earthquakes,
Palaeo- Macroseismology and Seismotectonics
17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00001

The Xianshuihe fault zone and the 2022 Luding earthquake (M6.8), East Tibet plateau

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Research Highlights

The Xianshuihe fault zone is a major active fault in Tibetan plateau, with a paleoseismic recurrence interval of ~200 yr; The 2022 M6.8 (Luding) earthquake occurred in a seismic gap along the southeastern section of the Xianshuihe fault zone, the surface rupture is 15.5 km long and the coseismic left-lateral displacements are 20-30 cm.

The Xianshuihe fault zone is one of the most active faults in eastern Tibetan plateau (e.g. Allen, et al., 1991) (Figure 1). It bounds the southern boundary of the Bayan Har block and plays an important role in the present-day deformation of the Tibetan plateau due to the continuing indentation of India into Eurasia (e.g., Molnar and Tapponnier, 1975; Tapponnier et al., 2001; Wang et al., 1998). It extends about 400 km with a strike of N30-40°W and shows a strong left-lateral strike-slip motion in late Cenozoic, with an accumulated displacement of ~60 km (Wang et al.,1998). It can be divided into the northwestern and southeastern parts according to its geometry, and each part consists of several segments (Fig.1). The northwestern part is simple in geometry and mostly single-stranded, while the southeastern part is more complicated. The Xianshuihe fault zone has a long-term slip rate of 10-15 mm/yr (Wen et al., 1989; Allen et al., 1991; Wang et al., 1998) and has been the site of many large earthquakes in historical time (Allen et al., 1991; Wang et al., 1998; Wen et al., 2008). According to historical records, almost all sections of the Xianshuihe fault zone have produced strong earthquakes in recent history. Eight M>7 earthquakes have been recorded along the Xianshuihe fault since 1725, which almost ruptured the whole length of the fault (Tang et al., 1993; Li et al., 1997). Surface ruptures of some earthquakes such as the M7.6 Luhuo earthquake in 1973 are still clear. Paleoseismic studies revealed many events across each segment and suggest a short recurrence interval of ~200 yr in Holocene (Li et al., 1997; Yan and Lin, 2017; Li et al., 2017; Liang et al., 2020).

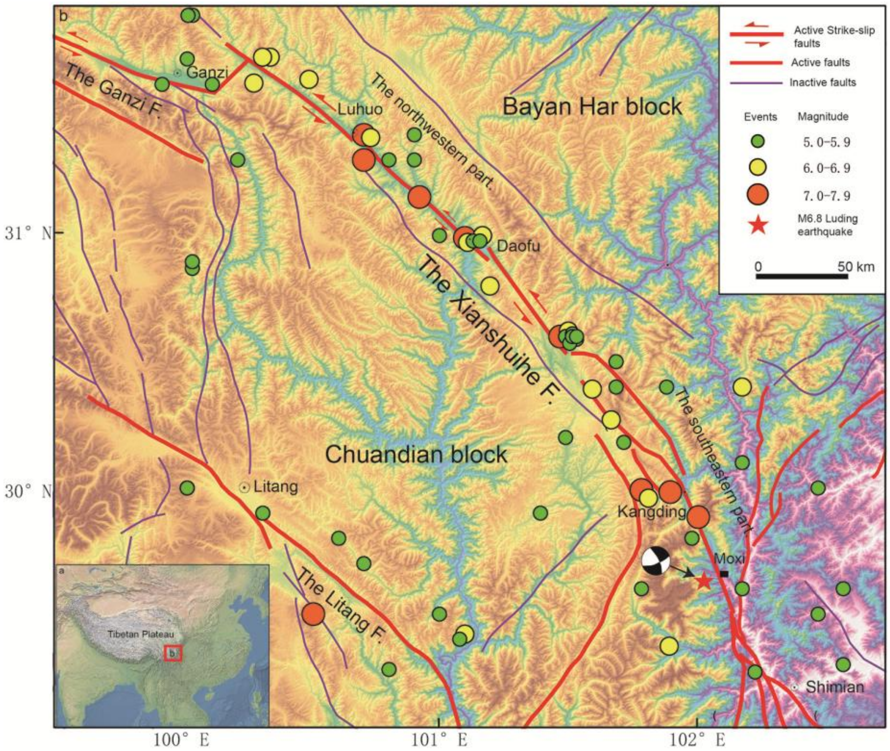

Figure 1. Map showing the location of the Xianhe fault zone and the epicenter of the M6.8 Luding earthquake. The red star represents the epicenter, the focal mechanism is from China Earthquake Network Center (CENC).

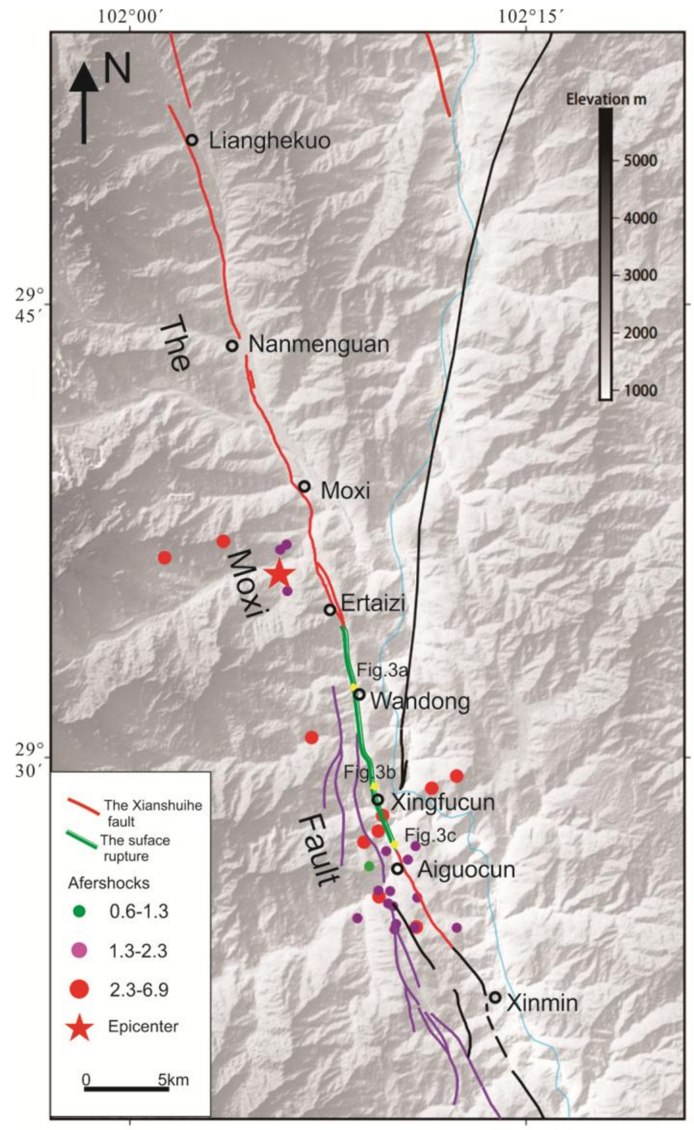

Figure 2. Maps showing the surface rupture zone and aftershock distribution (Before 2:00 PM, Sept. 5th, 2022).

On September 05, 2022, a Ms=6.8 earthquake (namely the Luding earthquake) occurred on the southeastern part of the Xianshuihe fault zone (Figure 1). The main tectonic structure around the epicenter area is the Moxi fault. The focal mechanism of the main shock and inversions of seismic data suggest that this event occurred on a northwest-trending, steeply dipping strike-slip fault, which is consistent with the trend and slip of the Moxi fault (a segment of the Xianshuihe fault zone). To determine the motion of the fault at the surface and then discuss the kinematics of rupturing process during the earthquake, we conducted a field investigation along the Moxi fault immediately after the earthquake. Seismic inversions of rupture progress suggest that this event nucleated near Moxi town and propagated unilaterally southeastward. The early aftershocks were also mainly distributed southeast of the epicenter (Figure 2). So, our field investigation mainly concentrated along the section southeast of the epicenter.

Figure 3. Field photographs showing co-seismic surface ruptures from the Ertaizi to Aiguocun village. (a) the Wandong village site, view to SE; (b) the Xingfucun village site, view to south; (c) the Aiguocun village site, view to south. See locations in Fig.2.

Satellite images show clear linear geomorphic features and fault depressions observed during the field work along this section. Surface ruptures were observed at Wandong village, Xingfu village and Aiguo village sites (Figure 3). Heavy landslides were also distributed along this section. Southeast of the Aiguo village, no surface rupture was observed. And no surface ruptures developed along the fault sections north of the epicenter. Thus, it can be concluded that there is a 15.5 km-long surface rupture zone developed along the Moxi fault (the section between Ertaizi and Aiguo village). Our field observations suggest that a 15.5-km-long coseismic surface rupture zone was produced during the 2022 event. The surface rupture zone trends northwest-southeast and shows a left-lateral strike slip of 20-30 cm, consistent with the strike and motion constrained by the focal mechanism. Combined with seismic data and geodetic observation results, our study suggests that the occurrence of the M6.8 Luding earthquake is due to the slip of the fault section southeast of the epicenter and then the event triggered a slip of the northwestern section of the Moxi fault.

The latest large earthquake in history records on the southeastern part of the Xianshuihe fault zone is a M7.7 event that ruptured both segments of this part in 1786 (Deng et al., 1986; Wang et al., 1988). Surface ruptures of this event can still be clearly observed along sections northwest of the town of Moxi. According to the field investigations (e.g., Deng et al., 1986; Wang et al., 1988; Li et al., 1997), no surface rupture zone was observed along the section that ruptured during the Luding Ms=6.8 earthquake. Thus, the Luding Ms=6.8 earthquake likely occurred in a seismic gap that may not have ruptured at least since 1786.

Acknowledgements

The field investigation of the 2022 Luding earthquake would not have been done without the dedicated effort in elaborate organization and careful coordination of IGCEA. This study was supported by the second Tibetan Plateau Scientific Expedition and Research program (2019QZKK0901) and National Natural Science Foundation of China (42072250).

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Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00002

Latest quaternary active faulting and Paleoseismology of the restraining bend in the Xianshuihe Fault Zone, Eastern Tibetan Plateau

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Abstract

The Xianshuihe Fault Zone (XSHF) is recognized as one of the most dynamically active strike-slip faults situated on the eastern Tibetan Plateau. Extending along a northwest-striking path, the XSHF exhibits a left-lateral displacement, and historical records indicate the occurrence of numerous significant seismic events measuring above M >7 and M >6.5 since the year 1700 CE. Although the northwest segment of the XSHF follows a linear and uninterrupted course spanning approximately 180 km, its geometric configuration undergoes a notable transformation near the Kangding segment. At this juncture, the fault bifurcates into four en-echelon faults, namely the Yalahe fault, Selaha fault, Mugecuo fault, and Zheduotang fault, before eventually converging into a singular fault trace within the Moxi segment. The region comprising the South Qianning segment, Kangding segment, and North Moxi segment, commonly referred to as the restraining bend region, occupies a distinctive position within the Xianshuihe Fault Zone and assumes a pivotal role in the assessment of seismic hazards. However, the extent of activity and the paleoearthquake sequence within the restraining bend region remain subjects of controversy. We meticulously delineated accurate fault traces and analyzed deformed landforms by employing a combination of imagery and aerial photographs, supplemented by thorough field observations. Geological and geomorphological evidence corroborating Holocene activities was obtained. Based on the findings from the trench work, we established a comprehensive paleoearthquake sequence and engaged in discussions concerning recurrence characteristics and potential correlations among paleoearthquakes. Remarkably, our investigations reveal that the restraining bend region may be susceptible to cascading rupture events during the occurrence of a single earthquake.

Keywords: Tibetan Plateau; Xianshuihe Fault Zone; Fault activity; Paleoseismology; Restraining bend

Introduction

The Xianshuihe Fault Zone (XSHF), serving as the boundary between the Sichuan-Yunnan block and Bayan Har block, acts as a prominent conduit for material movement and absorbs a significant portion of the crustal extrusion deformation (Li et al., 1997). Within the NW-striking, left-lateral XSHF, a considerable number of seismic events, including 8 earthquakes with magnitudes exceeding M7 and 29 earthquakes with magnitudes exceeding M6.5, have been documented since 1700 CE (Figure 1) (Wen et al., 2008). The South Qianning segment, Kangding segment, and North Moxi segment are situated within the restraining bend region of the Xianshuihe Fault Zone (XSHF), aptly named after its pronounced strike direction (Bai et al., 2021). In a north-to-south progression, the single fault trace observed in the Qianning segment branches into four fault segments in the Kangding segment before converging back into a single fault trace in the Moxi segment. Notably, both segments have demonstrated the potential for generating significant earthquakes (Ma et al., 2020). Among the most recent seismic events in these segments, the Qianning segment experienced a magnitude 7¼ earthquake in 1893, the Kangding segment was struck by a magnitude 7.5 earthquake in 1955, and the Moxi segment encountered a magnitude 7¾ earthquake in 1786.

As an active fault, the restraining bend region of the Xianshuihe Fault Zone (XSHF) lacks detailed information regarding its earthquake sequence, recurrence pattern, and recurrence period. The interrelation between the Qianning segment and Kangding segment in terms of rupture behavior remains unclear. In this study, we mapped accurate fault traces and deformed landforms based on detailed interpretations of high-resolution imagery and aerial photographs combined with field observations. We focus on investigating the paleoseismic activity of the Qianning segment and Kangding segment within the XSHF. Through our analysis, we examine the recurrence characteristics and establish correlations among paleoearthquakes. Finally, we engage in a discussion concerning the geometric straightening phenomenon observed in the bend of the XSHF.

Method

The surface traces were accurately mapped through a combination of field investigations and satellite image interpretations, utilizing high-resolution satellite imagery (Pléiades, 0.5 m × 0.5 m pixel resolution). In specific faulted areas, low-altitude photos were captured using an unmanned aerial vehicle (UAV) to obtain detailed topographic information. Paleoseismological trenching was employed as a crucial method to gain insights into the characteristics of paleoearthquakes and to provide predictions about the present and future behavior of the studied fault segments (Allen et al., 1986). Subsequently, approximately 100 photographs were captured, and the Agisoft Photoscan software was employed to merge these images and generate orthogonal mosaic images for further analysis, as demonstrated in previous studies (Reitman et al., 2015).

Radiocarbon-14 (^{14}C) dating methods were employed to constrain the deposition ages of the strata, with the ^{14}C samples being carefully prepared and analyzed at Beta Analytic Inc. in Miami, Florida, USA. An age model for the stratigraphy was established, and age distributions for the earthquakes were estimated using the OxCal v4.4.4 program, provided by the Oxford Radiocarbon Accelerator Unit (ORAU), following the methodology outlined by Lienkaemper and Ramsey (2009). To mitigate uncertainties associated with paleoearthquake events, a progressive constraining approach, as described by Mao et al. (1995), was employed to constrain the events and their respective ages. The coefficient of variation (CoV) of the recurrence interval has been increasingly used to quantitatively describe the recurrence behavior of earthquakes (Biasi et al., 2015; Goes et al., 1994). The CoV is defined as $CoV=\sigma T/\bar{T}$, where σT is the standard deviation of the recurrence interval, and $\bar{T}$ is the average recurrence interval (Guo et al., 2019). It indicates that the fault follows a quasiperiodic recurrence model if CoV is between 0-1 (Kagan and Jackson, 1991).

Results

For the Zheduotang fault (ZDTF), the ages of four deformation events are defined. Event 1 is the youngest event which occurred in between 5821-3148 yr BP. Event 2 occurred in between 13060-10745 yr BP. Event 3 occurred in between 13687-11420 yr BP. Event 4 occurred in 41443-13715 yr BP. According to the integration results of our analysis, the location of the northwestern segment of Zheduotang fault is defined. It is discovered that the NW segment of Zheduotang fault is located between the Kangding airport and Duoriagamo village which trends NW with a total length of 15 km. Additionally, the trace of Zheduotang fault is also defined. From north to south, Zheduotang fault passes through Duoriagamo village, Tonglilongba, Kangding airport, Zheduoshan nek, Ertaizidaoban and disappeared near Zheduotang village. Moreover, after Holocene, the Zheduotang fault is dominant by sinistral slip movement along with minor vertical component. The absence of the surface rupture in the NW segment of Zheduotang fault indicates that the 1955 M7.5 earthquake did not cause any surface rupture.

For the Yalahe fault (YLHF), seven paleoearthquakes occurring since 21000 yr BP were constrained from two sections and one trench. The ages of events E7–E1, from oldest to youngest, are 20975–20749 yr BP, 18981–18817 yr BP, 10437–10252 yr BP, 7168–6940 yr BP, 6319–6269 yr BP, 3465–2490 yr BP, and after 1380±60 CE, respectively, and the most recent event may correspond to the 1700 CE earthquake.

For the Qianning segment, seven paleoearthquakes occurring in Holocene were constrained. The ages of events E7–E1, from oldest to youngest, are 9360–8885, 7949–7520, 7395–7075, 6305–6160, 3517–3473, 875–710, 225–45 yr B.P., respectively. The most recent event is Qiangning M7¼ in 1893.

Conclusions

(1) The entire YLHF is a Holocene active fault, with an average earthquake recurrence interval of approximately 2524 years since ~12000 years.

(2) The Qianning segment, along with the Kangding segment, has the potential for cascading rupture during the same earthquake. A simultaneous rupture of the Qianning segment and Kangding segment, covering a combined distance of 135 km, would likely result in an earthquake with a magnitude of Mw=7.5.

(3) The original single deep structure of the fault transforms into a flower structure from the Qianning segment to the Kangding segment. The migration of activity from the Yalahe fault to the Selaha fault and Zheduotang fault can be interpreted as a kinematic consequence of the short-cutting process occurring in the

"Big Bend" within the Xianshuihe Fault Zone (Figure 2).

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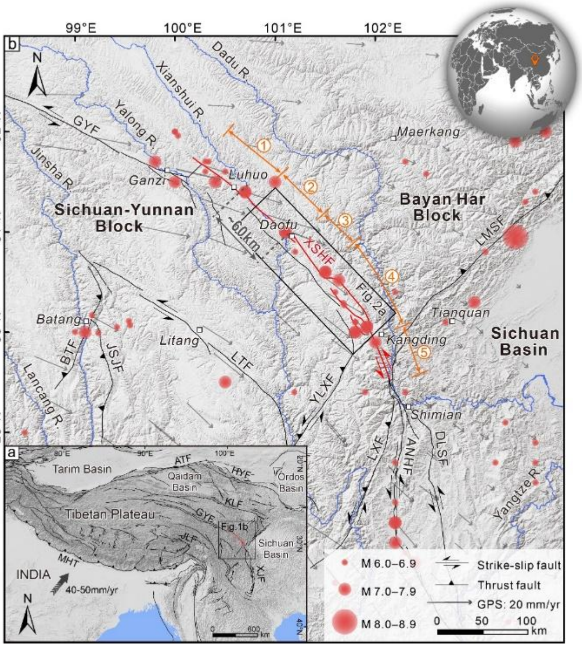

Figure 1. (a) DEM of the India-Asia collision zone. (b) Fault geometry (from a 1:4,000,000 Active Tectonic Map of China) and strong earthquake epicenters (from Data Sharing Infrastructure of National Earthquake Data Center) along the Xianshuihe Fault Zone. Main rivers, cities, active faults (those of the Xianshuihe Fault Zone in red), and tectonic blocks are labeled. The background is the digital elevation model (DEM) from the Shuttle Radar Topography Mission (SRTM), 90 m. GPS velocity data are from Liang et al., 2013. GYF=Ganzi-Yushu Fault; XSHF=Xianshuihe Fault Zone; LMSF=Longmenshan Fault; DLSF=Daliangshan Fault; ANHF=Anninghe Fault; LXF=Lijiang-Xiaojinhe Fault; YLXF=Yulongxi Fault; LTF=Litang Fault; JSJF=Jinshajiang Fault; BTF=Batang Fault; MHT=Main Himalayan Thrust; JLF=Jiali Fault; XJF=Xiaojiang Fault; KLF=Kunlun Fault; ATF=Altyn Tagh Fault; HYF=Haiyuan Fault. Numbers 1-5 represent Luhuo, Daofu, Qianning, Kangding and Moxi segments respectively.

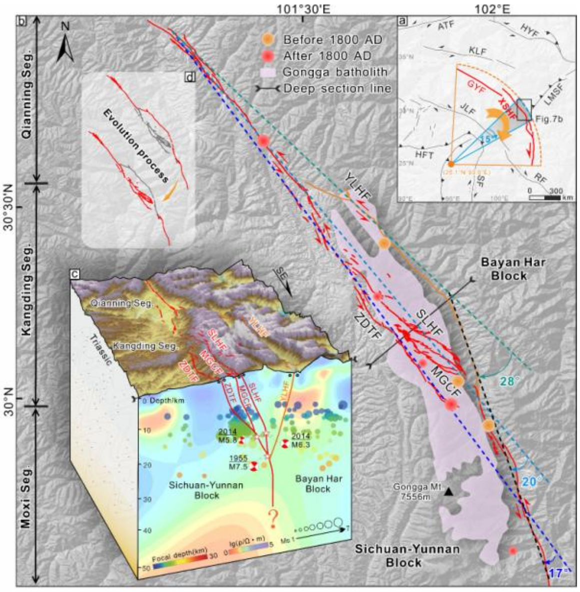

Figure 2. (a) Clockwise rotational motion of the eastern Tibet Plateau. (b) Fault geometry and strong earthquake epicenters of bend in the Xianshuihe Fault Zone. Colored dashed lines represent strike direction. YLHF =Yalahe Fault; SLHF=Selaha Fault; MGCF=Mugecuo South Fault; ZDTF=Zheduotang Fault. (c) 3D model of the bend of the Xianshuihe Fault Zone. (d) Activity evolution process of the bend in the Xianshuihe Fault Zone.

8th International Colloquium on Historical Earthquakes, Palaeo- Macroseismology and Seismotectonics

17-20 September 2023 - Lixouri, Greece

Bulletin of the Geological Society of Greece, Sp. Publ. 11

Ext. Abs. 00003

The August 1953 devastating earthquakes in the Ionian Sea: reviewing existing information and using new data sources with emphasis on the earthquake environmental effects

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Introduction

The August 1953 earthquake sequence, which featured three severe earthquakes—the major earthquake on August 12 (M_s=7.3 or M_w=7.0) as well as its foreshocks on August 9 (Ms=6.1, Mw=5.9) and 11 (Ms=6.8, Mw=6.6) of the same month—was the most damaging and deadliest disaster in the Ionian Islands' recent history. With the epicenters of foreshocks located offshore in eastern Cephalonia and southern Ithaki and of the major shock in southeastern Cephalonia, they mostly impacted the center and southern Ionian Islands, devastating Cephalonia, Ithaki, and Zakynthos, and were accompanied by post-earthquake fires that completely destroyed the towns of Argostoli and Zakynthos.

The existing literature on this earthquake sequence has concentrated on (a) the extensive structural damage to buildings and infrastructure in residential areas, (b) the impact on the local population, and (c) the emergency response and recovery actions carried out by the Greek authorities and the military forces, mostly from abroad, who rushed to assist. As a result, there is a rather precise record of human casualties and injuries, as well as a thorough account of the damage to the building stock of the islands. This approach, however, has left a significant gap in obtaining the whole picture of the impact of earthquakes on the environment, including landslides, liquefaction, hydrogeological anomalies, and tsunami, which were not widely recorded until recently. The official report of the Hellenic Institute of Geology and Underground Research (IGUR, 1954) only mentioned a small amount of rockfalls that caused damage to residential areas, while Stiros et al. (1994) and Pirazzoli et al. (1994) published their findings on coastal coseismic uplift primarily in eastern coastal Cephalonia that was attributed to the 1953 earthquakes almost 40 years after the sequence.

In this framework, focus was placed on the environmental effects of the earthquakes in the central and southern Ionian Islands, utilizing a variety of sources that provided a plethora of pertinent data. A representative distribution of the environmental effects caused by the 1953 earthquakes could be reconstructed thanks to the examination of various sources, which was not implemented for such a significant seismic sequence.

Methodology

Data and information on the accompanying phenomena of the August 1953 seismic sequence in the Ionian Sea were obtained from the following sources:

- All major academic databases, search engines, and scientific research sources, including GeoRef, Google Scholar, Science Direct, Scopus, Springer, and Journal Storage.
- Official deliverables and reports on the results of applied research programs for the area affected by the August 1953 earthquakes.
- Databases with newspapers of local and national circulation including the Press Museum of the Peloponnese – Epirus – Ionian Islands Daily Newspaper Editors Association, the Vikelaia Municipal Library of Herakleion Crete, the Digital Historical Archive of the Lambrakis Press Group, the Digital Library of Newspapers and Magazines of the National Library of Greece, and the Digital Library of the Greek Parliament. In addition, we used information contained in volumes of a local journal "I Kefalonitiki Proodos" (Greek: Η Κεφαλονίτικη Πρόοδος, lit: The Cephalonian Progress).
- Reliable online sources with related descriptions and testimonies of residents affected by the 1953 earthquakes.

These sources contain direct or indirect information on primary and secondary environmental effects induced by the August 1953 earthquakes in the area of the southern Ionian Islands, and they were evaluated for the first time by Mavroulis and Lekkas (2021), who provide more details on these sources. Additionally, the following related information was also reviewed by Mavroulis and Lekkas (2021):

- scientific papers published in proceedings of national and international conferences and in international scientific journals, which include information on the environmental effects induced by the August 1953 earthquakes
- official reports of field surveys and reconnaissance on the impact of the 1953 earthquakes on the natural and built environment of the southern Ionian Islands and
- scientific publications comprising information on the impact of the August 1953 earthquakes.

In addition, a field survey was carried out in areas affected by the 1953 earthquakes in order to determine the characteristics that favor the occurrence of such phenomena.

Results

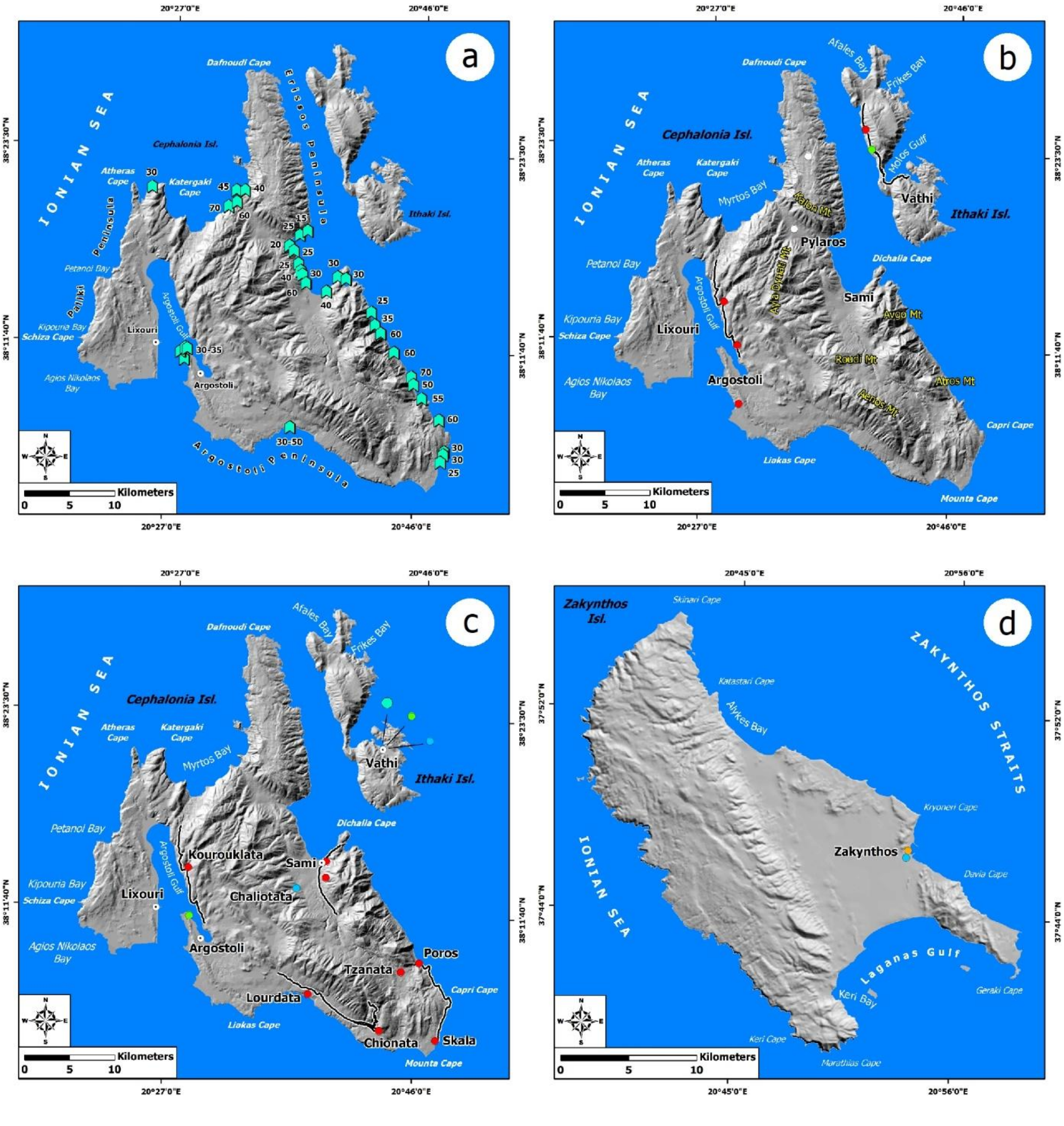
The earthquakes of 9, 11, and 12 August 1953 affected the central and southern parts of the Ionian Sea and caused numerous environmental effects in Cephalonia, Ithaki, and Zakynthos (Figure 1). In total, 120 cases of earthquake environmental effects were identified, comprising 33 primary cases and 87 secondary ones. In descending order of occurrence, slope failures, coseismic uplift, hydrological anomalies, ground cracks, tsunami, liquefaction, dust clouds, hydrocarbon-related phenomena, jumping stones, and vegetation effects were distributed mainly in Cephalonia Island and secondarily in Ithaki and Zakynthos Islands (Figure 1). In particular, primary effects, included permanent surface deformation, were mainly detected in eastern Cephalonia, which presented uplift up to 70 cm, while secondary effects were triggered in specific zones with characteristics that made them susceptible to the occurrence of earthquake-related hazards (Figure 1).

From the correlation between the inventory of the earthquake environmental effects and the susceptible zones, it is concluded that the majority of these effects were not randomly distributed in the affected islands, but occurred in certain zones with characteristics that make them susceptible to the occurrence of earthquake-related hazards. The zones affected by slope failures are characterized by intense morphology, with high and steep slopes attributed to strong uplift of tectonic origin and intense incision. They are composed of various lithologies and are mainly located along marginal faults, which have contributed to a significant reduction of the mechanical strength of the faulted formations. The zones where liquefaction phenomena have occurred comprise coastal areas composed of recent deposits, which are particularly susceptible to such phenomena during strong earthquake ground motion. The zones affected the most by anomalous waves / tsunami were the coastal parts of funnel-shaped gulfs in the affected Ionian Islands. Large-scale tsunami and related effects were not generated on the coast, but anomalous waves with a high potential for mild or moderate effects were triggered and reported in this strike-slip environment. As regards the onshore hydrological anomalies, they have been identified in water bodies, including lakes, and in groundwater extraction works, such as wells in residential and rural areas, which indicate a wide earthquake-induced disturbance of the aquifer.

Conclusions

In the context of this research, emphasis was placed on the environmental effects triggered by the earthquakes generated on August 9, 11 and 12, 1953, by reviewing the existing scientific information and using new sources with a wealth of relevant information. The result of this approach is the most complete record of these phenomena to date.

This information and the research are of great importance in reconstructing the type and distribution of the effects triggered by the most devastating earthquakes in the recent history of Greece. In addition, it outlines the type, distribution, and intensity of earthquake-related hazards and the impact of a similar future event in an area that has since experienced intense urban and infrastructural development, as well as in other areas with similar seismotectonic settings and geoenvironmental properties.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Cephalonia Isl.
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Dafnoudi Cape
Atheras Cape
Katergaki Cape
Petanoi Bay
Kipouria Bay
Schiza Cape
Agios Nikolaos Bay
Lixouri
Argostoli
Argostoli Gulf
Argostoli Peninsula
Erissos Peninsula
Paliki Peninsula
Afales Bay
Frikes Bay
Molos Gulf
Vathi
Myrtos Bay
Pylaros
Sami
Dichalia Cape
Liakas Cape
Capri Cape
Mounta Cape
Kourouklata
Chaliotata
Tzanata
Poros
Lourdata
Chionata
Skala
Zakynthos Isl.
Skinari Cape
Katastari Cape
Alykes Bay
Zakynthos
Kryoneri Cape
Davia Cape
Laganas Gulf
Keri Bay
Keri Cape
Marathias Cape
Geraki Cape
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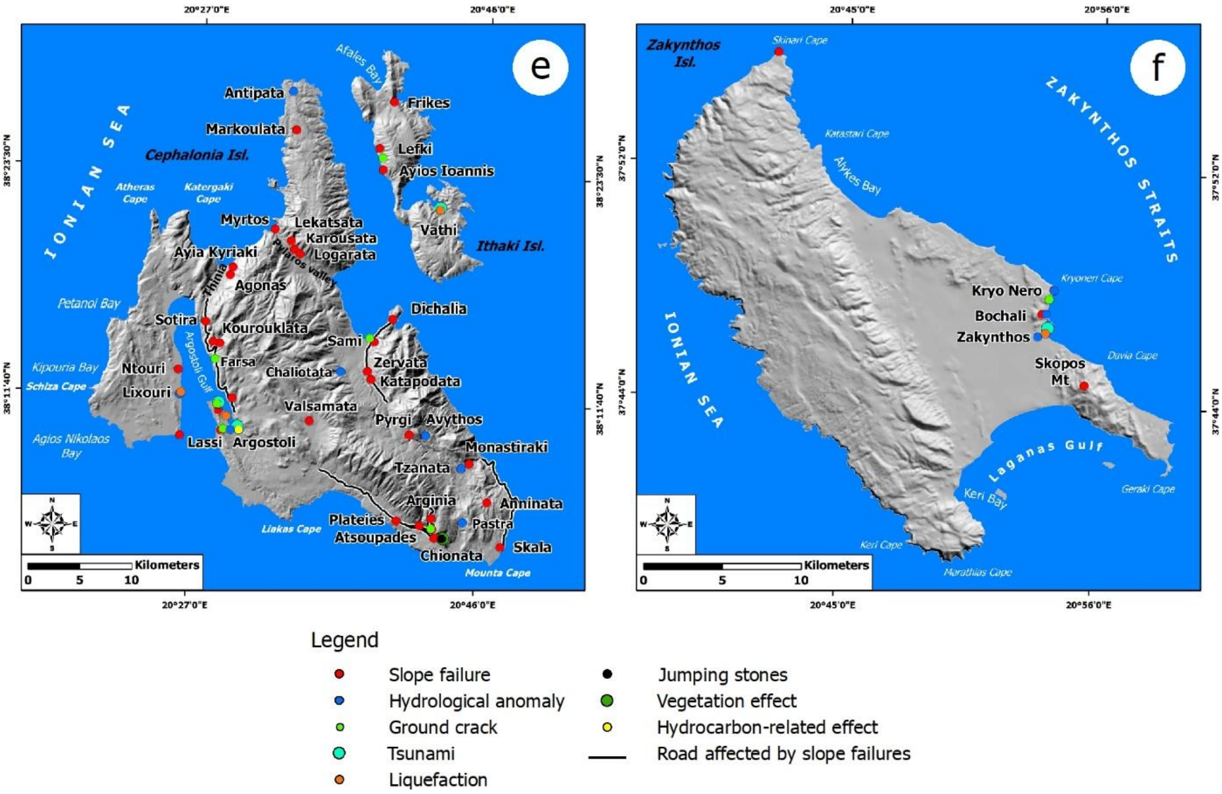

Figure 1. Primary effects caused by the 12 August 1953 earthquake (a) and secondary effects triggered by the 9 (b), 11 (c,d) and 12 (e,f) August 1953 earthquakes in the central and southern Ionian Islands.

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Seismicity and Geodynamics of central Ionian Islands, Greece: An Overview

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In 2003 an M_w6.3 earthquake struck the northern part of Lefkada Island, fifty-five (55) years after the last strong ($M_w \geq$6.0) earthquakes in 1948. Less than 11 years later, the 2014 Kefalonia doublet took place with two main shocks on 26 January (M_w6.1) and 3 February (M_w6.0). More recently, in 2015, a third seismic excitation started with an M_w6.5 earthquake that struck the southern part of Lefkada Island, this time. These main shocks were all along the Kefalonia Transform Fault Zone (KTFZ). We summarize observations and modeling concerning both the strong earthquake occurrence and lower magnitude seismicity in an attempt to give more insight in the geodynamics of the study area, by discussing and concluding the outstanding questions that remain to be addressed and investigated.

Past strong (M≥6.0) seismicity

It is noteworthy that historical information on the central Ionian Islands earthquakes starts in the 15th century, and beforehand alike in the rest Greek territory, although it exhibits the highest seismic activity. In particular, the first reported event occurred in 1444, when felt reports started to become available. The quantity and quality of these reports depend upon the development of the local towns and the severity of the damage. Reports describing earthquake destructions of Lefkada town are more numerous than for those in Kefalonia. Probably because of the proximity of the causative earthquake, although earthquakes along the Kefalonia fault segments are larger in general, some of them associated with offshore fault segments. This latter could be the reason that the number of earthquakes in early historical archives is smaller for Kefalonia than for Lefkada.

Figure 1 shows the sequence of the earthquakes that repeatedly caused damage and have estimated magnitudes M≥6.0. From an initial observation, we may notice that Lefkada earthquakes (shown in red) are more abundant before the middle of the 19th century, while this changes dramatically afterwards. This is unlikely to be attributed to the seismicity properties but that fewer felt events were reported from Kefalonia (shown in blue) before that time.

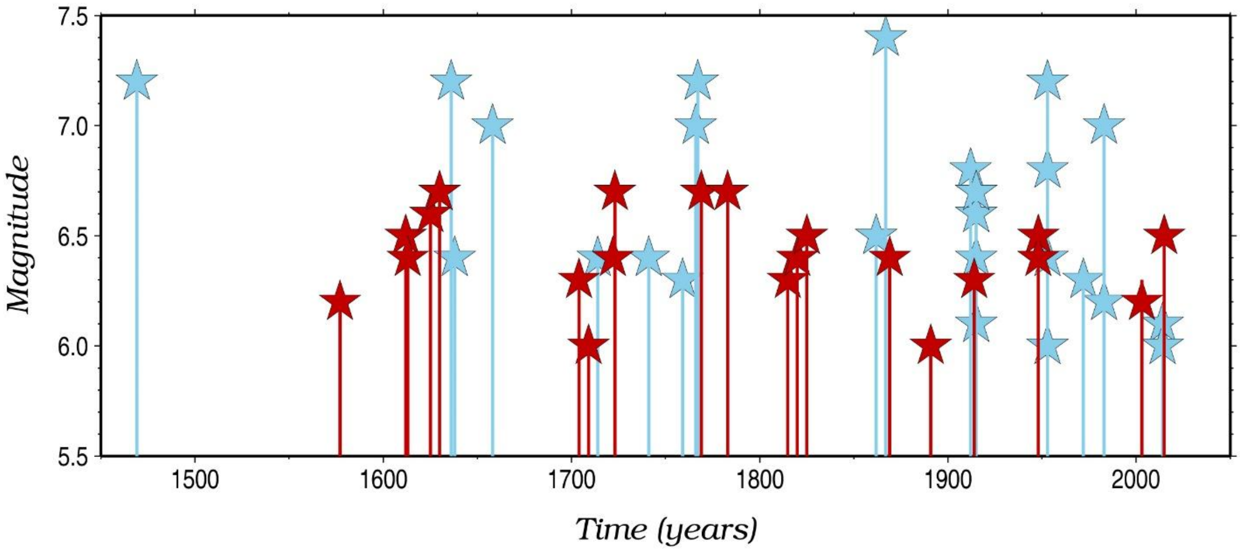

Figure 1. Earthquake activity in central Ionian Islands (lines and stars, red for Lefkada and blue for Kefalonia fault branch, respectively), after Papadimitriou et al. (2017).

Active faults and earthquake sequences

All the strong (M≥6.0) historical and instrumental earthquakes have occurred along a narrow strip either side of the western coastlines of both Islands, onto fault segments constituting the Kefalonia Transform Fault Zone Fault (KTFZ). Under the action of southwest–northeast directed compression and northwest–southeast extension stresses, deformation in the study area is dominated by right–lateral strike slip faulting, striking NNE along the Lefkada and NE along the Kefalonia branch of the KTFZ, respectively. Fault plane solutions of more recent occurrences evidenced the dextral strike slip faulting type of the KTFZ (Scordilis *et al.*, 1985; Kiratzi and Lansgton, 1991; Papadimitriou, 1993) and the characteristics of two main branches, namely the Kefalonia and Lefkada branch, the different strike and dimensions of which were afterwards confirmed (Kokinou *et al.*, 2006). The change in the strike of the dominant faults is also associated with transtensional and transpressional motion in Lefkada and Kefalonia, respectively.

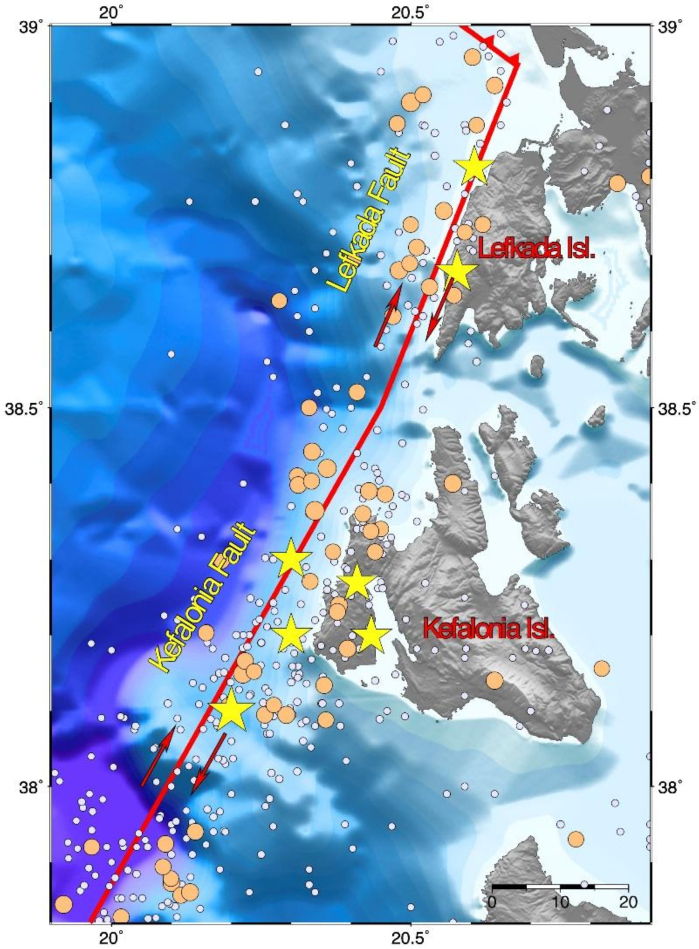

Figure 2. Morphology, major faults and seismicity since 1970 in Lefkada and Kefalonia Islands. Stars depict the M≥6.0 earthquakes, bigger circles the 5.9≥M≥5.0 and smaller circles the 4.9≥M≥4.5 ones.

The recent strong main shock activity started with the 2003 Lefkada (M_w6.3) with the rupture taking place on a right–lateral strike slip fault segment of 16 km length, oriented north–northeast to south–southwest bounding the western coast of the Island (Karakostas *et al.*, 2004). Based on a reconnaissance study on the 2014 faulting complexity Karakostas and Papadimitriou (2010) suggested that in addition to the segment that accommodated the main rupture, along strike adjacent fault segments to one direction only, secondary faults near the main rupture were activated. The 2014 Kefalonia doublet started on 26 January with the first main shock (M_w 6.1) and aftershock activity extending over 35 km, much longer than expected from the causative fault segment. The second (M_w 6.0) occurred on 3 February on an adjacent fault segment, where the aftershock distribution was remarkably sparse, evidently encouraged by the stress transfer of the first main shock (Karakostas *et al.*, 2015). The 2015 M_w6.5 earthquake occurred in the geographical adjacency of the 2003 main shock, again accommodating right–lateral strike slip motion (Papadimitriou *et al.*, 2017).

Coulomb stress changes

Observations on strong earthquake clustering alternating with relative quiescence periods, as well as impressive epicentral migration of strong earthquakes in a certain fault zone, are perfectly explained by stress transfer and triggering. In the Kefalonia Transform Fault Zone (KTFZ), the second major dextral strike slip zone in the Greek territory, the occurrence of large events during short time intervals compared with the periods of relative quiescence were justified by static stress triggering (Papadimitriou, 2002). The temporal history of strong (M≥6.3) earthquake occurrence showed that the two main fault branches of the KTFZ failed almost contemporarily, three times in the last 130 years. During each seismic excitation one or more earthquakes occurred in each fault, in a short time interval (two up to five years), followed by much longer quiet periods (30 up to 43 years). If this pattern is proven consistent with past earthquake occurrence, it will provide a tool to assess if a future event may signify the initiation of a new cluster of large earthquakes, contributing to the mitigation of the seismic hazard in the study area. The more recent clustering took place during 2003–2015 (Figure. 3), when adjoining fault segments along the KTFZ failed, for each one of them high positive ΔCFF values were calculated just before each strong (M≥6.0) main shock (Papadimitriou *et al.*, 2017).

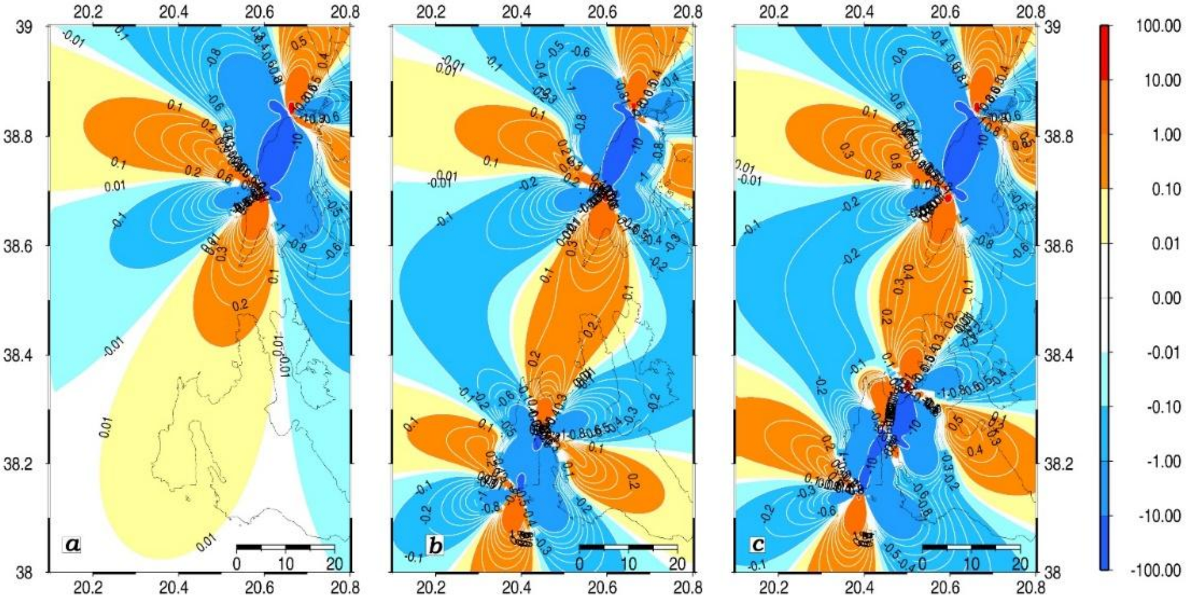

Figure 3. Coulomb stress changes due to the coseismic slips of the M≥6.0 main shocks that occurred in central Ionian Islands since 2003, calculated at a depth of 8 km. Changes are according to the scale of the top (in bars) and by the numbers in the contour lines. The stress field is calculated according to the faulting type of the 2015 main shock and is due to the coseismic slip of (a) the 2003 main shock, (b) the 2003 and the first 2014 main shock, and (c) the 2003 and both 2014 main shocks (after Papadimitriou *et al.*, 2017).

Acknowledgements

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Commission – Euratom. Neither the European Union nor the granting authority can be held responsible for them.

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Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00005

An investigation of low-magnitude earthquakes in present Southeastern Finland in 1751-1752

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Contemporary correspondence testifying to a sequence of low-magnitude earthquakes in present Southeastern Finland in 1751–1752 is investigated. The preserved original correspondence, 11 pages in total, is lavish by local standards: Earthquake entries from the 1700s in the national database are typically attested to by a solitary source, such as a concise newspaper account. Over 30 distinct events between the end of October and December 1751 (Julian calendar) can be discerned. The assignment of macroseismic intensity to the earthquakes is hampered by loud acoustic effects that accompany and/or constitute the observations. Maximum intensities are assessed at IV–V (European Macroseismic Scale 1998), and maximum macroseismic magnitudes in the range of M_M2.0–2.4. The events have probably been shallow and were observed at short epicentral distances. The data from 1751 provide an analog to modern macroseismic observations from geothermal stimulation experiments that have acted as a spur for considering seismic risk from low-magnitude earthquakes whose consequences have seldom previously been a matter for concern.

Introduction

Palaeoseismology and archaeoseismology are used to investigate the consequences of ancient and pre-instrumental large, shallow earthquakes. The wealth of information about considerable earthquakes that becomes available has a direct bearing on notions of long-term seismic hazard. With the help of macroseismology, it is also possible to investigate the transient effects of non-damaging, low-magnitude earthquakes that similarly lengthen the time span of available seismicity records. Small earthquakes do not contribute to seismic hazard as such but can be relevant locally; they are more than curiosities for seismicity assessments of low-seismicity regions where they dominate the available earthquake databases. The effects of low-magnitude earthquakes have seldom previously been a matter for concern until induced earthquakes from geothermal stimulation experiments have acted as a spur for attention in urban environments. The historical documentary materials of the effects provide an analog to modern macroseismic observations.

This investigation examines a sequence of low-magnitude earthquakes on the fringes of the Kingdom of Sweden in the mid-1700s, now Southeastern Finland. It began in October 1751, and written communication about the events continued until the following spring. The sequence occurred within the Vyborg rapakivi granite batholith (VRGB), which is composed of lighter material than the surrounding bedrock and is also significantly younger, 1.6–1.3 Ga old, from Proterozoic time (Elo and Korja, 1993). Similar protracted, low-magnitude earthquake sequences have been observed in the region, both in the pre-instrumental (Mäntyniemi, 2022) and instrumental (Uski *et al.*, 2006) eras (instrumental monitoring of local seismic events in the country began in the latter half of the 1950s) and, also, in the summer. Whether the earthquake sequences had the potential to evolve into higher-magnitude events is an essential question for the analysis of the seismic hazard of the Loviisa nuclear power plant, situated at a distance of approximately 28 km from the 1751 sequence.

At the time of the earthquakes, the region of interest was crossed by the state border between the Kingdom of Sweden and the Empire of Russia, as demarcated in the peace treaty of 1743 (Fig. 1). A river divided the municipality of Pyttis (Pyhtää in Finnish; the Swedish name is used here) in two, and the western part of Sweden came to be known as Swedish Pyttis (Ruotsinpyhtää in Finnish). Focus is on the village of Svenskby located in Swedish Pyttis.

Contemporary correspondence

The main documentation that has survived to the present day and testifies to the earthquake sequence is three letters written in the village of Svenskby, Pyttis, and the town of Degerby (today Lovi(i)sa) in 1751–1752 and sent to the Royal Swedish Academy of Sciences in Stockholm. The first correspondent, Carl (sometimes written as Karl) Östberg (1716–1775), vice pastor of the Pyttis parish, dated his letter on 22 November 1751.

Carl Johan von Holthusen (1715–1791), who dated his letter on 1 March 1752, was Captain of the Royal Swedish Regiment of Jönköping, stationed in the border area. The reports by Östberg and von Holthusen were read at the meetings of the Royal Swedish Academy of Sciences on 18 January and 4 April 1752, respectively. The third correspondent acted on the initiative of the Academy. Archiater Evald Ribe (1701–8 October 1752), a member of the Academy, requested David Starck (1710–1778), vicar of Degerby, to visit Svenskby and confirm that the observations of underground tremors and roar had been reported truthfully. Ribe's request was dated on 30 January 1752, but has not survived to the present day. David Starck dated his report on 30 March 1752. His visit to the village of Svenskby in February or March 1752 can be regarded as the first documented macroseismic field trip in the VRGB.

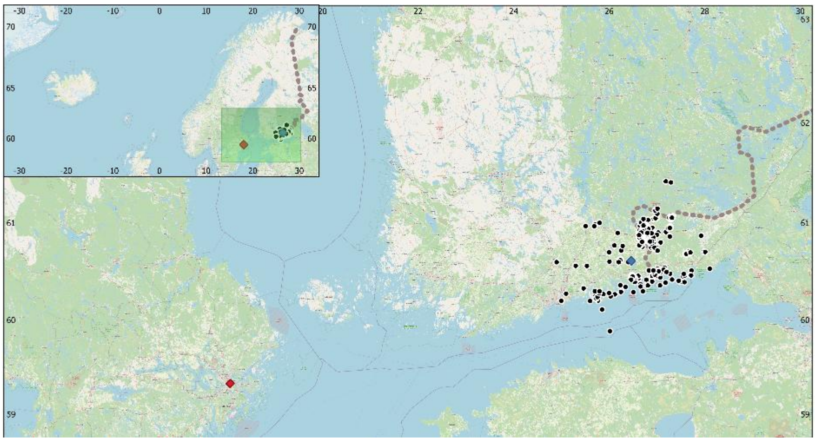

Figure 1. The target region. The blue diamond shows the village of Svenskby and the red diamond Stockholm. The black dots show earthquake epicenters inside a 100-km radius around Svenskby in 1610-19 June 2023. Most magnitudes are below M_L3. The dashed line is the border at the time of the earthquakes.

Analysis of the communications

The three reports agree in that the earthquakes were observed within a confined area. Östberg estimated that the bangs were heard within a distance of 500 steps Von Holthusen mentioned that the phenomena were not noticeable above a distance of half a (Swedish) mile, approximately 5 km. According to David Starck, the phenomena were also observed in another village located approximately 3 km southwest of Svenskby. No original reports are known from east of the border.

When attempting to assign macroseismic intensities to the observations, the many sensations of acoustic effects that accompany earthquake observations pose a discrepancy. The earthquake effects summarized by intensity are expected to follow ground shaking alone, so discerning them from audible observations becomes critical for small earthquakes. For example, local residents may be awakened or frightened by an abrupt underground roar rather than a tremor. Instrumental data have shown that earthquakes in the VRGB occur within the uppermost 2 km of the crust, which provides a reasonable explanation for the acoustic effects and consequent observations by local residents.

When estimating macroseismic intensities, the acoustic effects have been disregarded. For example, "farm animals (even outdoors) may be frightened" is a classification factor of intensity VI on the EMS-98 scale but, for example, von Holthusen primarily described various sounds that made horses and other creatures neigh and bellow on 5 November. A few persons losing their balance is also a classification factor of intensity VI, but it is considered to be an extreme effect, because the overall effects on houses and objects appear to have been less strong, and no damage was reported. The objects that fell or were shifted were light or precariously supported, such as splinter wood. On the other hand, the effects were not very weak: there were clear sensations of the house and ground uplifting, and effects on the movable property. Stove dampers and windowpanes rattling suggest intensity IV. The maximum intensity level is estimated at IV–V (EMS-98) due to insufficient descriptions for selecting either IV or V. The intensities express a cumulative effect, since it is not possible to separate the effects of individual events that occurred very close together in time.

The sparsity of earthquake data makes it difficult to establish intensity prediction equations for the Fennoscandian Shield, and even more so to construct one specifically for the VRGB to investigate whether attenuation properties there are different from those of the surrounding bedrock. No recent equations exist. Equation (1) for macroseismic magnitude, M_M, was based on 76 earthquakes in Fennoscandia in 1960–1979. It reads:

$$M_M = 0.38\ (\pm 0.25) + 1.14\ (\pm 0.18)\cdot \log R_F + 0.23\ (\pm 0.07)\cdot I_{max}, \quad (1)$$

where R_F is the radius of perceptibility in km, and I_{max} the maximum intensity. It is valid for intensities $3 \leq I \leq 6$–7 given on Medvedev-Sponheuer-Kárník or Modified Mercalli Intensity scale; however, they are similar to the EMS-98. Equation (1) was calibrated with the Uppsala local magnitude, M_L(UPP). For a better comparison to the present local magnitude scale used in Finland, 0.2–0.3 magnitudes should be subtracted from the obtained values (Uski, 1997). The distances reported above are taken to be more like diameters. For a maximum intensity IV–V (4.5), with the subtraction (0.25), the maximum macroseismic magnitude becomes $M_M 1.70 \pm 0.65$ and $M_M 2.05 \pm 0.70$ and using equation (1) for a radius of perceptibility 3 km and 6 km, respectively. The uncertainty is impractically large, so comparisons to modern macroseismic data from the VRGB are made in an attempt to restrict it.

For example, the contents of the macroseismic questionnaire refer to the night between 9 and 10 May 2003 as follows: ”There were 3–4 strong ‘bangs’ within an hour and about ten lesser ones, the first one shook the bed, and rattled the windowpanes and frightened me and my dog a lot.” The Finnish national seismic network recorded ten earthquakes in the VRGB between 21:18:40.50 on 9 May and 05:24:07.40 on 10 May (UTC, local time +3 h). A total of 16 events were recorded in May, and an additional two in October. The instrumental magnitudes were estimated to be in the range of $M_L 1.6$–2.1 (Uski *et al.*, 2006).

Over 30 distinct shocks can be discerned according to the reports. Table 1 shows the parameters estimated for the largest events on each date.

Table 1. Summary of the strongest events according to the correspondence.

Time*	**Intensity (EMS-98)**	**Magnitude (M_L)**	**Remark**
27–28 Oct 1751 nighttime	IV-V	2.1	2 events
30 Oct 10 p.m.	IV	1.9	1 event
5 Nov ** nighttime	IV	1.9	2 events
9–10 Nov	IV	1.9	2 events
17–18 Nov	IV-V	2.1	14 events***
11 Dec 8 p.m.	IV	1.9	1 event
14 Dec 6:30 a.m.	IV-V	2.1	1 event
25 Dec soon after 3 p.m.	IV	1.9	1 event

* Julian calendar **There may have been a separate sequence on 6 November 1751.*** not possible to separate the strong events

Discussion

The 1751 sequence is the only occurrence known for the VRGB in the entire century. One reason behind the attention the sequence received was most likely the prolonged duration, which increased the sensitivity of the population. However, the literacy rates of the local residents were extremely low at the time. The first reporter, Carl Östberg, was a member of the clergy, who were the most learned and literate at the time and often contributed to the reporting of various natural phenomena. By contrast, the presence of the military regiment in the area, including literate captain Carl Johan von Holthusen, was unusual. The time of peace made it possible for Captain von Holthusen to pay attention to natural phenomena; many tumultuous years of war had strongly affected the target area in the first half of the 1700s.

In modern times, enhanced geothermal systems (EGSs) have acted as a spur for considering seismic risk from low-magnitude earthquakes whose consequences have seldom previously been a matter for concern. EGSs can induce earthquakes, and because it is economically more beneficial to operate them within urban areas, the earthquakes are more likely to pose problems. A geothermal stimulation experiment of a ~6-km-deep well in the Finnish capital region during the summer of 2018 induced earthquakes with magnitudes up to M_L1.8. The local residents often observed these earthquakes, because they disrupted nighttime sleep and caused discomfort (Krenz *et al.*, 2022). The observations were at the threshold of human perception, which resulted in a variety of sensations. This was seen in the macroseismic questionnaires as a difficulty of characterizing the sensation. The questionnaire offered the options, either heard or felt, or both, which were favored differently by different respondents. In the village of Svenskby in 1751, the events were almost certainly shallow, as suggested by the instrumental records, but David Starck also reported that the observations given by local residents were either felt or heard. The macroseismic data from historical low-magnitude earthquake sequences provide analogs to modern ones, since they are less affected by changes in the built environment than higher-magnitude, damaging earthquakes.
The original investigation and the full list of references, as well as the related supplementary materials can be found in Mäntyniemi (2022).

Acknowledgements

Archivist Maria Asp is thanked for the copies of the original reports. The Academy of Finland is acknowledged for an international mobility grant (decision no. 325997).

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Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00006

POSEIDON: New data on offshore structures in the west Peloponnese - Ionian Islands Domain and implications for seismic hazards

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Our cruise POSEIDON from 10 to 22 June 2023, on Research Vessel (R/V) Laura Bassi, aimed at mapping the tectonic structure of arguably one of the most complex and comparatively little evaluated regions, with demonstrated seismic hazard, in the Mediterranean. The region encompassing this tectonic domain extends from the western Peloponnese across the Ionian Islands (Figure 1). Here, a complex fault system with numerous strands has developed in a region with dramatic lateral changes in deformation rates. This system has produced numerous large earthquakes, mostly offshore, recorded during the past few decades in the onshore Greek national seismological network(Hadad et al., 2020). However, the large Cephalonia 1953 M_w~6.8 event (Stiros et al., 1994) was recorded in comparatively few stations only. This earthquake is possibly the most destructive seismic event in recent Greek history, causing the collapse of ~85% of all buildings on Kefalonia, ~1000 deaths, and ~145k people homeless, (Saranga, 2017; Hore, 2019). The limited data on the 1953 earthquake has made it poorly understoodcomparatively with more recent, albeit less destructive events. The epicentreof the 1953 event is poorly located, and the location and dimensions of the causative fault are unconstrained. Likewise, the thrust fault focal mechanism, located E or SE of Kefalonia, has a hypocenter depth poorly defined from <50 km to <20 km, depending on the analysis. Surface geology studies of the islands interpret active shallow thrusting(Underhill, 1989), and it has been proposed that the 1953 event ruptured several of those faults. The goal of POSEIDON is to determine region fault system structure and kinematics.

The available bathymetric-topographic relief displays a rugged terrain from the Ionian Islands to the Peloponnese Peninsula with features that indicate active deformation. Major morpho-tectonic submarine structures around the islands trend from NE-SW to NNW-SSE, trending similar to the basins and ranges onshore the islands and their linear coastlines (Figure 1). Unfortunately, limited available seismic data has imaged those structures. A fold and thrust belt recognised onshore (Underhill, 1989), and imaged offshore in a bay SW of Kefalonia Island, appears with folds eroded and covered by Quaternary-to-recent unfolded sediment, indicating that at least locally they are inactive structures (Underhill, 2009). However, the elongated shallow troughs offshore that laterally project into the morphological trends of the islands, support widespread active faulting, and some of the larger structure may be have controlled the slip during the 1953 destructive event. Without proper seismic imaging, the seafloor relief is complicated for interpretation. It could potentially represent structures with a strike-slip to oblique component that kinematically link onshore and offshore structures or potentially with changes from trans-tension to oblique thrust component along strike.

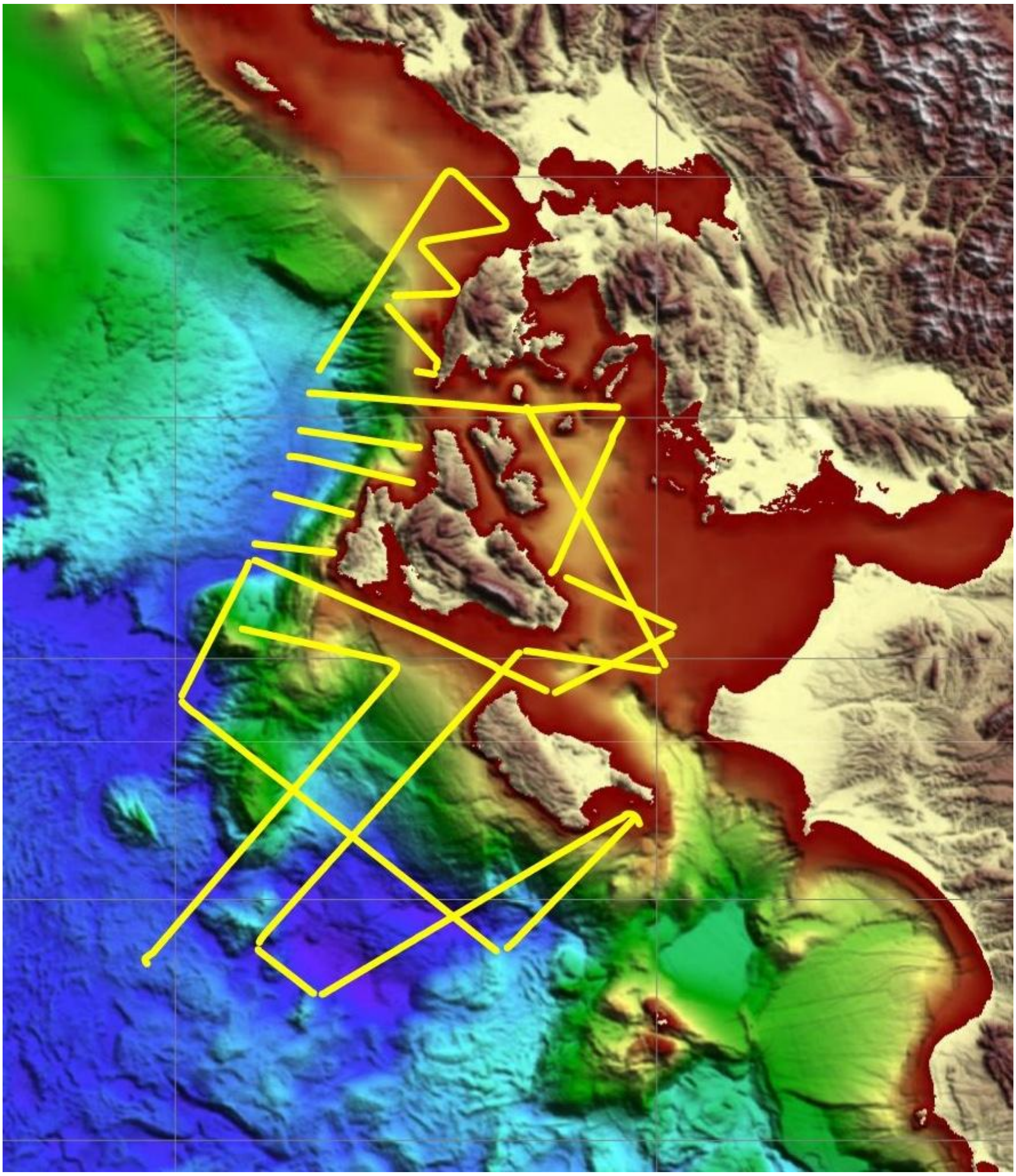

Figure 1. Seismic profiles from POSEIDON cruise plotted over the bathymetry of the region.

An additional complexity in the POSEIDON research area is that the upper-crust fault system discussed above, might be located above the mega-thrust fault of the Hellenic subduction zone, inferred to dip in a NE direction at ~25-40 km depth under the surface (Hansen et al., 2019, Haddad et al., 2020). The transition from the upper-crust seismogenic zone to the mega-thrust seismogenic zone is yet not understood in this region (Karastathis et al, 2015; Chousianitis&Konca 2019; Cirella et al, 2020). Thus, we may speculate that the devastating 1953 thrust earthquake might have ruptured the inter-plate mega-thrust. Alternately it might have occurred on a major splay fault, i.e. a structure with relatively steep dip, with surface expression, and that the splay roots at the mega-thrust. However, there have not been seismic images to test all these hypotheses.

Finally, the area of research of POSEIDON is located at the edge of the Ionian subducting slab, which is bounded to the NW by a lithospheric tear (Hansen et al., 2019). Thus, the geodynamic evolution of the slab, deep under the study area, may be partially driving shallow crustal tectonics, adding additional complexity to understanding the region. We may thus have the opportunity to study the (early) stages of a Subduction-Transform Edge Propagator (STEP) fault system (Govers&Wortel, 2005). This scenario is supported by deep imaging of the slab structure (Hansen et al., 2019), and appears in agreement with the abrupt lateral changes in the overriding plate deformation. Understanding the large-scale structure will be of importance to evaluate fault kinematics interpretation and model deformation numerically.

The seismic profiles recently collected during the POSEIDON cruise image the upper crust and the Moho discontinuity along many segments (Figure close up example). Therefore, the high-resolution bathymetry will able to image and map the structure of the main faults across the offshore region. The structure of the faults will be used to define their interrelations to understand the 3D fault systems, the kinematics of the main structures, their probable relation to the deep slab geodynamics and their potential relation to past earthquakes in the region. Furthermore the map of the fault structure in 3D will provide basic information necessary to help assess seismic hazards in this seismicallyvery active region.

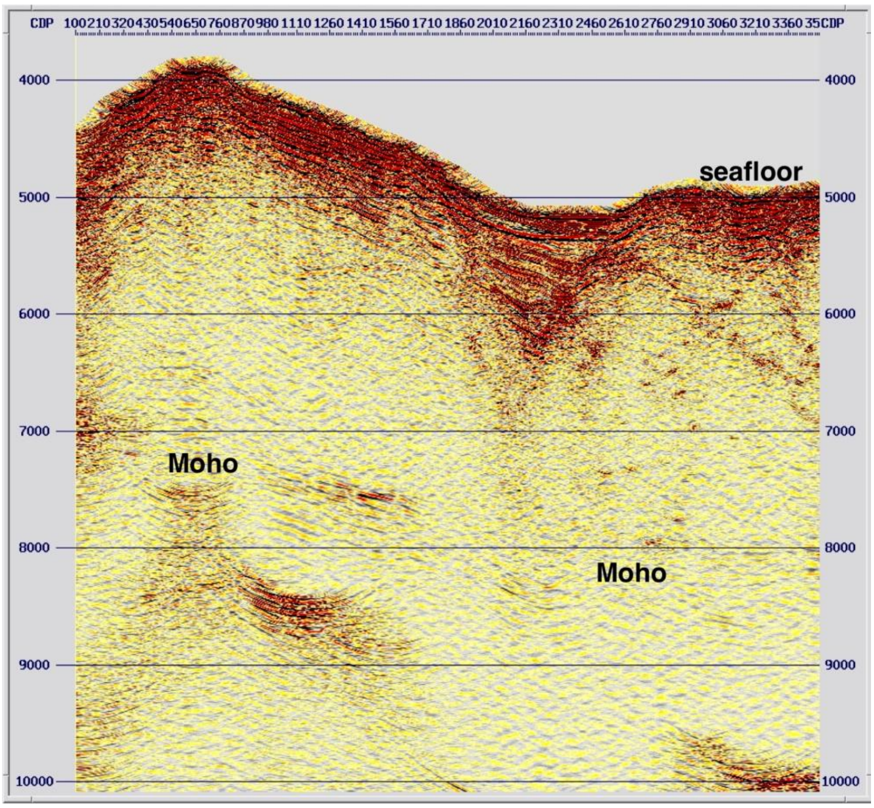

Figure 2. Segment of a POSEIDON seismic line imaging the seafloor, sediment cover and possibly the Moho boundary marking the base of the crust south of Zakynthos.

Acknowledgements

We acknowledge the professional and dedicated work of the Observatorio Geofisico Sperimentale (OGS-Trieste) technical party onboard the Italian Research Vessel (R/V) Laura Bassi, and the technical party of the Marine Technology Unit (UTM) from the Spanish National Research Council (CSIC), and their commitment to make the experiment a success. We also acknowledge the professional and dedicated work of the master, officers and crew of the R/V Laura Bassi during the POSEIDON experiment.

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Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00007

Archaeoseismological Study of two Rural Roman Buildings in Germania Superior

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Several rural Roman buildings in the Province of *Germania Superior* show striking collapse patterns of their walls. Slope movements and seismic ground motions or a combination of both come into consideration as the cause.

Introduction

Since the late 19th century excavations in the Roman province *Germania Superior* have revealed features of walls that have fallen ‘en bloc’. The two sites covered in this study are located near the modern cities of Hechingen-Stein and Oberndorf-Bochingen and have so far revealed the most impressive and extensive examples of this type of archaeological feature in South West Germany. Entire walls of several rural buildings have fallen to the outside, preserving the wall structure including the rows of building stones, window and door positions, as well as lintels and other construction details. The surroundings of the site have been hit by five damaging earthquakes with magnitudes above 5 and the two sites are about 18 km and 29 km away from the epicenter of the M_W 5.7 2011 earthquake. This close proximity to the seismic active area of the Hohenzollern Graben motivated to launch an archaeoseismological analysis of the damage process of these buildings.

Location and Archaeological Context

Systematic study of Roman structures (1st to 3rd century AD) excavated in the province of *Germania Superior* in modern south-west Germany revealed several sites (Fig. 1), where entire walls of buildings have toppled and the collapse patterns were preserved. These archaeological features differ greatly in extent, preservation and the type of Roman building they formed part of.

Some of these sites are in close proximity to the seismic active area of the Hohenzollern Graben and within the isoseismal of intensity VII of the 1911 earthquake near Ebingen, following a model by Stempniewski et al. (2008).

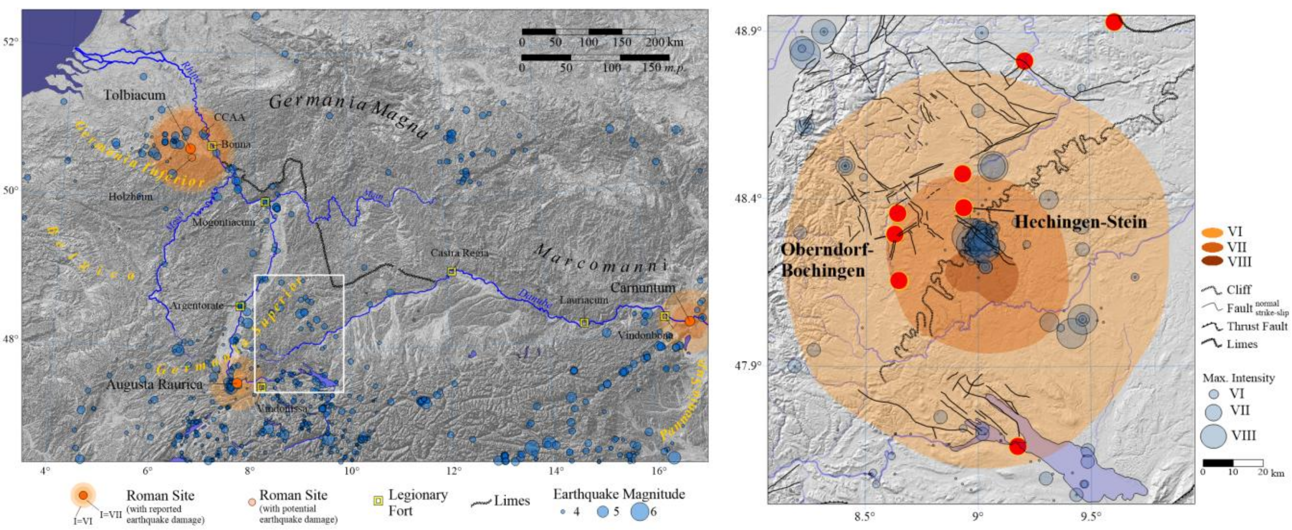

Figure 1. ***left*****: Map of the border region between the Roman Empire and Germania Magna. Blue dots show the locations of historic earthquakes which occurred between 1000 and 1899 based in the SHARE earthquake catalog (Stucci et al., 2013). The white rectangle indicates the limit of the detailed map on the *right*: red dots show sites where toppled Roman walls were found and blue circles the seismicity of the area from the earthquake catalog of Leydecker (2011). The size of the circles varies with the maximum intensity of the earthquakes which occurred between 813 and 2008. The shaded brown colors indicate areas of intensities VI, VII, and VII (legend) that were modeled by Stempniewski et al. (2008) for the 1911 earthquake close to Hechingen. Tectonic faults after geol. map of Baden-Württemberg (1998) and Sieberg and Lais (1925)**

The first of two sites covered in this study is at Hechingen-Stein (HES) (48.377°N 8.935°E) where structures of a *villa rustica* are located on a sloping hill. Some of the buildings of the complex have been restored and are part of an open-air museum. Figure 2 shows an aerial view of the site and the finding situation of the building M, which was probably used as a barn, located at the top of the slope.

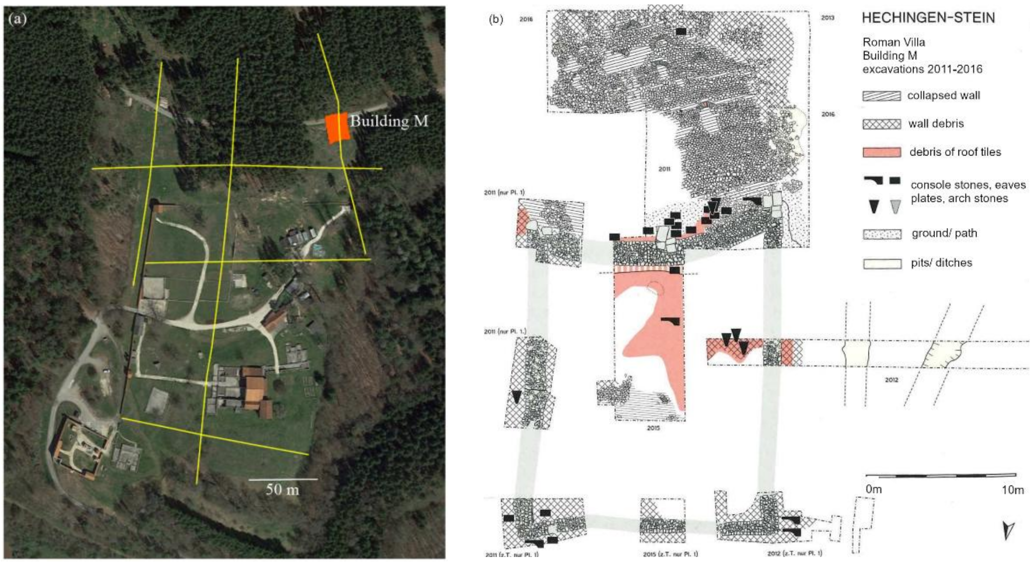

Figure 2. (a) Google Earth view of the archaeological site at Hechingen-Stein, yellow lines show the trend of geoelectric profiles and location of building M is indicated. (b) Excavation plan of the rural building M (Kortüm 2017), location is indicated in (a). Data from Landesamt für Denkmalpflege Baden-Württemberg

Figure 3 shows the finding situation of two barn-type buildings at Oberndorf-Bochingen (OBB) (48.297°N 8.631°E). The spectacular toppling patterns of the walls were first reported by Sommer (1995). While the courtyard wall of building #4 in Figure 2a shows debris piles at both sides, the southern and western wall of the barn toppled bonded, so that the rows of building blocks, windows, and a door opening can be clearly identified and measured for reconstructing the barns. The same bonded collapse exits at building #3 which is located about 50 m from the latter (Fig. 2b). Here, the complete gable wall was excavated, which allows the reconstruction of the building height. The foundations of both buildings do not show any sign of deformation.

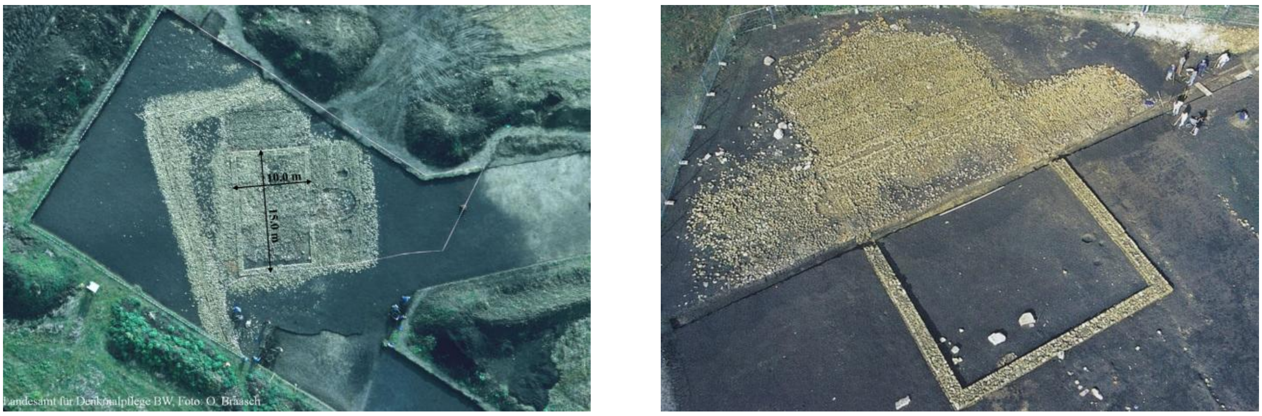

Figure 3. Arial view of the collapsed building #4 (a) and # 3 (b) at OBB. (b). Photos: Landesamt für Denkmalpflege Baden-Württemberg, Th. Schlipf

Decay Process

Main goal in archaeoseismology is to reveal the decay process of excavated structures and interpret the causes of observed damage. In both cases the bonded pattern of the toppled walls is a clear indicator of a sudden process. However, whether earthquake ground motions are a possible cause of such a sudden collapse or other causes like storm or snow load are possible as well is the central question of the project.

The slope situation in **HES** raises the question whether slope failure is a possible alternative cause. The subsurface of the slope was explored with five geoelectric tomography profiles (Fig. 1). These show that the underlaying hardrock of Stubensandstein formation is overlain by a layer of Knollenmergel which in the range of building M has a thickness of 10-12 m of which the top 4-5 m are interpreted as part of a sliding wedge. This is in general supported by preliminary results from seismic ambient noise measurements. Such slopes with Knollenmergel-cover in the area are known to be prone to hang sliding and a 3D digital terrain model of the site shows a slope angle of 13° and a clear slump toe at the foot of the hill. A 2D Finite Element model of slip circles of the slope indicates a factor of safety close to 1.0 even for static conditions. In case of earthquake ground motions and/or heavy rain events, an activation of the mass wasting process at the site is highly probable and both can explain the deformed and collapsed walls of building M.

In case of **OBB** however, the building ground is almost horizontal and a mass wasting processes as collapse-cause can be excluded. Probabilistic seismic hazard analysis provides response spectra which resemble the ground motions at a site for certain hazard levels. The recent earthquake hazard model for Europe (ESHM20, Danciu et al., 2021) suggests response spectra for various probability levels. Considering the possibility that the damage was caused by a rare event, we selected the spectra for return periods of 2500 and 5000 years. Table 1 lists the Peak Ground Accelerations (PGA) from this model for the two sites for the arithmetic mean and the 84% fractile, all values are for rock site conditions.

Table 1. Peak Ground Acceleration arithmetic mean (84% fractile) from model ESHM20 (Danciu et al., 2021).

Site	0.04% in 1 year (2500)	0.02% in 1 year (5000)
OBB	0.171g (0.204 g)	0.239 g (0.285 g)
HES	0.380 g (0.456 g)	0.510 g (0.577 g)

In the light of the PGAs ranging from 0.17 g to 0.57 g (Tab. 1) we plan to further explore the damage mechanisms and set limits to ground motion parameters by exposing discrete element models of the Roman buildings to measured ground motions selected from world-wide databases which are compatible with the spectra from the ESHM20 and include site amplifications based on in-situ HVSR measurements. First plausibility tests with analytic ground motions showed similar toppling patterns similar to those observed at OBB in some cases (Fig. 4).

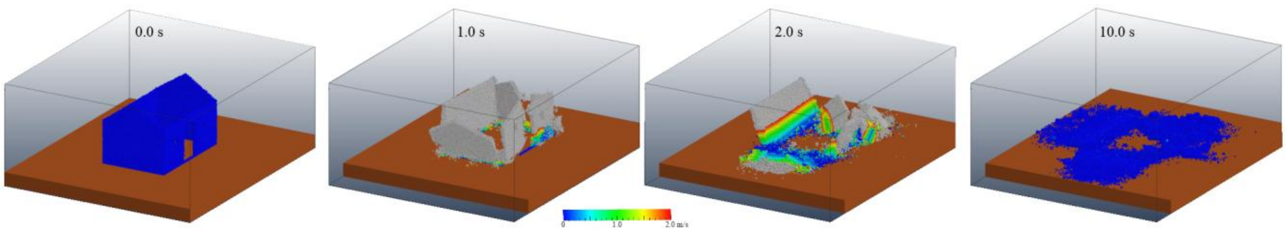

Figure 4. Snapshots of a discrete element model of building #3 from OBB under the load of a 1 Hz cycloidal pulse parallel to the longitudinal side of the structure (time of frames given on top). The color bar indicates the instantaneous velocity of elements; values above 2.0 m/s are in gray.

Summary and Conclusions

Rural Roman buildings close to the earthquake zone of the Hohenzollerngraben in southern Germany show toppling patterns which indicate a sudden collapse. While in case of the structure in Hechingen-Setin, slope failure, possibly induced by seismic shaking, contributed to the damage, preliminary dynamic tests of discrete element models support the hypothesis of a seismic cause of the 'en bloc' collapses of two barns in Oberndorf-Bochingen. Refined models of the structures and site specific ground motions will be used to further explore the decay process.

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8th International Colloquium on Historical Earthquakes,
Palaeo- Macroseismology and Seismotectonics
17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00008

The National Observatory of Athens active faults of Greece database (NOAFAULTs) version 2023

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Introduction

Since 2007 NOA has been building a comprehensive, regional dataset of active fault traces of seismogenic concern. The NOAFAULTs database of active faults of Greece was first published in 2013 (Ganas et al. 2013; versions 1.0 & 1.1; http://dx.doi.org/10.12681/bgsg.11079). In this paper we present the upgrades comprising the newer version of the database (version 5.0) (Figure 1). The motivation behind NOAFAULTs was a peri-Adriatic initiative of structural geologists, tectonicians and seismologists to compile a first map of active faults (Piccardi et al. 2007). At NOA, the concept was expanded towards compiling a digital database of active fault geometry and additional attributes (character of faulting, past seismicity etc.) primarily to support seismicity monitoring at the National Observatory of Athens (NOA). It has been constructed from published fault maps in peer-reviewed journals since 1972 while the number of the scientific papers that were included is 140 (in v5.0). The standard commercial software ARC GIS has been used to design and populate the database. In the follow-up versions (e.g., Ganas et al. 2018), more details on fault geometry, such as the strike, the dip-angle and the dip direction, and kinematics for each individual fault are included. For well-studied faults, information about the slip rate or the creep or the co-seismic slip is also reported. The vector fault layer was produced by on-screen digitization of the fault traces contained in the original papers at the National Observatory of Athens. The database is available to the scientific community in ESRI shapefile (SHP), KML/KMZ and TXT formats in WGS84 projection. The NOAFAULTs dataset includes 2916 crustal faults (incl. the Eurasia-Africa subduction front) spanning a total length of ~27894 km.

Characteristics of the database

In this version of the database, we continue to focus on the active faults of the upper (Aegean + Eurasian) plate (including south Albania and the Sea of Marmara) and the back-arc region of the Hellenic Arc, in general. We assigned a 6-digit unique identifier (ID; starting with letter GR for TU for Turkey etc.) to each fault record in the dataset to avoid possible ambiguities in identifying the faults. A number of 2916 crustal faults are now included. 91.4% of the active faults are normal faults, 5.2% are strike-slip faults and only 3.2% represent the reverse faults. Reliable data on slip rates is available for 215 faults. Also, data on instrumental and historical seismicity was recorded for 175 and 132 active faults, respectively. So far, the confirmed spatial correlation between epicentres of strong seismic events (both instrumental and historical) including paleoseismological and geological data on the same events from the literature and location of active faults allowed the identification of 111 events and corresponding seismic faults. The maximum recorded magnitude of those events ranges between M_w=5 to M_w=7.4. The NOAFAULTs database shows that the 54% of active faults imply high seismic risk level in the broader area of Greece (Figure 2). The notation high stems from the adopted threshold of 5 km for surface rupture length that is empirically related to an earthquake magnitude of M=5.5 (Wells and Coppersmith, 1994) and it does not consider exposure (vulnerability) levels. These active faults ($L \geq 5$ km) can generate surface faulting or strong ground motions that can cause serious damage to buildings and infrastructures and therefore represent a significant hazard, particularly in the densely populated and industrialized areas of Greece.

Moreover, 26 thematic layers are included in version 5.0 with information on seismic and GNSS networks, past strong earthquake locations, the most recent seismic zonation model for Greece (Vamvakaris et al. 2016), African slab isobath models etc. The database is available through our web portal application https://arcg.is/04Haer supported by ESRI. Recently, NOAFAULTs was included in the 2020 update of the European Fault-Source Model 2020 (EFSM20; Basili et al. 2022).

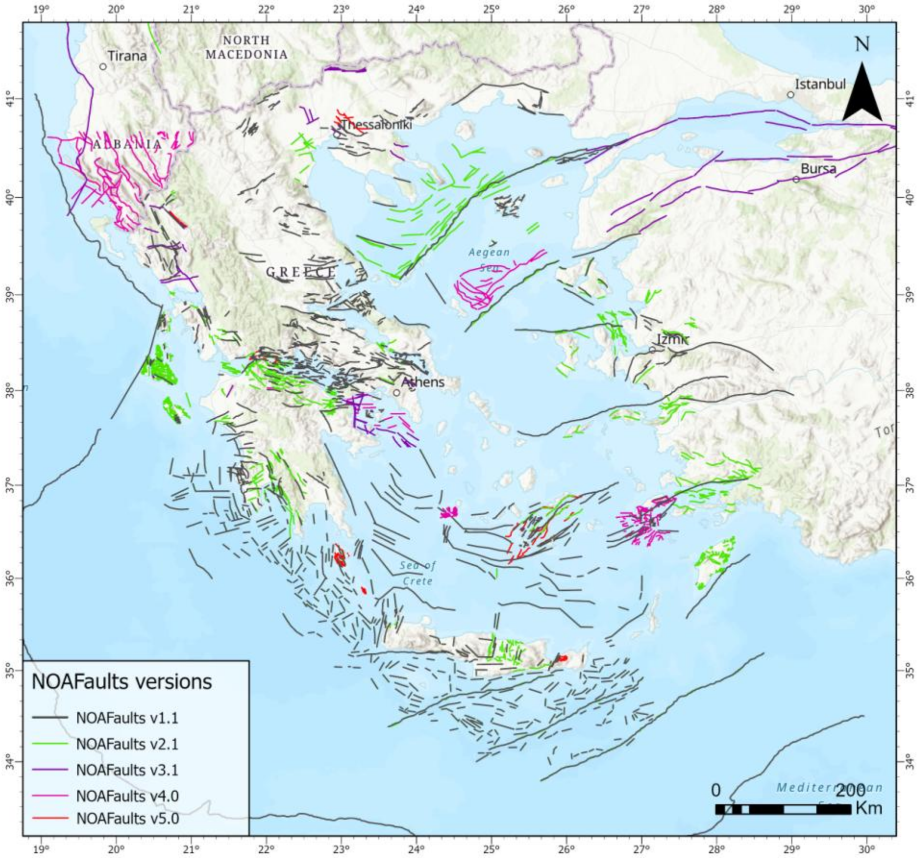

Figure 1 Relief map of the greater Aegean and the Hellenic Arc regions which displays the recurrent versions of the NOAFaults databases. We clearly see the add-ons with different colors in each version.

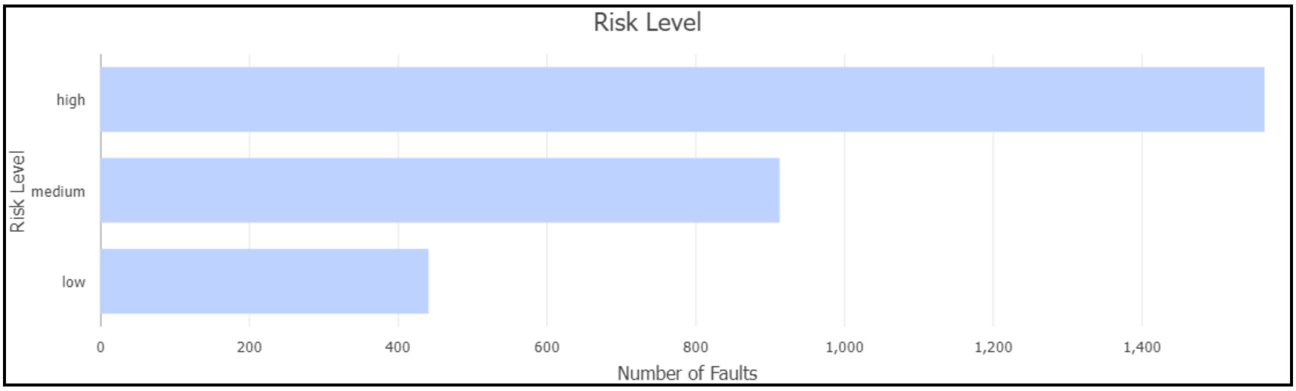

Figure 2 Chart which shows the statistics of the field of risk level of the database. 54% of active faults imply high seismic risk level, 31% of active faults imply medium seismic risk level and 15% imply low seismic risk level. The risk level is associated with earthquake magnitude potential which is in turn linked to fault length. The threshold between high and medium is 5 km and between medium and low 1 km, respectively.

Key words: Active faults, GIS, Hellenic Arc, Aegean, earthquakes

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From shallow to very shallow image of the highly active Kefalonia – Zakynthos fault system

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In May 2022 and June 2023 two oceanographic cruises were carried out around the Ionian Islands with the aim of defining the real geometry of the strike-slip fault system of Kefalonia and of the reverse faults present south of Zakynthos. The acquired multidisciplinary and multiresolution data will also allow to understand the dynamics of the area offshore the Peoloponnese peninsula, the deformation of the surface sediments at the transition of the two systems, i.e. from reverse fault system to strike-slip fault system, and the relationship between the recorded seismicity and mapped fault activity. To date, the analysis of the processed data has allowed us to define the tectonic and morphological complexity of the fault system affecting the investigated area.

Background

The area offshore the Peloponnese and the Ionian Islands (Cephalonia, Lefkada, Zakynthos and Ithaki), NW Greece, is characterized by a comparatively more intense instrumentally-recorded seismicity than any other region in the Mediterranean, often with tsunamigenic potential. During the last four decades, there have been several large earthquakes with Mw>6 in Kefalonia 1983, Strofades 1997, Lefkada 2015, Zakynthos 2018 (see references in Ganas et al., 2020). Based on focal mechanisms (Ganas et al., 2020; Papadimitriou et. al. 2021), Kefalonia system shows strike-slip movements, while Zakynthos is mainly affected by compression with a small transcurrent component. Although the several seismological studies (Cirella et al., 2020; Ganas et al. 2016) and modelling (Basili et al., 2013; Svigkas et al. 2019) that allowed to define the several fault plane solutions related with the main events, a clear image of fault planes related to the several events still not known.

Furthermore, a new discussion has recently emerged about the role played by the Kefalonian fault system. Although it has long been recognized as a Transform Fault (Scordilis et al., 1985), some authors have proposed it as a pro-STEP (Subduction-Transform-Edge-Propagator) fault (Ozbakir et al. 2020) formed simultaneously with Pliocene fragmentation of the Epirus fragment.

Objectives

Accordingly, two marine geophysical surveys have been carried out in 2022 and 2023 to acquire seismic and swath data in the study area. The scope of the surveys was to understand the deformation of shallow sediments, which are controlled by the geodynamic structure of the two complicated tectonic systems and to find some clues of STEP fault activity.

Methods

We acquired 437 km of high-resolution multichannel seismic (mcs) profiles and magnetic data (Ionians project 2022; Figure 1), 954 km of deep-penetration multichannel seismic profiles and more than 1700 km of sub-bottom profiler and swath data. Moreover, 2 gravity cores were acquired in the deepest parts of the area in turbiditic depocenters at 3.7 to 4.2 km water depth (Poseidon project 2023).

The high-resolution mcs were shoot every 6.25 m with one water-gun (total volume of 12 inc^3), recorded with a 75-long streamer, 24 active channels achieving a coverage of 600% and record length of 3072 ms (for more detail see Loreto et al., 2022). We performed standard processing from SEGD reading to post-stack time migration. Magnetic data were collected using a SeaSpy marine magnetometer towed 133 m respect to the stern.

The high-penetration mcs were shoot every 37.5 m with 4 synchronized Airgun (total volume of 1000 inc^3), recorded with a 1500-long streamer, 120 active channels, reaching a coverage of 2000% and record length of 12000 ms. Swath bathymetry was acquired with a Konsberg EM304, while the sub-bottom chirp profiles were acquired using Topas PS18. The two systems were synchronized by a k-sync to avoid any frequency interferences. The two gravity cores sampled 2.2 m and 2.7 m of sediments.

Results and Conclusions

In this contribution, we will present and discuss results from the geophysical survey mapping the shallow structure. The Kefalonia fault system is characterized by several faults bounding blocks with different kinematic movements changing along the fault strike. From the western part of the Kefalonia – Lefkada region towards southwest the fault changes from a narrow and very steep single fault scarp to a complex setting of fault planes (Figure 2) that rotate north-westward at the ending part. Southwest to Zakynthos several NE-SW structures, associated with the tectonic elements appear associated to landslides and to the recent seismicity recorded in the area.

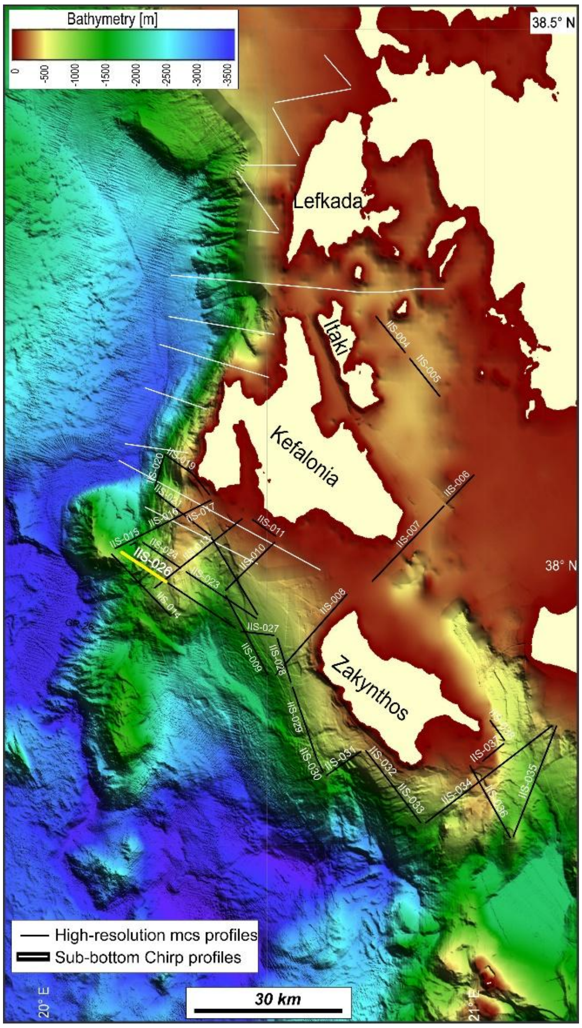

Figure 1. Location map of high-resolution mcs and some sub-bottom chirp profiles acquired during the Ionians 2022 and Poseidon 2023 cruises. Middle resolution morpho-bathymetry downloaded from the official Emodnet portal (DTM Release 2020; https://emodnet.ec.europa.eu/en/bathymetry) and gridded using the open-source GMT (Wessel and Smith, 2018).

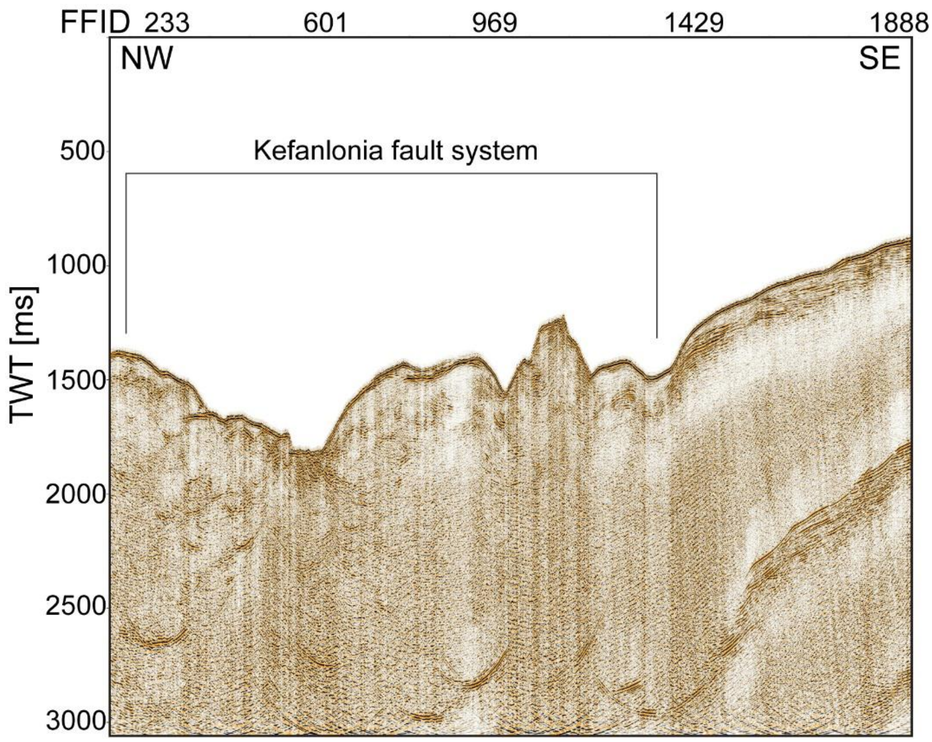

Figure 2. Seismic image of the southern part of Kefalonia fault system, seismic line IIS_26 (yellow line in Figure 1).

Acknowledgements

Thanks to the CNR for supporting the cruise with time ship, IONIANS 2022 project. Interpretation of seismic profile has been done using the Kindgom IHS Markit. Poseidon project has been supported by Eurofleet+ SEA02_13_POSEIDON. We thank all the OGS technician staff for the strong work they did in order to make the survey successful.

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The impact of environmental effects triggered by the 6 February 2023 Turkey-Syria earthquakes on the type and distribution of building damage

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Introduction

On 6 February 2023, two major earthquake events struck the southeastern part of Turkey and the northwestern part of Syria. The first Mw=7.8 earthquake struck at night (04:17 local time), and several hours later (13:24 local time) a second Mw=7.5 earthquake caused widespread impacts on the local population and the natural and built environment of 11 provinces in southeastern Turkey (Figure 1), home to nearly 14 million Turks and 2 million refugees from neighboring Syria. Human casualties amounted to 50,399 and injuries to 107,204, according to the latest official announcements (Government of Türkiye, 2023). Nearly 2.5 million people live in temporary settlements, while 1.6 million of them are staying in unofficial settlements (Government of Türkiye, 2023).

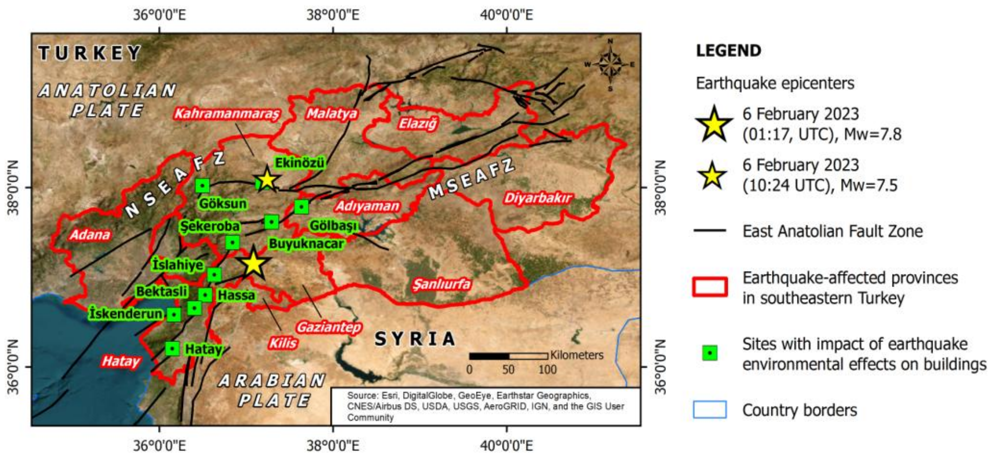

Figure 1. The provinces in southeastern Turkey affected by the 6 February 2023 earthquakes due to rupture of the East Anatolian Fault Zone (EAFZ). The sites where the earthquake environmental effects greatly affected the building stock are presented with green symbols and green letters. Red colors in symbols and letters correspond to the affected provinces. MSEAFZ: Main Strand of the EAFZ; NSEAFZ: Northern Strand of the EAFZ.

These high numbers of casualties, injured and homeless people are attributed to the extensive and very heavy structural damage generated in the earthquake-affected area. In particular, 518,009 buildings either collapsed or sustained heavy structural damage (Government of Türkiye, 2023), resulting in thousands of trapped residents and millions of affected people.

The obvious reasons that contributed to the large human and economic losses in southeastern Turkey comprised the large earthquake magnitude, the generation of the first earthquake during the night that found the majority of residents in their homes, the demographic characteristics of the region which include densely built-up and populated urban areas as well as the proximity of many residential areas to the seismogenic faults. The earthquakes caused primary effects, including extensive coseismic surface ruptures, and triggered secondary effects, including liquefaction and landslides, among others, that have largely shaped the type and distribution of the building damage.

This extended summary provides a presentation of the primary and secondary effects detected during post-event field surveys conducted by the authors in the southeastern part of Turkey and their contribution to the type and distribution of the observed building damage.

Methodology

The data presented in this study have been obtained from post-event field surveys conducted by the authors in several severely affected urban centers in the earthquake-affected area of East Anatolia. The field surveys were conducted both shortly after the devastating earthquakes (6–11 February) and 2 months after the earthquake (31 March–6 April), when access within severely affected urban centers was allowed after the completion of extensive search and rescue operations, providing the opportunity to obtain on-site data.

The authors collected data in the disaster field by applying traditional field mapping techniques and innovative methods, including the deployment of Unmanned Aircraft Systems (UAS). The unmanned aerial photo imaging contributed to the direct identification of the primary and secondary effects of earthquakes within densely built areas and the direct mapping of their impact on the built fabric.

Impact of coseismic ruptures on buildings

The coseismic surface ruptures intersected with cities, towns, and settlements, resulting in a major impact on the performance of buildings and infrastructure during the earthquake. In most cases, the intersection of these ruptures with the built environment resulted in very heavy structural damage to buildings, which mostly collapsed, while infrastructure was partially or completely destroyed. Characteristic examples of this impact were detected along both strands of the EAFZ (Figure 1), which ruptured in early February 2023. Several observations on such impact were made along the main strand of the EAFZ, in particular from southwest to northeast in İslahiye area (Gaziantep province), in Şekeroba town (Kahramanmaraş province) (Figures 2a–2f) and in Gölbaşı town (Adiymanan province). Furthermore, similar impact was detected in the building stock along the northern strand of the EAFZ, in particular in the Ekinözü area (Kahramanmaraş province) along the Sügü segment and in the Göksun area (Kahramanmaraş province) along the Çardak segment. The effects on buildings in these areas are not only attributed to the left-lateral offset along the fault but also to the formation of structures along it, which typically develop in strike-slip settings and include pull-apart basins and pop-up ridges at various observation scales (Figures 2a–2f).

Impact of liquefaction phenomena on buildings founded close to water bodies

In the provinces affected by the 6 February 2023 earthquakes, many cities, towns, and settlements are built within structures typical of strike-slip settings, such as pull-apart basins filled with recent Quaternary deposits. The evolution of such structures is controlled by ongoing tectonic processes and by active and seismic faults located mainly at their margins. Furthermore, they host water bodies, resulting in recent deposits and conditions of increased instability along their shores as well as high water table. Typical examples of such areas with recorded severe earthquake impact are the Gölbaşı pull-apart basin in the northern part of the affected area, in which the homonymous city is built; the Antakya-Samandağ corridor, in the southern part of the affected area, within which Antakya and Samandağ are built; and the alluvial plain at the front of Ahir mountain, where Kahramanmaraş is located.

In these areas, the Mw=7.8 earthquake triggered several secondary effects that caused additional impact on buildings and structures. These phenomena mainly included liquefaction and extensive lateral spreading. They were initially observed on agricultural land, where they partially covered large areas with liquefied material that reached the surface through ground cracks, resulting in no damage to the building stock. They were also detected within severely affected residential areas in the form of ground cracks attributed to lateral spreading. Lateral spreading was characterized by very large and highly non-uniform ground deformation, causing stretching of building foundations and associated damage.

Such impact was captured within the town of Gölbaşı (Adiymanan Province) (Figures 2g–2i) and the coastal town of İskenderun (Hatay Province). A common characteristic of these areas is that they have properties that make them susceptible to liquefaction. These properties include recent deposits with sand and silt as the main lithology, and water-saturated soils, since these areas are located near a lake (Gölbaşı) and the sea (İskenderun). The generated building damage, especially in the first case of the foundation in a lakeside environment, was typical of liquefaction phenomena and the loss of load-bearing capacity of the foundation. It included mainly (a) tilting and subsidence of the building without damage to the superstructure, (b) pancake-type collapse, and (c) outspread multi-layer collapse (Figures 2g–2i).

Another typical case of impact attributed to construction within a basin and foundation close to water bodies is the Antakya city, located within the Antakya-Samandağ corridor at the southern end of the earthquake-affected area. During our field reconnaissance in Antakya city, we detected that the most frequent and continuous collapses are located in the part of the city constructed next to the current Orontes riverbed and built up by Holocene alluvial deposits composed of pebbles, sands, and clays. Taking into account the age and the lithology of the Holocene deposits observed along the Orontes River, the fact that these deposits are saturated with water due to the river water table and the high values of maximum ground acceleration in the area, it is concluded that these deposits, on which a large part of Antakya was built, are highly susceptible to liquefaction phenomena in cases of intense earthquake ground motion. This was amply demonstrated north of the Antakya-Samandağ corridor, in particular in the southern part of the Amik Basin, where extensive liquefaction phenomena occurred, including ground cracks and ejection of liquefied material, sand boils, and lateral spreading along or close to the Orontes river bed.

Impact of landslides on buildings close to steep slopes

Regarding the landslides caused by the 6 February 2023 earthquakes, they are mainly distributed on steep slopes on the margins and within the macrostructures of the affected area, where semi-mountainous and mountainous parts occur.

Landslides were triggered on steep slopes on the margins and within the macrostructures of the affected area. They did not have extensive effects on the buildings of the large residential complexes of cities and towns in the earthquake-affected area, but only in limited cases of semi-mountainous and mountainous settlements. In these settlements, landslides affected buildings causing not only non-structural damage but also severe structural damage. Typical examples of settlements with landslide impact on their built fabric are the Bektasli village (Kirikhan district, Hatay province) and the Buyuknacar village (Pazarcik district, Kahramanmaras province). The majority of the landslide-induced damage is related to damage to infrastructure, in particular segments of the road network.

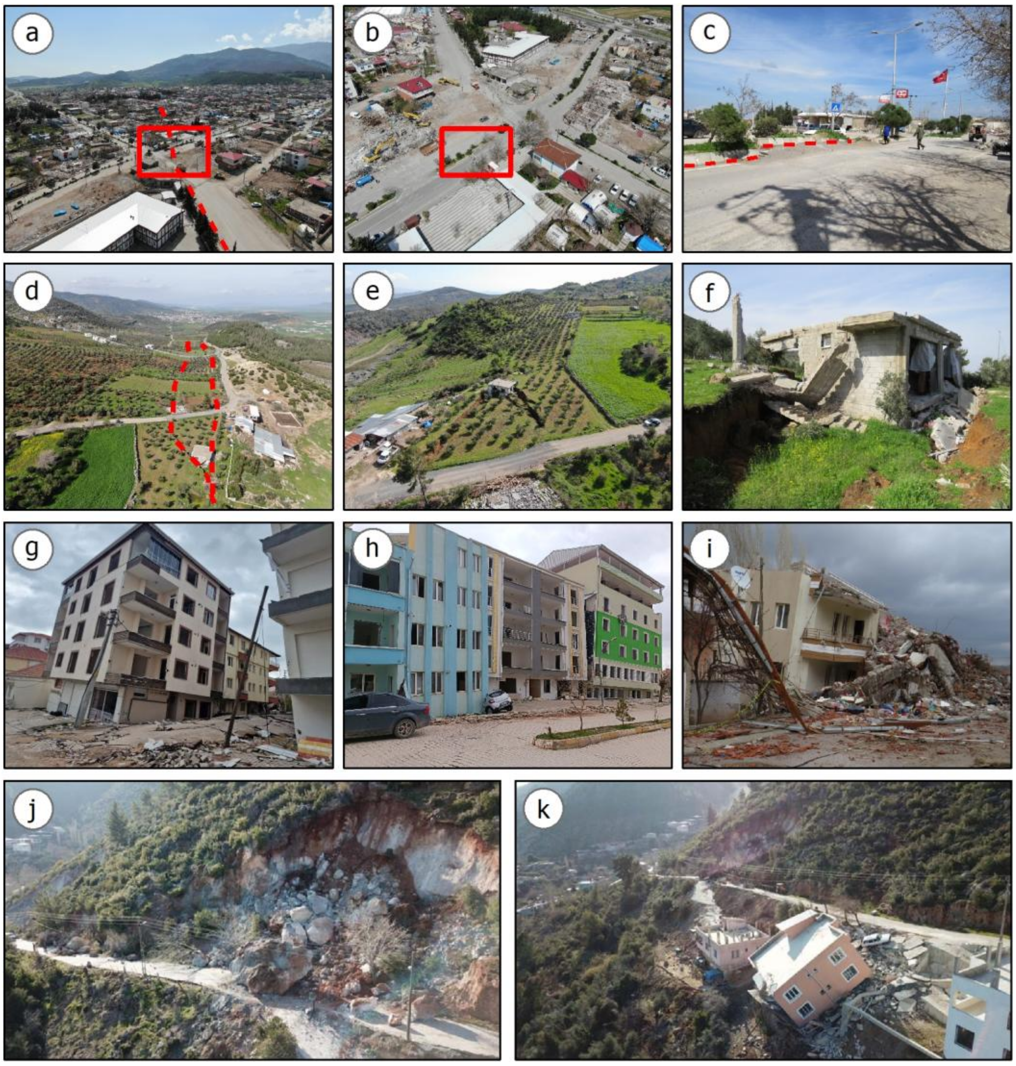

Figure 2. (a) Coseismic surface ruptures (red dotted lines) in Sekeroba town resulting in collapses along and on either side of them. (a, b) Drone views of the intersection (red polygon) where a pop-up ridge resulted in deformation of the road (c) and collapse of the adjacent structures. (d,e,f) Coseismic surface ruptures (red dotted lines) in Şekeroba-Yeşilyurt area resulting in partial and total collapse of structures. (e,f) A reinforced-concrete structure located at the intersection of surface ruptures was completely destroyed. (g-i) Damage to buildings and non-uniform ground deformation in Gölbaşı town, which has been heavily affected by ground deformation attributed to liquefaction and lateral spreading. (j,k) Earthquake-triggered rockfalls in Bektaşlı village (Kırıkhan district, Hatay province) and related impact on buildings.

Conclusions

The presented data and examples show the significant impact of the primary and secondary environmental effects triggered by the 6 February 2023 earthquakes on the type and spatial distribution of building damage in southeastern Turkey. The identification of zones susceptible to the occurrence of these effects is very important for the comprehensive seismic hazard assessment and the mitigation of the impact on buildings and infrastructure in residential areas and consequently on their population by similar destructive seismic events in the future.

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Investigating the homogeneity of Italian macroseismic data

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The Italian Macroseismic Database DBMI15 (Locati *et al.*, 2022) contains nearly 124,000 intensity data related to 3229 Italian earthquakes in the period 1000-2020 that provide a unique picture of the effects of past Italian earthquakes. These data are derived from 191 different sources of information collected and made available through the Italian Archive of Historical Earthquake Data ASMI (Rovida *et al.*, 2017). The types of data sources contributing macroseismic intensities to DBMI15 are manifold and comprise other databases (i.e. The Italian Catalogue of Strong Italian Earthquakes CFTI14med; Guidoboni *et al.*, 2007), historical macroseismic studies, macroseismic bulletins, the results of macroseismic field surveys of recent earthquakes and so on. Such a variety of studies represents the scientific heritage of a long research tradition in the field of historical seismology and macroseismology. Indeed, the compilation of DBMI15 implies only the homogenization of the geographical coordinates and the placenames of the localities associated with macroseismic observations, and the standardisation of non-numerical effect descriptions (e.g. “felt”, “damage”, etc; see Locati *et al.*, 2022). As a drawback, this amount of studies fed DBMI15 with intensity data assessed by diverse authors and methodologies, in different periods and possibly under different project frameworks and assumptions, and in a few cases even without using the same macroseismic intensity scale.

In this situation, to which extent Italian macroseismic data can be considered homogeneous? Which are the main reasons for possible inhomogeneities? How much any supposed inhomogeneity does affect the applications of macroseismic intensities?

To answer the above questions and try to evaluate the level of homogeneity of DBMI15 we performed a series of tests comparing macroseismic intensities with virtual estimates of ground shaking, starting from the locations and magnitudes provided by the Italian Parametric Earthquake Catalogue CPTI15 (Rovida *et al.*, 2020, 2022).

As a first test, we computed and analysed the differences between observed intensities as reported in DBMI15 and those estimated with a recent intensity prediction equation (IPE) by Gomez Capera et al. (2023). We investigated these differences from the spatial and temporal perspectives and according to the different sources providing the data.

As a second test, for all the intensity data in DBMI15 we computed the corresponding PGA and 1.0s spectral acceleration with the ITA18 Ground Motion Model (Lanzano *et al.*, 2019). We then performed the same analysis in terms of temporal, spatial, and study-dependent variations. We also analysed the results of the test comparing data expressed in the MCS and EMS-98 scale.

Although preliminary, the results show that Italian macroseismic data are sufficiently homogeneous and, despite their nature, properly correlate with ground motion parameters, considering the uncertainties associated with both measures.

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8th International Colloquium on Historical Earthquakes, Palaeo- Macroseismology and Seismotectonics

17-20 September 2023 - Lixouri, Greece

Bulletin of the Geological Society of Greece, Sp. Publ. 11

Ext. Abs. 00012

Crowdsourced data and their utility for rapid earthquake impact assessment: The example of the 2023 M7.8 Kahramanmaraş, Türkiye, earthquake

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Abstract

The devastating 2023 M7.8 Kahramanmaraş earthquake in Türkiye is a good example of the challenges of rapid and reliable impact assessment. For example, the final death toll was 56,000 but the best fatality estimate from the USGS PAGER system remained below 1,000 for hours and did not exceed 10,000 even after incorporating local accelerometric data two days later (Goldberg et al., 2023). The methodology is not in question, this is an illustration of the large and intrinsic uncertainties affecting rapid earthquake impact assessment in the absence of dense in-situ observations and limitations of predictive loss models more generally. The purpose of this work is to demonstrate that in the absence of a dense, real-time accelerometric network, eyewitness observations, such as those crowdsourced by the LastQuake system, provide a suitable alternative for constraining rapid impact evaluations.

The work is divided into 3 parts. First, we present the LastQuake system, then the main characteristics of the collected data and how they can be used for impact assessment. Finally, we present a retrospective study carried out in collaboration with the USGS and ETH to illustrate how the integration of EMSC data could have contributed to an improved fatality estimate in the immediate aftermath of the devastating M7.8 Kahramanmaraş earthquake.

The LastQuake system and characteristics of the data collected

LastQuake is a multi-component rapid information and crowdsourcing system for global earthquake eyewitnesses (Bossu et al., 2018a). It consists of a smartphone application, a website for mobile devices, an established Twitter bot, as well as a newly released bot on the messaging app Telegram. Eyewitnesses are engaged by offering them what they are looking for after an earthquake: fast information. The efficiency of this engagement is directly linked with the ability to provide early information, even before seismic data is available, by detecting the online reaction of eyewitnesses. Felt tremors trigger information-seeking behaviour, which is reflected in a sudden increase in traffic to our website and/or our app, and/or in the rate of published tweets containing the keyword "earthquake" in the local language of the felt area. These spikes are automatically detected, typically within 15 to 90 seconds after the time of the earthquake, independent of seismic data, and are called "crowdsourced detections". They generate a message on the LastQuake system requesting eyewitnesses' confirmations, initiating rapid and massive crowdsourcing of their observations often before a first seismic location is available.

There are 3 types of crowdsourced data – felt reports, pictures and comments – that are collected via the website or the app and recently using the Telegram bot (that is still experimental at this stage). There is also a Twitter bot that redirects Twitter users to these tools. Felt reports are the main dataset; they are collected through a series of 12 cartoons representing the 12 levels of the EMS-98 macroseismic scale. Users can then also attach a comment to the reports to express their felt experience in their own language. Geo-localised images are also collected and published only after manual validation. Derived intensities from felt reports correlate well with the USGS DYFI ("Did You Feel It?") data. However, like all online macroseismic questionnaires, it is unlikely to map intensities above 8 to 9. There are three main reasons for this limitation. First, high intensities tend to be spatially localised, whereas intensities are based on a spatial averaging of felt reports. Furthermore, the rate of crowdsourcing is, at least initially, lower in affected areas than in more distant ones ("the doughnut effect", Bossu et al., 2018b), as people are first concerned about their safety and that of their loved ones. Lastly, assigning higher intensities requires engineering judgement about each structure's vulnerability and damage grade, information not known or reported on felt forms.

In 2022, there were 250,000 felt reports collected, 28% of which were collected before the first seismic location was announced (median time for first seismic location: 3.5 minutes). The median collection time for felt reports is 10 minutes. It is longer for damaging earthquakes.

Using crowdsourced data for rapid impact assessment

Felt reports remain the main data set for rapid impact assessment (Figure 1). Intensity curves as a function of epicentral distance are routinely generated for all felt earthquakes. Recently, Quitoriano and Wald developed a method to ingest the reports into ShakeMap in a manner consistent with the ingestion of DYFI data (Quitoriano et al., 2023). For large magnitude earthquakes, Böse et al. (2021) adapted the FinDer algorithm, which determines a line-source model from dense accelerometric data using a template matching approach, replacing these data with the felt reports. First results are available within 10 minutes. Lilienkamp et al. (2023) developed a model to estimate the probability of an earthquake being damaging by analysing the characteristics of felt reports collected within 10 minutes of the earthquake, independent of any seismic data. This could pave the way for a fully automated 'traffic light'-based system of impact reporting.

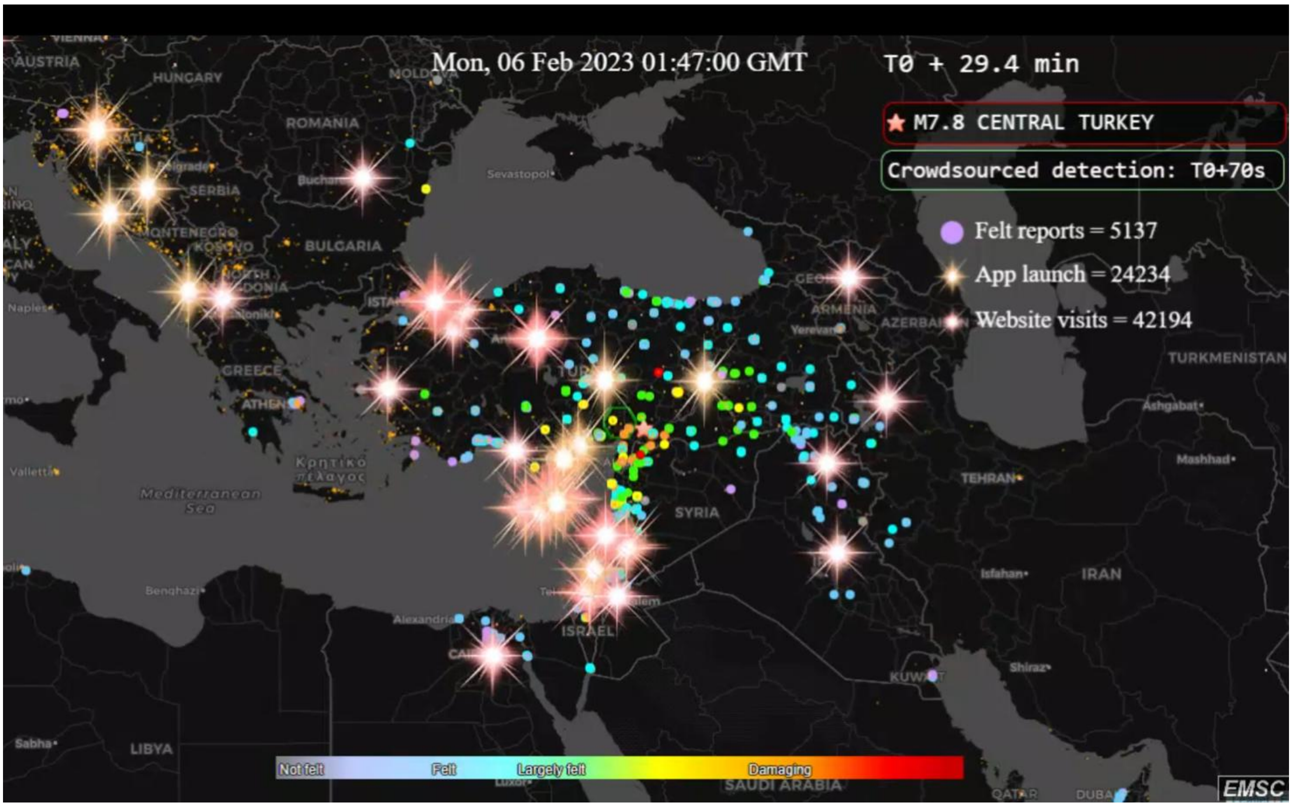

Figure 1. The LastQuake system 29 minutes after the 6 February 2023 earthquake in Turkey. The earthquake was detected in 70 seconds (green hexagon) by the activity generated on the LastQuake system, i.e. almost 4 minutes before the seismic location (star) became available. More than 5,000 reports (coloured dots) were collected in the first 30 minutes. Visits to the website and the opening of the smartphone application are represented by a flash of light. The flashes of light in Balkans correspond to reactions following receipt of the notification on the smartphone application, (the earthquake was not felt in this area).

Geo-located imagery, once validated, provides a visual indication of the very local level of damage and as such can potentially provide additional information compared to felt reports, and may provide information for high intensity levels that are not achievable through felt reports.

Retrospective study of the M7.8 Kahramanmaraş earthquake, Türkiye

As this study is not yet finalised, only preliminary results are here in presented. The first part validates the methodology for deriving intensity from felt reports by comparing the values with an instrumentally constrained intensity map (Hancilar et al., 2023). The first fatality estimate was made within 2 hrs of the earthquake by estimating the number of people within isoseismic VIII assuming a point source and applying the expected fatality rate (Jaiswal and Wald, 2010). This resulted in an estimate of more than 34,000 fatalities, a value known to be severely underestimated due to the invalid point source approximation for such a magnitude and the impossibility of estimating the isoseismal for higher intensity values. In the study, the effects of integrating the felt reports and the line model derived from these felt reports in the PAGER fatality estimate are presented. In this example, the operational use of EMSC crowdsourced data in the Shake Map system could have improved the rapid estimation of the death toll.

Acknowledgements

Authors want to thank the CEA/LDG, EMSC host for its invaluable support as well as its members, data contributors and LastQuake users without which this study would not exist.

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17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00013

Deformation Pattern and Mapping of Earthquake ruptures of the 6 February 2023 M7.8 & M7.6 earthquakes (Türkiye) through sub-pixel correlation method on InSAR

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Extended Abstract

Introduction

We used C-band SAR (Sentinel-1) data in order to extract information about the ground displacements that occurred due to the 6 February 2023 M_w=7.8 (01:17:35 UTC) and M7.6 (10:24:49 UTC) earthquakes in southeast Türkiye. We retrieved the ascending and descending satellite data (in SLC format) from the Alaska Satellite facility and from the Copernicus Hub of ESA. We used differential SAR (DInSAR) and the sub-pixel correlation methods to retrieve the surface motions in both range direction and in azimuth (along satellite track) direction. We processed the SAR images using the open-source (ISCE) v2 software (https://github.com/isce-framework/isce2) and we applied pixel offset tracking through the cross correlation of the amplitude of the primary (before the earthquakes) and the secondary (after the earthquakes) images. Here, we present the pixel offset method results and our interpretations.

Results and Discussion

The pixel offset method gave us the capability to map the surface rupture extent of the left-lateral strike-slip fault segments along the East Anatolian Fault Zone (EAFZ; from Adiyaman to Antakya; Fig. 1) and the E-W oriented Sürgü fault (SF; ruptured during the M7.6 event; Melgar et al. 2023; Tsironi and Ganas, 2023). We also identified the splay fault known as Nurdağı-Pazarcık fault which is also left-lateral (NPF; Melgar et al. 2023), where the rupture process began and a second splay fault in the area of Adiyaman near the main trace of EAFZ (see position 60 along the profile C-C'). Thus, we mapped the total 2023 rupture length of the EAFZ which is ~ 400 km. Based on displacement profiles (see lines A-A', B-B' and C-C' in Fig. 1) we suggest that the maximum displacement was ~ 7 m in the range direction (along the central area of EAFZ and SF) (Fig.1; see position 25 along the profile B-B'). Such large offsets were reported by field surveys (e.g. Golberg et al. 2023). The ruptures of SF and EAF seem to not be connected at the surface. The surface rupture of the SF turns towards north at the east endpoint of the rupture. Also, at the western termination of SF, another (orthogonal) branch of fault rupture was identified.

An extraordinary element of the complexity of the rupture is the identification of a complex structure where the EAF 2023 rupture seems to penetrate a possible pull-apart basin between two rupture segments of the main fault, in the area near the city of İslahiye. Also, the maximum displacement of the NPF (the splay fault) was found ~ 1 m. It is necessary to clarify that the total displacement field as mapped by InSAR has occurred by the combined motion of the two mainshocks, as well as, possibly by some large-magnitude aftershocks and post-seismic afterslip.

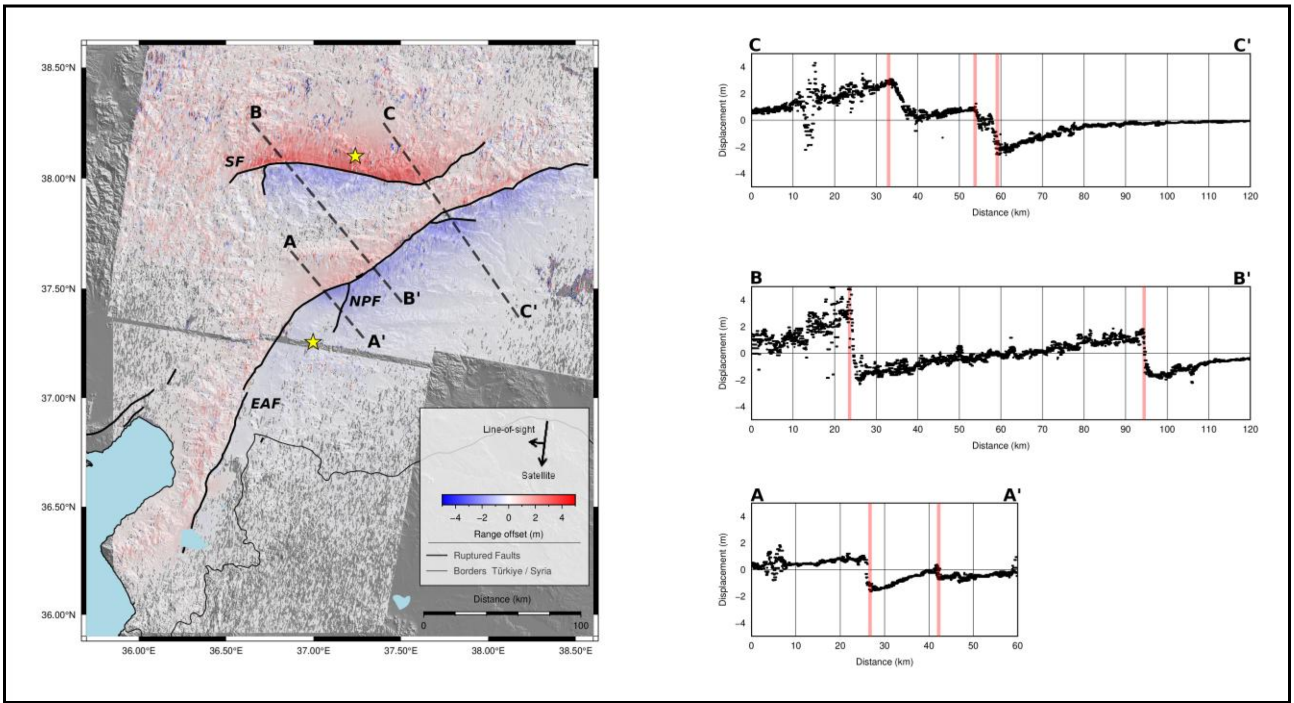

Figure 1: Displacement map produced by pixel offset method of descending track. Positive values show range increase, negative values range decrease, respectively. The black lines show the traced ruptures. The dashed lines indicate the cross-sections. We constructed cross-sections through our displacement data in order to estimate the maximum displacement on the ground surface. We estimated that the maximum displacement was about 7 m in range direction in some places where the maximum slip of the ruptures occurred (section B-B'; central area of EAF and SF). Also, the maximum displacement of the NPF was approximately 1 m (section A-A'). The total displacement occurred by the two main earthquakes as well as possibly by some large-magnitude aftershocks.

Key words: Active faults, Türkiye, ruptures; InSAR; earthquakes

Acknowledgments

This research was supported by the Hellenic Foundation for Research and Innovation (HFRI) under the 3rd Call for HFRI PhD Fellowships (Fellowship Number: 05176). A KMZ file with rupture traces can be downloaded from Zenodo (Tsironi and Ganas, 2023).

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Compressional interseismic deformation and crustal uplift through geodetic and geological investigations onshore Paliki peninsula, Cephalonia, Greece

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Extended Abstract

Introduction

In this study, we present an updated analysis of space geodetic data, including InSAR and GNSS, to assess the pattern of ground velocities on the Paliki peninsula in western Cephalonia, Greece, following the work by Tsironi et al. (2022, 2023). The region of Paliki is prone to frequent earthquakes, due to its proximity to the fast-slipping Cephalonia Transform Fault (CTF), a 140 km long, right-lateral strike-slip fault zone that accommodates the relative motion between the African (Apulia) and Aegean lithospheric plates (e.g., Louvari et al. 1999). Our analysis covers the period from 2016 to 2022 and leverages the LiCSBAS, an open-source package (https://github.com/yumorishita/LiCSBAS), for InSAR time series analysis with the N-SBAS method. For more details on the InSAR data processing please refer to Tsironi et al. (2022). New geological data on active faults onshore Paliki are also presented.

Results and interpretation

The results of the ongoing geological field work and the GNSS/InSAR analysis demonstrate that active faults on the Paliki peninsula are oriented approximately N-S and exhibit detectable slip rates. The horizontal component of movement is dominant, also providing evidence of right-lateral strike-slip faulting onshore the peninsula. The InSAR velocity field also indicates post-seismic motion along the ruptured plane of the 3 February 2014 M5.9 strike-slip earthquake in the northwest part of the peninsula, near Atheras (Fig. 1a; Boncori et al. 2015). Moreover, our analysis has identified other possible active structures, including both strike-slip and thrust faults, confirmed by geological data (see Fig. 1 for fault lines).

Based on the E-W component of the velocity field, the Gulf of Argostoli may host a large active fault zone with possible structures including the N-S Lixouri fault (Fig. 1) and the possible offshore prolongation of the active NNW-SSE, east-dipping thrust faults near Argostoli (Cushing et al., 2020) which accommodate the compressional component of strain onshore. A ~2 mm/yr E-W compression is clearly visible across the Gulf (Fig. 1a). Also, according to the motion pattern of the N-S component of velocity of GNSS data, the whole peninsula is moving towards the south (with respect to stable Europe) but with an increase of the relative amplitude about 4.0 mm/yr between KIPO and ARGO GNSS stations (located 12.3 km apart). This indicates the presence of shear strain in the direction NNE-SSW.

The coastal town of Lixouri undergoes gentle interseismic uplift, as evidenced by positive line-of-sight values in both satellite imaging geometries and their vector decomposition (Fig. 1b). The vertical velocities also demonstrate a change of rate of uplift from west towards east. The uplift rate decreases dramatically in Argostoli area. This combined evidence (E-W and Up-Down velocity pattern) indicates that the inferred fault zone inside the Gulf of Argostoli is accumulating interseismic strain and may corresponds to a possible crustal block boundary between Paliki (west) and central Cephalonia (east) as it was suggested by Ganas et al. (2015) and Sakkas and Lagios (2017).

Overall, our results suggest a complex deformation pattern on the Paliki peninsula as evidenced by both horizontal and vertical geodetic motions. The integration of geodetic data with field geological data such as the identification of the February 2014 seismic fault provides a valuable tool for the long-term monitoring of active faults.

Key words: Cephalonia, interseismic deformation, InSAR, GNSS

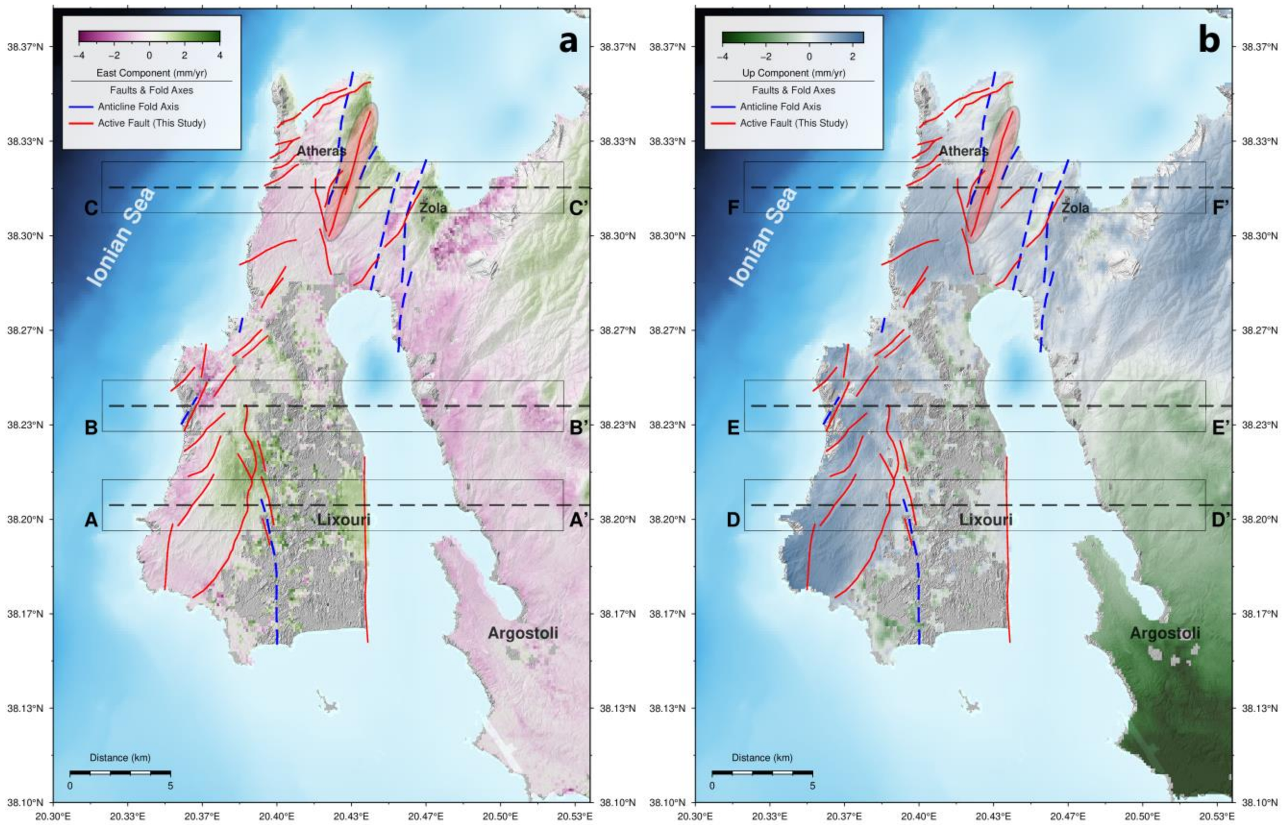

Figure 1 a) The map shows the GNSS-calibrated InSAR velocity field for the East (E) Component in mm/yr. Map (b) shows the velocity field for the Up (U) component in mm/yr. The blue dashed lines represent the anticline fold axes from IGME sheets Cephalonia North and Cephalonia South through the mapping from British Petroleum in 1964. The red lines represent the active faults of this study through field observations onshore Paliki peninsula. The red halo at the north part of Paliki peninsula represents the seismic fault trace of the 3 February 2014 earthquake.

Acknowledgments

This research was supported by the Hellenic Foundation for Research and Innovation (HFRI) under the 3rd Call for HFRI PhD Fellowships (Fellowship Number: 05176). Also, we acknowledge the project '*Στρατηγικής Ολοκληρωμένης Χωρικής Επένδυσης (ΟΧΕ) στην περιοχή της Παλικής Κεφαλονιάς*' from the National Kapodistrian University of Athens for funding.

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8th International Colloquium on Historical Earthquakes, Palaeo-Macroseismology and Seismotectonics

17-20 September 2023 - Lixouri, Greece

Bulletin of the Geological Society of Greece, Sp. Publ. 11

Ext. Abs. 00015

An Updated 19th Century Earthquake Catalog for the Rhine-Meuse-Schelde (DE, NL, BE) Region from Historical Macroseismic Data

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Research Highlights

Careful (re-)evaluation of known and newly found sources with macroseismic data resulted in an updated 19th century earthquake catalog including at least 136 felt earthquakes within the Rhine-Meuse-Schelde region. Maximum magnitude and intensity are Ms 5.4 and VIII, respectively.

Motivation and study area

The Lower Rhine Embayment (LRE; crossing the borders between DE, NL and BE) is an active seismic zone in NW Europe. In the intraplate region around the LRE, i.e., the zone between the Rhenish Massif and the North Sea, seismicity is scarcer, yet larger events have occurred, with magnitudes above M_L 6. Composing a complete pre-instrumental seismic catalog of this intraplate region is essential for seismic hazard assessment. Although earlier works have composed (partial) 19th century catalogs (e.g., Houtgast 1991, Perrey 1845, Sponheuer 1901), these works are outdated and not the object of historical criticism. Two major problems were (i) the neglection of cross-border macroseismic data and (ii) neglection of intensities below IV leading to the absence of low-magnitude events and aftershocks in the catalog. The Royal Observatory of Belgium (ROB), the Seismological Station Bensberg from the University of Cologne (BNS) and the Royal Meteorology Institute of the Netherlands (KNMI) joined forces to compose a reliable earthquake catalog for the 19th century based on multilingual original sources. The studied area includes the northeast part of France, namely the regions of Nord-Pas-de Calais, Picardy, Champagne-Ardenne and Lorraine, as well as the Grand Duchy of Luxembourg, a part of western Germany bounded by the Rhine and the whole territories of Belgium and the Netherlands. Together with the catalog, fake and doubtful earthquake lists were composed with explanations why the events had been previously falsely classified (e.g., storm and thunder events, mining events, explosions, etc.)

Source evaluation

From the existing catalogs, we critically evaluated all events by revisiting original sources, from narrative and administrative sources in libraries and in archives. New sources were added to the historical database and each event date has been verified in the original source documents.

Several types of sources were consulted:

- Contemporaneous scientific works of larger events.
- Narrative sources, including diaries, chronicles, family books, church and accounting books, and letters.
- Administrative sources, which often described earthquake effects and damage. In the regional archives of Duisburg (DE), we stumbled upon the first official standardized macroseismic survey sent out by the authorities of Prussia to local mayors for regional events. All 25 events of this database have been included in our 19th century catalog, but the macroseismic data points (MDPs) corresponding to the impact of these events remain uncovered (Knuts et al. 2018).
- Contemporaneous press articles, which have been most useful to estimate the felt region, although one must be careful due to the copying tendency.

The 19th century earthquake catalog and its MDPs

The evaluation of more than 500 sources led to an earthquake catalog containing at least 136 felt earthquakes in the Rhine-Meuse-Schelde (DE, NL, BE) region (Figure 1). The impact of these events is demonstrated by the spatial distribution of at least 2200 MDPs, i.e., a number still growing at the time of writing due to ongoing source evaluation. Many of these events had damaging effects as shown by the EMS-98 (Grünthal 1998) VI+ intensities on Fig. 1. The largest events of the catalog are listed in Table 1.

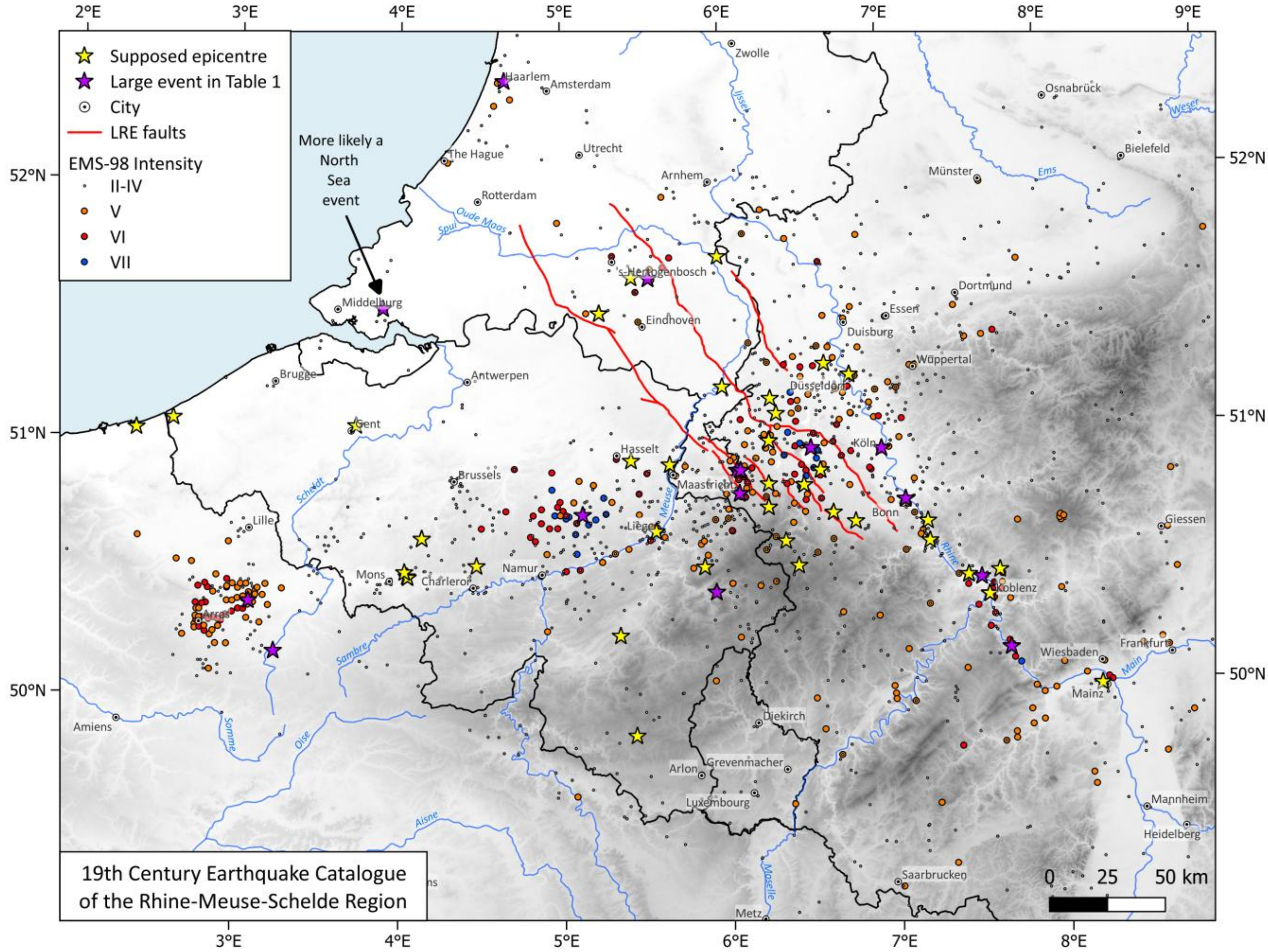

Figure 1. 19th century seismic events (stars) in the Rhine-Meuse-Schelde region and their damaging MDPs (colored dots).

Table 1. Largest events in the 19th century catalog (purple stars in Fig.1). N° Sources with * indicate that this is a minimum estimation as more sources may be listed in the official Prussian macroseismic database. Magnitude estimation is the subject of ongoing research. T.b.d.: To be determined.

Date	Time	Epicenter	Country	Magnitude	N° MDPs	Imax	N° Sources
1828.02.23	08:30	Hannut	BE	Ms 5.4	152	VII	86*
1828.12.03	18:30	Stavelot	BE	Mw 4.0	135	VII	66*
1843.04.06	05:30	Veghel	NL		36	V	43
1846.07.29	21:24	St Goar	DE	Ms 4.8	312	VII	59*
1848.10.19	07:00	North Sea	-		18	V	31
1857.01.24	07:03	Cambrai	FR		22	V	2
1868.11.17	16:--	Köln	DE		19	V	11*
1869.03.17	09:30	Bonn	DE		19	IV	2*
1869.10.02	23:45	Engers	DE		24	VI	3*
1873.10.19	20:15	Herzogenrath	NL		27	V	6
1873.10.22	09:45	Herzogenrath	DE	Ms 4.7	131	VII	22*
1873.10.31	11:48	Herzogenrath	DE		21	t.b.d.	5
1877.06.24	07:53	Herzogenrath	DE	Ms 4.7	148	VIII	32*
1878.08.26	08:50	Tollhausen	DE	Ms 5.4	491	VIII	78*
1878.08.26	11:--	Tollhausen	DE		30	t.b.d.	30*
1878.12.10	23:28	Tollhausen	DE		62	t.b.d.	19*
1881.11.18	23:14	Aachen	DE		261	VI	61*
1883.03.17	05:15	Haarlem	NL		19	t.b.d.	8
1890.03.17	23:--	Oedekoven (Alfter)	DE		21	V	2*
1896.09.02	21:10	Scarpe Valley (Douai)	FR	Ms 5.0	167	VII	46*

Magnitude and depth re-evaluation of larger events

In previous studies and catalogs, epicenter locations were simply supposed to be located where the strongest macroseismic effects were reported, clearly neglecting site effects (which are omnipresent in a deep basin such as the LRE as shown by recent macroseismic data, Van Noten *et al.*, 2017). Using only isoseismals to derive source parameters resulted in uncertain locations due to the use of geographically sparse intensities derived from 19th century reports. To evaluate magnitude and depth source parameters, we follow the method of Hinzen and Oemisch (2001) who calibrated the Bakun and Wentworth (1997) approach using a training set of 20th and 21st century earthquakes in the Northern and Middle Rhine area. In our magnitude and depth estimation, we combine seven intensity attenuation laws applicable to stable continental Europe. This method is explained in more detail in Dost *et al.* (2023, this volume), who use a similar approach for source parameter analysis of the 1932 Uden earthquake (NL). Moreover, this method has already proven to be successful in the re-evaluation of the e.g., 1828 Hannut (BE), 1828 Spa (BE) and 1896 Scarpe Valley (FR) earthquakes (Kusman *et al.*, 2010, *Knuts et al.*, 2015, Camelbeeck *et al.*, 2021). In our calculations, intermediate intensities were used to avoid intensity over- or underestimation. For events with low number of intensities (< 10), a weighted barycenter approach was first tested on events with a high number of MDPs and can be applied for events with lower number of MDPs for source parameter analysis. Future efforts will focus on finishing magnitudes and depths for all events in the catalog so they can be imported in AHEAD.

Acknowledgements

We sincerely thank Elisabeth Knuts and Pierre Alexandre for their years of devoted research in historical seismology.

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8th International Colloquium on Historical Earthquakes, Palaeo-Macroseismology and Seismotectonics

17-20 September 2023 - Lixouri, Greece

Bulletin of the Geological Society of Greece, Sp. Publl. 11

Ext. Abs. 00016

European Historical Earthquakes in the Middle Ages and Renaissance: A Critical Review of Historical Sources and Earthquake Catalogues between 284 and 1550

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** presenting author*

Research Highlights

We advertise the new historical seismology book of P. Alexandre and D. Alexandre-Lamotte (in press) which presents a full overview of original written sources of earthquakes in Europe and Asia Minor from 284 to 1550.

An updated earthquake catalog

For a long period, from the middle of the 16th century until about 1980, research in historical seismology produced only worthless compilations because they were prepared by authors who did not respect the rules of historical criticism. Since then, the participation of historians in seismological research has allowed the birth of new publications elaborated according to these rules.

In the introduction, the book first explains the history of historical seismology in the Antiquity, the Middle Ages and the Renaissance and shows how we have moved on from worthless catalogs compiled from the 16th to the 20th centuries, to new critical compilations, compiled since the 1980s thanks to collaboration between seismologists and historians. The book continues with methodological problems that researchers face in their work on historical seismology.

The first part of the work is a critical study of 2,489 sources, both narrative and administrative, classified in a geographical order (see Table 1 for an overview of all studied regions). Most sources (2,117) are narrative sources (annals, chronicles, annotations, etc.), mostly of an annalistic type; the others (372) are administrative documents, reporting damage caused by the tremors. All texts reporting earthquakes, gathered from sources from late Antiquity, the Middle Ages and the first half of the 16th century, are reviewed to retain only the original elements, emanating from reliable contemporaries. Second-hand texts were rejected when they copied known sources - sometimes distorting them - and therefore duplicated them. Only when original sources were lost, second-hand texts were used, provided that the provenance of these sources has been clearly identified by historians' studies. Particular attention has been paid to the places where the original sources were written as we believe that many mentions of earthquakes without any geographical detail of the earthquake location refer to only locally felt tremors.

The second part of the book is a catalog of 4,641 original texts, either from first-hand sources or from original lost sources (1,273). For each earthquake, the source texts are given in their original language (e.g., see example in Latin in Figure 1 as source for the 29 March 1000 earthquake near Liège, Belgium), except for those (12%) written in non-Latin characters and for which only translations by other authors are given and the text(s) were analyzed, with necessary chronological or toponymic corrections. These analyses left no stone unturned in determining the date, duration, number of tremors, zone of perceptibility and local intensities of each telluric episode.

Figure 1. Original source in Latin found in the *Annales of Liège*. The source mentions: « *terraemotus factus est permaximus* » translated as *« There was a very large earthquake »* in the year 1000 (*M*).
Source: 1000.03.29 Annales S. Jacobi Leodiensis

The evaluation of these sources resulted in an earthquake database including 1,507 events. This catalog is accompanied by 4,702 "macroseismic datapoints" (MDP), i.e., all points - regions or localities - where each of the 1,507 seismic events were felt. Figure 2 gives an overview of the geographical distribution of the MDP catalog in Europe and Minor Asia. For 37 earthquakes, additional efforts were performed to expand the "felt" response into a simplified intensity, if the source allowed deriving how the event was perceived or if any damage was described in the MDP.

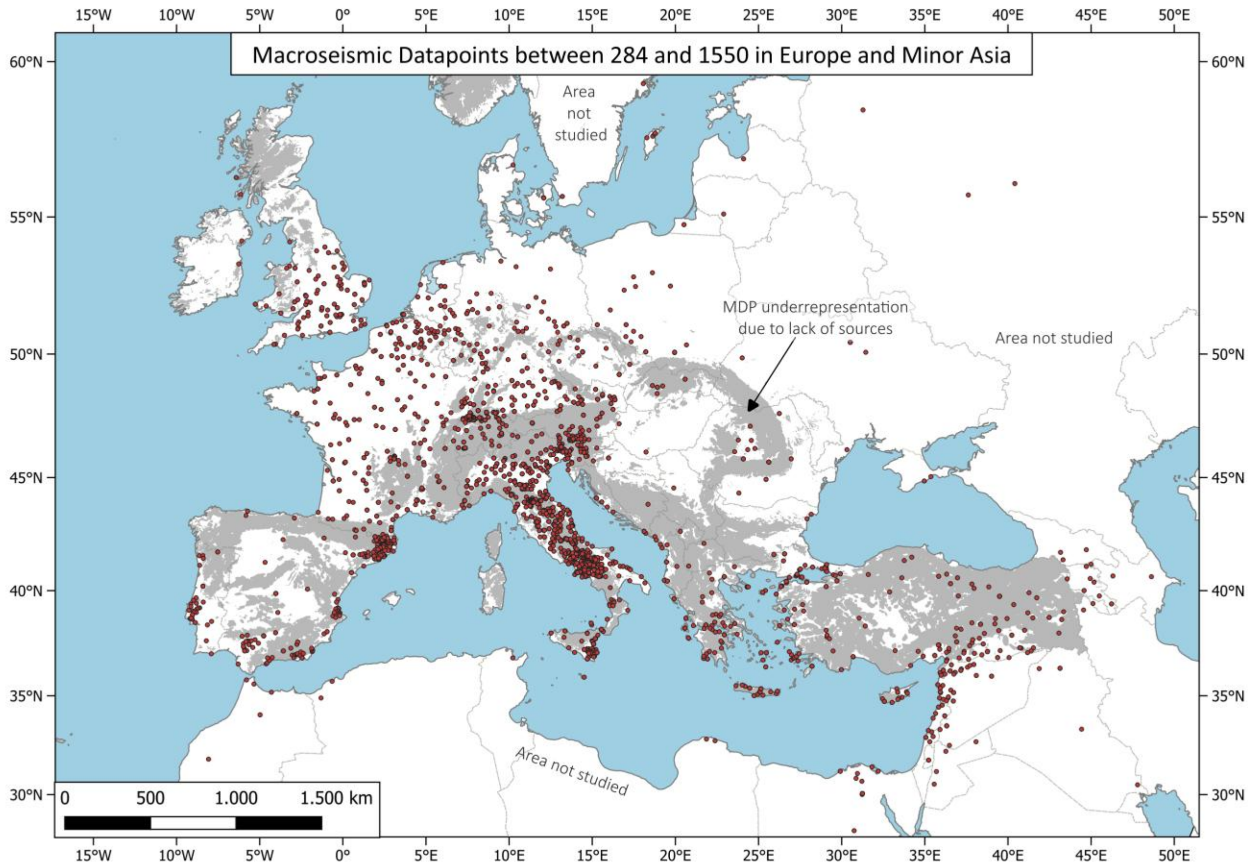

Figure 2. Overview of 4 702 MDPs (red dots) representing 1 507 felt earthquakes in Europe and Asia Minor.

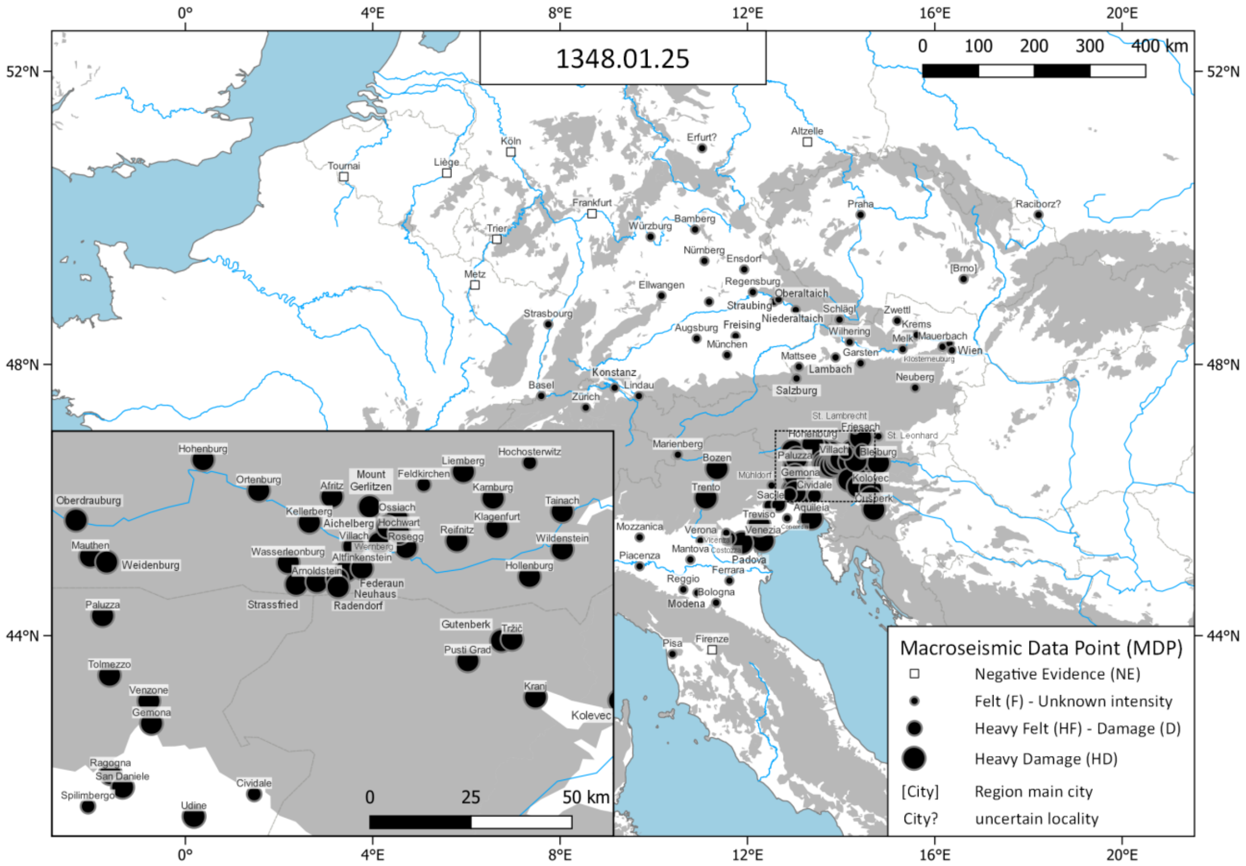

Figure 3. Historical macroseismic map of the 25 January 1348 earthquake near Villach (AU) using a simplified intensity scale.

This allowed using the following simplified intensity scale:

- NE: Negative Evidence
- F: Felt, but with unknown intensity
- HF-D: Heavy Felt, with damage (D)
- HD: Heavy Damage

Figure 3 shows an example of the 25 January 1348 earthquake near Villach in Austria.

Finally, the third part of the book consists of a catalog of false data on real earthquakes and 1,585 false earthquakes conveyed by the traditional catalogs (from 1840 to the present day) and for which we have found no trace in the reliable sources of European history. This information comes partly from compilations of von Hoff (1840) and Perrey (1844-1849) to the present day.

It should be kept in mind that it is an illusion to believe that medieval chronicles allow the establishment of continuous and homogeneous earthquake catalogs. Some regions and periods are not represented in the available documentation. For example, the Vrancea area in Romania has been a region of high seismicity since ages but sources are lacking to compose a medieval historical catalog of this region (see underrepresentation of MDPs in Figure 1).

The aim of this book is to provide the most reliable corpus of data possible from medieval and Renaissance sources for seismologists studying seismic hazard in Europe.

Table 1. Overview of Middle Ages and Renaissance regions and their position in current Europe (in brackets).

- Wallonia – Hainaut – Walloon Flanders (BE, FR)
- Flanders - Brabant - Limburg - Zeeland (BE, NL)
- Picardy - Artois (FR)
- Champagne (FR)
- Lorraine (FR)
- Alsace (FR)
- Île-De-France - Orléanais (FR)

- Berry (FR)
- Burgundy (FR)
- Normandy (FR)
- Anjou - Maine - Touraine (FR)
- Poitou - Saintonge (FR)
- Brittany (FR)
- Franche-Comté (FR)
- Savoye – French-speaking Switzerland - Dauphiné - Forez (FR, CH)
- Auvergne - Velay (FR)
- Limousin - Périgord (FR)
- Gascony - Béarn (FR)
- Languedoc - Quercy – Rouergue (FR)
- Provence - Southern Dauphiné - Cottian Alps (FR, IT)
- Holland - Gelderland – Duchy of Cleves (NL, DE)
- Friesland (NL)
- Rhineland (DE)
- Palatinate - Southern Franconia (DE)
- Saxony - Overijssel (DE, NL)
- Thuringia (DE)
- Hesse (DE)
- Franconia (DE)
- Swabia - German-speaking Switzerland (DE, CH)
- Bavaria - Tyrol - Upper Austria (DE, AT)
- Rhaetia - Vintschgau (CH, IT)
- Brandenburg – Wagria (DE)
- Misnia – Osterland (DE, SE)
- Lusatia (DE, PL)
- Pomerania (PL, DE)
- Silesia (PL)
- Greater Poland - Lesser Poland (PL)
- Mazovia (PL)
- Prussia (RU, PL)
- Bohemia (CZ)
- Moravia (CZ)
- Lower Austria - Styria (AT)
- Carinthia (AT)
- Liguria - Lunigiana (IT)
- Piedmont (IT)
- Lombardy (IT)
- Veneto (IT)
- Friuli (IT)
- Emilia-Romagna-Northern Marches (IT)
- Tuscany (IT)
- Umbria (IT)
- Piceno (IT)
- Abruzzo - Sabina - Cicolano (IT)
- Lazio - Southern Etruria (IT)
- Sardinia (IT)
- Campania (IT)
- Samnium - Irpinia (IT)
- Apulia - Capitanata - Salento (IT)
- Lucania - Principato (IT)
- Calabria (IT)
- Sicily (IT)
- Malta (MT)
- Catalonia – Roussillon – Valencia (ES)
- Aragon (ES)
- Basque Country - Navarre (ES, FR)
- Castile (ES)
- Asturias (ES)
- Andalusia - Murcia (ES)
- Galicia (ES)
- Portugal (PT)
- Kent (GB)
- Sussex (GB)
- Wessex – Devon (GB)
- Essex - Middlesex (GB)
- East Anglia (GB)
- Middle England (GB)
- Northumbria - Cumbria (GB)
- Wales (GB)
- Isle of Man (GB)
- Scotland (GB)
- Ireland (IR, GB)
- Denmark - Skåne (DK, SE)
- Gotland (SE)
- Sweden (SE)
- Iceland (IS)
- Livonia (EE, LV)
- Slovakia (SK)
- Hungary (HU)
- Transylvania - Siebenbürgen (RO)
- Slovenia – Carniola (SI)
- Istria (HR, SI)
- Dalmatia (HR)
- Northern Croatia (HR)
- Eastern Europe - Asia Minor - Near East - North Africa

Acknowledgements

We thank the Royal Observatory of Belgium for financial support to publish this book.

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8th International Colloquium on Historical Earthquakes,
Palaeo- Macroseismology and Seismotectonics
17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00017

A review and present status of macroseismic studies in Catalonia

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The evolution of the study of macroseismic effects of earthquakes in Catalonia is presented. From the first attempts of historical earthquake catalogues to the recently introduced automatic analysis of questionnaires, a long way has been toured and new projects are on way.

Introduction

Macroseismic studies in Catalonia have a tradition that started in the early years of the XX Century. Even though these studies were not pioneering ones in Europe (maybe because the last decades of the XIX Century were characterized by a quite quiescent seismic period), they show specific characteristics worth to analyze.

A few attempts to assemble Catalan historical earthquakes information can be already identified in the XIX Century (Bolòs, 1841; Teixidor, 1884). But the interest in cataloguing past earthquakes and classifying macroseismic effects flourished in the first decade of the XX Century. The first catalogues were compiled by geologists and naturalists practicing tectonic studies (Mengel,1909; Cazurro, 1908; Faura, 1913).

At the same time (1905) a new astronomical, meteorological and seismic observatory, the Fabra Observatory, was created in Barcelona. Its first director, Josep Comas i Solà was really active in seismology in the first years. The case had been that in occasion of an earthquake widely felt near Barcelona, on February 18, 1907, he undertook the first macroseismic survey in Catalonia. On April 19, 1907 he presented to the Academy of Sciences the first macroseismic map of an earthquake that occurred in this region (Comas i Solà, 1907). This practice continued from that year onwards.

The sistematization of macroseismic studies: Eduard Fontserè

In 1914, Fontserè took in charge of the seismic station and studies. Also active in meteorology, and already acquainted with observer networks, he organized, since 1914, a network of “macroseismic observers”. Their members filled out printed questionnaires anytime they felt an earthquake or received instructions to do so from the newspapers. The network permitted an increased coverage of observations in case of a felt earthquake and published macroseismic reports (Fontserè, 1916-1918). After 1930 the publication of regular reports about felt earthquakes decayed, but the records continued to be properly collected and studied and they have been fully preserved at the observatory offices.

Spanish Civil War was a halt in the activities of Fontserè as meteorologist (he was identified as pertaining to the “lossers” and the Catalan Meteorological Service, under its direction, dismantled); but he continued the regular studies of perceived earthquakes until his death, in 1970. Also, he collected, all his life, information about past historical earthquakes and this effort was published as a complete catalogue just after his death (Fontserè and Iglèsies, 1970). It was the most comprehensive ever published for the Pyrenean and Mediterranean coast of Spain, but without parametric information.

Fontserè monopolized the macroseismic studies in Catalonia for a period of more than fifty years (1914-1970). This singularity offers some advantages, but also weaknesses. As advantages we find the homogeneity in the acquisition and processing of macroseismic data and, due to his meticulous character, the proper collection and classification of the obtained records. But his longevity, and the fact that after the civil war he became somehow isolated from the international seismological community, played against the natural evolution and actualization of macroseimic studies. At his death, in 1970, the seismic questionnaire was totally outdated as it was the same implemented in 1914 and felt intensities were evaluated using the FM scale of X degrees.

The actualization period

After Fontserè's death, the collection of macroseismic information was continued at the Fabra Observatory. Although changes were not spectacular, they were fundamental. Seismic questionnaires were modernized and macroseismic evaluation was done using, at first, the MMI scale and, after few years, the MSK scale. Also, annual summaries were presented in actualized form.

During the seventies, seismology developed as discipline in the University of Barcelona and new contributions joined those of the Fabra observatory. The firsts regional parametric catalogues were published (Suriñach and Roca, 1982) and reevaluations of the largest earthquakes were attempted (Banda and Correig, 1984).

In 1983 the new Catalan Geological Survey (SGC) becomes operative. A unit devoted to the analysis and study of the regional seismicity, seismic hazard and risk was created. It deployed a regional seismic network and, since 1984, it included the collection and study of macroseismic information previously developed, almost in altruist form, by the Fabra observatory. This key change, from a private organization to a public one, was smooth because the task was developed by the same persons, now hired by the SGC. The seismological unit continues these tasks up to the present, even though its organic dependence evolved and now it is a part of the Cartographical and Geologic Institute of Catalonia (ICGC).

One of the objectives of the new institution was (and continues to be) the study of the seismic hazard and risk in the Catalan region. As the largest earthquakes recorded in the region occurred in the past centuries, before the establishment of the instrumental records, a proper determination of the characteristics of the most significative historical earthquakes became necessary. These objectives coincided in time with the general rebirth of the interest for macroseismic studies in Europe after its decay in the sixties. For these reasons the SGC devoted specific efforts to improve the catalogue of historical seismicity and to perform multidisciplinary studies involving historians, architects and engineers to determine the macroseismic effects of those old earthquakes, mainly occurred in the XIV and XV Centuries. These investigations allowed contacts with other foreign groups with similar objectives and to participate in the more wide projects being developed then in Europe (RHISE, BEECD, NERIES). These studies extended in time for more than twenty years and their results can be synthetized in the catalogue of felt earthquakes published by Susagna and Goula (1999) and a book devoted to the large earthquakes that occurred in the Middle Ages (Olivera et al., 2006) that is freely available at our website (https://www.icgc.cat/en/Citizens/Explore-Catalonia/Earthquakes/Seismic-information-and-maps-collections).

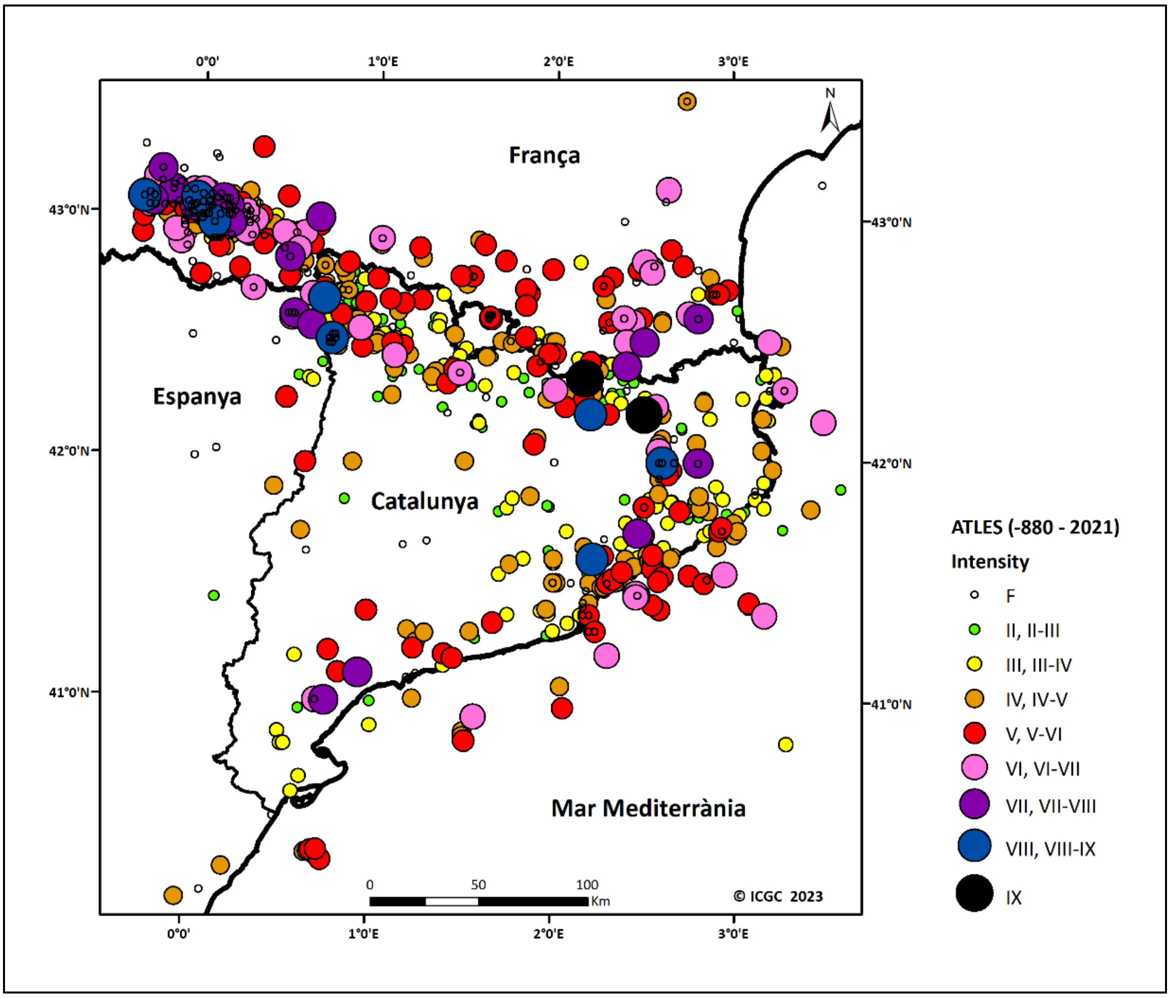

Figure 1. Epicenters, with their associated epicentral intensities (Imax), for all felt earthquakes that occurred in the area covered by the Catalan Seismic Network in the period 800 B.C. -2021A.D.

Present developments and new challenges

After the publication of the revised catalogue and studies at the turn of this Century, the main efforts switched to the deployment of a new digital seismic network. For this reason, new macroseismic studies centered on the regular evaluation of present recorded macroseismic effects, acquired mainly through the online questionnaire, introduced in 2011.

In the last years, a new impulse has been given to macroseismic studies. From one side, automatic assessment of the macroseismic intensity in near real time has been implemented since 2021. For this purpose, a new macroseismic questionnaire was developed, collected data are stored at a database, and an internal web application, called WebMacro, was created allowing multiparameter queries, download of intensity data, questionnaires review, etc. Currently, the automatic intensity evaluations are being compared to those obtained manually to calibrate the automatic evaluation algorithm and improve its quality. WebMacro will provide reliable intensity assessments in just a few minutes after questionnaires are received and will contribute to provide more reliable intensity information to local civil protection services and enhance other near-real time services provided by ICGC, as ShakeMap.

Recent years have seen a development of paleoseismological and archaeoseismological studies in Catalonia (e.g., Turu and Gascon, 2010; Perea et al., 2012; Briceño-Sarmiento et al., 2022; and references therein). Also, review of historical seismicity became easier as many archive references of difficult access have been posted on archive websites. Moreover, a recent revision of ICGC catalogues shows some heterogeneities and inconsistencies. The XIV and XV centuries have been widely studied, instead, the XVI-XIX century period needs more efforts. At the same time, new data on Pyrenean earthquakes has become available through the SISFRANCE website (https://sisfrance.net/). Also, all available seismic questionnaires, at Fabra Observatory and the ICGC, since 1914 have been scanned.

All these facts point out that it is time for a new general revision and update of our seismic catalogue of historical earthquakes. In parallel, we see the need for a specific catalogue of damaging effects of earthquakes useful for seismic risk studies. We plan to do them in the next years and put the results at disposal of the scientific community through the MIDOP (Locati and Cassera, 2010) platform.

Finally, we should remember that all these efforts have, as a final goal, to obtain a better characterization of the seismic risk.

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8th International Colloquium on Historical Earthquakes,
Palaeo- Macroseismology and Seismotectonics
17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 000018

Re-assessment of the Macroseismic Intensity Source Parameters for the M_L 5.0 1932 Uden earthquake, the Netherlands

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Research Highlights

The build-up of a macroseismic data base for the Netherlands and construction of reproduceable macroseismic source parameters for the second largest known event. Uncertainties are investigated by using multiple attenuation relations and a jackknife procedure.

The 1932 Uden earthquake

The discovery of the original letters sent to the KNMI in the Netherlands during the period 1925-1938 containing reports of felt events in the Netherlands, allowed the buildup of a macroseismic database for the Netherlands (NL), which is at this moment not available. In this period, the second largest known event took place near Uden (M_L 5.0, 1932-11-20) along one of the boundary faults of the Lower Rhine Embayment. The original data, i.e., Dutch letters sent to the KNMI, are scanned, transcribed and will be available for research. The availability of these original source data allowed a re-interpretation of the macroseismic intensities (430 IDPs in NL for the main shock) in the EMS-98 scale and a comparison with the analysis carried out by van Dijk (KNMI, 1934). Results for these NL data show mainly an intensity reduction in the IDP $\leq$ 5 range. At the same time, the Royal Observatory of Belgium already organized its official macroseismic surveys by sending out official questionnaires to the mayors of the Belgian municipalities (e.g. Neefs et al., 2023, this volume). Due to this effort, the far field earthquake effects of this event (540 MDPs in BE) could be mapped, and site effects can be studied. This event was also felt in western Germany and original source data were already studied by Meidow (1994).

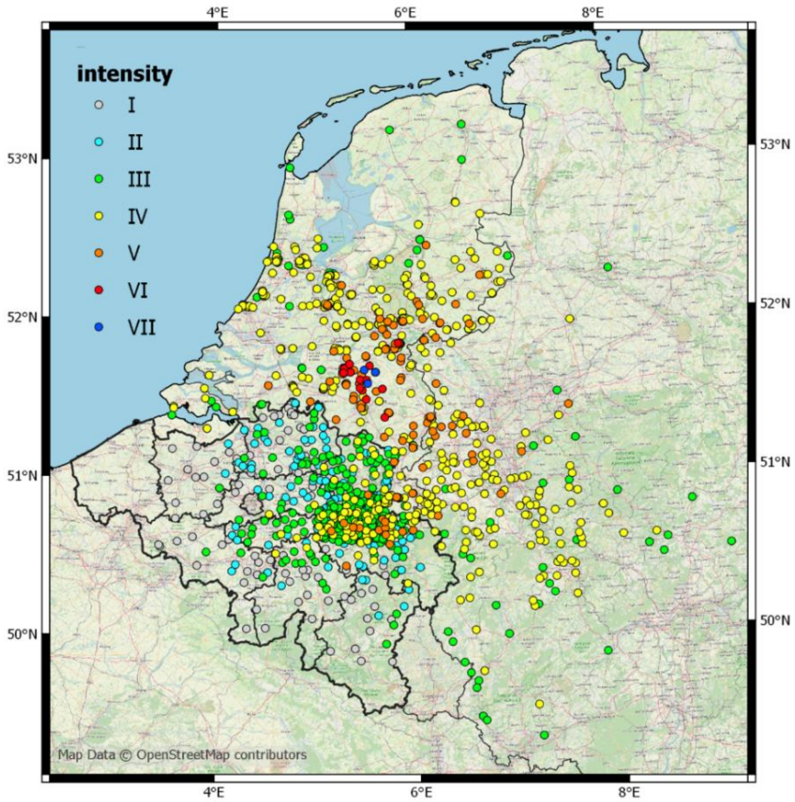

Figure 1: Cross-border macroseismic field of the 1932 Uden earthquake in the Netherlands.

The 1932 Uden event was analyzed by Hinzen & Oemisch (2001) (HO) using the Bakun & Wentworth (1997, 1999) method applied to the original combined dataset. In their paper, an intensity attenuation law applicable for the Lower Rhine Embayment was derived which, when applied on the 1932 Uden data, resulted in a slightly higher magnitude (M_L= 5.30 ± (0.12/0.18)). Our re-interpretation of the intensities slightly reduced the magnitude to M_L= 4.85±(0.12/0.18)). Macroseismic location of the event did not change significantly.

The effect of the applied HO attenuation law on these results was investigated by adding three more attenuation relations: Bakun and Scotti (2006), Gruenthal et al. (2009) and Ambraseys (1985). Results show a stable result for both location and magnitude. The uncertainties in the location results, however, are different. The linear relation, derived by HO, shows in general an uncertainty ellipse twice the size of a non-linear attenuation relation. The reason is that the linear relations underestimate the high intensities, which are most important in the location procedure. We also carried out a jackknife procedure to check the uncertainties in the location procedures and concluded that for the 1932 event uncertainties are within the 50% confidence level of the BW method.

Our attenuation and source parameter analysis of the 1932 Uden earthquake, an event with many IDPs, is important for the source evaluation of other poorly documented 19th century events that occurred in the vicinity of the 1932 Uden event in the period 1843-1848 (see also Van Noten *et al.*, 2023, this volume).

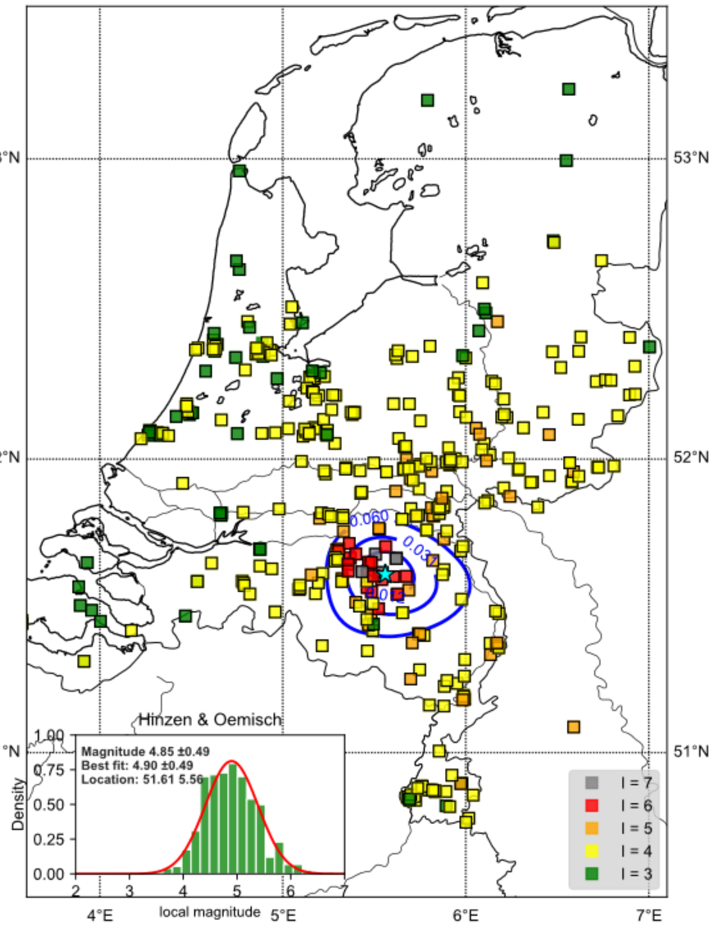

Figure 2: Magnitude and location (blue star) estimation of the 1932 Uden earthquake using the Bakun and Wentworth (1997, 1999) method and the re-assessed intensity values for the Netherlands. Confidence levels (50%,80% and 95%) in blue.

Acknowledgements

We thank Klaus-G Hinzen, Thierry Camelbeeck and Thomas Lecocq for discussions and for sharing their datasets.

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Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 000019

MacrosisData: Safeguarding and promoting the heritage of French macroseismic surveys carried out between 1921 and 1996.

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BCSF-Rénass, the French Central Seismological Bureau and National Seismic Monitoring Network, has been responsible for estimating macroseismic intensities in France since 1921 (fig. 1). As such, its archives all the documents resulting from macroseismic surveys carried out since that date (forms, letters, maps, newspaper articles, macroseismic reports, etc.). Between 1921 and 1996, 960 earthquakes were surveyed to estimate macroseismic intensities (severity of ground shaking) by sending paper forms to the municipalities (Sira et al. 2021). This represents 29 linear meters of archival documents (fig. 2). The aim of the MacrosisData project is to safeguard, disseminate and promote this collection, unique in France, through an online database.

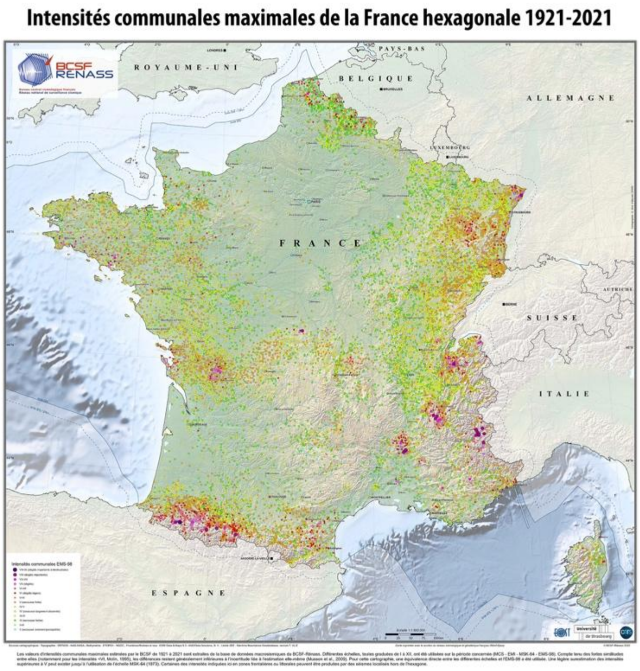

Figure 1: Map of maximum communal macroseismic intensities in France (1921 - 2022),
doi:10.25577/6w78-nn28

Background

Over the last ten years or so, the French seismological, geodetic and gravity communities have come together around of Résif-Epos (Réseau sismologique et géodésique français - European Plate Observing System).

The aim of the Résif-Epos "Seismicity Transverse Action" is to coordinate all work on French seismicity within a single, transversal structure, with the aim of increasing the efficiency and visibility of the work carried out. Axis 3 of this action concerns the collection and analysis of macroseismic data (historical and contemporary). It is in this area that the desire to safeguard a unique legacy was born, through the implementation of a documentary digitization project. This project is scheduled to run from 2020 to 2025.

Objective

The main objective is to bring together all digitized macroseismic survey documents in a dedicated database, to enable access to information in line with the so-called FAIR principles (Findable, Accessible, Interoperable, Reusable). Over and above the aspect of preserving and safeguarding archival macroseismic data (Sira et al. 2021b), this project will provide data for numerous innovative scientific studies (data mining, macroseismic revisions, building studies, communal vulnerabilities, human behavior, updated macroseismic scales, etc.).

Method

This multi-year project began in 2020 with the creation of a Data Plan Management (on a project scale), data description, documentation and associated data quality, legal (General Data Protection Regulation - GDPR) and ethical requirements through to ongoing data storage and backup.

Documents are digitized by a specialized company that provides Acrobat PDF format documents.

After digitization, the scanned documents are qualitatively checked. The "survey" files for each event are segmented by document type (letter, press, forms, cards, photos, etc.).

The data is then associated with a metadata file describing its characteristics and limits of use. Municipal geographical indexation is associated with the data, enabling geographic selections to be made.

A database and its consultation interface are being created (2023-2025) to store and enable attribute and geographic queries on the database.

This phase is based on the Huma-Num IR research infrastructure (https://huma-num.fr) of the French Ministry of Higher Education and Research, which implements this digital infrastructure enabling scientific communities to develop, implement and preserve research data and tools over the long term - in an open science and shared data approach.

Results

Since 2020, 86% of the files in the 1921 - 1996 collection have been digitized. This digitization phase concerns almost 200,000 pages in PDF format, or almost 150 GB of data.

A test phase for the database and its consultation interface is scheduled for late 2023, to validate the final product design.

The project aims to be operational by 2025.

Figure 2. BCSF-Rénass macroseismic archive room.

Conclusion

In the recent context of development of new analysis and processing tools for Big Data, it is the responsibility of observatories to make archived documentary resources available in a form that can be exploited numerically. This type of project is undoubtedly an opportunity to enable new interpretations of data or updates of macroseismic intensities. Under the General Data Protection Regulation, however, the use of such data, which may contain personal data, remains important before the age of 50, and requires specific declarations of research purpose. This digital form of macroseismic data, often segmented at the border, can also facilitate the association of cross-border data for a contemporary revision of past macroseismic studies.

Acknowledgements

This project receives technical support from the archives department of the Université de Strasbourg and IR Huma-Num.

The Phun (Plateforme d'humanités numériques), Huma-Num's regional relay (Alsace region), has helped our project to be positively validated at national level.

The digitization of documents, the processing of information and the creation of the database have been made possible thanks to the financial support of the Ecole et Observatoire des sciences de la Terre (UAR 830 of the CNRS) and Résif-Epos.

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8th International Colloquium on Historical Earthquakes,
Palaeo- Macroseismology and Seismotectonics
17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00020

Exploiting the Best of Both Worlds: a Journey from the Catalogue of Strong Earthquakes in Italy (CFTI) to the Database of Italy's Seismogenic Sources (DISS), and Back

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Historical earthquake data and active tectonics observations are close relatives: while the latter illustrate where the largest seismogenic faults may be located and what their potential could be, the former provide living evidence for any seismotectonic hypotheses (or speculations) on the extent and degree of activity of such faults.

The above statement is quite obvious and somehow undisputable; and yet, up to relatively recent times many scientists – and SHA practitioners in particular – did not go much beyond plotting earthquakes in 2D on a map of surface-breaking, presumed active faults. This was indeed a rather limited perspective, for at least three good reasons:

- mapping an earthquake caused by an extended fault (10-50 km) as a point is misleading and conceptually wrong: based on standard empirical relations, the point source approximation may be acceptable only up to about M 5.0;

- many surface-breaking faults – especially bedrock fault scarps not clearly involving Quaternary deposits, a common occurrence in the Italian Apennines – are likely to be either fossil features emphasized by differential erosion, or hierarchically secondary ruptures, or sympathetic/distributed ruptures; all of these occurrences are difficult to associate with the underlying master fault and often totally independent from it, both spatially and kinematically;

- at least in Italy, many faults capable of generating large earthquakes escape identification because they are hidden, or downright blind; not to mention those lying offshore, and hence largely inaccessible.

It is generally established that the instrumental record alone is insufficient not only for attempting seismic hazard calculations, but even for delineating slow-slipping, hence potentially silent seismogenic faults. Therefore, the Italian practitioners, as well as their European counterparts, have been faced with an inescapable dilemma: trust the often inaccurate and incomplete historical earthquake record, or rely on the scant and potentially deceitful record supplied by field geology? Thus far, the historical record always prevailed; its limitations were generally perceived as being smaller and overall more manageable than those characterizing the active fault record. We maintain that, at least up to the end of the past century, this perception was largely correct; certainly in Italy, but also in most of the central Mediterranean.

Could these two worlds be merged into one? Could the limitations of one realm be compensated by the strengths of the other, and *vice versa*? Hardly, although their ultimate target is the same: understanding the occurrence and recurrence of large earthquakes and projecting them into the future. This happens for two fundamental reasons.

The first: it is widely accepted that identifying active and potentially seismogenic faults in Italy is especially hard. The field record illustrates well the integral of a long tectonic history but it is difficult to decipher if we are concerned with youthful geological processes, such as seismicity. In principle, at least, historical seismology allows us to focus on a time-window of earthquake activity that is both shorter and very detailed, and it is therefore crucial for constructing a seismogenic source model: but doing so requires developing shared, complementary strategies supported by a common language.

Here comes the second reason: both worlds were – and still are – populated by scientists possessing drastically different cultural backgrounds, focusing on youthful scientific disciplines, seldom taught in universities; new fields that required the utmost attention and concentration, leaving little room for interaction with their peers from nearby fields (often not even perceived as such). As a result, for many years the effects of a large earthquake and its causative geological processes were seen as totally separate entities. Ironically, something similar was pointed out back in 1958 by Charles Richter, who wrote that "... *Because of the dispersion of seismological literature, geologists often overlook or ignore it. A recent paper on the geomorphology of a highly seismic region discusses rift valleys and faults, but ignores well-described faulting on two historical occasions, omits study of earthquake locations ... and ends with an airy generality to the effect that the frequent earthquakes show that block movements are still going on...*" (Richter, 1958, page 7).

In Italy, and probably in most of Europe, things did not change much until the second half of the 1990s, when the publication of the Catalogo dei Forti Terremoti in Italia (CFTI: Boschi et al., 1995) and the Database Osservazioni Macrosismiche (DOM4.1: Monachesi & Stucchi, 1997) triggered a silent revolution in historical seismology, giving new momentum to a rather slowly evolving discipline. Taking advantage from the progress of databases and GIS systems and from faster and cheaper hardware, historical seismology turned from merely descriptive to fully quantitative; its vaguely subjective outcomes suddenly become reproducible and ready to be entered in probabilistic calculations (Slejko et al., 2022).

Meanwhile, Italian geologists started making totally new inferences on ongoing seismogenic processes. Increased data resolution and manageability allowed large earthquakes to be explored in detail, often revealing unexpected source complexities and setting new constraints on the location and magnitude of the largest shocks. On the one hand, several key earthquakes of the XX century contributed to unraveling the arrangement and behavior of large seismogenic fault systems, greatly supporting seismotectonic interpretations in areas dominated by extreme tectonic complexity and blind faulting. On the other hand, the continuity and similarity of geological structures across extended seismogenic trends allowed for delineating seismogenic sources whose latest rupture is too old to be documented in the historical record. The gap between the two disciplines was ideally *bridged* by Boxer: a computer code first elaborated to locate all major Italian earthquakes and assess their magnitude, and later extended to make inferences about the size and orientation of their causative faults, or *boxes* (Gasperini et al., 1999). These circumstances eventually led to the publication of a prototype of the DISS database (Valensise and Pantosti, 2000; Fig. 1); its later versions have progressively turned all intensity-based sources into full fledged geology/geophysics/seismology-based sources (Basili et al., 2008; DISS Working Group, 2021).

The lack of communication between historical seismologists and earthquake geologists had finally come to an end: data and ideas started flowing back and forth, leading to an improvement of knowledge both on historical earthquakes and on their causative faults. The two worlds had finally merged into one.

The rest is recent history. Over the past 15 years or so, historical data have been used systematically to calculate earthquake budgets, to be compared with geodetic evidence for ongoing strain and fault slip rates, thus strengthening earthquake recurrence models devised for seismic hazard assessment. Historical seismology definitely increased its relevance in the modern SHA practice, far beyond the mere computation of "activity rates"; at least in Europe, its fate is now closely intertwined with that of seismotectonics and earthquake geology.

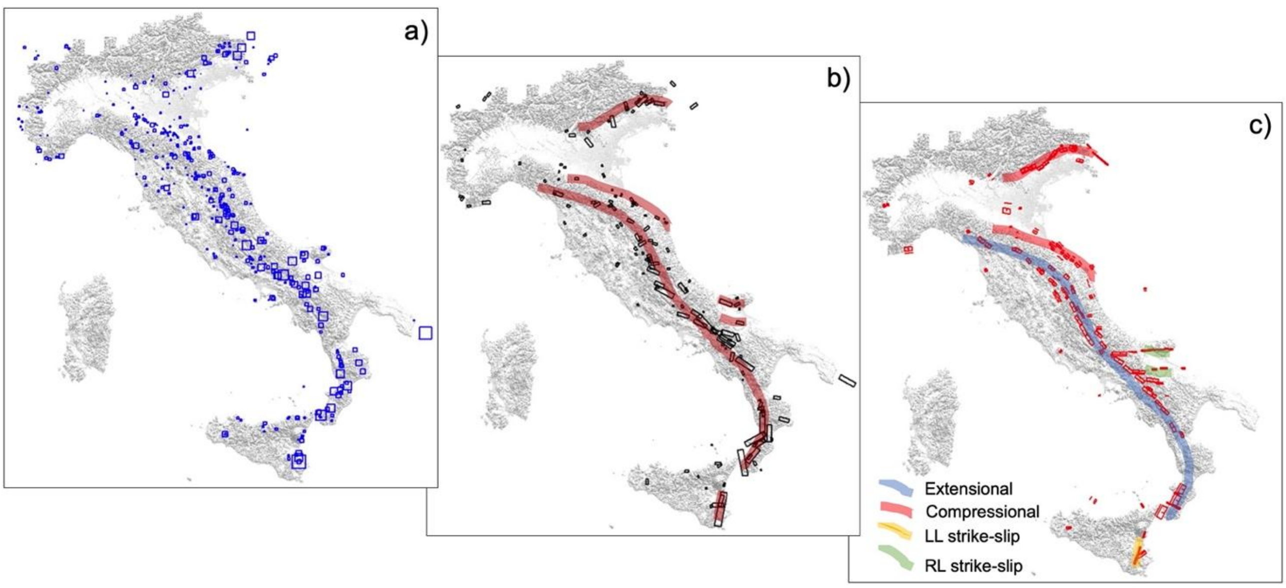

Figure 1 - Conceptual flow of the three subsequent steps leading from the historical information available in the second half of the 1990s to the prototype of the Database of Individual Seismogenic Sources (DISS v. 1.0): a) organization of the intensity data into a homogeneous database formed by all the earthquakes of M_w 5.5 and larger, ready for automatic processing; b) calculation of *intensity-based equivalent seismogenic sources* using Boxer, and delineation of basic trends of active faults; c) derivation of a number of geological-geophysical sources, starting from the historical evidence combined with instrumental and field observations, and delineation of better-identified tectonic trends (from Valensise et al., 2020).

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8th International Colloquium on Historical Earthquakes, Palaeo-Macroseismology and Seismotectonics

17-20 September 2023 - Lixouri, Greece

Bulletin of the Geological Society of Greece, Sp. Publ. 11

Ext. Abs. 00021

A probabilistic approach for integrating macroseismic intensity data

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Characterizing earthquake effects at given localities through the use of macroseismic scales (e.g., EMS-98 – Grünthal, 1998) is essential for several seismological analyses such as the compilation of parametric earthquake catalogs (e.g., Rovida et al., 2023) which allow the seismological knowledge of a given area to be extended as far back in time as possible. This requires recovering historical documentation that describes the entity of the shaking at the sites. The availability of such information principally depends on the period, size, and location of the event and is hampered by the survival of the sources, the chances of retrieving them, and the capability of analyzing them. This implies that intensity distributions of historical events may present important gaps, which also depend on the density and importance of the settlements affected by the earthquakes. To fill these gaps, documented seismic effects may be integrated with "synthetic" intensities, which can be estimated in different ways. In this regard, we present a probabilistic approach, described in Antonucci et al. (2021). The key element is a combination, through a Bayesian approach, of probabilistic estimates provided by an Intensity Prediction Equation (IPE) constrained by observed intensities that are spatially close to the site of interest. In particular, the intensity value at the site is first calculated with the IPE by Lolli et al. (2019) as a normal probability distribution with the average μ and the standard deviation σ from the epicentral parameters of the Italian Parametric Earthquake Catalog - CPTI15 (Rovida et al., 2020). This probability is then constrained with the intensity data documented at the sites within 20 km for the same earthquake and contained in the Italian Macroseismic Database – DBMI15 (Locati et al., 2022). To verify the impact of using this procedure rather than the IPE alone to predict intensity values, we computed the differences between the observed intensity values as reported in the DBMI15 and (i) the intensity values computed with the only use of IPE and (ii) the intensity values estimated with the proposed procedure. This test demonstrates that the intensity values obtained through the proposed approach better reproduce the observed intensities than using the IPE, with more than 90% of differences between predicted and observed intensity values being within one intensity degree. This approach was then applied to 228 Italian sites to detect seismic effects of past earthquakes that could be missing, for several reasons. The results show some possible gaps in the macroseismic data contained in DBMI15, despite their quality and quantity, with the number of potentially lost effects at the selected sites strongly decreasing with increasing intensity. In particular, this analysis shows that, at most of the considered sites, effects of intensity ≥ 6 should probably have occurred at least once, but they are not contained in the macroseismic database. Conversely, the number of unreported earthquake effects with higher intensities (i.e., ≥ 8) was estimated at a few sites. In addition, the geographical distribution of potentially lost information reflects the heterogeneity of the seismic activity over the Italian territory. Indeed, few potentially undocumented effects were computed at the sites located in a large part of northwestern Italy, in the central Alps, and the southern Adriatic region and Sicily compared to those estimated in central and southern Italy (principally along the Apennines), independently of the considered intensity level. As reported in Antonucci et al. (2023), unreported macroseismic data of any intensity might be related to earthquakes of any size and period, including the most recent and strong ones, and the outcomes obtained are strictly dependent on the reliability of the parameters contained in the input seismic catalog as well as on the adopted IPE.

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8^{th} International Colloquium on Historical Earthquakes,
Palaeo- Macroseismology and Seismotectonics
17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00022

CalIPE: an open-source tool for Intensity Prediction Equation Calibration.

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The CalIPE package is an open-source package that calibrates IPEs and offers the possibility to explore some of the epistemic uncertainties affecting IPE calibration.

The magnitude of an historical earthquake is typically estimated by comparing its intensity distribution to those predicted by intensity prediction equations (IPEs) that predict shaking intensity with distance from the earthquake source. Papers discussing the calibration of IPE are regularly published (e.g. Ambraseys 1985, Bakun and Scotti, 2006, Baumont et al 2018, Gasperini 1999, 2010). However, the computer codes used to perform the calibration are often not included in the publication, with the exception of the Boxer package code (Gasperini 1999, 2010). The Boxer package provides both the possibility to calibrate an IPE and to apply it. Recently, an alternative open-source python package QUake-MD (Provost and Scotti, 2020) was published that allows applying IPEs on macroseismic intensity data to estimate both depth and magnitude probability density function for historical earthquakes, based on uncertainties of the intensity data and the epistemic uncertainty of the IPEs. The epistemic uncertainty inherent in the calibration of IPEs is taken into account in QUake-MD by applying different IPEs. The present work aims to provide the necessary tool to calibrate alternative IPEs.

The CalIPE, which stands for **Cal**ibration **IPE**, package (in prep.) calibrates IPEs compatible with QUake-MD, based on the following mathematical formulation:

$$I = C_1 + C_2 M + \beta \log_{10}\left(\sqrt{Depi^2 + depth^2}\right) + \gamma\left(\sqrt{Depi^2 + depth^2}\right)$$

Where I is the intensity at epicentral distance Depi, C_1 and C_2 are the magnitude coefficients, β and γ the geometric and intrinsic attenuation coefficients respectively, M the magnitude of the earthquake and *depth* the hypocentral depth of the earthquake. With CalIPE it is also possible to explore some of the epistemic uncertainties affecting IPE calibration (e.g. choice of the calibration data).

Two types of data are used: synthetic data and real data. The synthetic data are used to ensure that the calibration algorithm accurately estimates the coefficients with perfect data. Synthetic data were estimated assuming reasonable values for C_1, C_2, β and γ coefficients and a set of magnitude/depth couples to compute intensity for different epicentral intensity. For the real data, calibration earthquakes are selected from French data.

Intensity data are regrouped in intensity bins. Since most of the published studies are based on intensity binned data, rather than on individual intensity data points, CalIPE allows the user to rely on different indicators RAVG, ROBS, RP50 and RP84. The two first indicators compute an epicentral distance weighted mean of the intensity data points within the intensity bin, with an intensity bin width of 1 and 0.25 unit for RAVG and ROBS respectively. The RP50 and RP84 indicators compute epicentral distance weighted percentiles for each intensity bin, with an intensity bin width of 0.25 unit. RP50 compute the weighted median and RP84 the 84^{th} percentile of the epicentral distances. The weight of each intensity data point depends on the quality associated.

Two calibration strategies are developed. In both strategies, the user can choose to ignore the γ attenuation coefficient, like in Bakun and Scotti (2006).

The first strategy is a two-steps calibration, where first the attenuation coefficients β and γ, along with epicentral intensity and depth are inverted, then the C_1, C_2 coefficients are inverted. The calibration of the attenuation coefficients is done by using the Köveslighety (1907) formula, where I_0 is the epicentral intensity:

$$I = I_0 + \beta \log_{10}\left(\frac{\sqrt{Depi^2 + depth^2}}{depth}\right) + \gamma\left(\frac{\sqrt{Depi^2 + depth^2}}{depth}\right)$$

Because there is a trade-off between depth and Io, it is paramount, in this first step, to invert depth and epicentral intensity considering minimal and maximal values that represent their uncertainties. Depth, I_0 and the attenuation coefficients are successively inverted through a non-linear least-square inversion. Initial values are then needed for the attenuation coefficients and each I_0 and depth.

The C_1 and the C_2 coefficients are then estimated in the second step. For each value of the attenuation coefficients inverted in the first step, CalIPE calibrates the corresponding C_1 and the C_2 coefficients. The associated probability estimated in the first step is then attributed to this IPE. The user can choose if the I_0 should be included as an intensity data in the inversion process and if depth should be inverted along C_1 and the C_2 coefficients (within minimal and maximal values that represent depth uncertainties). A non-linear least-square inversion is used, and initial values are needed. In this two-step procedure it is also possible to calibrate a regional C_1 coefficient.

The second strategy is a one-step calibration, where all coefficients, i.e. C_1, C_2, β and γ, along with depth, are inverted. Depth is inverted for each calibration earthquake within minimal and maximal values representing their respective uncertainties. A non-linear least-square inversion is used, so initial values of each coefficient and depth are needed. Inversion of a regional C_1 has been successfully tested with the synthetic data, however inversion of both a regional C_1 and a regional attenuation did not pass the tests with synthetic data. For this reason, inversion of a regional C_1 is for the moment is not included in the CalIPE package.

Epistemic uncertainty affecting the IPEs calibration can be explored using the two different implemented calibration strategies. The CalIPE package includes also tools to create subsets of the calibration dataset: uncertainties about the choice of calibration earthquakes can also be explored. Different initial values can also be used to explore the epistemic uncertainty linked to their choice in the calibration process. Different weighting scheme are also available.

Tools to control and test the calibration process are also available. One example is shown Figure 1, with an intensity residual analysis after the attenuation calibration step of the two-step strategy for the French data. The results are quite good, within mean residuals smaller than 0.25 for the within-event intensity residuals and smaller than 0.1 for between-event residual. No clear tendency with the explored variables is seen.

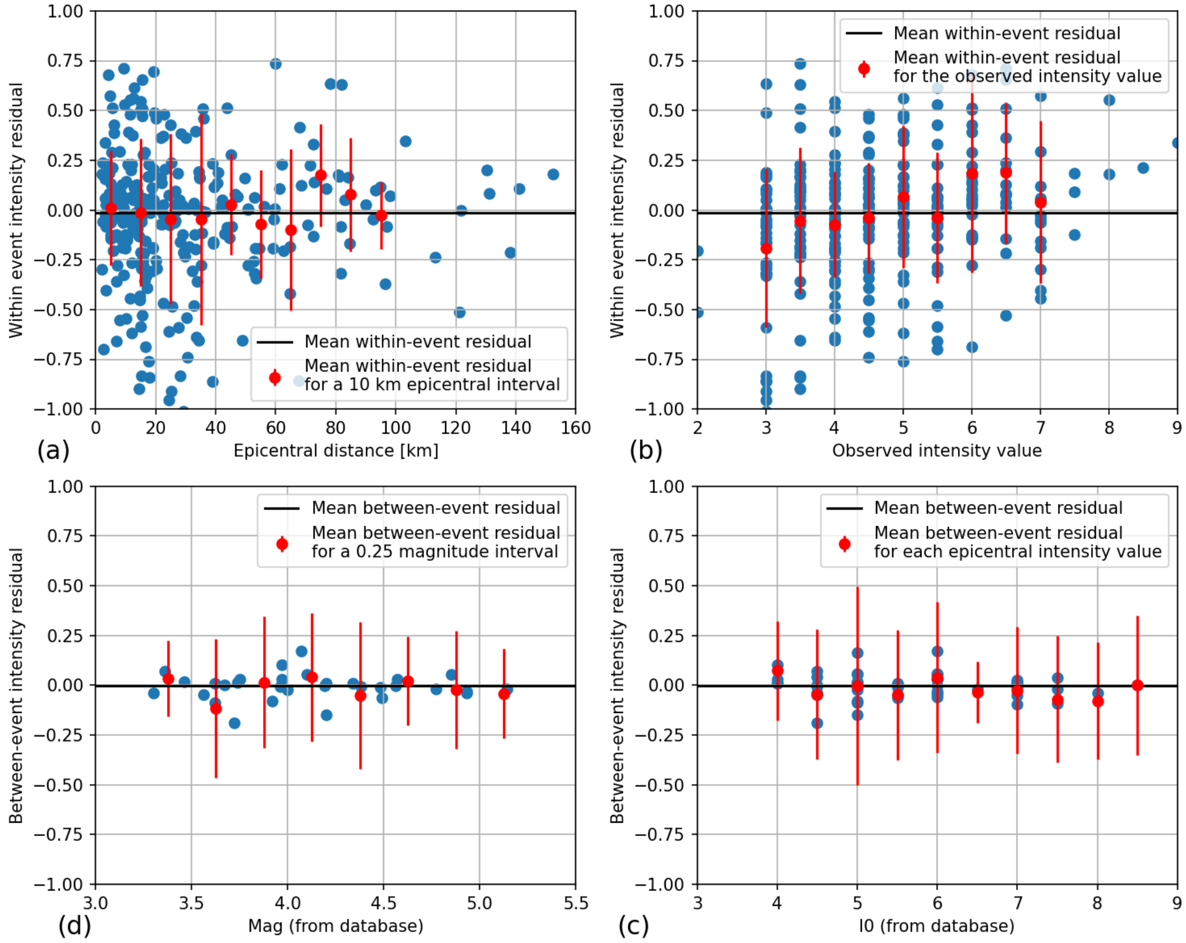

Figure 1: intensity residual analysis after the attenuation calibration step of the two-step strategy. Application to French data. Subplot (a): within-event residual with respect of epicentral distance. The mean residual is computed if more than xx data are within the 10 km epicentral distance bin. Subplot (b): within-event residual in respect with observed intensity values. The mean residual is computed if more than xx data are within the intensity bin. Subplot (c): between-event intensity residual with respect of magnitude values. Subplot (d): between-event intensity residual with respect of epicentral intensity values.

The CalIPE package (in prep.) is an open-source package that calibrates IPEs and offers the possibility to explore some of the epistemic uncertainties affecting IPE calibration. The results, using synthetic and real data are both satisfying. If real data is used to design inversion algorithm and to test the calibration of IPEs on real data, testing on synthetic data is a decisive element during the development of CalIPE to discard or validate the different inversion schemes. Therefore, using synthetic data to test developed algorithms is strongly recommended. The CalIPE package will be released soon on github as an open-source code: you are welcome to fork it and to participate to its development as soon it is released.

Acknowledgements

This work is funded by the IRSN. I would like to thank the BERSSIN team for their feedback during the CalIPE development and especially Oona Scotti for her support. Finally, I would like to thank my first beta user Chloé Van Uxen.

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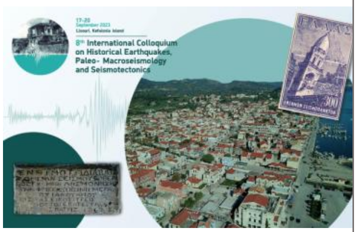

8th International Colloquium on Historical Earthquakes,

Palaeo- Macroseismology and Seismotectonics

17-20 September 2023 - Lixouri, Greece

Bulletin of the Geological Society of Greece, Sp. Publ. 11

Ext. Abs. 00023

Merging macroseismic data from field surveys and online questionnaires in Italy

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The availability of macroseismic intensity data related to recent earthquakes has important consequences in seismology. In Italy macroseismic databases cover more than a thousand years (i.e. DBMI15, Locati *et al.*, 2022), and this data extends the time coverage of seismic histories of inhabited places - lists of earthquakes felt in a place - with data on recent earthquakes coherent with those of past events. In addition, when combined with instrumentally recorded data, intensity data provide the required input for robust calibrations of Ground Motion to Intensity Conversion Equations (GMICEs) and Intensity Prediction Equations (IPE) which, in turn, allow a multiplicity of cascading studies. For example, these relations are in turn useful for the calibration of the assessment of the parameters of past earthquakes (i.e., Gasperini *et al.*, 1999, 2010; Bakun and Wentworth, 1997), for which only macroseismic intensity data assessed from historical records are available.

In Italy, INGV collects macroseismic intensities related to recent earthquakes in two distinct ways: i) through field surveys conducted by the QUEST (QUick Earthquake Survey Team, https://quest.ingv.it/) group after potentially damaging earthquakes, and ii) by means of online questionnaires under the HSIT ("Hai Sentito il Terremoto?" in Italian, that translates to "Did you feel the earthquake?", https://www.hsit.it/; Tosi *et al.*, 2007) initiative.

The QUEST team, composed of well-trained seismologists, started operating in the year 2000, and since then has surveyed more than 2000 inhabited localities hit by about 50 damaging earthquakes. QUEST is triggered when an earthquake of magnitude around 5 occurs and involves a variable number of surveyors subdivided into operative teams. The number of groups performing the fieldwork depends on the extension of the area potentially affected, and the complexity of the territory (i.e. number of localities in the area, their size, and condition of the road network). Besides the group operating in the field, additional people operate remotely for supporting the planning of operations, for example, suggesting places to visit because of damage reports in the news, and progressively collecting and processing the collected data. Clearly, the area that can be surveyed by QUEST is quite limited, and it usually covers the near field (see example in Figure.1, left). In this way, only the damaged area is delimited, and only a few localities where people merely felt the earthquake are surveyed. Intensities are assessed on the basis of the EMS-98 scale (Grünthal, 1998), and sometimes also with the MCS scale (Sieberg, 1923). QUEST survey data are often used to integrate damage reports performed by civil protection.

The HSIT procedure started collecting data in 2007 through a web-based questionnaire compiled by untrained citizens (Tosi *et al.*, 2015) on a voluntary basis and provides both MCS and EMS-98 intensity estimates together with a series of additional perceived effects. The earthquakes considered have a lower magnitude threshold with respect to those surveyed by QUEST, and in the last 15 years of activity, intensities for more than 15,000 earthquakes are available. When instruments locate an earthquake that may have been felt by the population, an automatic procedure is triggered, the new event is created on the web portal, and an email is sent to correspondents -roughly 28000 who spontaneously subscribed to the service- located within a certain magnitude-dependent distance from the epicentre. All questionnaires received are processed in real-time and the results in terms of assessed intensities and reported effects are published also in real-time on the web. Questionnaires that do not satisfy a series of quality checks are disregarded. The resulting assessed intensities cover the far field (see example in Figure.1, right), well beyond the damaged area, whereas in the case of strong damage effects, the near field may lack information because the population does not contribute questionnaires, generating the so-called "doughnut effect" (Bossu *et al.*, 2017).

After several years of separate training, testing, and collection of data, the QUEST and HSIT teams decided that the time has come for the two groups to converge with the scope of providing a single and comprehensive assessment of the effects of contemporary earthquakes. This requires the identification of the key issues to address for making the two sets of data as coherent as possible and in continuity with data related to past earthquakes. The final goal is to be able to provide final users with an updated Italian Macroseismic Database (DBMI) as homogeneous as possible.

The first step is to provide the intensity estimate for the same geographical unit.

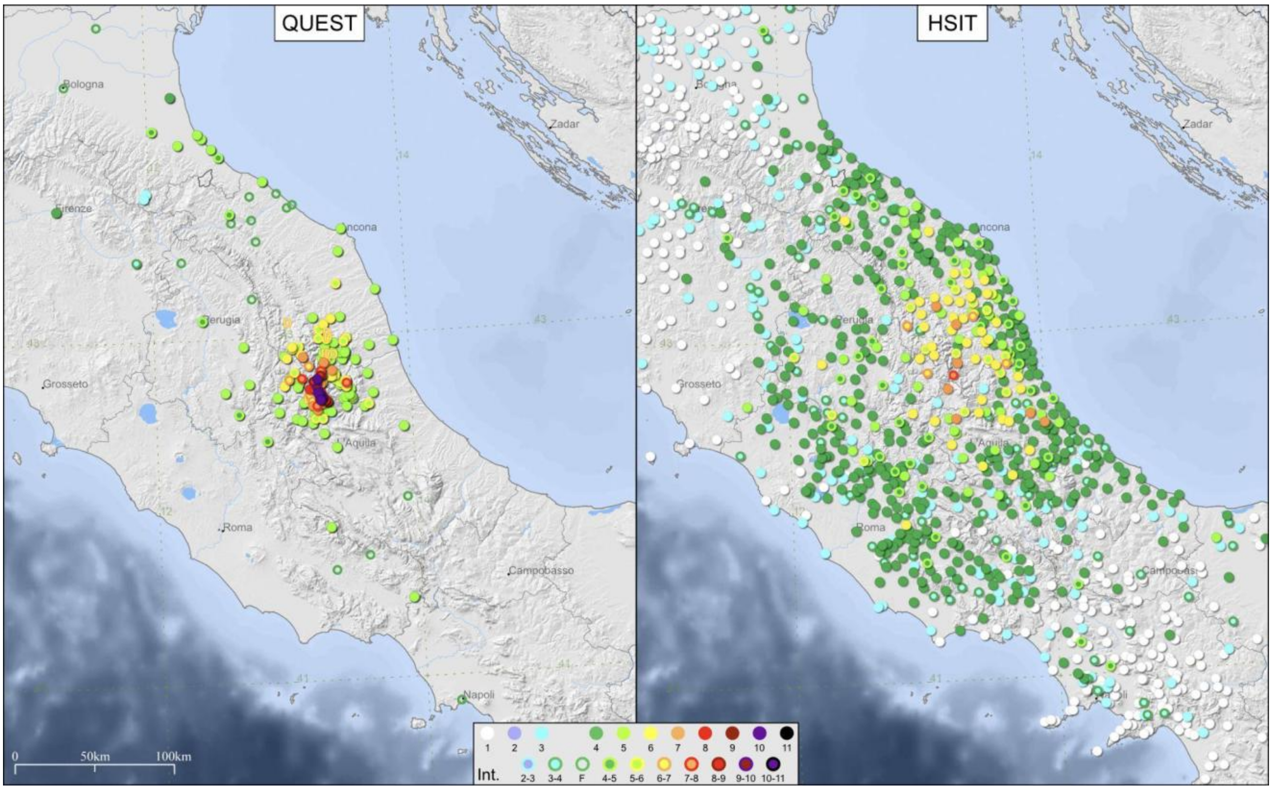

Figure 1. Comparison of the EMS-98 macroseismic intensities of the 24 August 2016 earthquake in Central Italy assessed by the QUEST macroseismic survey team (left) and using the HSIT online questionnaires (right).

All macroseismic studies providing intensity data related to Italian earthquakes are collected, archived, and geographically homogenised based on a common Gazetteer in the framework of ASMI, the Italian Archive of Historical Earthquake Data (Rovida *et al.*, 2017). These intensities are associated with inhabited places, also called localities, following as much as possible the quite vague definition of the geographical area to which the intensity should be associated provided by the macroseismic scales. The EMS-98 scale in particular cites *"intensity should not be assigned to a single building or street; neither should a single intensity be assigned to a metropolis or a county. In general circumstances, the smallest place should be no smaller than a village, and the largest no larger than a moderately-sized European town [...] It is also desirable to assign values to locations which are reasonably homogeneous, especially with regard to soil types, otherwise the range of shaking effects reported may be very large"*. Leaving big cities aside, Italian localities are on average quite stable geographical units over the centuries, even if they may have changed their name over time, or quite rarely, they may have been relocated for a variety of reasons, such as destruction as a consequence of earthquakes, massive landslides, or recursive floods.

Intensities assessed by HSIT are instead related to an entire municipality. Taking into account that in Italy a municipality usually includes dozens of localities, and in mountain areas may cover hundreds of square kilometres with very different building types and geomorphological conditions, we conveyed that HSIT should experiment with intensity assessment based on inhabited localities.

Localities are then physical settlements on the territory that are not affected by unstable administrative subdivisions characterising the municipalities. Suffice to say that the ISTAT, the National Institute of

Statistics, which is officially responsible for defining and updating the administrative geographical boundaries, publishes variations on a yearly basis. In fact, every year a series of municipalities merge or separate, making a few municipalities appearing and disappearing over the years. In addition, single localities may sometimes pass from one municipality to another.

As a first experiment, we aggregated the HSIT questionnaires adopting the polygons corresponding to each inhabited locality as defined by ISTAT instead of the polygons representing entire municipalities. This required a revision of the algorithm on the basis of the geographical aggregation of the questionnaires, collected at the level of the street address, and the processing of the responses. The results are analysed and compared with data collected by QUEST surveys when available.

The presentation at the 8th International Colloquium on Historical Earthquakes, Palaeo-Macroseismology and Seismotectonics will illustrate the overall activity, giving a preliminary overview of the result of these first steps that may hopefully lead to a more comprehensive macroseismic picture of recent earthquakes.

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8th International Colloquium on Historical Earthquakes, Palaeo-Macroseismology and Seismotectonics
17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00024

Macroseismic study of major trans-border historical earthquake-effects on Romania

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Abstract

As regards the earthquakes occurred in Romania both in the pre-instrumental and instrumental era, as it is already known, besides Vrancea subcrustal earthquakes that strongly lay their mark on Romania's seismicity, significant impact results from the earthquakes generated by crustal seismic sources, with high intensity near the epicenter, including in the trans-border regions. Such an earthquake occurred at the end of the 19th century, on 14 October 1892, at 6.50 a.m. (GMT), that caused serious damage in some places in Bulgaria-Romania trans-border area, among the densely populated cities of both countries and just only 100 km away from Bucharest, 145 km from Constanta respectively. In this study we present historical information about the macroseismic effects of this trans-border crustal earthquake, descriptions that were obtained as a result of searching in various types of historical sources. Each available historical information was evaluated and the corresponding macroseismic intensity assigned in terms of the MSK macroseismic scale.

Introduction

Since ancient times, certain areas of the globe, including those from our country, have been struck by devastating earthquakes and many of the monuments of ancient civilizations have been smashed out by their destructive action. On 14 October 1892 the border region between Romania and Bulgaria was striked by a major earthquake, being located not far from important sites where nuclear power plants were to be built in the 1980s (Cernavoda NPP) or could be built in future. The earthquake was felt on the territory of several countries: Rep. of Moldova, Ukraine, Turkey, Serbia (Glavcheva and Radu, 1994). According to the same catalogue this earthquake had $M_W = 6.5$, h = 10 km, I_0=VIII MSK (Oncescu et al., 2000-uptaded).

Objectives

Although other studies on this earthquake were published (e.g. Glavcheva and Radu, 1994), a detailed investigation of documentary sources was performed, in archives storing the documents of old book stock. Therefore, in this macroseismic study we intend to reevaluate the already known as well as the newly collected data sources. Great attention has been devoted to the new archival records on effects and not only, which were not taken into account in previous studies. In the archives, we found published reports and most importantly the original records regarding the effects of the earthquake (Constantin et al., 2009). The collected records allowed us to increase the number of macroseismic observations, including new information in the damaged area from the Romanian territory. The results have been then interpreted in terms of MSK macroseismic scale (Medvedev et al., 1967; STAS 3684-71).

Effects of the October 1892 earthquake

The 1892 earthquake occurred in the northern part of northeast Bulgaria, in Dulovo seismogenic zone was followed by long-lasting aftershock sequence (Glavcheva et al., 2003). Figure 1 presents the epicentral distribution of the earthquakes with $M \geq 4.0$ occurred in the NE Bulgaria and the epicenter location of the 1892 Dulovo earthquake. According to Shebalin et al. (1998) in this earthquake 100 people were killed. In the study elaborated by Glavcheva and Radu (1994) the main source parameters have been derived from the intensity distribution. They obtained the seismic source location in south Dobrodja at a depth of a minimum 35 km, epicentral intensity VIII MSK and the corresponding magnitude up to 7.0 (Table 1). In the Romanian territory the shaken area was about 210.000 km^2 (Atanasiu, 1961). To the north, the earthquake was felt up to the bending area of Carpathians, to the NE part was felt as far as Iasi and to western part up to Drobeta Turnu – Severin. The most significant effects of the earthquake were recorded in the areas of Romanian Plain.

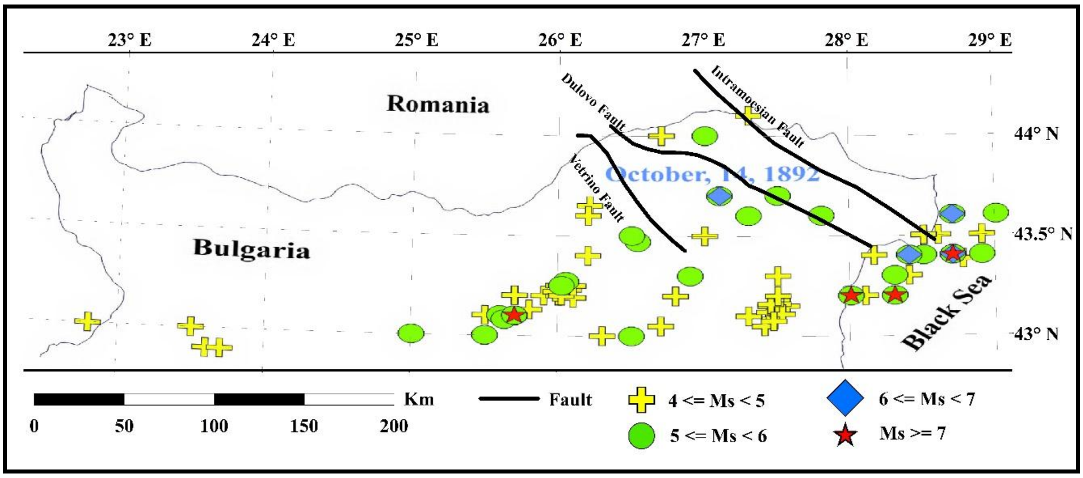

Fig. 1- Seismicity of the NE part of Bulgaria (M≥4)

Table 1 – Parameters of the October 14, 1892 earthquake proposed by various studies

Nr.	Author	Time (GMT)	I_0	Lat. N	Long. E	h (km)	Mag
1	Shebalin et al. (1974)	06:54	VIII (MSK)	43.30	27.60		
2	Constantinescu and Marza (1980)	06:50	VIII (MSK)	43.50	27.60	10	6.5
3	Glavcheva and Radu (1994)	04:54	VIII (MSK)	43.75	26.91	35-50	~7.5

In the following lines are summarized the most important effects observed in some of the affected places. In Calarasi (approx. 60 km from the epicenter) many buildings suffered damage: large cracks in walls, collapsed chimneys and fall of large pieces of plaster. Most damaged localities were Calarasi, Oltenita, Giurgiu, Medgidia, Constanta. Several cracks were mentioned in the alluvial ground in Oltenita where water leaked from the ground after the earthquake. In Tulcea many collapsed chimneys and few cracks in the ceiling of a store were noticed and for Babadag few collapsed chimneys and ceilings. In Ostrov, which is situated at an epicentral distance of about 50 km, many collapsed chimneys and large cracks in walls of many buildings were noticed. Earthquake sounds were also reported for the 14 October 1892 event. According to the available data, 18 sites where unusual noises related to the main shock were reported.

However, many localities in Romania feature an inherent potential for site effects. Particularly, those situated along Danube River where there are large alluvial deposits which show unfavorable soil conditions. Local amplifications of ground motion and non–linear effects are likely to occur in such areas during an earthquake. The risk to settlements from those areas is therefore increasing.

Geotectonic background

The epicentral area of 1892 Dulovo earthquake is situated in the southeastern part of the Moesian Platform, in the Valahian segment. Specific to the SE Moesian Platform is the fact that the most important faults have only been recognized by industrial geophysical works and drilling (Shanov et al., 2010). Only few faults that were later activated and situated close to the earthquake area were geologically observed on the surface (Shanov et al., 2010). In this area, the most important for geological models are the Intramoesian fault and Dulovo fault (Bokov and Chemberski, 1987) (Fig. 1). A segment of the Dulovo fault, most likely activated during the 1892 earthquake, has been accepted as a realistic model for its occurrence (Shanov et al., 2010).

Results and discussion

In all, the collected and interpreted information was turned into observations for about 78 places affected by the 1892 earthquake in the Romanian territory, which allowed us to assess the macroseismic intensities for these sites. These values are determined from data coming from several sources among which we mention: Hepites (1893), Draghiceanu (1896), Rethly (1952), Florinesco (1958) etc., as well as an important number of unpublished information gathered from recently discovered sources, not used in other study (Constantin et al., 2009; Constantin, 2015) which will supplement the existing data.

The reevaluation of the intensities for 1892 earthquake revealed the fact that the intensities obtained have about the same values with those obtained by other authors, except of few places. In other words, the intensity values in the two studies (previous and present) result to be approximately similar, in some cases with differences represented by uncertainties between full degrees in the seismic scale. However, in this work the descriptions of the earthquake effects provided by the new sources which there weren't used until now were used.

In order to obtain as many values of the macroseismic intensity as possible and thus for determining the real macroseismic field of each historical earthquake, much more information is necessary, which practically *"is waiting"* to be discovered within the multitude of existing reports in various types of historical sources that have not been searched until now. In general, each new discovered data offer a more accurate picture of each historical earthquake.

Acknowledgements

This paper was carried out within Nucleu Program SOL4RISC, supported by MCI, project no PN23360201, Project PNRR- DTEClimate nr. 760008/31.12.2023 and AFROS Project PN-III-P4-ID-PCE-2020-1361, supported by UEFISCDI.

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8th International Colloquium on Historical Earthquakes,
Palaeo- Macroseismology and Seismotectonics
17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00025

A Probabilistic Seismic Hazard Assessment for Kefalonia and Ithaca (Western Greece).

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Research Highlights

- We present a Probabilistic Seismic Hazard Assessment for Kefalonia and Ithaca (Western Greece).
- High Peak Ground Acceleration and Velocity (PGA and PGV) values were computed for the study area that surpass the regulations of the current Greek Building Code.

Kefalonia and Ithaca are part of the Ionian Islands in Western Greece that comprise one of the most seismically active regions within the Mediterranean Sea (Sakkas et al., 2010; Sakkas et al., 2022), as indicated by the abundance of M_w>4.0 events (Figure 1). Notable historical earthquakes have affected the study area, such as the 22 July 1767 M_w = 7.2 and the 12 October 1769 M_w = 7.2 (Stucchi et al., 2013) ones that caused extensive damage, reaching a maximum intensity of I_{max} = 10 (Makropoulos and Kouskouna, 1994). Within four days, three strong earthquakes occurred, causing almost complete destruction in Kefalonia and Ithaca (Kouskouna et al., 2021). The first shock was the 9 August 1953 M_w = 6.4, which was followed two days later by a stronger event (M_w = 6.8). Finally, the largest earthquake of this sequence was the 12 August 1953 M_w = 7.0 event, occurring in SE Kefalonia. The 26 January 2014 M_w = 6.1 and the 3 February 2014 M_w = 5.8 (Makropoulos et al., 2012, updated) earthquakes, struck near the densely populated areas of Lixouri and Argostoli, resulting in significant infrastructure damage and the triggering of geological effects (Valkaniotis et al., 2014; Bonatis et al., 2021). Furthermore, the M_w = 6.3 17 November 2015 earthquake took place close to the SW coast of Lefkas. The fault plane solutions of these earthquakes illustrate the predominant strike slip faulting type in the study area (Kapetanidis and Kassaras, 2019). Considering the high seismicity and the potential for future strong earthquakes in Kefalonia and Ithaca, it is crucial to reassess the seismic hazard by introducing variability in the seismotectonic models and Ground Motion Prediction Equations (GMPEs) through a logic tree approach to minimize epistemic uncertainties.

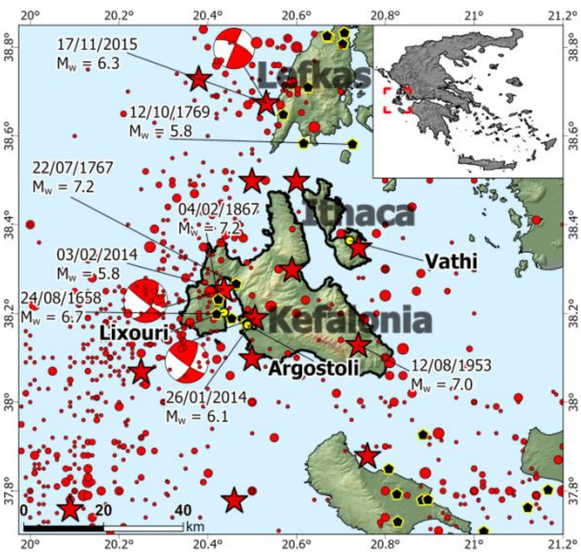

Figure 1. Seismotectonic map of the study area. Pre-1900 epicenters are from Stucchi et al. (2013), whereas post-1900 ones are from the updated Makropoulos et al. (2012) catalogue. Beachballs are from Kapetanidis and Kassaras (2019).

Two area-source-seismotectonic models are used (Figure 2): the European Seismic Hazard Model 2013 (ESHM13) developed by Woessner et al. (2015), and its updated version by Danciu et al. (2021), known as ESHM20. The earthquake catalogue plays a vital role in conducting PSHA, since a statistical analysis is performed for each area source to obtain the necessary seismicity parameters, which are the magnitude of completeness (M_c), the a and b values of the Gutenberg-Richter Frequency Magnitude Distribution (FMD), and the maximum expected magnitude (M_u). To determine M_c, a, and b values, we utilized the maximum curvature (MAXC) method. The computation of M_u was carried out using the Robson-Whitlock-Cooke (R-W-C) equation (Robson and Whitlock, 1964; Cooke, 1979). PGA and PGV were estimated by applying the Greek GMPEs presented in Table 1. In order to account for the variability and minimize uncertainties, we computed PGA and PGV for Return Periods (RPs) of 475 and 950 years using an equal logic tree approach.

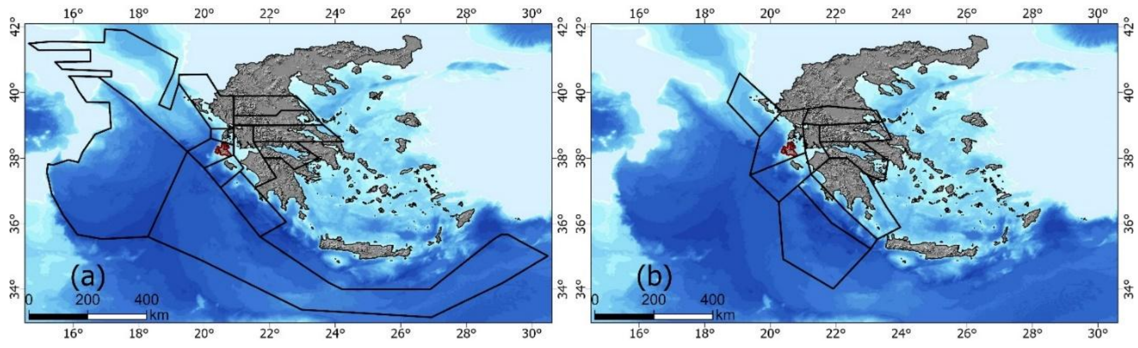

Figure 2. The adopted area sources from the ESHM13 (a) and ESHM20 (b).

Table 1. The selected GMPEs for the estimation of PGA and PGV.

Parameter	GMPE
PGA	Margaris et al. (2002)
	Skarlatoudis et al. (2003)
	Danciu and Tselentis (2007)
	Sakkas (2016)
	Chousianitis et al. (2018)
PGV	Margaris et al. (2002)
	Danciu and Tselentis (2007)
	Skarlatoudis et al. (2007)
	Chousianitis et al. (2018)

The spatial distribution of PGA for return periods of 475 and 950 years is depicted in Figure 3a and Figure 3b, respectively. It is evident that the lowest seismic hazard levels are situated towards the southeastern edge of Kefalonia, whereas the highest ones are at the western part of the study area. The highest PGA for the first RP is 500 cm/s² and the lowest 420 cm/s². In the case of the second RP, the highest PGA is 620 cm/s², and the lowest one 530 cm/s². The spatial distribution of Peak Ground Velocity (PGV) follows a similar pattern to that of PGA. The highest determined PGV value for the 475 RP is 36 cm/s, and for the second 40 cm/s.

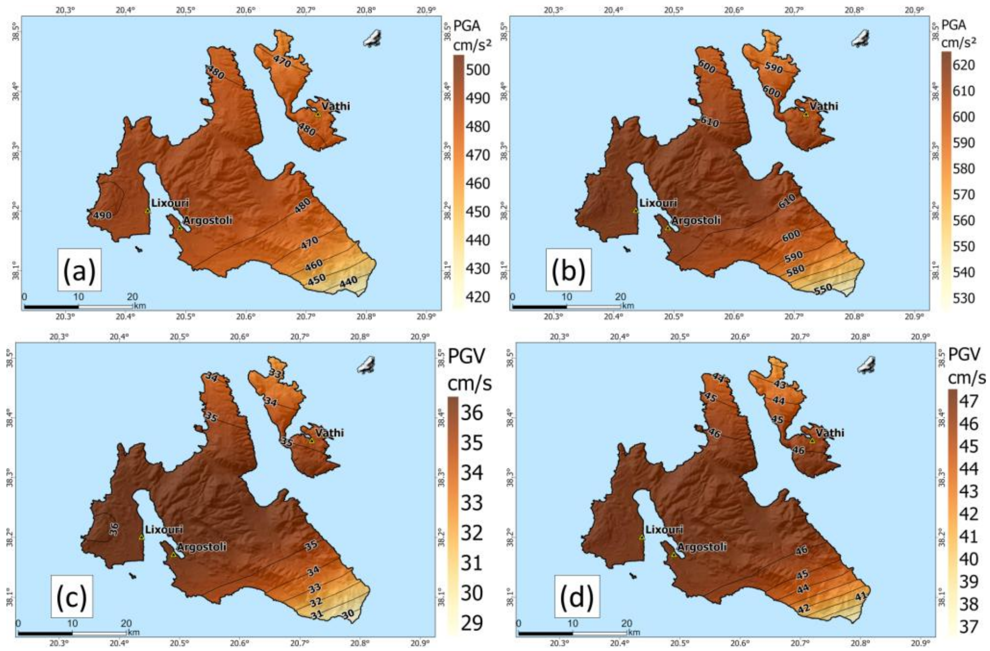

Figure 3. Maps showing the spatial distribution of PGA (a, b) and PGV (c, d) for RPs of 475 years (left) and 950 years (right).

Considering the potential occurrence of future strong earthquakes in the study area, it is crucial to regularly update the assessment of seismic hazard in the area by incorporating new data. The objective of this study was to develop a PSHA for Kefalonia and Ithaca with reduced uncertainties. To achieve that, we introduced variations in the area sources and GMPEs to generate multiple outcomes for seismic hazard and consider them simultaneously to improve the accuracy of the results. The PSHA revealed that the seismic hazard levels exhibit a slight variation, but they surpass the regulations of the current Greek Building Code (EAK, 2003). The southeastern edge of Kefalonia has the lowest PGA and PGV values.

Previous PSHA studies have been conducted for the Ionian Islands, including Kefalonia and Ithaca and they can offer valuable insights to compare and assess the results of the present work. One such study conducted by Bonatis (2020) has shown similar PGA values for Kefalonia and Ithaca, particularly upon the utilization of the same GMPEs. However, other PSHAs conducted by Woessner et al. (2015) and Danciu et al. (2021) have proposed higher values due to the significantly greater M_u that is assigned in each area source in those studies.

A future comprehensive seismic microzonation study would be a decisive step to identify local site effects that will be included into PSHA. Furthermore, conducting a disaggregation analysis of the results could prove beneficial due to the identification of the specific combination of magnitude and distance that contributes most to the amplification of hazard. Such a detailed analysis would enhance our understanding of the specific factors influencing the seismic hazard in Kefalonia and Ithaca.

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Palaeo- Macroseismology and Seismotectonics
17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00026

Discrepancy Between Traditional and Online Intensities – Revisiting the Relation Between Two Different Macroseismic Datasets in Belgium.

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Research highlights

A significant underestimation of the traditional intensity data for the only event in Belgium for which both traditional and online intensity data is available, uncovers a large discrepancy between the two macroseismic datasets with major implications for at least decades of collected macroseismic data.

Introduction

Belgian macroseismic data consists of traditional macroseismic data, collected through single communal macroseismic questionnaires for each affected Belgian municipality, and online collected macroseismic data since 2002, based on the "*Did You Feel It?*" (DYFI) procedure of the USGS (Wald *et al.*, 1999). The M_L 5.0 Alsdorf-Eschweiler (AE) 2002-07-22 event took place in the early morning (07:45 AM) with its epicenter located in Western Germany. The event was assigned a maximal intensity of VI on the EMS98 intensity scale and was widely felt in Germany and Belgium (Hinzen, 2005). It is the only event for which both traditional and online intensity data are available in Belgium. Camelbeeck *et al.* (2003) briefly compared the two data types and argued that both procedures resulted in a similar macroseismic field. The main differences were that the online procedure results in 1) more homogeneous intensity results for adjacent municipalities, 2) a larger felt radius, and 3) a lower number of observations of the maximal intensity IV, on the EMS98 intensity scale, observed in Belgium. A recent review of the traditional macroseismic database (Neefs *et al.*, 2022), however, shows a significant and consistent underestimation of the traditional data for the AE event in Belgium. Consequently, the comparison of Camelbeeck *et al.* (2003) may no longer be valid. Furthermore, up to recently, the common practice at the ROB to process online macroseismic data was, first, to compute the intensity of each individual submission, and second, to average intensities within each municipality. In the current procedure, aggregation is applied by first grouping observations within each municipality and then assigning a single intensity to it. Here, we reevaluate the traditional intensity data of the AE event by assessing intensity automatically by mimicking "expert judgement" and comparing it with the new online intensity data obtained by aggregation.

The original Alsdorf-Eschweiler 2002 earthquake macroseismic datasets

The Royal Observatory of Belgium actively collects macroseismic intensity data of earthquakes affecting the Belgian territory since 1925 at the latest (Fourmarier and Legraye, 1926), by sending official questionnaires to the mayors of selected Belgian municipalities. While officially still in use, the questionnaire for the AE event was the last to be sent out, due to a lack of significant events in the past two decades and is thus the most recent event for which traditional data are available. The questionnaire was sent to each municipality in Belgium and 500 out of 589 answers were received. These were analyzed, and intensities were assigned manually by expert judgement.

On the date of the AE earthquake, the online macroseismic data collection application of the ROB was launched. The USGS DYFI algorithm was used for intensity computation, with the only difference of not using aggregation. The web address of the online questionnaire was shared through media and in total 6193 submissions were received, of which 215 were discarded due to inconsistency issues or unknown locations.

Both traditional and online macroseismic data are briefly described in Camelbeeck *et al.* (2003) and a maximal macroseismic intensity of IV was assigned to Belgium. Their results are reproduced in Figure 1, with the minor difference that we use intensity ranges (e.g. III-IV), while the authors of the original paper opted to only use the minimum intensity values instead. The macroseismic field for both data types are rather similar. The most significant difference is the higher online intensities at larger distances in the west of the country where traditional data shows dominantly not felt intensities.

As part of a large-scale review of the 20th century Belgian traditional macroseismic database, an inconsistency was discovered for the macroseismic intensity data for the AE event. As intensity assignment is subjective, different seismologists may assign slightly different intensities with the same information, the discrepancy between the original and the reviewed data for this event is remarkable. Intensity assignments for many municipalities are consistently one full intensity degree in the reviewed data.

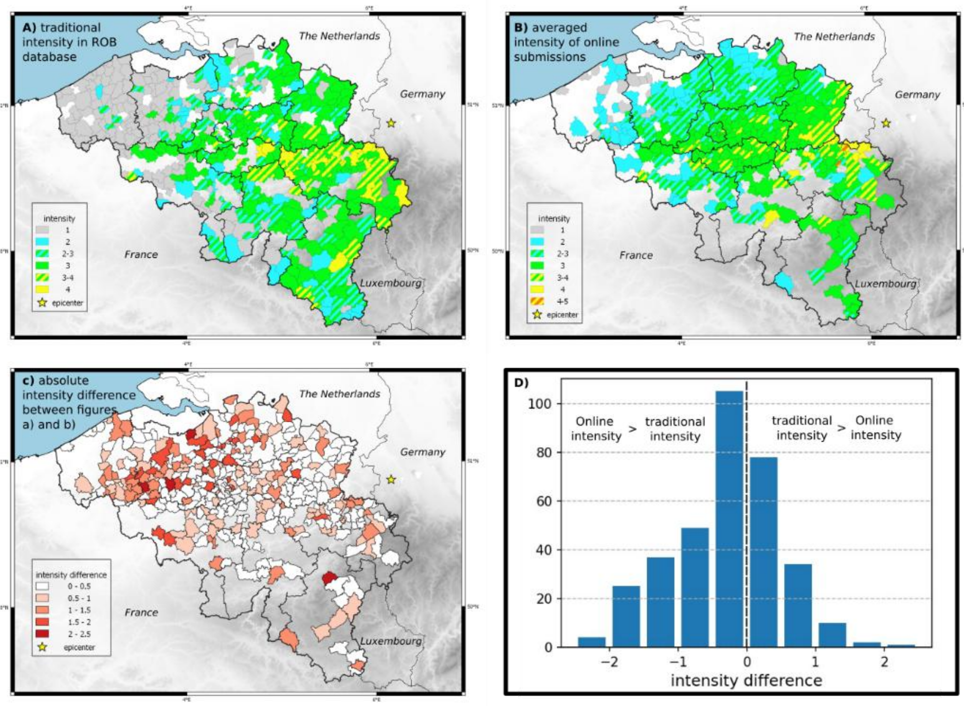

Figure 1. Original macroseismic datasets of the M_L 5.0 Alsdorf-Eschweiler 2002-07-22 earthquake and relation between A) traditional municipal intensities and B) online intensities. C) Mapped intensity difference and D) histogram representation for municipalities with both types of macroseismic data.

Creating new AE earthquake macroseismic intensity datasets

To visualize the discrepancy between the originally assigned intensity and the answers on the questionnaires, the questionnaires have been reanalyzed automatically by a new algorithm designed to mimic "expert judgement" and to be in accordance with other traditional intensity datasets from older events. The algorithm assigns scores based on the answers of the questionnaires to five new classes for each municipality. These classes are ‘weakly felt’, ‘strongly felt’, ‘weak effects to objects’, ‘strong effects to objects’ and ‘damage’. The scores given to these different classes are used to assign new intensities. For intensities V to VII, the classes ‘strongly felt’, ‘strong effects to objects’ and ‘damage’ are considered, while for intensities II-IV, the ‘weakly felt’ and ‘weak effects to objects” are used. The algorithm starts with assuming the highest intensity considered, intensity VII. If the requirements for intensity VII are not met, the algorithm continues with intensity VI, etc., until the satisfied intensity with the score is computed. The weights assigned to each question and the thresholds needed for each intensity have been modified to correlate the results with expert judgment. Compared to Camelbeeck *et al.* (2002), aggregation was used for online intensities, and only municipalities with three or more accepted submissions were considered.

Results

Comparing the original (Figure 1) and revised (Figure 2) datasets show a large discrepancy for the traditional intensities. For large parts of the country, the intensity increased with a full intensity value. While intensity IV is only assigned to a few municipalities originally, the revised dataset shows intensity IV for most municipalities. The maximal intensity is increased to V for three municipalities and twelve municipalities were assigned intensity IV-V. The number of intensities II and III have been drastically reduced. The differences between the original and revised online intensities are less drastic as aggregation results in a slight intensity increase at closer epicentral distances and a slight decrease at larger distances. Comparing the revised datasets uncovers a large discrepancy in assigned intensities (Figures 2C and 2D) all throughout the country.

Discussion and conclusions

For the last two decades, the collection of macroseismic intensity data in Belgium only occurred through the online application of the ROB with the assumption that online intensity roughly equals traditional intensity. By revising both traditional and online intensities, this assumption may no longer be valid.

Through automation, the traditional intensity dataset now reports intensities up to intensity V, which corresponds well to the reported light damages and panic among the inhabitants, according to the European Macroseismic scale (EMS98; Grünthal, 1998). The large number of intensity IV values in the revised traditional dataset may look inflated, but all questionnaires from these municipalities indicated that 1) many people felt the earthquake or that at least a few people felt it outside, and 2) multiple effects were observed to objects such as swinging, shaking, vibrating, rattling or moving. A known issue with the traditional questionnaires is that there is no information on the quantity of people that observed a certain effect. Indicating the occurrence of a certain earthquake effect might be based on the testimony of a single individual or it could have been observed by every household. The assumption is that the questionnaire is representative

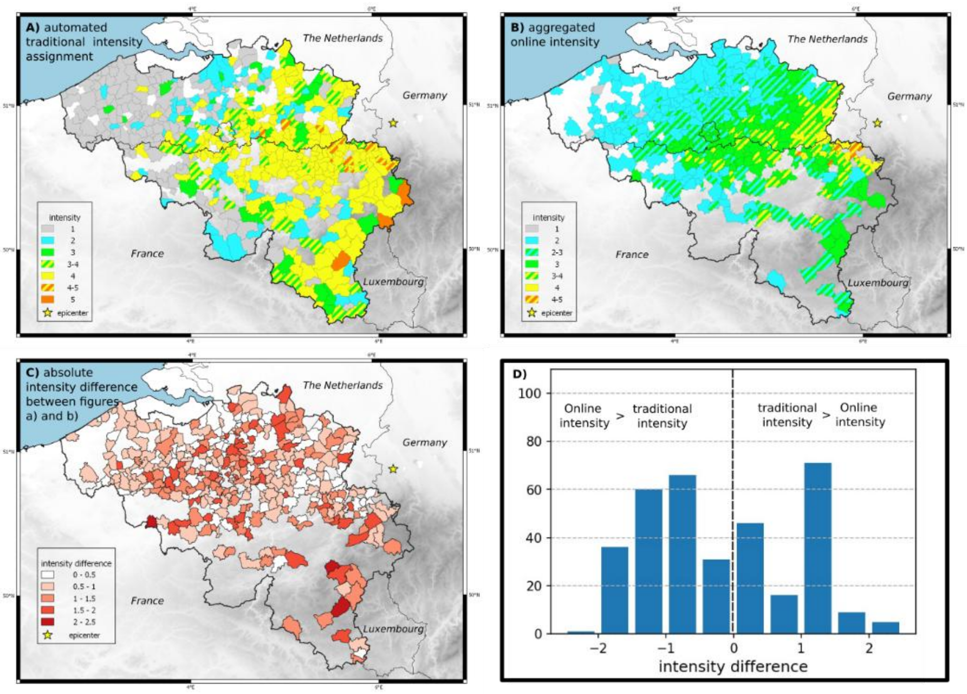

Figure 2. Revised macroseismic intensity datasets for the M_L 5.0 Alsdorf-Eschweiler 2002-07-22 earthquake. A) Automated traditional intensities. B) Aggregated online intensities. C) Mapped intensity difference and D) histogram representation for municipalities for both types of macroseismic datasets

for the entire municipality and its quality will depend on the effort of the official completing the survey to inform himself about the effects of the earthquake. The benefit of the online questionnaires is that the quantity of the occurrence of all effects are available.

The large discrepancy between the revised traditional and online datasets hints to at least one of them being erroneous or inaccurate. The revised traditional dataset is now more in accordance with how traditional questionnaires have been analyzed at the ROB throughout the 20th century. Then again, the online DYFI procedure is a widely used and tested procedure with satisfactory correlations to traditional intensity data from all over the world (e.g., Wald et al., 2010). Even though the DYFI application has been calibrated to traditional MMI intensities from the US and not EMS98 intensities, both scales can be considered equivalent (Musson, 2010).

In conclusion, the revision of traditional and online intensities of the ML 5.0 Alsdorf-Eschweiler 2002-07-22 event uncovers a significant discrepancy between both datatypes. While its cause is unknown, if the discrepancy between the two data types is indeed as significant as described here, this may have major implications for either the last two decades of online collected intensity data or an entire century of traditional macroseismic data.

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Palaeo- Macroseismology and Seismotectonics
17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00027

Macroseismic Effects of the Seismic Sequence Starting on 22nd of May 2023 in the Western Part of Romania

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Based on the catalogues published by Oros and Oros (2009) and Oros et al. (2008) the western part of Romania, named Banat region is composed by four seismogenic zones where the strongest earthquakes with Imax obs=VIII EMS were located. Oros (2011) defined the seismicity zones that are correlated to the geotectonic units, based on $M_w \geq 5.3$ earthquakes distribution: two of them are located within the western Plain of Romania between Arad-Sânnicolau Mare (to the North) and Banloc-Voiteg-Timisoara (in the central zone). The other two are in the south Carpathian Orogen, known as Oravita-Moldova Noua and Mehadia-Orsova seismic zones (Oros and Diaconescu, 2015 and Oros, 2011). Oros and Oros (2009) have grouped the seismicity patterns of earthquakes occurrence in time as follows: i) Foreshocks – Mainshock – Aftershocks, ii) Mainshock – Aftershocks and iii) Swarms, based on the catalogues of Oros et al. (2008). Oros and Oros (2009) also emphasized long-time behavior of the large magnitude earthquakes with its apparent migration from the northern (Arad-Sânnicolau Mare) and southern (Oravita-Moldova Noua and Mehadia-Orsova) edges of the region (high level of activity before 1900) to the central part of the region (high level of activity after 1900). This behaviour could be connected to the variation of the tectonic regime.

The present paper deals with a seismic sequence situated in the northern part of the Banat region, at the limit with the Crisana-Maramures seismogenic zone (Radulian et. al, 2000) (Figure 1, Table 1)).

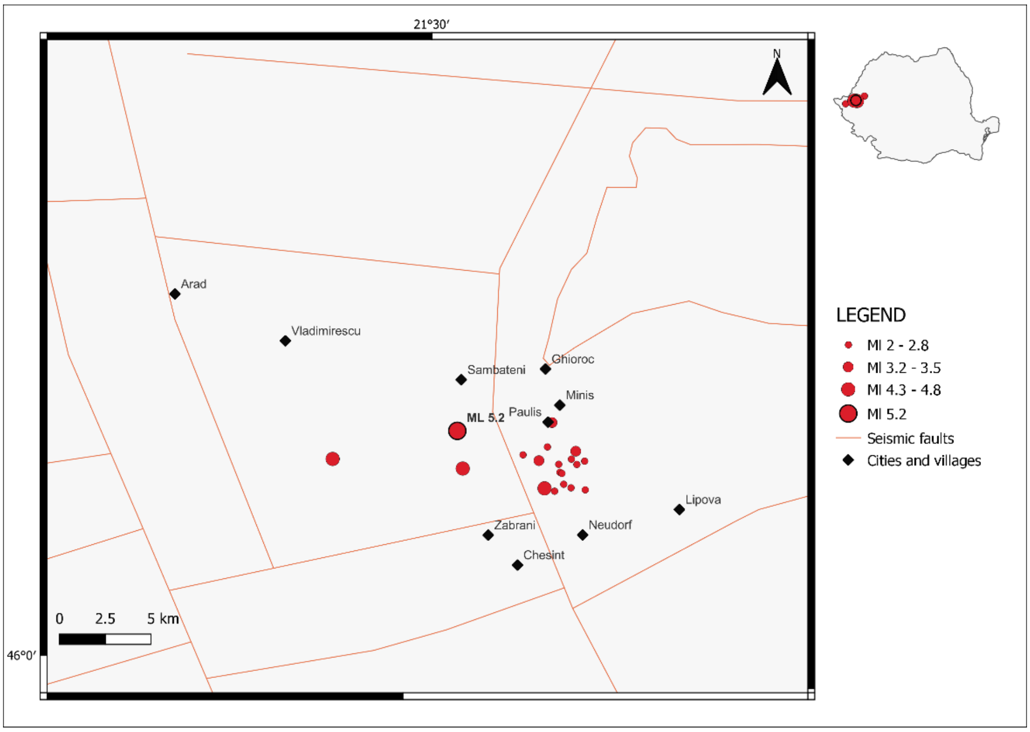


Figure 1. Earthquakes with M_L>2.0 occurred in 2023 inside an area bordered by 20-23 degrees of longitude East and 45.5-47 degrees of latitude North. The May-June 2023 seismic sequence. The seismic line fault layer after Raileanu V. et al. (2008).

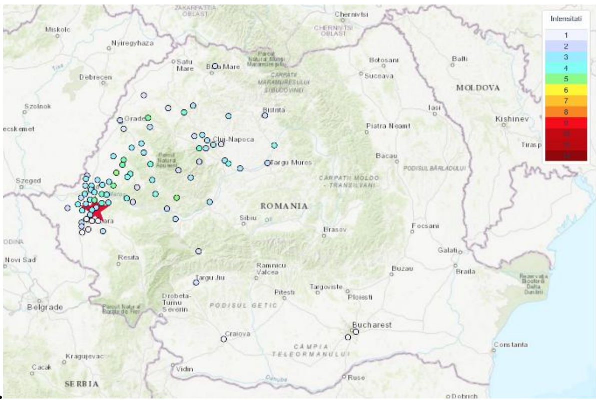
The sequence started on 22nd of May with a M_L=4.8 earthquake, followed at less than two hours later, in the same location by a second shock with a magnitude of M_L=4.4, and in the next 10 days by other 10 events with magnitudes between 2.0 and 4.3 M_L, located at the same latitude but shifted around 10 kilometers to the East.

On the 6th of June 2023, the largest shock of the sequence with M_L=5.2 hits the area, just in the middle of the aftershocks area, and was followed by other 6 events with magnitudes between 2.0 and 3.2 in the next day, and after that it stopped. The sequence also included many earthquakes with magnitudes below 2.0, but the location errors were too large, so that we have decided to not include them in the map of Figure 1. In Table 1, only the earthquakes with $M_L \geq 2.0$ are listed.

Table 1. Earthquakes with M_L≥2.0 occurred in 2023 inside an area bordered by 20-23 degrees of longitude East and 45.5-47 degrees of latitude North.

Day and time	lat (°N)	lon (°E)	Depth (Km)	Magnitude	Feedback	Imax
2023-06-07 6:27	46.0954	21.607	7.3	2.2	0	
2023-06-07 5:57	46.1007	21.6054	8.9	2.8	0	
2023-06-07 0:56	46.1134	21.5944	7.8	2	0	
2023-06-06 18:04	46.1255	21.5969	5.5	3.2	199	V
2023-06-06 18:02	46.0938	21.6123	5.3	2.1	0	
2023-06-06 17:26	46.1194	21.5303	7.2	5.2	2450	VII
2023-06-02 16:57	46.109	21.5774	11.9	2.2	0	
2023-05-29 3:25	46.1119	21.6145	3.4	3.5	198	IV
2023-05-23 21:42	46.1065	21.5888	6.9	3.2	200	IV
2023-05-23 20:32	46.0918	21.6008	10.7	2.6	0	
2023-05-23 20:30	46.0931	21.6224	6.7	2.4	0	
2023-05-23 20:25	46.1054	21.6157	8.3	2.1	0	
2023-05-23 16:15	46.101	21.5353	6.8	4.3	496	V
2023-05-23 2:12	46.1012	21.604	9.5	2.6	0	
2023-05-22 23:48	46.1051	21.6029	9.8	2	0	
2023-05-22 21:21	46.1072	21.6211	2.3	2.4	0	
2023-05-22 20:26	46.1079	21.6117	10.2	2	0	
2023-05-22 19:55	46.093	21.5936	6.3	4.4	718	VI
2023-05-22 17:46	46.1029	21.4432	8.7	4.8	1787	VI
2023-02-23 9:44	46.3042	22.009	2	2.1	0	
2023-01-01 8:03	45.9637	20.9525	14.5	2.5	0	

All events with magnitudes larger that 3.0, had answers about macroseismic effects to the online questionnaires (see Table 1), and the two largest shocks were felt at distances of more than 200 Km away from the epicenters (Figures 2a and 2b). The fact that the M_L4.4 earthquake had the same reported maximum intensity, can be explained either by the fear induced by the first earthquake or by the possibility that the answer was given for the 4.8 earthquake that occurred only 2 hours before.

a. 

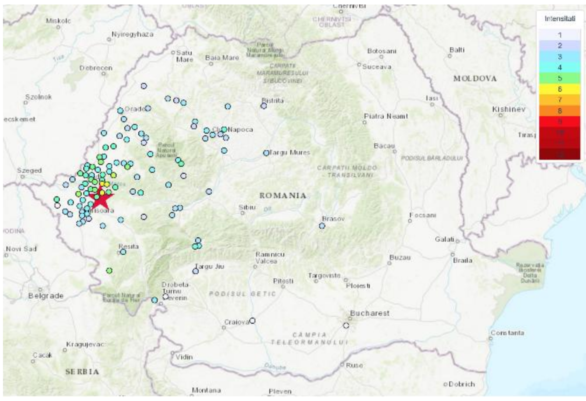
b. 

Figure 2. Macroseismic answers obtained for each territorial unit, using the feedback reported online by the population after a. 22nd of May and b. 6th of June earthquakes.

The number of answers to the questionnaires is given in the sixth column of Table 1 and the maximum reported macroseismic intensity is given in the last column of Table 1, for all earthquakes with M_L>3.0. One important observation is that for all earthquakes there were answers almost to the north of the epicenter, even if to the south the large city Timisoara is located, at less than 50 kilometers away. Most people from Timisoara reported that they didn't feel or slightly felt the earthquakes. This distribution of intensities is under study, and we will present some conclusions at the conference.

In Figure 3 some photos are shown that were taken by one of the coauthors of the paper, and from the press, published in local journals. These photos certify the intensities reported by the population.

Figure 3. Photos taken by authors of the paper immediately after the 5.2 earthquake in the epicentral zone

Acknowledgements

This paper was carried out within Nucleu Program SOL4RISC, supported by MCI, project no PN23360201, Project PNRR- DTEClimate nr. 760008/31.12.2023 and AFROS Project PN-III-P4-ID-PCE-2020-1361, supported by UEFISCDI.

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Palaeo- Macroseismology and Seismotectonics
17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publ.11
Ext. Abs. 00028

Earthquake Detection and Rapid Notification in Kefalonia island (Greece): A Machine Learning Approach

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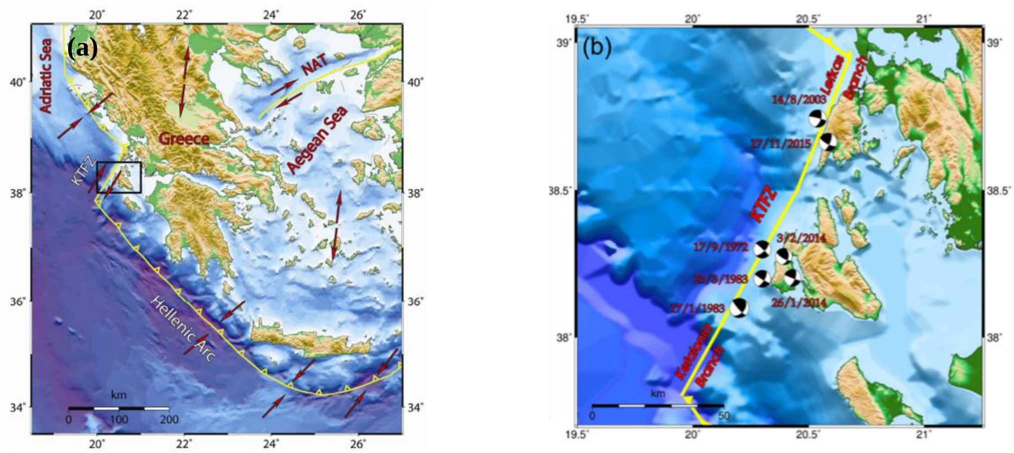
The timely and accurate notification of earthquake occurrenceplays a critical role in mitigating their potential impact. Machine Learning (ML) techniques are employed for this purpose, which have proven to be valuable tools in various scientific fields, including Seismology and application in processing seismic data.This work explores the use of ML to improve earthquake notifications in the KefaloniaIsland of Greece (Figure 1a).The Central Ionian Islands area stands out with the highest seismic moment rate not only in Greece but in the entire Mediterranean region. The study areaexperiencescontinuously highseismic activity and occasional destructive historical and instrumental earthquakes (Figure 1b, Table 1), making essential to develop effective systems for detecting and alerting residents and authorities about impending earthquakes.

The region itself acts as an active boundary, linking the oceanic subduction to the south (PapazachosandComninakis, 1970) with the continental collision to the north (Clement et al., 2000; McKenzie, 1978). These significant active boundaries are connected through the Kefalonia Transform Fault Zone (KTFZ), which is characterized by dextral strike-slip focal mechanisms and exhibits a thrust component (Scordilis et al., 1985; Kiratzi and Langston, 1991; Papadimitriou, 1993) (Fig. 1a). The KTFZ comprises two primary fault branches: the Lefkadabranch in the northern part, which strikes in a NNE-SSW direction, and the Kefalonia branch in the southern part, with a slightly different NE-SW strike (Louvari et al., 1999; Papazachos et al., 1998) (Fig. 1).Papadimitriou and Papazachos (1985) found that the seismicity of the broader region of the Ionian Islands, considering 41 earthquakes with magnitude ≥ 6.5 that occurred in the area during the period 1592–1975, has an average rate of one earthquake with magnitude ≥6.5 per decade.Over time, seismic events have caused the destruction of urban areas, leading to widespread damage and loss of life. The most severe incident occurred during the 1953 paroxysm, which consisted of four events: on 9th August (M6.4), 11th August (M6.8), 12th August (M7.2), and 21st October (M6.3). These earthquakes had a devastating impact, nearly completely demolishing structures on Kefalonia Island. Moreover the 2014doublet (M_w6.1 and M_w6.0) occurred in the southern and the central part of the peninsula, respectively, shed light on the kinematic and structural properties of the activated portions of the KTFZ (Karakostas et al., 2015).



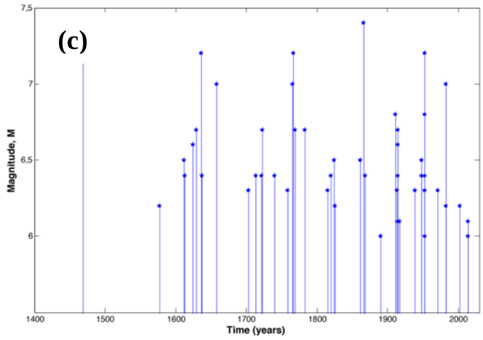


Figure 1. a.Map displays the primary geodynamic characteristics of the Aegean region and its surrounding areas. Active boundaries are represented by solid lines on the map. Arrows are used to indicate the approximate direction of relative plate motion. The study area is marked by a square on the map. Key features highlighted on the map include the Kefalonia Transform Fault Zone (KTFZ) and the North Aegean Trough (NAT) (modified by Karakostas et al., 2014) b. Study area is characterized by several major active boundaries. To the south, there is a subduction front. Moving northwards, the Kefalonia Transform Fault Zone (KTFZ) is prominently featured, comprising the Kefalonia and Lefkas branches. Further north, the collision boundary is observed, situated north of Lefkas Island.Additionally, the map uses black beach balls to represent the fault plane solutions of the most significant recent earthquakes in the region with M≥6.0 (modified by Bonatis et al., 2021) c. Earthquakes with a value of M ≥ 6.0 in the region of the Central Ionian Islands during the period from 1469 to 2015, plotted as a function of time (Kourouklas, 2015).

Table 1. Table of historical and recorded earthquakes occurred in the area with M≥7.0 (Papazachos and Papazachou, 2003; Kourouklas, 2015).

Date	Time	Lat (º)	Lon (º)	Depth (km)	Magnitude (M)
1469 Spring		38.3	20.50	-	7.2
30/09/1636		38.10	20.30	-	7.2
24/08/1658		38.20	20.40	-	7.0
24/07/1766	05:00:00	38.10	20.40	-	7.0
22/07/1767	04:00:00	38.30	20.40	-	7.2
04/02/1867	04:19:00	38.39	20.52	-	7.4
12/08/1953	09:23:52	38.30	20.80	-	7.2
23/03/1983	12:41:31	38.10	20.20	7.0	7.0

This study focuses on collecting and processing a comprehensive dataset of earthquakes in real-time and create a notification that contains time, magnitude and epicenter of an earthquake.The seismological center of Aristotle University of Thessaloniki (AUTH) analyzes earthquakes (finding their focal parameters), 24 hours/365days using recordings from the Hellenic Unified Seismological Network (HUSN). Therefore, it is crucial for every analyst on duty to be alerted promptly about significant earthquakes with a magnitude above 4.0 or smaller earthquakes with a magnitude ranging from 2.5≤M<4.0, if the epicenter is close to inhabitedareas or cities where people are highly concerned about the occurrence of earthquakes.

For this purpose, a mobile application was developed, which calls each analyst and informs them about the location, time, and magnitude of an earthquake that occurred in a specific area, using automated earthquake solutions. We thought it would be essential to expand this application beyond the seismic analysts of the seismological station, allowing every citizen, community, civil protection agency, or any authority (e.g., municipalities, schools, police, fire department, etc.) to use it. This way, they can be promptly informed in case of an earthquake in a particular area. Kefalonia, due to its high daily seismic activity and the destructive historical earthquakes, serves as an excellent case study for implementing this specific application.

The dataset includes a catalog of earthquakes from 2020 to 2023 and demographic data for the region of Kefalonia.The program has been trained to gather GIS population data within a certain radius around an earthquake epicenter. If an earthquake occurs, for example, with a magnitude of M≥4.0 in Lixouri, taking into account the attenuation relationships and the population density around the city, the program selects which areas to call in order to provide earthquake notifications.

The entire process has been implemented and tested as part of the Microsoft competition titled "Global Azure Bootcamp 2018 – Using Azure Functions and Microsoft Cognitive Services for near real–time earthquake notifications" winning the third place.The application has been improved by considering both the population in a specific area and the attenuation relationships based on the earthquake magnitude.Certainly, Kefalonia can be used as a testing ground for the application. With its high seismic activity and a history of destructive earthquakes, Kefalonia provides an excellent opportunity to test the functionality of the application and assess its effectiveness. Testing in the region can provide significant data and insights for improving the application and evaluating its accuracy and efficiency under real conditions.

Acknowledgements

The authors wish to express their sincere and profound thanks to software engineer Spyrou George for many useful suggestions and ideas as far as software development concerns. This work is partially funded by the Union of Municipalities of the Ionian Islands.

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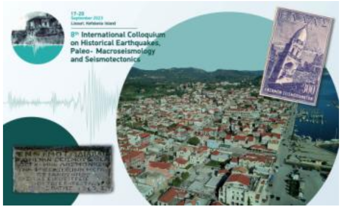

8th International Colloquium on Historical Earthquakes,
Palaeo- Macroseismology and Seismotectonics
17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00029

Site effects at the seismological stations in the islands of Kefalonia and Lefkada.

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The evaluation of site effect influence on seismological recordings of permanent stations located on the islands of Lefkada and Kefalonia (W. Greece), is presented in this study. The main goal was to investigate local magnitude overestimation issues, that have been observed and statistically verified.

The ground motion recorded at surface generally depends on source, path and local peculiarities. The site-effects are caused by the modification of seismic waves because of geological and topographic variations near the surface of the Earth. The Horizontal to Vertical Spectral Ratio (HVSR) (Bard *et al.*, 2004; Molnar *et al.*, 2022), a non-reference site technique has been applied on ambient vibration and earthquake recordings in order to estimate local site effects and the resonance frequencies of the uppermost sedimentary layers.

The resonance frequencies and corresponding H/V ratio amplitudes have been estimated for 8 seismological stations located on the islands of Lefkada and Kefalonia, belonging to network HT (Permanent Regional Seismological Network operated by the Aristotle University of Thessaloniki, doi:10.7914/SN/HT). The algorithm used is an open-source Python package called HvsrPy, which provides also the ability to check for azimuthal variations of these values (Cheng *et al.*, 2020; Vantassel *et al.*, 2020). The stability of data has been checked for seasonal and diurnal variations from multiple datasets. For each site the H/V spectral ratio was calculated (Figure 1), both for ambient noise and earthquakes, and the results that show a high H/V ratio, have been correlated with local geology.

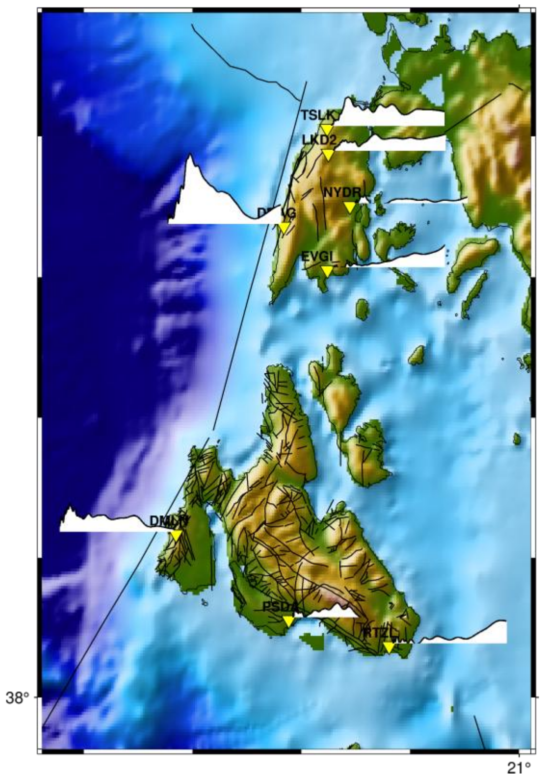

Figure 1. Average HVSR results.

High amplification values are observed at at least one station (DRAG, HT) (Figure 2), and they have been associated with the existence of a sedimentary valley, created by Dragano Fault (Papathanasiou *et al.*, 2017). Close by measurements that have been conducted on bedrock, show much lower amplifications, verifying the effects of the sedimentary valley.

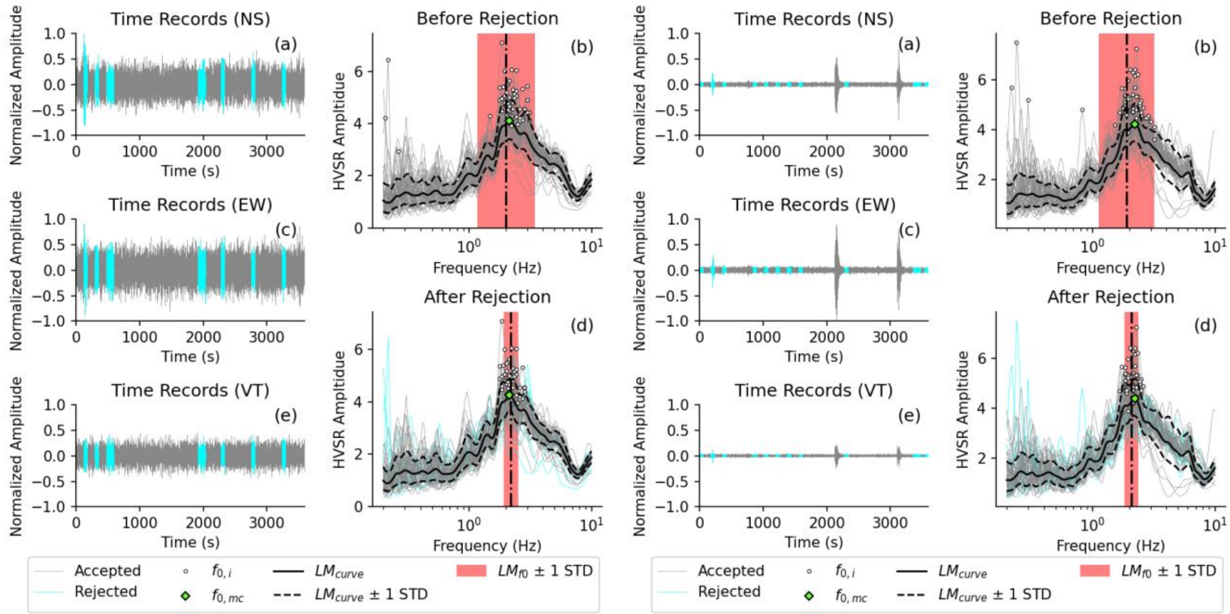

Figure 2. HVSR results for station DRAG: (a) for noise signal (b) for earthquake.

Furthermore, the azimuthal variations of site effects at this site have been investigated (Figure 3), and they show that the minimum amplitude is noticeable on azimuth 0°-10° (parallel to the basin), while the maximum amplitude is observed between 90°-120° (perpendicular to the basin). The amplitudes vary by a factor of between 4 and 6 (~30%).

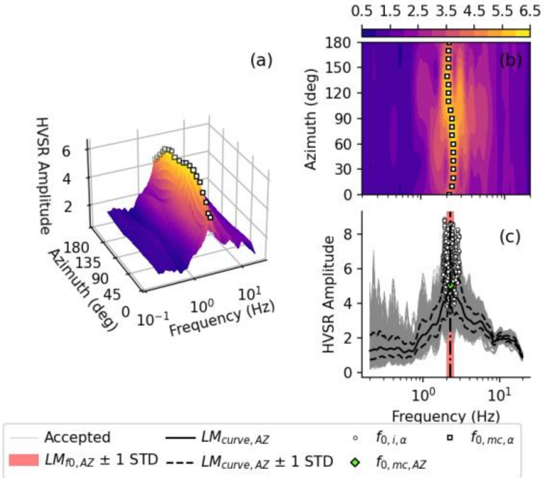

Figure 3. HVSR azimuthal variations for station DRAG and corresponding cross sections.

Finally, HVSR results have been simulated with frequency dependent polynomial equations (Figure 4), whose roots are proposed as site effect correction values for the horizontal components, in station metadata files (.resp,.xml).

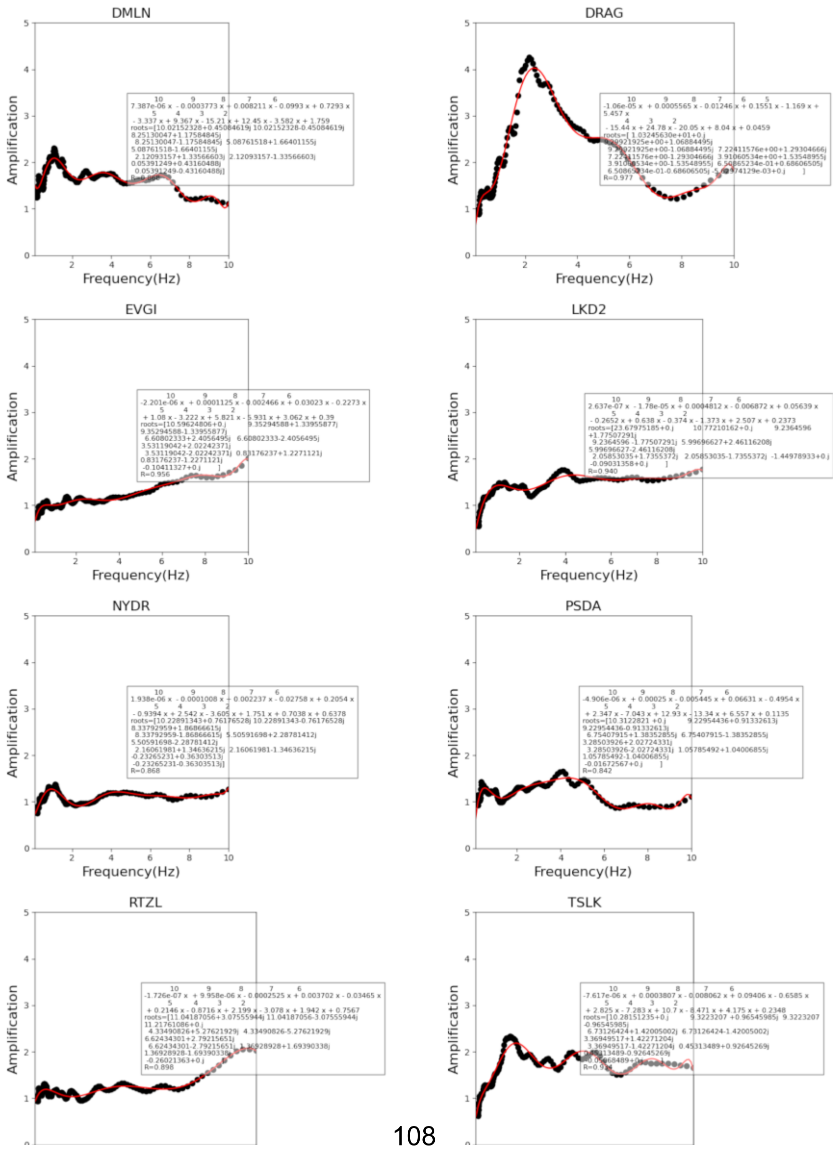

Figure 4. Polynomial fits for HVSR curves for all of the stations.

Acknowledgements

This study is financially supported by the association of Municipalities of Ionian Islands (PED-IN)

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8th International Colloquium on Historical Earthquakes,
Palaeo- Macroseismology and Seismotectonics
17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00030

Using ultra-high resolution methodologies to imaging active submarine faults: The STRENGTH 2023 cruise in the Alboran sea

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Introduction

Great earthquakes and the possibility to generate destructive tsunamis are geohazards of key societal concern, as they may impact world economies, disturb submarine structures and affect coastal areas with the associated risk for local populations (Bilham, 2010). We still have in our mind catastrophic episodes, such as the giant events of the Sumatra earthquake and tsunami in 2004 in the Indian Ocean of magnitude (Mw) 8.7, and the Tohoku-Oki earthquake and tsunami in 2011 in the northwest of Japan, of magnitude (Mw) 9.0-9.1. Nevertheless, seismic events of moderate to large magnitude (Mw 6-7.3) in areas of low to moderate tectonic deformation, and with long recurrence intervals, such as the Alboran Sea in the Western Mediterranean, might also have a significant effect. Accordingly, during the last decades there has been an expansion of paleoseismology to marine areas, both on-fault and off-fault investigations (Pantosti et al., 2011; Perea et al., 2021a).

Even if paleoseismological analysis has been mainly applied to very active areas such as California and Cascadia margins (Goldfinger et al., 2012; Perea et al., 2021b) or New Zealand (Lamarche et al., 2006), areas of relatively slow tectonic deformation with faults capable of generating large-magnitude earthquakes (Mw > 6) with long recurrence intervals (> 1000 yr), such as the faults in the Alboran Sea, deserve special attention. During the last decade, a continuous effort has been made to adapt the paleoseismological approach to slow active faults offshore. However, even the most advanced hull-mounted or deep-towed marine geophysical instrumentation do not provide the same degree of observation detail and accuracy as the current paleoseismological techniques used onland, such as trenching. A way around this limitation is offered by the use of Autonomous Underwater Vehicles (AUV) and Remotely Operated Vehicles (ROV). The use of this high-technology equipment is crucial to improve our knowledge about seismic and tsunami hazard.

The STRENGTH cruise consisted in a 38-day in situ investigation using state-of-the-art underwater vehicles and scientific equipment (AUV, ROV, ocean bottom seismometers, towed high-resolution side-scan sonar and high-resolution seismics) to survey the active seismogenic faults in the Alboran Sea (Al Idrissi Fault, Carboneras Fault and North-South Faults; Fig. 1), located at the SE Iberian and NE Moroccan margins. The main objective of the STRENGHT cruise was to acquire high- and ultra-high-resolution data to characterize in detail the 3D structure (i.e. seafloor and sub-seafloor) of the largest active fault systems in the Alboran Sea, to appraise the role of these systems, as potential seismic and tsunami generators, and to determine the crustal domains they bound. In order to achieve such a high degree of resolution we needed to use cutting-edge marine equipment that allow a metric resolution in surface mapping (geomorphic evidence) and at depth (stratigraphic evidence).

Geological Setting: The Eastern Alboran Sea

The Alboran Sea was formed during the Neogene by westward migration of the mountain front and late-orogenic crustal extension coeval with the plate-convergence between the African and Eurasian plates (Platt and Vissers, 1989; Comas et al., 1999; Booth-Rea et al., 2007). From the Late Miocene to Holocene, a contractive reorganization with the implantation of a NNW-SSE maximum horizontal shortening direction has been responsible for the present-day morphology of the basin (Martínez-García et al., 2017; Estrada et al., 2018; Perea et al., 2018; Gràcia et al., 2019).

Regional seismicity in the Ibero-Maghrebian region is diffuse and does not clearly delineate the present-day European-African plate boundary (Palano et al., 2015). Broadly, the area is characterized by continuous, shallow seismic events of low to moderate magnitude (Mw < 5.5) (Buforn et al., 1995; Stich et al., 2010). Even though a number of historical large earthquakes have occurred, such as the Torrevieja (1829, I=X), Vera (1518, I=IX) and Almería (1522, I=IX with possible submarine epicenter) earthquakes (Martínez Solares and Mezcua, 2002).

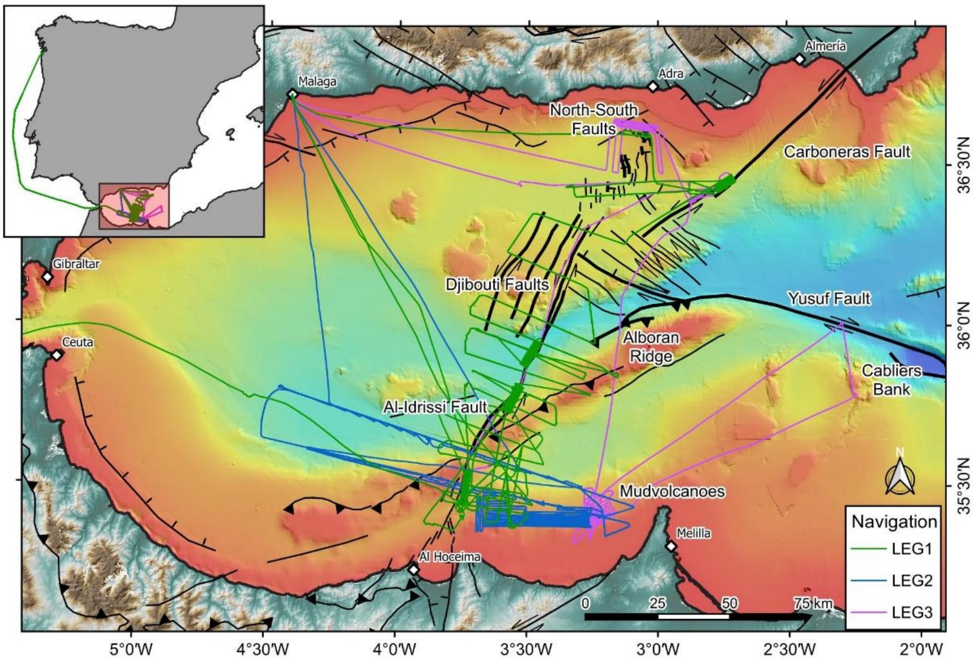

Figure 1. Map of Alboran Sea showing the main fault systems and the navigation carried out during the STRENGTH cruise.

The main fault systems in the Alboran Sea, the Carboneras, the Al Idrissi, the Yusuf and the Alboran Ridge Faults (Fig. 1), have been well characterized (i.e. geometry and kinematics, seismostratigraphy, seismic potential) during previous studies. The Carboneras fault is the southernmost fault system of the Eastern Betics Shear Zone (Fig. 1). It is a left-lateral strike-slip fault trending NE-SW. It has a length of about 150 km that includes a segment that runs on land and two segments that run at sea. In the offshore, the estimated slip rate for the Quaternary is about 1.3 mm/year (Moreno, 2011). The Al-Idrissi fault is located between the coasts of Morocco and the Djibouti plateau (Fig. 1). The fault is a left-lateral strike-slip fault system, that is composed of three segments, north, central and south, with an approximate direction NNE-SSW and 180 km long (Gràcia et al., 2019). Finally, the Yusuf and Alboran Ridge faults could be the largest structure located in the Alboran Sea with a length of about 230 km, going from the vicinity of the city of Oran in Algeria and crossing the Alboran Channel to intersect with the Djibouti Faults (Fig. 1). The Yusuf Fault is made up of two main segments that, in the area where they overlap, have generated the formation of a pull-apart basin (Perea et al., 2018; Gràcia et al., 2019; Gómez de la Peña et al., 2022). This is a right-hand strike-slip fault, but towards its western termination it arches and a reverse component becomes predominant. This zone with predominance of the inverse component corresponds to the northern termination of the inverse fault system of the Alboran Ridge thrust fault, the activity of which has caused the uplift of a NE-SW trending ridge. The slip rate of the Yusuf fault might range between 2.3 and 5.6 mm/year and for the Alboran Ridge between 1.8 and 3.0, for the last 5.3 Ma in both cases (Gómez de la Peña et al., 2022).

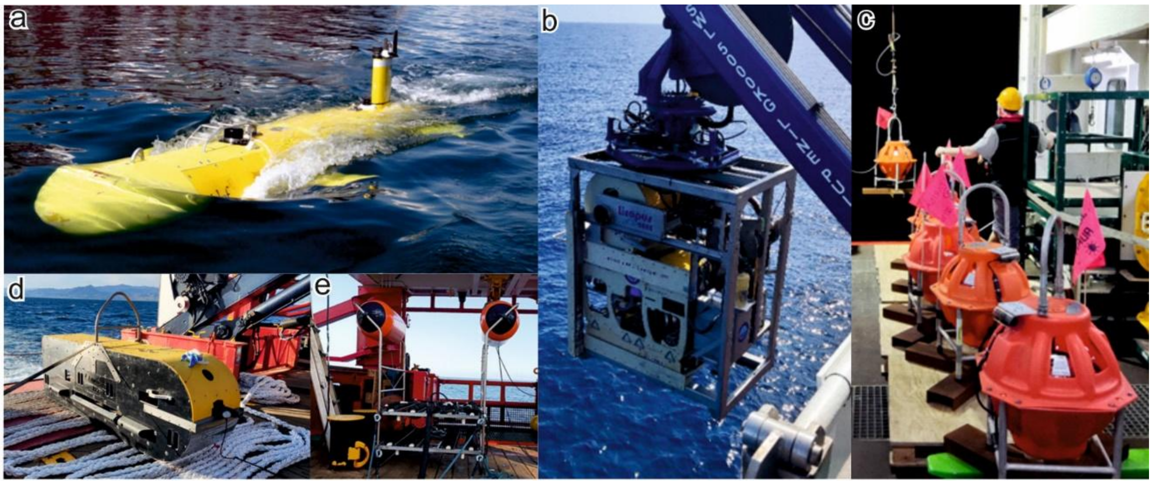

Figure 2. High-technological equipment used during the STRENGTH cruise. a) Autonomous Underwater Vehicle (AUV) AsterX (Ifremer, France); b) Remotely Operated Vehicles (ROV) Liropus (IEO, Spain); c) Ocean Bottom Seismometers (OBS) (Ifremer, France, and UTM, Spain); d) high-resolution side scan sonar DT-1 Edgetech (UTM, Spain); and e) high-resolution sparker seismic system (UTM, Spain).

The STRENGTH Cruise and Equipment

The STRENGTH cruise (Fig. 1) had allocated ship time onboard the Spanish RV Sarmiento de Gamboa to carry out an in situ marine active tectonics and paleoseismic investigation of active faults and its associated processes. The first part of the cruise (Leg 1: March 15 - April 1; 18 days) was devoted to acoustic seafloor investigation to acquire seafloor micro-bathymetry and high-resolution seismic reflection data searching for fault ruptures and on-fault/near-fault co-seismic seafloor deformation. To this we used the AUV “AsterX” (Fig. 2a) and a high-resolution sparker seismic system and digital multichannel streamer (Fig. 2e). The second part of the cruise (Leg 2: April 3 to 11, 9 days), was devoted to acquire wide-angle seismic data using ocean bottom seismometers or OBS (Fig. 2c) to determine crustal structures and domains in the southern Alboran Sea. The third and final part of the STRENGTH cruise (Leg 3: April 13 to 21, 9 days) aimed to have direct visual seafloor exploration (i.e. scarps related to earthquake ruptures) using the ROV “Liropus” (Fig. 2b) and acquire high-resolution side scan sonar data with the DT-1 Edgetech (Fig. 2d). The preliminary onboard processing and analyses of the acquired data show evidence of the Quaternary activity on the studied fault systems.

Acknowledgements

This research was supported by the grant STRENGTH (PID2019-104668RB-I00) funded by MCIN/AEI/10.13039/501100011033. This project acknowledges the ‘Severo Ochoa Centre of Excellence’ accreditation (CEX2019-000928-S), the grant UNrIDDLE (2018-T1/AMB-11039) “Atracción de Talento Investigador” call 2018 funded by Comunidad de Madrid and the Ocean Facilities Exchange Group (OFEG) for allowing us to use the AUV “AsterX” from IFREMER. We also acknowledge the Captain, the officers and crew of the R/V Sarmiento de Gamboa for their professional work during cruise operations, which made possible the success of the STRENGTH cruise. We thank all the UTM-CSIC, IFREMER/GENAVIR (Leg 1), IFREMER (Leg 2) and ACSM-IEO (Leg 3) technical teams are deeply acknowledged for their professionalism, collaboration, and expertise in using their vehicles and equipment. Finally, we also thank the UTM-CSIC ship managers Miguel Angel Ojeda and Javier Prades for their collaboration with the cruise logistics and planning, and the director Jordi Sorribas for their constant help and support.

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Reassessing seismicity and seismic hazard in offshore areas: The case of the Alboran Sea (western Mediterranean)

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Introduction

The potential occurrence of large earthquakes and their capacity to trigger devastating tsunamis poses a significant geohazard that raises crucial societal concerns. Such events possess the ability to disrupt submarine structures, impact coastal regions, and have far-reaching consequences on global economies, thereby posing a risk to local populations (Bilham, 2010). Recent history serves as a stark reminder of the catastrophic nature of these occurrences, exemplified by the colossal Sumatra earthquake and tsunami in 2004 within the Indian Ocean (M_w8.7) or the Tohoku-Oki earthquake and tsunami that struck the northwest region of Japan in 2011 (M_w9.0–9.1). Nonetheless, it is vital to recognize that earthquakes with moderate to large magnitudes (M_w>5.5) in regions characterized by low to moderate tectonic deformation, and featuring long intervals between events, can also exert a substantial impact. The Alboran Sea situated in the Western Mediterranean is one such area of concern. Consequently, in recent decades, there has been a notable expansion in the interest to identify the active faults and to enhance our understanding about their seismic activity and probable aftermaths.

The main objective of STRENGTH project is to characterize the structure, development, and associated seismicity of the large fault systems in the Alboran Sea and its implication on seismic hazard and risk on coastal areas. Knowledge on the location and characterization of active structures in this region has been greatly improved in recent studies. Nevertheless, the potential association of offshore seismicity to specific faults has not yet been undertaken in a systematic way. The STRENGTH project aims to link a more detailed and precise characterizations of active faults in the Alboran Sea to offshore earthquakes to understand better the main earthquake sources in the area. To this respect, we are revisiting and analyzing the historical earthquake records and macroseismic information, and relocating the instrumental earthquakes registered in the last two decades, with a non–linear probabilistic approach jointly with high–resolution local/regional velocity models. The study focuses on: a) characterizing the 3D–structure of the fault systems and their evolution, and identifying the active faults that may have generated large–earthquakes; b) associating moderate to low magnitude seismicity and seismicity clusters to specific faults; and c) modeling ground motions in coastal areas based on fault characterization and recorded seismicity. The expected results will contribute to an improved assessment of the seismic hazard and risk in the Alboran Sea Region.

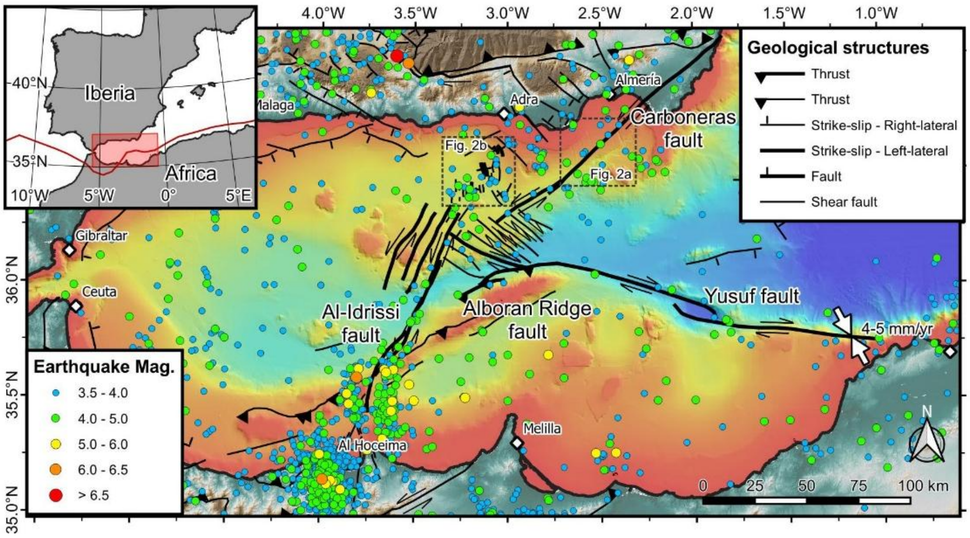

Figure 1. Map of Alboran Sea showing the main fault systems and the seismicity (1916–2023) from the IGN catalog.

The Eastern Alboran Sea: Seismological and Geological Settings

The Alboran Sea is a Neogene basin formed by crustal extension related to the subduction system in the Gibraltar Arc. At present, left-lateral and right-lateral strike-slip faults trending NE-SW and WNW-ESE, respectively, accommodate part of the strain related to the NW-SE convergence (4-5.5 mm/yr) between the African and Eurasian plates (DeMets et al., 2015). Consequently, the Alboran Sea shows a remarkable seismic activity, mainly concentrated along what is known as the Trans-Alboran Shear Zone (De Larouzière et al., 1988), but it does not clearly delineate the present-day European-African plate boundary (Palano et al., 2015). This seismicity (Fig. 1) is mainly characterized by low to moderate magnitude events, usually with M_w<5.5 (e.g., Buforn et al., 1995; Stich et al., 2010). Nevertheless, large and destructive earthquakes have occurred in the region, such as the 1522 Almería (IEMS98 VIII-IX; Spain), the 1790 Oran (IMSK IX-X; Algeria), the 1804 Dalias (IEMS98 VIII-IX; Spain), the 1910 Adra (IEMS98 VIII and M_w6.1; Spain), the 1994 and 2004 Al-Hoceima (M_w6.0 and 6.4, respectively; Morocco), and the 2016 Al–Idrissi (M_w6.4; Morocco) events (Martínez Solares and Mezcua, 2002; Buforn et al., 2017; Gràcia et al., 2019).

In previous studies, the main fault systems in the Alboran Sea have been identified and mapped (Fig. 1). Among them, the Carboneras fault is a left-lateral strike-slip fault that trends NE-SW and stretches for about 150 km, including a segment onshore and two offshore segments (Moreno et al., 2016). To the south of Carboneras fault, there is the left-lateral strike-slip Al-Idrissi fault, which is composed of three segments, namely north, central, and south, with an approximate direction of NNE-SSW and a length of 180 km (Gràcia et al., 2019). Finally, the Yusuf and Alboran Ridge faults, potentially the largest structure in the Alboran Sea, extend for approximately 230 km (Perea et al., 2018; Gràcia et al., 2019; Gómez de la Peña et al., 2022). The Yusuf Fault comprises two main segments, which have created a pull-apart basin where they overlap. Initially a right-lateral strike-slip fault, it arches towards its western termination, where a reverse component becomes dominant. This zone of inverse faulting corresponds to the northern termination of the Alboran Ridge thrust fault.

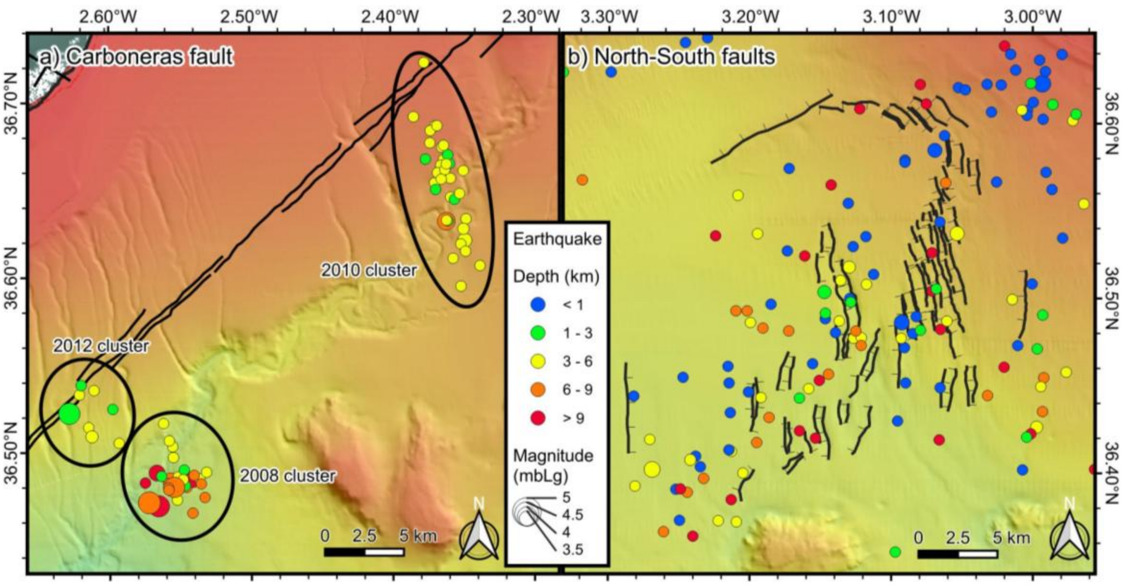

Figure 2. Maps showing the relocated seismicity occurred in the north Alboran Sea between 2000–2021. a) Carboneras fault area with the clusters occurred in 2008, 2010 and 2012. b) North–South faults area. The location of the areas in the Alboran Sea is shown in Figure 1.

Hypocenter Relocation of Moderate Seismic Activity

An accurate determination of the hypocentral location of this seismicity is a key point for a better knowledge of the active tectonics and may contribute to better trace and characterize active faults and to image their rupture area and, hence, to improve seismic and tsunami hazard assessments. One of the main goals of the STENGTH project is to analyze the recent seismicity in the Alboran domain by performing a high–precision hypocenter relocation of shallow earthquakes recorded in the area during the last two decades. More precise hypocentral locations will allow us to image well–defined lineaments, dominant strike directions and clustering near active structures and to better determine causative faults within the known fault systems.

For this purpose, we perform a two–step relocation process: a) an absolute location using a non–linear probabilistic algorithm (NonLinLoc) (Lomax et al., 2014) and a regional 3-D P-wave tomography velocity model for the Alboran-Betic-Rif system (El Moudnib et al., 2015); b) a relative location by means of double-difference location algorithm (HypoDD) (Waldhauser, 2001) for selected significant seismic sequences. This approach will allow us firstly to account for differences in the propagation of seismic waves in the heterogeneous Alboran domain, providing maximum likelihood hypocentres and complete information on location uncertainties and, secondly, to improve relative hypocentral locations and clustering along specific faults.

We applied these methodologies to the North Alboran region, to study the seismicity for the period 2000-2021. Despite the limitations on the station coverage, we relocated a subset of well-constrained M≥2.0 earthquakes located near the North-South faults (NSF) and the Carboneras Fault offshore segment (CF) (Fig. 2). Results for the CF area, display three clear clusters, corresponding to seismic sequences occurred in 2008, 2010 and 2012, respectively. The northernmost cluster shows a clear NW-SE lineament and shallow-depth distribution with hypocenters grouped up to 6 km depth. The other two clusters, are located in the SW edge of the CF; one lies above the CF in the channel zone and shows a very vertical concentration (up to 10 km depth) that would be in accordance with the known geometry of the fault; and the other cluster, to the SE of the previous one, also shows some clustering and verticality, although it does not appear to be directly related to the CF. On the contrary, the seismicity in the NSF zone is widely dispersed throughout the area and does not show a spatial arrangement indicating the presence of clusters, nor very clear alignments. However, relocated earthquakes are distributed along a NE-SW band about 20 km wide, up to 15 km depth, and slightly dipping to the SE. Further comparison with the known faults in the area would be necessary.

Modelling faults for comprehensive seismic hazard assessment

The characterization of active faults, although key in earthquake hazard modelling, is based on general broad models. Usually, geological information is essential to delineate areal zones of uniform seismicity, but a detailed understanding of the behavior of active faults is very seldom incorporated in the quantitative seismic hazard assessment (SHA). Based on the results described above, the source model for SHA will be developed by incorporating the precise determination of location of hypocenters, a review on historical seismicity and the characterization of the main fault systems. STRENGTH will develop an updated regional model with both, improved delineation of seismic sources and improved activity parameters of faults (fault slip rates, earthquake rates) based on the newly available geological data. The resulting earthquake rates as modelled through SHERIFS code (Chartier et al., 2019) will be tested against the earthquake catalogue of the region. A seismic hazard assessment methodology based on Monte Carlo simulation (Garcia-Fernandez et al., 2018) and using a Pan-European ground motion model (García-Fernández et al., 2019) validated through recent accelerogram recordings in the region will provide acceleration exceedance probability curves for selected main coastal urban environments and critical coastal infrastructures.

Acknowledgements

This research was supported by the grant STRENGTH (PID2019-104668RB-I00) funded by MCIN/AEI/10.13039/501100011033. This project acknowledges the 'Severo Ochoa Centre of Excellence' accreditation (CEX2019-000928-S) and the grant UNrIDDLE (2018-T1/AMB-11039) "Atracción de Talento Investigador" call 2018 funded by Comunidad de Madrid.

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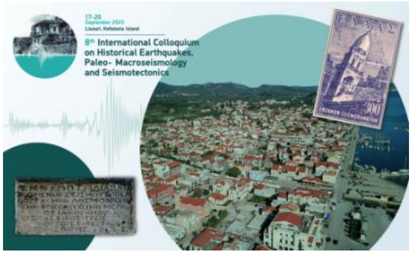

8th International Colloquium on Historical Earthquakes,
Palaeo- Macroseismology and Seismotectonics
17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00032

Towards a Database for Archaeoseismology

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Research Highlights

A system is offered for classification of deformation of masonry buildings, caused by earthquakes. Our purpose is to bring a large set of photographic data, arranged in a simple, logical way, to assist researchers in identifying seismic damage.

Why?

Guidoboni and Santoro Bianchi (1995) raised the problem that no systematic collection of data on earthquake-caused damage exists. They suggested the compilation of a thematic atlas, a set of case histories, in the field of archaeoseismology to help identification of features and assign them to specific causative agents. They emphasized that methodological aspects in this field are not always explicit, therefore each case is developed independently of other known case histories; in other words "each researcher finds his own earthquake".

Palaeontology, which involves the description of numerous fossils, and comparing them to other fossils described worldwide, has found the way out of this situation centuries ago. Various methods (initially graphical, then photographical) were used to store the visual information. Reference to these published data were done through the *synonym list*, which is an essential component of descriptive palaeontological works even today. These contain the year of publication, the name of the fossil used by the cited author, and a detailed bibliographic reference under the individual figure or part of a photographic plate.

Here we offer a morphological, non-genetic system of deformation features caused by past earthquakes to be used as a database or atlas. Reference to this rich collection of imagery will be a synonym list of archaeoseismology.

Material

The material used consists of photographs taken by the authors and those extracted from PDF files of published papers by the Systools Toolbox software in JPG format. Currently there are 924 photos arranged in 113 directories. The material is growing weekly. The source is 255 articles, books and book chapters. 157 articles are waiting to be utilized until the meeeting in Lixouri. The database contains a list of references of all items used in Word format. Additionally ADB contains all of the original papers, so the location, archaeological age and other conditions of the items can be easily checked. It is planned to be publicly available with a detailed description and explanation published in the Earth System Science Data or another electronic journal. It will also be available in the repository of the Library of the Hungarian Academy of Sciences (http://real.mtak.hu). Total volume of the database is 1.5 GB as of July 2023.

Structure

The contents are arranged in a mechanical, formal, non-genetic way (Figure 1), based on the initial suggestion of Kázmér (2015). On first level of the directory tree there are (0) on-fault displacements separated from (A) off-fault damage. On the second level separation of damage features are for (1) individual masonry blocks, (2) in-plane and (3) out-of-plane damage affecting single walls, (4) damaged adjacent walls, (5) damaged whole buildings, then (6) damaged floors with or without adjacent upright walls. Examples of (7) total collapse follow, and (B) repairs of damaged walls and floors, and (C) construction methods applied to make a building resilient to seismic shaking. Finally, there are photos of features looking like seismic damage, but which are surely not.

Contents and example

Figure 2 was created to be an Appendix to the article on a folded Roman road in Celeia, Slovenia (Kázmér *et* *al.*, 2023) to illustrate similar features documented in eight other sites. The composite figure was used to convince the scientific editor on our interpretation of the deformation of seismic origin. However, it was removed from the final version due to copyright concerns of the technical editor of MDPI, publisher of the journal Quaternary.

Acknowledgements

Thanks are due to Ernest Moro (Padova, Italy), with whom we took the initial steps together in developing this database. The late Barnabás Géczy, professor of Palaeontology at Eövös University in Budapest, Hungary, set the standards high for any aspiring scientist by developing and maintaining a database of visual information on Jurassic ammonites in the pre-computer age. His work serves as an example in the current venture.

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│   │   │   ├[04_Mortise-and-tenon - stone]
│   │   │   ├[05_Mortise-and-tenon_metal]
│   │   │   ├[06_Iron_anchors]
│   │   │   ├[07_Interlocking_masonry_in_arch_lintel]
│   │   │   ├[08_Interlocking_masonry_in_wall_horizontal_stress]
│   │   │   ├[09_Interlocking_masonry_in_wall_vertical]
│   │   │   ├[10_Hatil_horizontal_timber_in_masonry]
│   │   │   ├[11_Timber-laced_masonry]
│   │   │   ├[12_Alternating_layers_brick_stone_masonry]
│   │   │   ├[13_Wooden_beams_embedded_in_wall]
│   │   │   ├[14_base_isolators]
│   │   │   └[tervezett_gyengeségi_zónák]
│   │   ├[D_NON-SEISMIC]
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Figure. 1. Structure of the Archaeosesimological Database.

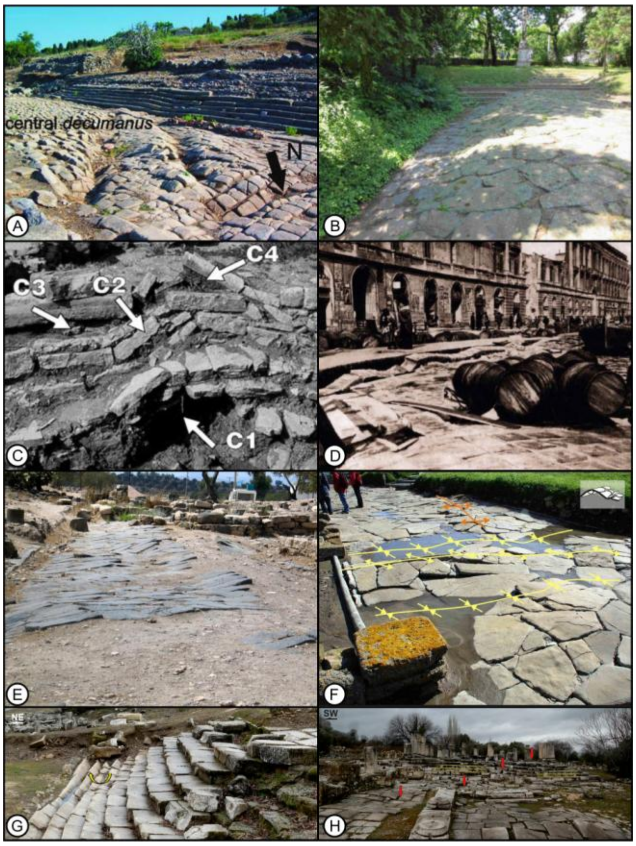

Figure 2. Examples of deformed roads and floors of buildings caused by earthquake. Figures are in the Archaeoseismological Database. Caption below is from the original submitted manucript for Kázmér et al. (2023).

A. Strong undulating deformation in the road-bed of the *central decumanus* at the Greco-Roman site of Tindari, Sicily, associated with a 4th-century earthquake (Barbano *et al.* 2014, fig. 9d). B. Uneven subsidence of a Roman road in Savaria (the Roman Garden, Szombathely, Hungary), caused by seismically induced liquefaction of the subsoil. Archaeoseismological Database photo #2156 (Kázmér & Győri 2020). C. Seismically-induced landslide caused folded and upthrusted remains at the NW corner of the Forum. C1: Folded roman pavement AD 40–60; C2: Faulted house ashlars AD 40–60; C3: Demolition horizon AD 40–60; C4: Upthrusted house-basement AD 350–395 (Silva *et al.* 2005). D. Liquefaction destroyed the port in Messina during the 1908 earthquake (Carcione & Kozák 2008). E. Liquefaction-induced deformation of a Roman road in Umm Qais (Gadara), Jordan (Fandi 2018). F. Anticlines and synclines formed in the pavement of the *decumanus maximus* of Baelo Claudia (Cádiz, Spain), caused by the earthquake which destroyed the town in ~350-395 AD. (Rodriguez-Pascua *et al.* 2016, fig. 6). G. Tilted and folded pavement and stairs of the Propylon in Lagina (Western Anatolia, Turkey) (Karabacak 2016, fig. 8b). H. Severely deformed floor in the Lagina sacred complex (western Anatolia, Turkey) (Karabacak 2016, fig. 10).

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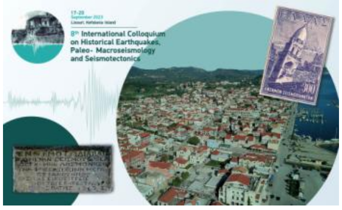

8th International Colloquium on Historical Earthquakes,

Palaeo- Macroseismology and Seismotectonics

17-20 September 2023 - Lixouri, Greece

Bulletin of the Geological Society of Greece, Sp. Publ. 11

Ext. Abs. 00033

The Database of the Catalogue of Strong Earthquakes in Italy and in the Mediterranean Area (CFTI): Exploring Historical Seismology Through Modern Web Tools

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CFTI, the Catalogue of Strong Earthquakes in Italy and Mediterranean Area, is an analytical inventory that stores in a large database the results of four decades of research in Historical Seismology on Italy and on the Mediterranean area.

CFTI is both parametrical and analytical, as for most of the analyzed earthquakes it features descriptive summaries of both the effects of each specific event at each individual location, and of its overall social and economic impact. But it is also a fully transparent database, as for each investigated earthquake sequence it provides a complete bibliography of all available testimonies of scholars and casual observers: many of such testimonies are supplied on-line, either in the form of the original source or as a transcription.

Since the beginning of the research in 1983, the Working Group developed a specific computerized cataloging scheme of all historical materials identified along selected research paths. The work was extremely extensive from its very beginning; numerous previously unknown or poorly known earthquakes were added to the previously available wealth of knowledge. The method used for unearthing and organizing the new information and the resulting elaborations has been gradually refined and consolidated in the subsequent versions of the CFTI.

The current version of the catalogue, termed CFTI5Med (Guidoboni et al., 2018; Guidoboni et al., 2019; Figure 1), includes 1,167 earthquakes for the Italian area and 473 earthquakes for the extended Mediterranean region (the latter section deals exclusively with ancient and medieval events). It hence draws from an extremely valuable and unique documentary and historical heritage: one of the most important in the world, in terms of quantity, quality and geographic distribution of the available information, and also in terms of the relevant chronological interval, spanning over two millennia (from the 8th century B.C. to the 15th century for Mediterranean area; from the 5th century B.C. to the 20th century for Italy).

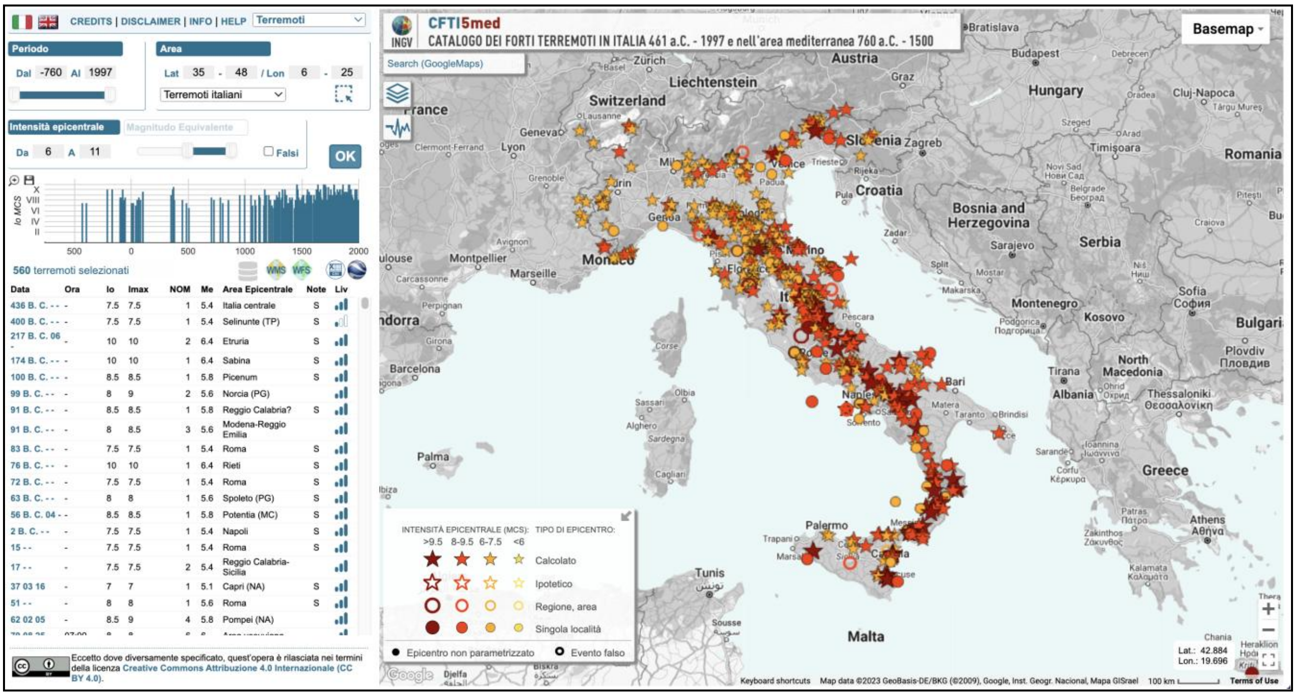

Figure 1. CFTI5Med web interface

Since the release of CFTI5Med, which features an entirely renovated and advanced web interface, we added various datasets and developed new IT tools. We present the four main products (tools and datasets) in a separate abstract (Sgattoni et al., 2023). Our aim was to enable diverse specialist and non-specialist users – including scholars, civil protection officers, teachers, students, professionals, and simply curious citizens – to explore and analyze efficiently the extensive wealth of data stored in the Catalogue. We remark that the early versions of CFTI were crucial in the inception and development of DISS, the Italian Database of Individual Seismogenic Sources (for details please refer to the abstract by Valensise et al., 2023).

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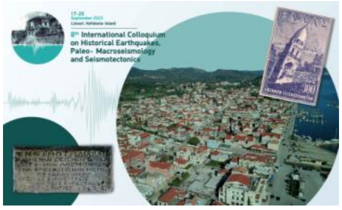

8th International Colloquium on Historical Earthquakes,
Palaeo- Macroseismology and Seismotectonics
17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 000034

Advanced Web Tools in Historical Seismology: the CFTI Laboratory Experience

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Since the release of CFTI5Med (Guidoboni *et al.*, 2018; Guidoboni *et al.*, 2019, Tarabusi *et al.*, 2023), featuring an entirely renovated and advanced web interface, we added various datasets and developed new IT tools. Our aim was to enable diverse specialist and non-specialist users – including scholars, civil protection officers, teachers, students, professionals, and simply curious citizens – to explore and analyze efficiently the extensive wealth of data stored in the Catalogue. We present here four of its main components (tools and datasets).

CFTIcompare (https://cfti.ingv.it/compare/) is a web-based tool that allows for a visual comparison of the effects of two different earthquakes, or of the intensity data supplied by two different studies of the same earthquake (Figure 1).

The comparison is performed on a geographical basis, and may concern either data from the CFTI alone (which are shown along with summaries of the effects for each individual location) – for example to compare the effects of two earthquakes that occurred in adjacent areas – or from other databases (e.g. ASMI, DBMI, Hai sentito il terremoto?).

The user may also use his/her own dataset, provided that it has been organized following one of the three allowed input formats.

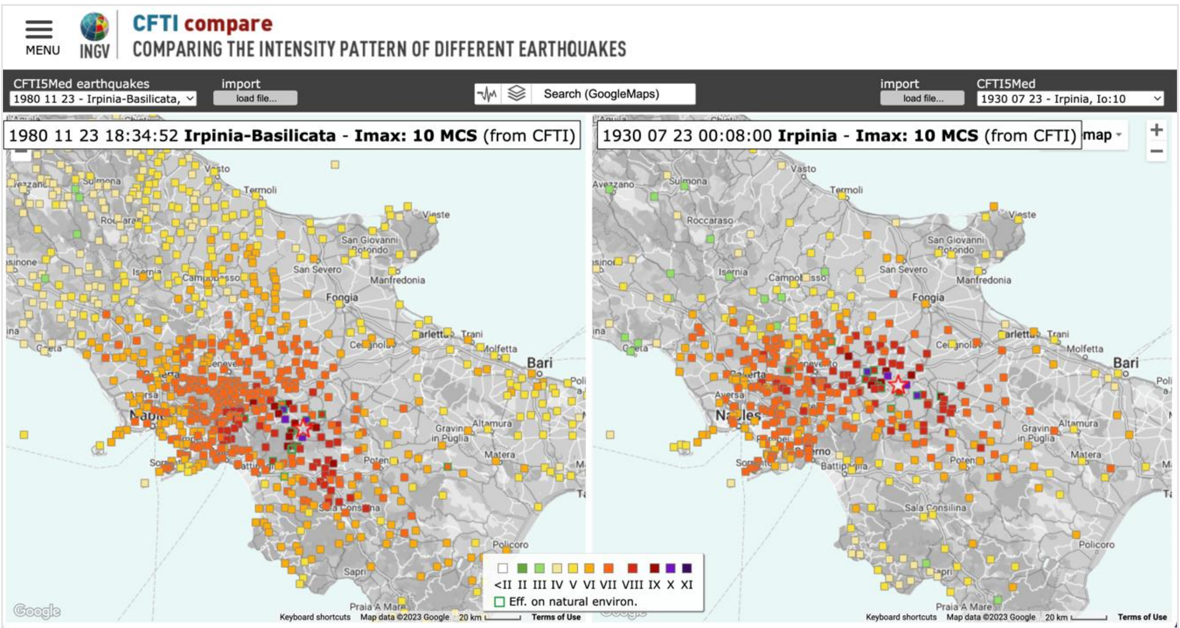

Figure 1. CFTIcompare web interface

CFTIvisual (https://cfti.ingv.it/visual/, Bianchi *et al.*, 2022) is the Atlas of visual sources on Italian historical earthquakes (Figure 2).

About four decades of investigation of Italian historical earthquakes led to the retrieval of many visual sources (engravings, paintings, photographs, film documents, etc.) that may be useful to scholars from different disciplines for supplementing information on the estimation of damage, on the response of institutions, on scientific observations, etc.

Currently the Atlas allows for advanced consultation of all visual sources concerning Italian earthquakes that can be freely published. Dedicated links allow connecting the sources to contextual descriptive information from CFTI.

CFTIsequences (https://cfti.ingv.it/sequences_demo/) displays the earthquake sequences reported in the current version of the CFTI through interactive graphs and maps (Figure 3).

It is the result of synergistic collaboration among the various skills that exist in the CFTI Working Group and allows users to consult the available data for individual shocks and for individual locations while keeping all descriptive textual comments visible.

Since publication of its first release (1995), the CFTI paid much attention to the existence of any foreshocks and aftershocks and of their time and space evolution. This was accomplished by dedicating a specific descriptive commentary to these shocks.

This product is fully functional: it currently contains two sequences for demonstration purposes only, but will soon provide data from more than 100 sequences stored in the CFTI.

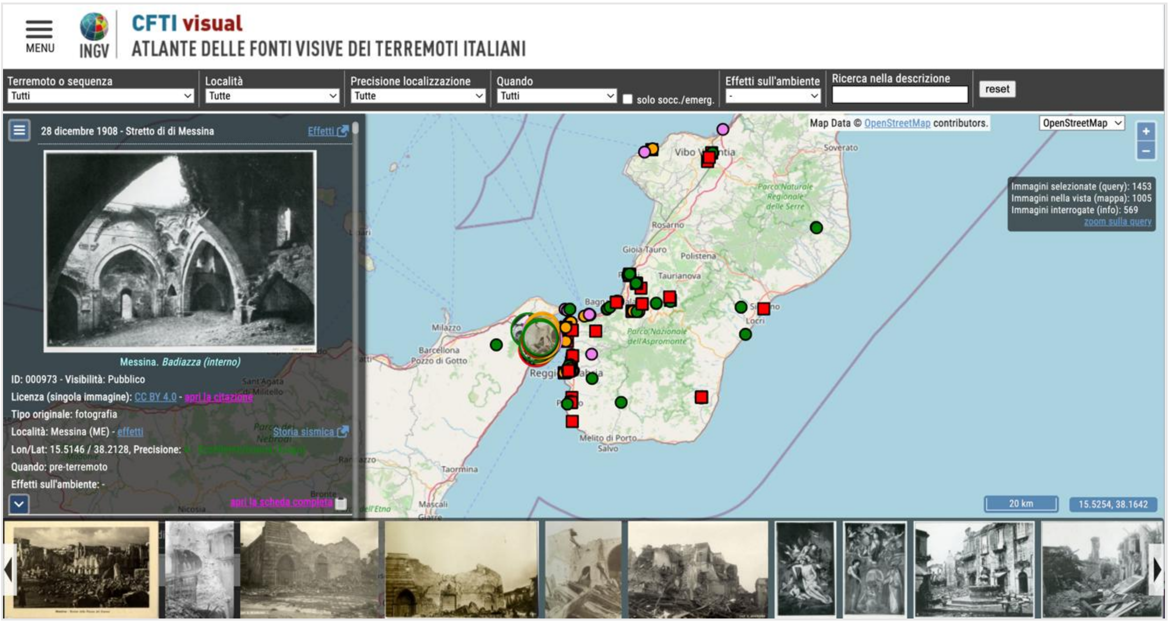

Figure 2. CFTIvisual web interface

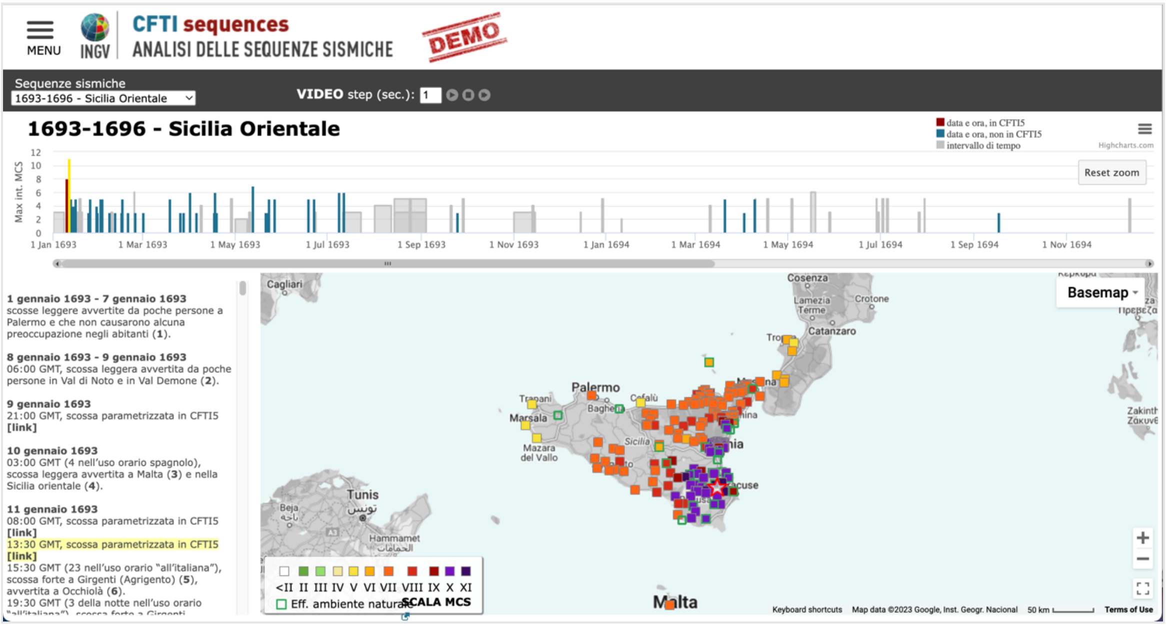

Figure 3. CFTIsequences web interface

CFTIlandslides is the Italian database of historical earthquake-induced landslides (Figure 4).

The investigation of earthquake-induced environmental phenomena is becoming increasingly critical for civil protection agencies. In particular, earthquake-triggered landslides may cause significant losses and may delay rescue operations across large areas.

The combination of a relatively frequent seismic release with a very high landslide susceptibility makes the Italian territory especially prone to the occurrence of earthquake-induced landslides.

This is a new dataset that was developed starting from the effects on the natural environment stored in CFTI5Med. It features over 1,000 landslides, subdivided into classes based on location accuracy and type of movement. It is addressed to a large audience of potential users, including researchers and scholars, administrators and technicians belonging to local institutions, civil protection authorities.

A single, comprehensive web portal is currently under development to provide access to all these products.

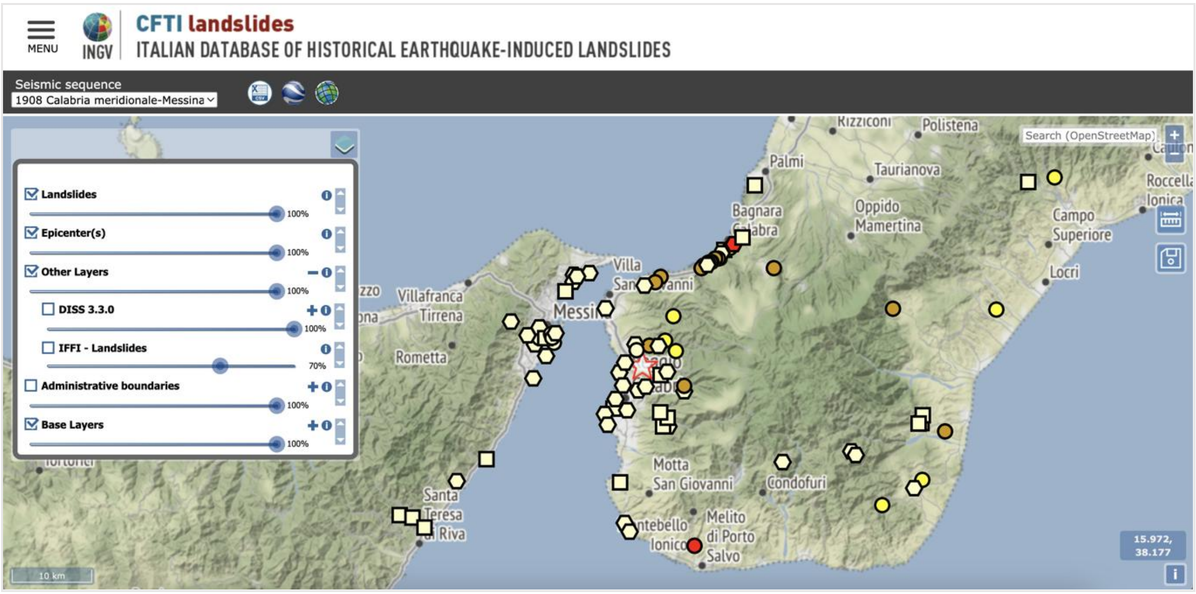

Figure 4. CFTIlandslide web interface, showing its main information layers

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8th International Colloquium on Historical Earthquakes,
Palaeo- Macroseismology and Seismotectonics
17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00035

Forgotten Earthquakes and Where to Look for Them (and Also Why…)

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Roughly from the 1980s onwards, a revival of historical seismology studies took place, which led to the production of the parametric earthquake catalogues now available in Italy and Europe. These studies profited greatly from the pioneering work of such scholars as Bonito (1691), Hoff (1840; 1841), Perrey (1848), Baratta (1901), and other early collectors of descriptive earthquake data. Most of the pre-1900 earthquakes included in current parametric catalogues, such as Rovida *et al.* (2022), had been already identified by 16th-19th centuries earthquake compilations. But what about earthquakes "forgotten" by those compilations? In the past two decades, systematic searches have been initiated to recover information on earthquakes that were not included in the early descriptive compilations and consequently were omitted from the parametric catalogues. The results of these surveys show that there is still ample room for improvement, particularly in some time-windows and geographic areas.

Background

Collecting information on historical earthquakes has a long-standing tradition in Italy. Notably, in 1691, Marcello Bonito meticulously compiled an extensive list of earthquakes from around the world by painstakingly analyzing a vast array of scholarly works and historical sources. These sources ranged from ancient classics to medieval and contemporary chronicles, archival records, and journalistic sources, spanning the last decades of the 17th century. In the following centuries, several scholars continued Bonito's work compiling earthquake lists, often with a regional or local outlook. Then, after the political unification of Italy, in November 1894, the Ufficio Centrale di Meteorologia e Geodinamica of Rome launched a large-scale project involving a network of correspondents (directors of meteorological observatories, librarians, scholars) in the collection of information on earthquakes of local interest from meteorological registers, local chronicles, and historiographic works. The project was headed by Mario Baratta, who drew upon the wealth of records provided by his correspondents and the centuries-old tradition of historical earthquake studies in Italy, to compile his magnum opus, *I terremoti d'Italia* (1901). This huge treatise plays a pivotal role in identifying most of the earthquakes that occurred before 1900 included in the first modern parametric catalogue of Italy (Postpischl, 1985) of which the current Catalogo Parametrico dei Terremoti Italiani (Rovida *et al*., 2022) is the latest development.

An essential but often overlooked aspect of Baratta's methodology was his selective approach to publishing earthquake information. He chose to include in his publication only those earthquakes that were described as "very strong, strong, ruinous, and disastrous" by seismologists, effectively setting a damage threshold for inclusion. As a result of this selection process, it is possible that some potentially damaging earthquakes were not included, especially if the local compilers had not conducted a thorough or careful job. This selective approach might have also been employed in other European countries where similar compilation work was undertaken by Baratta's contemporaries or predecessors, such as Perrey, Volger, and others.

Objectives

We wanted to check (1) whether some historical Italian earthquakes either failed to attract the attention of the compilers of pre-1900s historical earthquake lists that are the background of current parametric reference catalogues, or were discarded by the latest and most authoritative of them (Baratta, 1901), and (2) whether some of these discarded earthquakes could be relevant for purposes of seismic hazard assessment on a regional or local scale. Therefore, many such events were discovered, for which we also started investigating the reasons for such a large loss of information.

Methods

The main strategies used to identify "forgotten" earthquakes are extensively described in our only published study on the topic to date (Camassi *et al*., 2011). We started with the systematic perusal of "serial" historical sources (chronicles, diaries, gazettes and newspapers, meteorological registers, and so on). We inventoried "earthquake traces" of two main kinds: descriptions of earthquake damage and undamaging, but strong and fear-inducing shocks (the latter, recorded at one location, might hint at larger effects elsewhere). We then checked other serial sources, if available, earthquake compilations from the second half of the 19th century and also the regional catalogues produced in the 1970s for merging into the PFG catalogue (Postpischl, 1985). Some of them – such as Iaccarino and Molin (1978), merged into Postpischl (1985) with the code 501 - conserve traces of non-parametric reports that, when connected to information on other localities, allow to reconstruct significant scenarios. Camassi *et al*. (2011) was part of a research project that had other main objectives, but in following years we continued to keep track of clues related to "forgotten" earthquakes or potentially unknown to parametric catalogues, and to update their inventory, which is now very large indeed.

Case-Histories

The following cases include earthquakes for which the Italian regional parametric catalogues assessed incomplete parameters that were inherited by the first national catalogue (Postpischl, 1985) and later discarded by the current parametric catalogue (Rovida *et al.*, 2022) and earthquakes completely "forgotten" by earthquake catalogues.

The earthquake of **3 February 1545** (Figure 1) was located in Udine by Iaccarino and Molin (1978) regional catalogue, with no epicentral intensity, with the explicitly stated intention of keeping track of a "possible earthquake" on which nothing was known apart from the date. It was included in Postpischl (1985) but discarded by later catalogues. We discovered that Iaccarino and Molin (1978) derived their information from a regional compilation (Tommasi, 1888) that quoted a 16th-century report by a notary in Udine and that there are other records of a strong shock felt at the time in Belluno (Piloni, 1607) and Treviso (Berengo, 1545). This suggests a major earthquake occurred at a location still to be discovered.

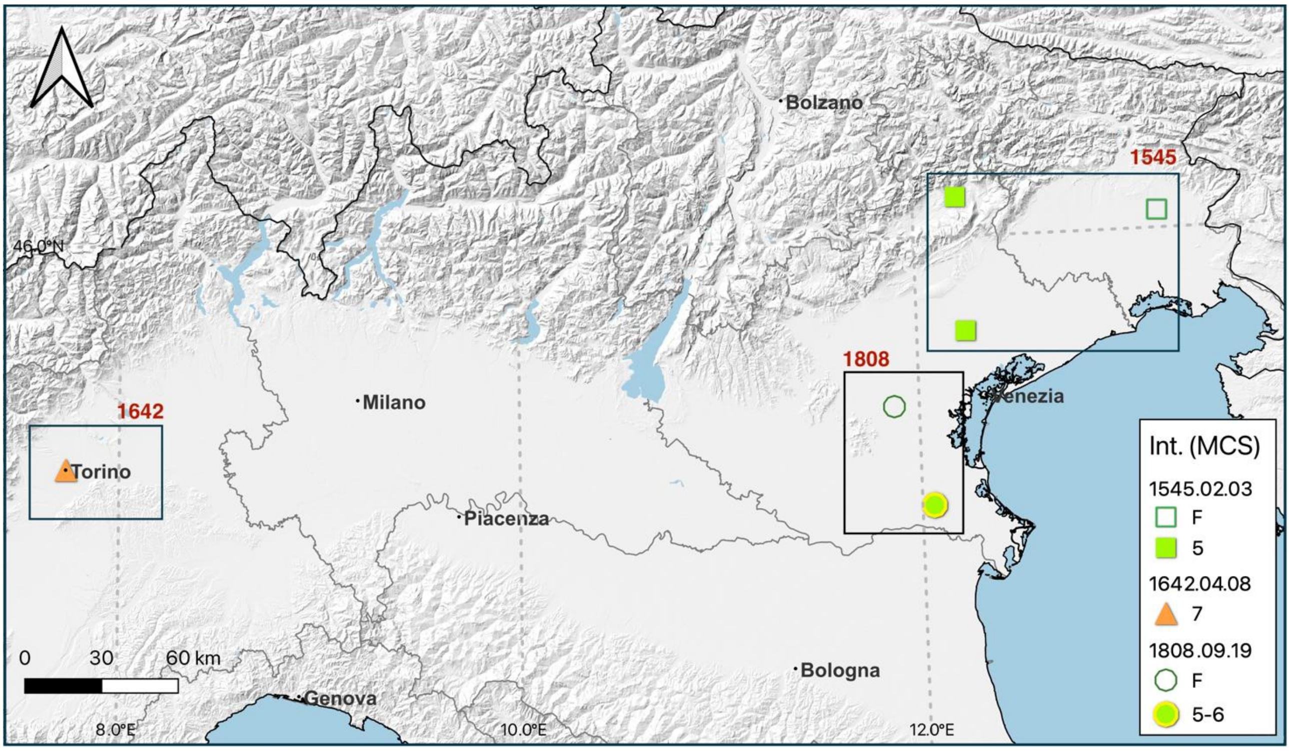

Figure 1. Traces of unknown or forgotten earthquakes

The **8 April 1642** earthquake (Figure 1) damaged a number of buildings and caused more than 1000 chimneys to collapse in Turin, according to a contemporary Milanese *avviso* (handwritten newsletter). This could be the highest effect in Turin's seismic history. It was picked up by some 18th-century German compilations but remained unknown to Italian compilations and catalogues. It is reasonable to think that it escaped the attention of Italian witnesses because of being contemporary with a much more internationally important event, such as the final phase of the Thirty Years War.

The earthquake of **8 November 1743** (Figure 2) damaged Rieti and was felt in Roma. Several Italian and

European contemporary gazettes mentioned it, but it remained unknown to earthquake compilations and parametric catalogues, possibly being overshadowed by the great 20 February 1743 Ionian earthquake, which was itself felt over most of Italy.

The story of the **29 September 1808** earthquake (Figure 1) is similar to the one of 1545: located in Padua without epicentral intensity by Iaccarino and Molin (1978), it was included in the Postpischl (1985) catalogue but discarded by later catalogues up to Rovida *et al.* (2022) because of its lack of intensity. We discovered that an Adria contemporary chronicle (Guarnieri *et al.*, 2010) reports significant damage (fall of chimneys) caused by this earthquake. This allows the shift of its epicentral location southwards, to an area off the main communication routes and much less "important" than Padua.

Finally, there is the singular case of a very recent earthquake, which occurred on **3 February 1949** (Figure 2), that is totally unknown to Postpischl (1985). The recent publication of a study on instrumental data from northeastern Italy (Sandron *et al.*, 2014) wrested it from oblivion, leading it to be included in the CPTI15 catalogue (Rovida *et al.*, 2002) but without parameters. A quick historical search, based mainly on journalistic sources, brings it to light as an event of considerable interest.

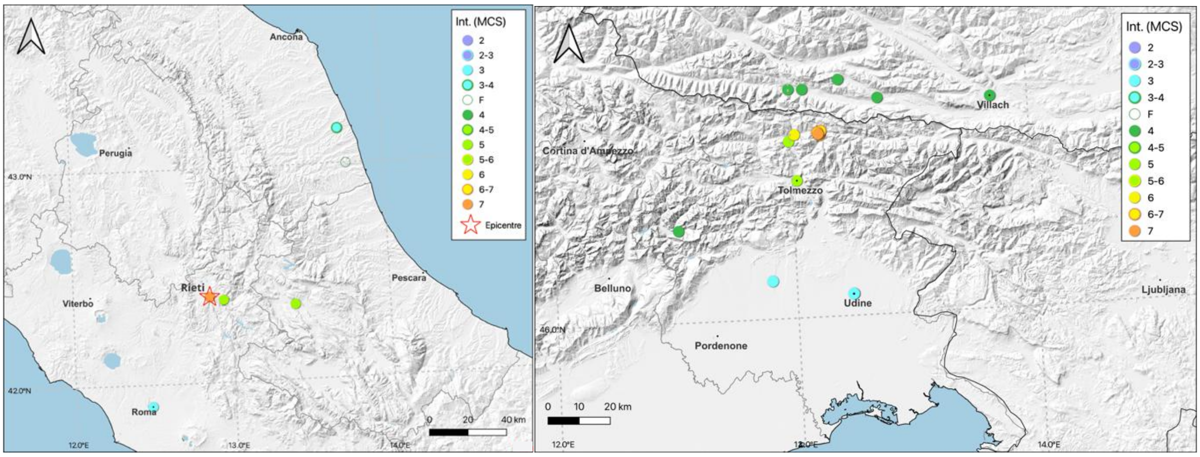

Figure 2. Macroseismic intensity distribution map of the 28 November 1743 earthquake - on the left - and the 3 February 1949 earthquake - on the right; the red star shows the macroseismic epicentre from this study

Conclusions

Many earthquakes, of moderate energy but important enough for seismic hazard assessment, are still unknown to parametric catalogues, for many reasons. The geographic situation of some areas, the concurrence of other phenomena more likely to attract the attention of potential witnesses; errors in the compilation of parametric catalogues of the 1980s. Understanding how information can be lost, is useful to plan search strategies to retrieve "forgotten" earthquakes.

A loss of information certainly occurs in a historical period, roughly between the last two decades of the 18th century and 1860, when the journalistic network loses efficiency and only recovers in the second half of the 19th century with the birth of the great national newspapers.

Acknowledgments

Research activities have been carried out in the frame of the Italian PRIN Project "Fault segmentation and seismotectonics of active thrust systems: the Northern Apennines and Southern Alps laboratories for new Seismic Hazard Assessments in Northern Italy (NASA4SHA)" (PI R. Caputo, UR Responsible E. Falcucci). Many thanks to Antonio Bruno for sharing the report on the 1545 earthquake.

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8th International Colloquium on Historical Earthquakes,
Palaeo- Macroseismology and Seismotectonics
17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00036

Macroseismic intensity: A disaster risk management perspective

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Disaster management is a difficult task that requires the collaboration of and coordination between various stakeholders in the case of an incident. Usually, the management of a disaster is divided into four phases: prevention and mitigation, preparedness, response and recovery (FEMA, 2006). In a more simplified way, the disaster management phases can be simply mentioned as: before, during and after the event. In most cases the limits between these phases are not clear and present overlapping.

In all cases of an incident occurrence the primary objective is to avoid loss of lives. During an emergency, various stakeholders are engaged: first responders (fire services, police, paramedics), civil protection, public authorities, volunteers, citizens and even private companies. Citizens play a key role in the management of a disaster. It has been understood, for many years now, that the involvement of citizens and communities is a major need of practitioners. But what is the role of the earthquake effects, i.e., macroseismic observations? How macroseismic intensity data can make response more efficient and citizens more involved in the whole process?

The FIRE-IN project, an EU Horizon 2020 funded networking project of practitioners, academia and industry, recognizes the involvement of the community as a major capability with four main challenges (Miralles *et al.*, 2021):

- Develop public self-protection and awareness.
- Involve communities and key stakeholders as active actors in risk management.
- Negotiate the values with communities before the emergency.
- Cultural change towards risk tolerance and resilience.

In brief, the attitude of citizens expecting from the authorities to take all actions should change; they should be actively involved in the process of disaster management. In many cases, especially earthquakes, emergency responders may need time to reach the incident location, as the affected area is usually extensive and multiple localities have been damaged. It is common knowledge that earthquakes affect both the urban and rural environment. For example, access to a location may not be possible due to damage in the road network, electricity and communications may also not be available.

During the Tohoku, Japan, 2011 earthquake according to the most recent official statistics of the Japan Reconstruction Agency (November 2022), 121,966 buildings were completely destroyed, 282,941 almost destroyed and 748,461 partially destroyed. As a result, 20,000 people lost their lives, over 2,500 are still officially missing, 6,000 suffered injuries and overall, 470,000 people evacuated their houses. In addition to that, extensive damage to roads, airports and railways due to both the earthquake and tsunami made the effort for response and recovery even more difficult. The 2023 earthquakes in Turkey cost the lives of 42,310 people, 108,368 were injured and 173,000 buildings in 11 provinces collapsed or were heavily damaged (Source: Reliefweb).

In such conditions, response is extremely difficult to handle. Restoration and recovery of society to the prior status needs several years, of the order of a decade, to be completed. Public authorities, emergency responders, citizens, private sector, and, in general, all involved stakeholders should be prepared for the worst-case scenarios, even if they may seem of low probability and high impact. The general trend is to “expect the unexpected”.

The study of earthquakes began with simple observations of their impacts on humans, the environment, objects and buildings. Thus, the macroscopic study of earthquakes was the first to produce scientific results related to earthquakes. For historical earthquakes, the only available information relies on macroseismic descriptions of the effects. The macroseismic scales were developed since the early 17th century as an index classifying the impacts of earthquakes in a homogenized way. Nowadays, macroseismic data can be used to create numerical simulations of damage distribution.

Since seismographs and accelerographs were developed, macroseismic observations stood aside in scientific studies. Nevertheless, the web and artificial intelligence support the collection of macroseismic data directly from the citizens through the internet or social media. The “Did you feel it” application of the United States Geological Survey (USGS) (Wald et *al.*, 2011) as well as the Euro-Mediterranean Seismological Centre (EMSC) web application “LastQuake” (Bossu et *al.*, 2018) and citizen seismology provide valuable data to scientists for macroseismic studies. In addition, AI algorithms isolating earthquake information from crowdsourcing platforms, help to collect data providing an initial picture of an incident and can later be used for scientific analyses.

Macroseismic intensity maps prevail in disaster management, especially during the response phase, when compared with Peak Ground Acceleration (PGA) shaking maps. Macroseismic intensity provides information on the potential damage grade, the vulnerability of buildings and the number of damaged buildings, while PGA maps provide information related to the recorded PGA value at a specific site, without any information on potential damage. A PGA map needs of further elaboration and review in terms of expected damage. Moreover, macroseimic intensities as indexes from 1 to 12, in MMI (Wood and Neumman, 1931; Stover and Coffman, 1996) and EMS-98 (Grünthal, 1998) are much easier to be read and understood by a non-seismologist. Different types of maps are needed for the various stakeholders (Xu *et al.*, 2020). An example of how easier macroseismic maps can be read are those presented in Figure 1, from the Mw6.1, 26 January 2014 and Mw5.9, 3 February 2014 earthquakes in Kefalonia. On these maps, the three different layers PGA, PGV, and Intensity are depicted, with the easiest to read and understand being the intensity map.

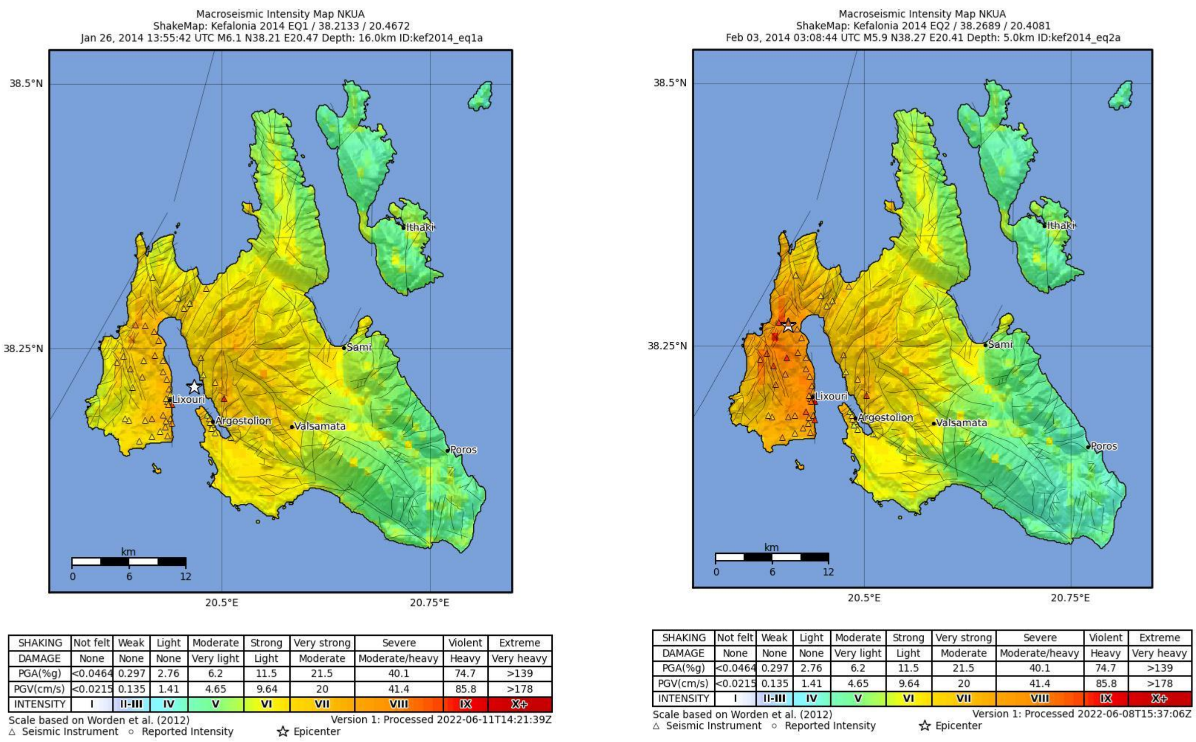

Figure 1. Example of ShakeMaps from the 2014 Mw6.1 and Mw5.9 earthquakes in Kefalonia, Greece. Images from the National and Kapodistrian University of Athens.

Macroseismology can also support two important processes: (a) citizen awareness and (b) citizen engagement. The fact that macroseimic scales include simple integer numbers based on descriptions, makes it much easier for everyone to understand and fill in a macroseismic questionnaire. In addition, technological advancement can transform every citizen to a “sensor”, or data provider. By engaging citizens in such a process, they automatically change their culture, as they become aware of the phenomenon, understand its consequences, train themselves in self-protection measures and how to provide assistance, if necessary, thus covering the need for more first responders.

It is well known that the vulnerability of buildings and infrastructure directly affects the damage caused by earthquakes. This, combined with seismic hazard results, leads to seismic risk assessment, which is used to express all expected losses due to an earthquake event. In the framework of the scientific project “KNETSEISRL (NSRF2014-2020) - Knowledge NETworks SEISmic Risks Lixouri”, a detailed analysis of the vulnerability of the buildings in Lixouri town was performed, as well as the expected damage distribution in the case of a strong earthquake. For vulnerability, we used the available Census 2011 building data from Hellenic Statistical Authority (ELSTAT, 2015), in situ building forensics performed after the 2014 Mw6.1 and Mw5.9 earthquakes, as well as additional vulnerability assessment based on EMS98 (Grünthal, 1998). For the expected damage distribution, we used the method developed by Lagomarsino and Giovinazzi (2006) for the building blocks of Lixouri. The adopted earthquake scenario was a simulation of the 3 February 2014 Mw5.9 event. All results are presented in Figure 2. The damage scenario showed that the majority (64.8%) of Lixouri building blocks present expected damage grade 2, a 17.6% damage grade 3, a 12.6% damage grade 1 and a 5.0% expected damage grade 4. The highest damage grades are expected close to the port.

Damage grades are closely linked to macroseismic intensity along with the building vulnerability. Figure 2 can easily be used for disaster risk response purposes, especially along with a macroseismic intensity map, providing core information to emergency units and efficient response.

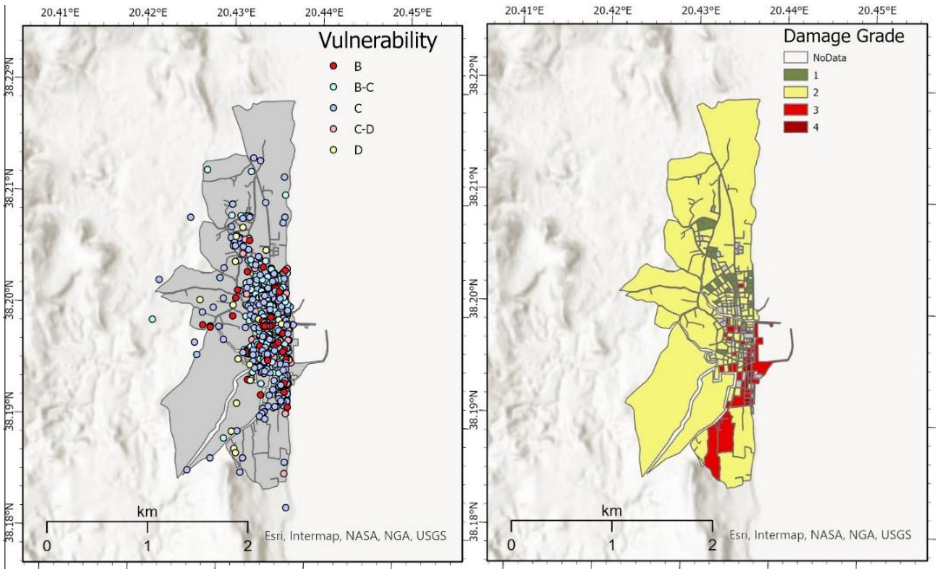

Figure 2. Spatial distribution of the available building stock in Lixouri, in respect to their vulnerability (left). Map showing the expected damage degree in case of a strong earthquake (right).

Acknowledgements

We acknowledge funding by the “New technologies, research and innovation for the creation of poles of attraction” project in the framework of the National Strategic Reference Framework (NSRF) 2014-2020, Regional Operational Programme “Ionian Islands 2014–2020”.

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8th International Colloquium on Historical Earthquakes,
Palaeo- Macroseismology and Seismotectonics
17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00037

Contribution of the local Paliki seismological stations to the monitoring of seismicity in the area of Cephalonia Island, Greece, assessed by machine-learning and probabilistic event detection methods.

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Introduction

The significant increase in the amount of available waveform data from seismological stations has made imperative the application of more sophisticated methods for their automatic analysis. The latest advances in artificial intelligence have greatly improved the efficiency and effectiveness of machine-learning models, allowing for the recognition of the arrival time and type of seismic wave and distinguishing between earthquakes and noise. The deployment of local seismological networks is important for the improvement of seismic monitoring in an area, both in terms of detectability and the reduction of location errors. The former is due to the availability of a larger number of stations that can detect local events of smaller magnitude, as a minimum number of arrival times is required to produce a valid location. The latter is due to the improvement in azimuthal coverage, allowing for hypocentral solutions to be better constrained than with a sparser network of fewer stations.

The area of the Paliki peninsula on Cephalonia Island (Figure 1) has been the site of two major earthquakes in 2014, which caused significant damage to nearby structures. In April 2022, two stations equipped with wide-band sensors (GEObit GEOtiny) were installed at Paliki peninsula by the Seismological Laboratory of the National and Kapodistrian University of Athens (NKUA-SL; HA network), namely ATHR (Atheras) at the northern edge, and HAVD (Havdata) at the mid-southern part of Paliki (Figure 2b). In addition, a RaspberryShake4D device (station LX11) was installed in the town hall of Lixouri, on the eastern coast of southern Paliki (Figure 2b). These stations could potentially improve the detectability and reduce the hypocentral uncertainties of events that occur both on Paliki as well as in the broader area of Cephalonia Island, supplementing the available existing stations of the regional Hellenic Unified Seismic Network (HUSN). In this work, we employ a machine-learning model to automatically analyze the seismic waveform data in the broader area of Cephalonia Island for the period between 14 April 2022 (when the stations of the HA network were installed on Paliki) and 30 June 2023.

Data and methods

We applied the EQTransformer model (Mousavi et al., 2020), implemented in the SeisBench toolbox (Woollam et al., 2022), to automatically identify and pick the arrival times of P- and S-waves at HUSN stations installed on the Ionian Islands. We used a model pre-trained with data from Italy (INSTANCE dataset; Michelini et al., 2021). This produced a dataset of arrival times on a per-day basis. One of the advantages of this method is that it does not require data pre-processing, as it can distinguish between noise and signal without having to apply a filter, e.g. a band-pass Butterworth filter. The automatic picking algorithm works on the 24-hour continuous records of the stations, on all the available components. For the RaspberryShake4D device (LX11), we use only the vertical component of the equipped geophone. Another issue is that this instrument is installed in a busy town hall, which affects the data quality, with the recordings containing a significant amount of anthropogenic noise. As the picker recognizes the arrival times of different wave types (P or S) and assigns a specific probability to each measurement, a higher probability threshold was set for LX11, as it produced a large number of artificial picks due to noise.

Next, we applied a Bayesian Gaussian mixture model implemented in the GaMMA method (Zhu et al., 2022). This procedure operates on the arrival times produced by EQTransformer to associate them with events, at an approximate hypocenter and origin time. This creates a dataset of events with their respective arrival times and estimated locations. The GaMMA method can also estimate event magnitudes if the signal amplitudes are provided in the input, but these have not been incorporated in the present study. The current build of this code uses a homogeneous velocity model for P and S wave propagation. Finally, to acquire better hypocentral locations using the arrival-time data picked by EQTransformer and associated with specific events using the GaMMA method, we applied the single-event location code HypoInverse, employing a 1D velocity model for Cephalonia Island (Karakonstantis, 2017). This also provides information on the location uncertainties, and poorly resolved events can be filtered out.

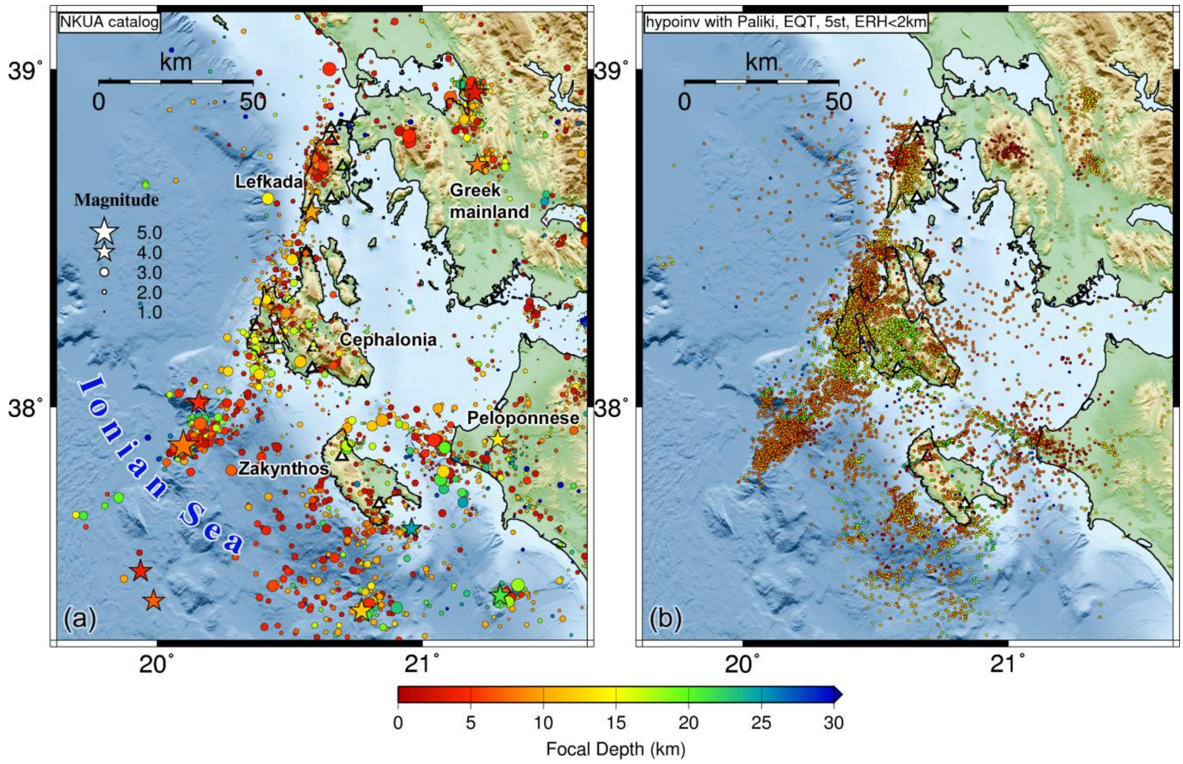

Figure 1. Seismicity in the Ionian Islands area between 14 April 2022 and 30 June 2023, (a) 3,233 events from the NKUA-SL database of using all available HUSN stations, (b) 12,206 events from the preliminary results of this study, employing machine-learning and probabilistic event association, using only stations deployed in the Ionian Islands (at least 5 stations, ERH ≤ 2km). Stations are depicted as triangles.

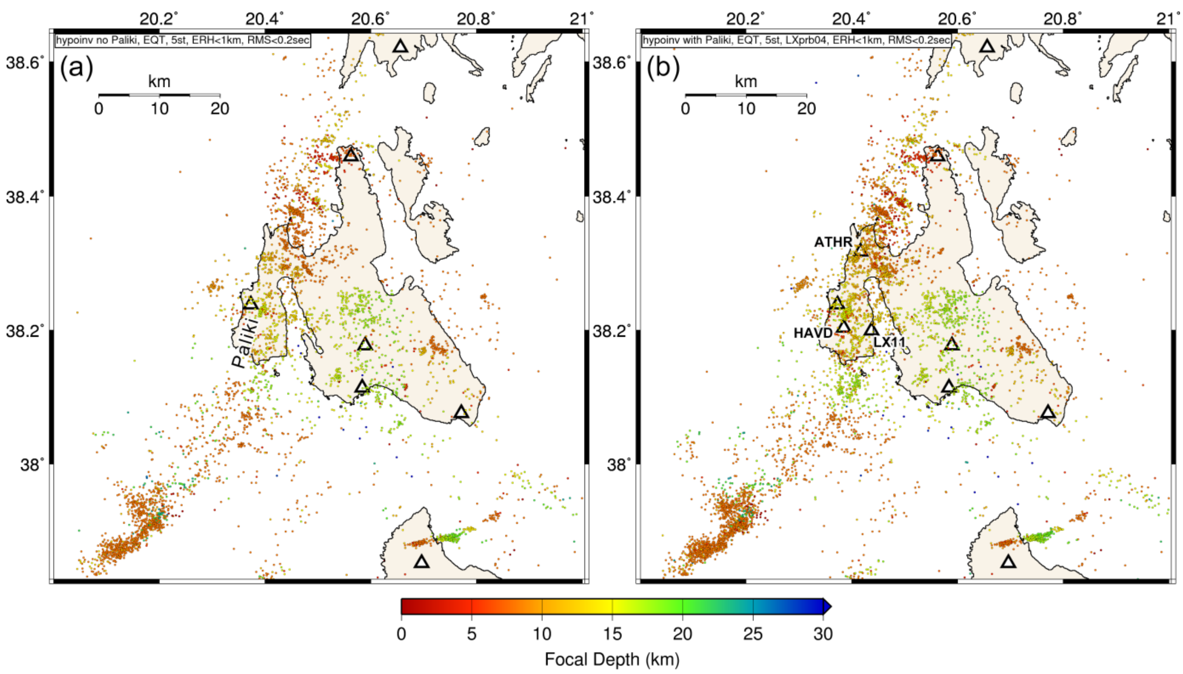

Figure 2. Seismicity of Cephalonia Island between 14 April 2022 and 30 June 2023 from the preliminary results of this study, (a) 5,239 events resolved using stations deployed in the Ionian Islands, but without the stations of HA network on the Paliki peninsula, (b) 7,017 events resolved when including the stations of HA network on Paliki peninsula (at least 5 stations, ERH≤1km, RMS error≤0.2sec). Stations are depicted as triangles.

Results

We examine different configurations of GaMMA method in terms of the requirement for a minimum number of total picks or P-wave picks, as well as with and without the contribution of the HA network stations on Paliki peninsula, to assess the contribution of the latter to the detectability and improvement in the constraint of hypocentral locations. Figure 1b demonstrates the robustness of the machine learning and probabilistic event association procedures and their capability to create a seismic catalog, even including events located well outside the bounds of the employed network. Figure 1a shows the routine locations of the more significant earthquakes in the area, automatically detected using SeisComP (https://www.seiscomp3.org/, accessed July 2023) with data from HUSN, then reviewed by an analyst at NKUA-SL. Note that no M≥4.0 events have occurred on Cephalonia during the period of study. The largest event in the area was an M=5.3 earthquake that occurred on 8 September 2022, about 40 km SW of Cephalonia, generating a seismicity cluster that was detected by both manual and automatic analysis. Figure 1b shows the events automatically detected and located in this study, using only stations on the Ionian Islands, selected by a minimum of 5 stations and ERH≤2km. This shows that the seismic activity is generally well detected and even areas of sparse seismicity in the routine catalog were populated by more events, forming spatial clusters.

In the more restricted area of Cephalonia Island (Figure 2), the results show a larger number of detected events when data from the additional three stations at Paliki are included; however, noise is increased in the spatial distribution, likely due to false detections or poorly resolved events. For a better comparison, the same uncertainty filters have been used in both cases, requiring at least five P-wave arrival-time picks (i.e., 5 stations), ERH≤1km, and RMS travel-time residual ≤ 0.2sec. Some earthquakes presented in Figure 2b could also be resolved without the HA network stations at Paliki, however, with larger errors, which caused them to be filtered out. Improved epicenters can be mainly seen in an offshore cluster south of Paliki. The microseismicity on Paliki becomes denser, as a result of the improved detectability.

Conclusions

We applied a machine-learning model (EQTransformer) for automatically determining P- and S-wave arrival times, coupled with a probabilistic Gaussian Mixture Model Association (GaMMA) method to associate picks with earthquake events in the broader area of Cephalonia, using stations deployed in the Ionian Islands. We showcase the capability of these methods to successfully create an earthquake catalog, even including offshore and other out-of-network areas. Furthermore, we demonstrate the improvement, in terms of event detectability and hypocentral location uncertainties, of the addition of three local stations of the HA network on the Paliki peninsula. This highlights their importance for seismicity monitoring and likely Earthquake Early Warning applications. Although these preliminary results are already promising, more tests, including different models and configurations, will likely further improve the resulting catalog. The incorporation of amplitude measurements can facilitate event-association with the GaMMA method and also provide magnitude estimates.

Acknowledgements

We acknowledge funding by the “New technologies, research and innovation for the creation of poles of attraction” project in the framework of the National Strategic Reference Framework (NSRF) 2014-2020, Regional Operational Programme “Ionian Islands 2014–2020”. Waveform data from stations of HA (University of Athens, 2008), HL (National Observatory of Athens, Institute of Geodynamics, Athens, 1975), HT (Aristotle University of Thessaloniki, 1981), and HP (University of Patras, 2000) networks were acquired from the European Integrated Data Archive (EIDA) node, hosted at GI-NOA (Evangelidis et al., 2021; http://eida.gein.noa.gr/, accessed July 2023). Maps were created with Generic Mapping Tools (Wessel & Smith, 1998).

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Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00038

Large Historical Earthquakes (1000-1900) Around the East Anatolian Fault Zone

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The earthquakes of February 2023 took place in an area which belongs to what N.N. Ambraseys called the *"border zone"*, that is the contact between the Euro-Asiatic and the Arabian plates. In this zone Ambraseys (1989) evidenced a period which he called *"temporary quiescence*", "with only three large (M6.6-6.8) earthquakes in the 20th century", followed by the Elazig sequence of 2020. Then the earthquakes of 2023 came, the main one of them more or less where Duman and Emre (2013) suggested *("the Pazarcik and Amanos segments have the potential to produce destructive earthquakes in the near future")*. The entire sequence covered about two third of the historical seismicity of the EAFZ (Figure 1).

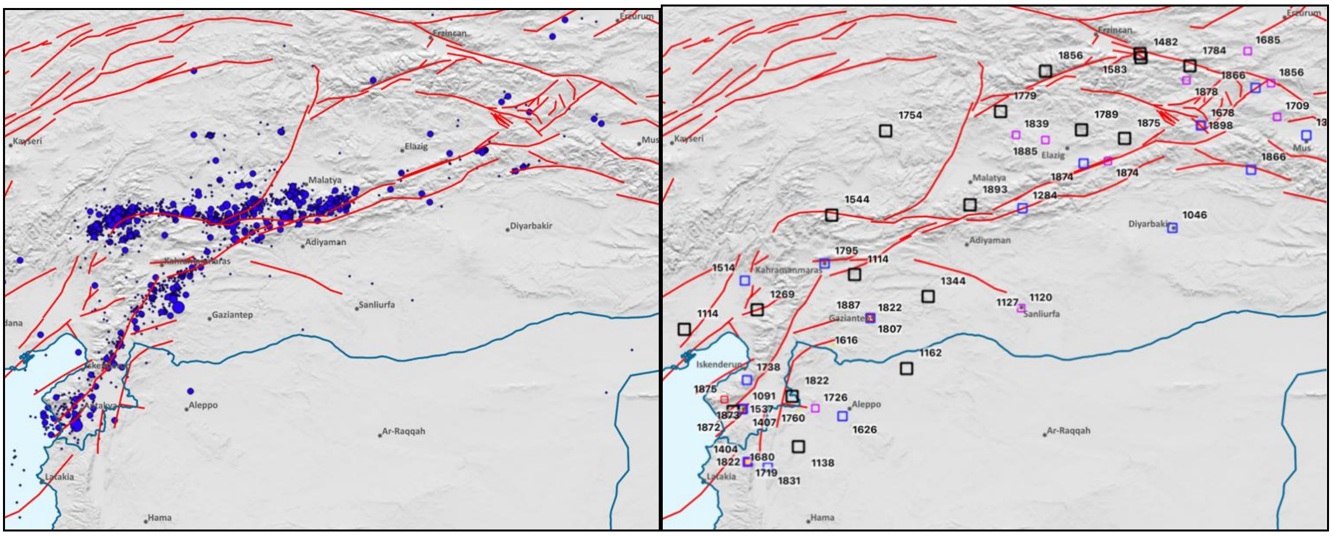

Figure 1. Left: area covered by the 2023 sequence. Right: historical (1000-1900) seismicity along the EAFZ.

The long-term seismicity of the area is rather well known, thanks to the availability of a large number of historical sources: many earthquakes are known to have occurred before the Roman times and since, with main reference to the South-Eastern portion of the EAFZ. Many important cities, such as Aleppo and Antakya above all, have themselves a long-term history, which also reflects in a long-term earthquake history (Figure 2).

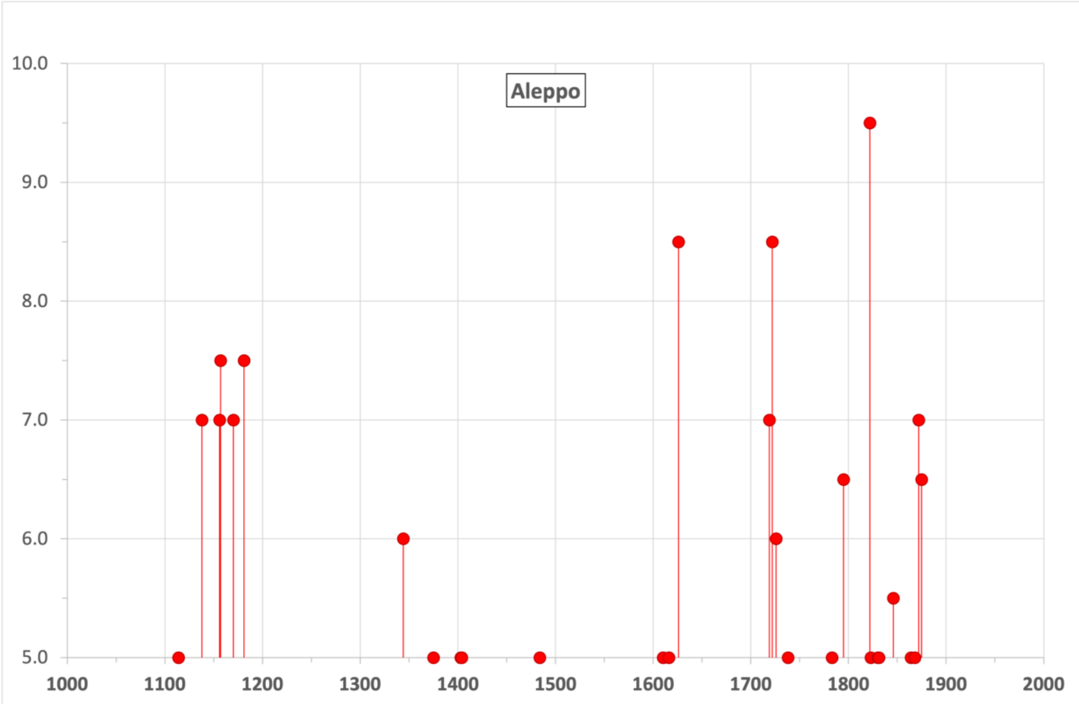

Figure 2. Earthquake history (1000-1900) of Aleppo.

Historical earthquake records have been put together and analyzed in several papers and compilations; the most recent of which are Soysal *et al.* (1981), Ambraseys and Finkel (1995), Guidoboni and Comastri (2005), Sbeinati *et al.* (2005) and several works culminating in the volume by Ambraseys (2009). However, time, location and size of many earthquakes remain debatable because earthquake parameters are often determined on the basis of scanty information; therefore, historical earthquake catalogues show contradictory values.

The most recent Turkish earthquake catalogue is the one by Tan *et al.* (2008), but Duman *et al.* (2018) admit that *"Despite the long historical record of the Anatolia region, a historical earthquake catalogue for Turkey, compiled with modern methodology, is not yet available"*. As a matter of fact, updated regional, historical earthquake catalogues compiled in the frame of international projects such as SHARE (Stucchi *et al.*, 2013; Sesetyan *et al.*, 2013) and EMME (Zare *et al.*, 2014) are not very well known nor were they used by most researchers investigating earthquake sources in the Anatolian area. Users prefer picking up from varied catalogues, with the result of possibly duplicating earthquakes or "resuscitating" fake events that had already been eliminated by one catalogue but not by another one (see for instance Hubert Ferrari *et al.*, 2020): *"Finally, we used the earthquake catalogue of Tan et al. (2008) combined with those of Ambraseys (2009), Guidoboni and Comastri (2005), and Guidoboni et al. (1994) to compute the cumulative number of earthquakes felt around the EAF Zone"*.

To improve this situation, in the last few years a complete reappraisal of the historical earthquakes of the Anatolian area has been undertaken, with the aim of providing an updated earthquake catalogue of the area compiled according to modern methodology. An overview of this initiative is found in Stucchi *et al.* (2022), while some results are found in Sesetyan *et al.* (2020); the earthquakes of EAFZ were among the investigated ones, and here we present some results, anticipated by Sesetyan *et al.* (2023).

The scope of this paper is assessing the available knowledge and providing more reliable earthquake parameters, as far as data allow. To this end, we revised the available sources of information with the aim of identifying some fake or duplicated events and providing an updated picture of the macroseismic effect of several medium-to-large earthquakes. After retrieving, critically evaluating and comparing the available historical records, we assigned macroseismic intensities, in terms of EMS-98, to the localities where this was possible. Localities were then geocoded: in some case this was not an easy task to perform, owing to the fact that place-names are often given in different languages and also because they underwent changes along the centuries. From the intensity distributions, when possible, we then determined location, size and related uncertainty of each earthquake by using the repeatable method called "Boxer" (Gasperini *et al.* 1999; 2010). When the number of data points was not enough, magnitude was determined from epicentral intensity (Io) by means of an ad-hoc relationship. Both methods have been calibrated against good quality instrumental data.

Among the main results, we were able to assess Mw values greater than 7.0 for about ten earthquakes, including two that were previously unknown to the available earthquake catalogues. Uncertainties seldom exceed 0.5. Two earthquakes have Mw values in the same order as the first earthquake of 2023.

Acknowledgements

Authors are indebted with Ruben Tatevossian (Institute of Physics of the Earth, Moscow, Russia) for supplying information on the investigated earthquakes.

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8th International Colloquium on Historical Earthquakes,
Palaeo- Macroseismology and Seismotectonics
17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publl. 11
Ext. Abs. 00039

3D finite element analysis of seismic response of a slender stalagmite

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Research Highlights

In the lecture planned for the Colloquium a finite element method (FEM) model of a slender, 4.3m stalagmite located in Plavecka Priepast cave (Figures 1 and 2) will be analyzed in detail with respect to its dynamic modal properties and seismic fragility. The main reason of this study is to gain long-term seismic hazard information for the surroundings of the investigated cave. A robust FEM model of the stalagmite will be presented and results of its modal properties and seismic response will be discussed as well.

Introduction

Typical fragile geological features (FGFs) are precariously balanced rocks studied in numerous papers (e.g., Brune, 2002, 1996, 1999; Ludwig *et al.*, 2015) or speleothems which represent separate branch of paleoseismology (e.g., Becker *et al.*, 2006; Ferranti *et al.*, 2019; Gribovszki *et al.*, 2018, 2017; Lacave *et al.*, 2004; Pace *et al.*, 2020; Paskaleva *et al.*, 2006) or serve other scientific studies (e.g., Engel *et al.*, 2020; Moseley *et al.*, 2014). Although the role of speleothems in calibrating seismic hazard is not straightforward (Gilli, 2005; Lacave *et al.*, 2004), their unique fragility is used in many papers aiming at verifying seismic hazard and, in particular, to put constraints on predicted Peak Ground Accelerations (PGA) of seismic hazard studies so that the observed speleothem was not damaged. This way the long-term seismic hazard studies for monumental structures like large dams or nuclear power plants can be better validated.

Typically, they are modeled as single-degree-of-freedom systems or other models of the simple, uniform vertical cantilever beams or other oscillating systems behaving like inverse pendulums. From a mechanical point of view, these models are very simplistic, while some of the fragile geological features are rather complicated in their size and shape. Besides, PGA is relatively a simple measure of seismic intensity because also other ground motion parameters may influence damage of the speleothems. Namely, these could be strong motion duration and spectral content of the seismic ground motion.

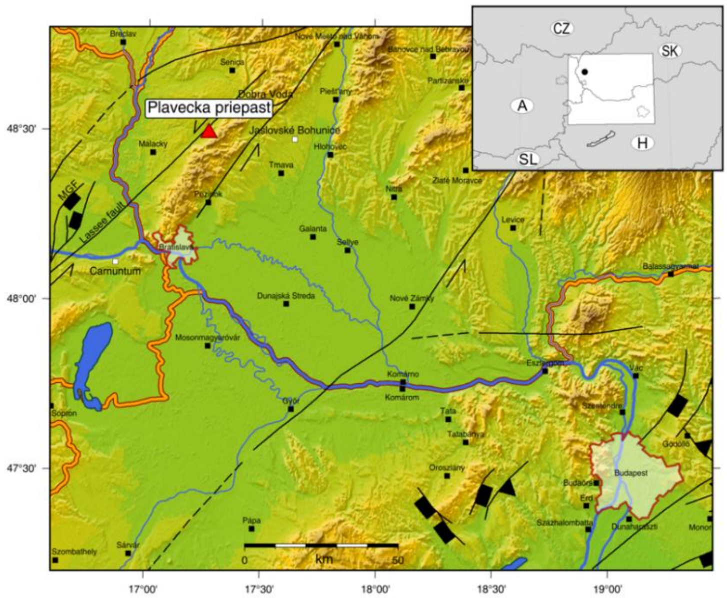

Figure 1. Location of the "*Plavecká Priepast*" stalagmite.

So far, there were only very few attempts to apply more detailed modeling methodologies to study the seismic motion of FGFs, particularly to use the FEM. The first such paper can probably be attributed to Hall (1996), who used 2D finite element stress modeling of statical equilibrium of six rock columns located in the Chiricahua Mountains, Arizona.

Recently Martin et al. (2020) carried out an analysis of ambient vibrations of so-called "Minaret" stalagmite 4.5 m high and with approximately 17-20 cm width, from Han-sur-Lesse cave located 80 meters underground in Wallonia, Belgium. The Authors used ultra-sensitive geophones to collect peaks values of amplitudes of extremely small ambient vibrations in three directions at the ground surface, at the stalagmite base, and at the height of 2.52 m.

Description of the FEM model and its calibration

In a recent paper (Zembaty *et al.*, 2023) a 3D FEM model of the 4.3m stalagmite measured in Plavecka Priepast cave (Figure 2) is presented. Results of its modal analyses based on data acquired using a 1-D, velocity sensor attached to that stalagmite at a height of 1.5 m are given in detail. The stalagmite is shown in Figure 2 together with a frame of Cartesian reference system and directions of applied seismic excitations.

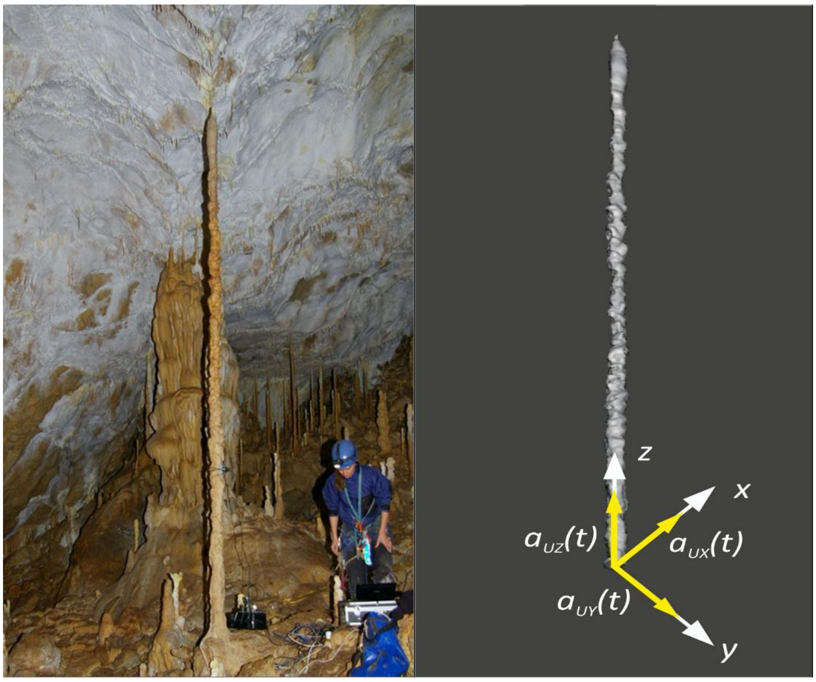

Figure 2. Photograph of 4.3m stalagmite in Plavecká Priepast cave and system of geometric axes applied in its analysis (*X-EW, Y-SN, Z-UP*) and its seismic accelerations (a_{UX}, a_{UY}, a_{UZ}).

The model consisted of 600 025 finite elements which generated 2 835 879 dynamic degrees of freedom and was used to compute seismic response to a selected, underground time history seismic record (for details see Zembaty *et al.*, 2023). In Figure 3 a fragment of the FEM mesh of the stalagmite is shown in detail. The whole view of the FEM model is also available at this link: https://z.zembaty.po.opole.pl/SupplementaryStalagmite.html

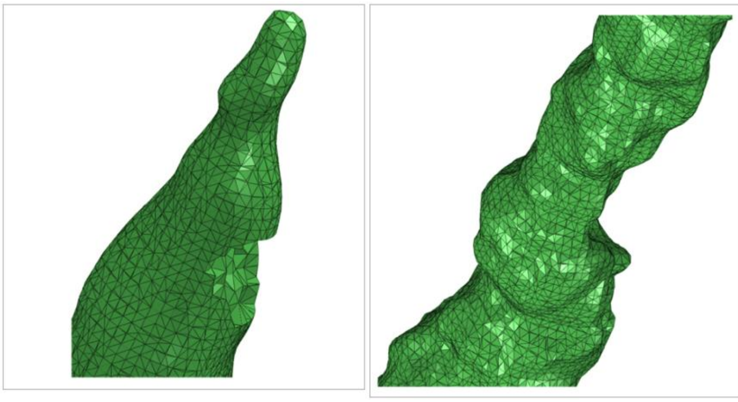

Figure 3. Details of Finite Element Method mesh of the modeled stalagmite in Plavecka Priepast cave

Results and conclusions

An analysis of the eigenproblem of the FEM model and subsequent Hilbert-Huang modal extraction (Zembaty *et al.*, 2023) gave natural frequencies and modal damping ratios presented in Table 1. Dynamic analyses of cantilever beams modeled as 3-dimensional bodies lead to conclusion that the natural frequencies of slender stalagmites will appear clustered in pairs. For these reasons the results of modal analyses are shown in Table 1 as "lower" and "upper" modes. Not all respective damping ratios could effectively be extracted, yet their extremely low values, well below 1% can easily be noted. The FEM model of the stalagmite was applied in seismic response analyses which led to a conclusion that the stalagmite may withstand seismic excitations with the ultimate horizontal peak ground velocity of 3.4 mm/s which is not far from the value obtained by Bottelin *et al.* (2020) for other slender speleothems (2.4 mm/s). For details of the seismic response analyses of the "Plavecka Priepast" stalamite see: Zembaty *et al.* (2023).

Table 1. Modal parameters of the "Plavecká Priepast" stalagmite.

Mode of vibration	Natural frequency	ξ
mode 1_{low}	2.96 Hz	-
mode 1_{up}	3.19 Hz	0.11 %
mode 2_{low}	14.50 Hz	0.14 %
mode 2_{up}	16.13 Hz	0.20 %
mode 3_{low}	35.72 Hz	0.20 %
mode 3_{up}	40.51 Hz	0.52 %

In May 2023 the Plavecka Priepast cave was revisited with an aim to improve the 3D vibration data acquisition of this and other stalagmites in this cave. The measurements were carried out simultaneously in two perpendicular planes using very accurate laser vibrometer (Polytec VibroGo). During the 8ICHISTEQ updated results of measurements of these stalagmites and their numerical analyses will be reported.

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8th International Colloquium on Historical Earthquakes, Palaeo- Macroseismology and Seismotectonics
17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00040

Quantifying Uncertainties in Magnitude – Depth Estimates of Earthquakes from Macroseismic Intensities - Application in Volos & Aigio, Greece

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In this study, the open source code Quake-MD (Provost & Scotti, 2020), written in Python, is applied to determine macroseismic earthquake parameters, i.e., magnitude, depth (and their calculated uncertainty) and to reassign epicentral intensity. The estimation of earthquake depth has always been considered a difficult task, especially when it deals with historical earthquakes. In spite of the various methods, formulas and programs for depth determination, until now, it is calculated with considerable uncertainty. One of these methods recently introduced is QUake-MD. The approach of calculating parameters and their uncertainties is achieved through (a) collection of Intensity Data Points (IDPs) and (b) calibration of Intensity Prediction Equations (IPEs), unique for different countries or regions. Here, we apply QUake – MD to a number of historical and instrumental earthquakes in the Gulf of Corinth and Central Greece, to calculate earthquake parameters. We then compare our results to those derived in similar previous studies, using tools, such as MEEP, BOXER, etc.

After a macroseismic study, the collected information (questionnaires, photos, texts, etc.) leads to the assignment of a number of IDPs. Each IDP represents a specific georeferenced point with an intensity value. The more the macroseismic observations, the more accurate the IDPs values. In addition, a variety of IDP values results in a broader database and more accurate results with minimized errors and, therefore, reduced uncertainties.

The Intensity Prediction Equations (IPEs) are empirical formulas used to estimate earthquake magnitude and depth using macroseismic data. The IPEs are calibrated with instrumental data, using the IDPs, as well as earthquake magnitude and depth from the existing catalogs, and depend on the different seismotectonic characteristics and soil conditions of each study area. The general numerical type of IPEs used in QUake-MD is the following:

$$I = C_1 + C_2M + \beta log D_{hypo} + \gamma D_{hypo}$$

where I is the intensity, M the magnitude, C_1 & C_2 the magnitude coefficients, β & γ the intensity attenuation coefficients, and Dhypo the hypocentral distance associated with the intensity value.

Quake-MD uses the binning strategy (RAVG), in order to calculate and conclude in the final magnitude – depth solution. Except for the basic use of the source code, Quake-MD also provides the end user the choice of visualising the data, creating a scaled colored map of intensity data distribution.

Both the regions of Volos and Aigio are located in tectonically active environments, the first in Thessaly basin, the latter being a part of the Western Corinth Gulf. The Corinth rift is an asymmetric half-graben characterized by E-W normal faulting (Palyvos, et al., 2005), while the western part of the Gulf is its most active region, with an extension rate reaching 15 mm/yr (Briole et al., 2021). On the other hand, Thessaly lies on the Aegean microplate, undergoing internal crustal deformation due to the relative plate motion against the adjacent Anatolian and Nubian plates (Lazos et al., 2021). In general, Thessaly is characterized by three tectonic phases since Neogene; A ca. E-W orientated compression during early to middle Miocene, a NE-SW orientated extension during Pliocene – Early Pleistocene, and a ca. N-S orientated extension since middle Pleistocene (Caputo & Pavlides (1993). According to Papadimitriou & Karakostas (2003), apart from the continental collision to the north and oceanic subduction to the south, Thessaly is also affected by the dextral strike-slip Cephalonia transform fault (CTF), as well as the northward motion of the Arabian plate that pushes the smaller Anatolian plate westwards along the North Anatolian fault (NAF), continuing along the North Aegean trough (NAT) region, which is the boundary between the Eurasian and Aegean plates.

The process starts with the collection of the data: the selection of events and their IDPs. Five events from two areas of Greece, Volos and Aigio were selected: three historical and two instrumental for Volos and four historical and one instrumental for Aigio. The aim was to get a variety of events and data and apply QUake – MD in both instrumentally recorded and historical earthquakes, comparing the accuracy and uncertainties of the results.

QUake-MD requires several specific input files. While constructing these input files, the quality for the IDPs and for the epicentral intensity must be defined. QUake-MD translates the qualities, based on the SisFrance quality range scale from A to C, A being reliable, B fair and C uncertain while for the epicentral intensity quality uses a scale from A to E, A being reliable and E, uncertain.

In the beginning of the process, the program enables data visualization. Specifically, before running QUake – MD, the end user can witness the distribution of the IDPs on a map and a diagram of the macroseismic intensity as a function of epicentral distance. In this study, the data visualization is used to reduce or/and avoid biased IDPs, meaning either IDPs with higher intensity values far away from the epicenter, or low intensity values very close to the epicenter.

We calculated adjusted IPEs for our study areas as follows: using the study by Papazachos & Papaioannou (1997), we were able to calculate one IPE that applies to the whole area of Greece, which we used for both Volos and Aigio. Then, by combining the studies of Howell & Schultz (1975) and Kouskouna et al. (1988), we calculated five IPEs exclusively for the area of Volos that depend on the magnitude range.

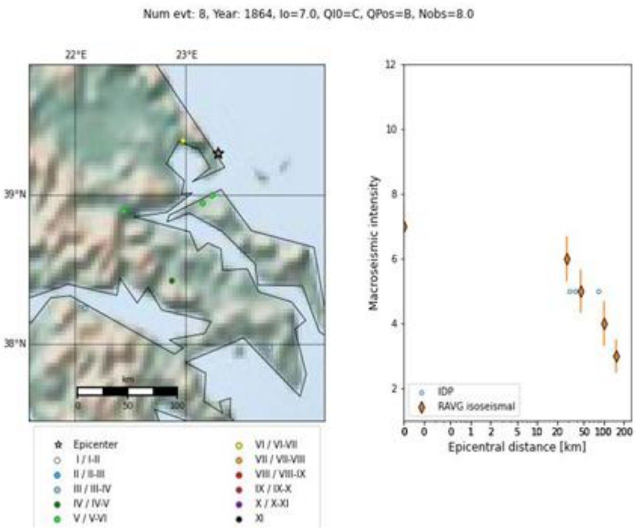

Figure 1: Data visualization for the 1864 Volos event.

In the example for the 1864 Volos event, we had 8 IDPs and the epicentral location was imported from Stucchi et al. (2013) catalog (39.319N, 23.105E). We proceeded with one data visualization attempt, since the data is limited, in order to include them all in the process (Figure 1). We used in total 6 IPEs, 5 for the area of Volos and 1 for the whole area of Greece. We made several runs of QUake-MD; with all IPEs, only with the IPEs for Volos and with the IPE for Greece (P&P).

We used different algorithms to calculate the parameters of the event, such as MEEP and Boxer, and combined their results with the already existing ones from Stucchi et al. (2013).

The results for the magnitude values are satisfactory for all the runs, when compared to the catalog results. The results for the epicentral intensity value are also quite similar. The major differences are observed in the depth values where, when using all the IPEs and the P&P IPE, the depth is clearly characterized by higher values (Table 1). However, the depth results generated by QUake-MD do not match the catalog results, and even the values that derive from the P&P IPE, which are the highest ones, seem to underestimate the depth.

Method	Magnitude - M	Depth - H	Epicentral Intensity - I_0
All IPEs	5.84	7.02	7.01
Volos IPEs	5.82	3.07	6.97
P&P IPE	5.87	12.76	7.06
MEEP (dI=0.5) (Kouskouna et al., 2010)	5.80 ± 0.20	20	n/a
MEEP (dI=2.0) (Kouskouna et al., 2010)	6.10 ± 0.30	20	n/a
Catalog (Stucchi et al., 2013)	5.96	n/a	6

Table 1: Results of different QUake-MD runs for the 1864 Volos event.

Another example is the 1889 historical event in Aigio, for which we had 124 IDPs. The epicentral location was imported based on the Stucchi et al. (2013) catalog (38.250N, 22.083E). While the results from the first visualization were acceptable (Figure 2), we proceeded with two more runs by excluding six extreme IDPs, in order to correct the distribution (Figure 3).

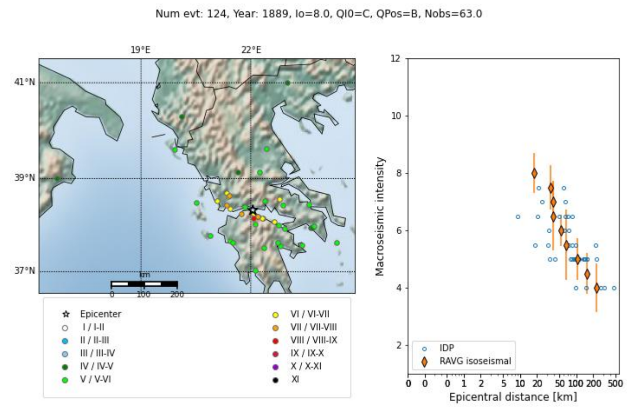

Figure 2: First data visualization for the event of 1889.

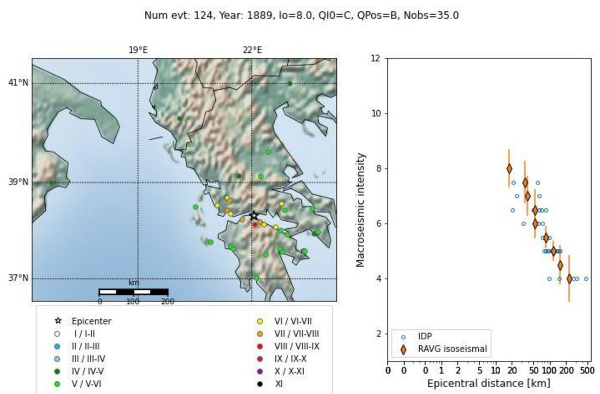

Figure 3: Final data visualization for the event of 1889 with the exclusion of the extreme IDPs.

The results from the three runs seem satisfactory; the final magnitude value is found to be close to the one calculated in the catalog, taking also into account its uncertainty (Table 2).

Method	Magnitude - M	Depth - H	Epicentral Intensity - I_0
All IDPs	6.7	10.08	8.73
Removal of extreme points (intensity 5 & 5.5)	6.72	10.29	8.74
Removal of extreme point (intensity 6.5)	6.37	10.38	8.75
Catalog (Stucchi et al., 2013)	6.43 (±0.33)	n/a	8

Table 2: Results for the 1889 Aigio event.

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8th International Colloquium on Historical Earthquakes,
Palaeo- Macroseismology and Seismotectonics
17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00041

Revision of the Focal Parameters of Earthquakes in the S-SE Of the Iberian Peninsula (1900-1962)

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The objective of this study is to revise the Seismic Catalogue of the National Geographic Institute of Spain (IGN, Instituto Geográfico Nacional) for the largest earthquakes occurred in the S-SE zone of the Iberian Peninsula during the period 1900-1962 using all the available information, some of them not used previously. These observations are very heterogeneous, so we have also established a methodology, that allow to evaluate the seismic information and thus be able to carry out a joint analysis of the all the available data.

We have selected 16 earthquakes with maximum intensity larger than V and re-evaluated the intensity and the epicenter. All these earthquakes are located between 36.0ºN and 39.5ºN and between 1.0ºE and 4.0ºW, that is the area which present the higher seismic activity of Spain (Spain presents low or moderate seismic activity in comparison with other countries but, in Spain, this is the area with most seismic activity). The selected earthquakes are distributed in two periods 1900-1923 and 1924-1962. These periods have been stablished based on the available seismic information and also based on the available seismic instrumentation in those groups of years, using the same time periods proposed by Martínez Solares *et al.* (2013).

In these periods, data and observations are very variated and heterogenous and the types of sources also change from one earthquake to another. Information available are macroseismic questionaries in some earthquakes, seismic bulletins and seismic catalogues, specific studies, isoseismal maps, seismograms, photographs and videos records, sometimes. So, we have studied all the presented macroseismic and instrumental information using different techniques. The techniques include macroseismic methods such as Bakun localization method (Bakun and Wentworth, 1997), Boxer method (Gasperini *et al.*, 1999) and MEEP method (Musson and Jiménez, 2008) and instrumental methods such as Hypocenter (Lienert and Haskov, 1995).

Our results (Table 1) show that at the IGN intensity was overestimated for 9 events with greater variations than one intensity degree in 4 earthquakes (for example from VII to V-VI on November 25th, 1913, earthquake, in Granada). The main factor for these changes in the intensity are due to the use of the EMS-98 scale (European Macroseismic Scale; Grünthal, 1998) that considers the vulnerability of buildings. Only for the April 25th, 1912, earthquake, intensity was underestimated, IV versus the new IV-V intensity (EMS-98 scale).

Table 1: Re-evaluated seismic parameters for the 1900-1962 period in this study.

ID	Date	Origin Time (UTC)	Intensity (EMS-98) [IGN data]	Intensity Data Points (1)	Latitude [IGN data]	Longitude [IGN data]	Epicenter type (M: Macroseismic I: Instrumental)	Epicenter variation (Km)
EQ1	16/04/1907	17:30:00	VII [=]	2	37.76 [37.80]	-1.51 [-1.50]	M	5
EQ2	01/07/1909	14:12:18	VI [VII]	5 (+18)	37.97 [38.00]	-0.65 [-0.67]	M	4
EQ3	21/03/1911	14:15:35	VII-VIII [=]	11 (+3)	38.02 [=]	-1.25 [=]	M	-
EQ4	03/04/1911	11:11:11	VII [=]	9 (+4)	38.07 [38.08]	-1.26 [-1.25]	M	2

EQ5	22/04/1912	3:22:45	V-VI [VII]	1	37.13 [37.13]	-2.73 [-2.72]	M	1
EQ6	25/04/1912	20:35:00	IV-V [IV]	1	38.08 [38.10]	-1.25 [-1.20]	M	5
EQ7	11/08/1913	1:05:48	VII [=]	5	36.93 [36.80]	-3.63 [-3.20]	M	41
EQ8	25/11/1913	2:27:29	V-VI [VII]	1 (+1)	37.80 [37.78]	-2.55 [-2.53]	M	2
EQ9	28/11/1916	22:05:46	VI [VII]	2 (+7)	38.52 [38.57]	-0.96 [-0.95]	M	5
EQ10	10/09/1919	10:40:31	VII-VIII [=]	85 (+5)	38.07[37.98]	-0.80 [-0.87]	M	11
EQ11	12/06/1926	23:29:22	V [VI]	14 (+8)	36.68 [36.77]	-2.43 [-2.37]	I	11
EQ12	05/03/1932	2:10:26	V-VI [VII]	15 (+9)	37.40 [37.42]	-2.42 [-2.45]	M	3
EQ13	23/02/1944	22:34:10	IV-V [VII]	7 (+6)	38.19 [38.17]	-1.14 [-1.15]	M	3
EQ14	01/07/1945	3:18:04	VI-VII [VII]	3 (+5)	38.80 [=]	-0.58 [=]	M	-
EQ15	23/06/1948	3:43:58	VII [=]	6 (+1)	38.15 [38.05]	-1.77 [-1.76]	M	11
EQ16	19/04/1956	18:38:54	VII [VII-VIII]	14	37.19 [=]	-3.68 [=]	I	-

1: Numbers in brackets means the number of places where the only information is that the earthquake has been felt (F) or has caused damage (D), but it is not possible to assign a single value of intensity with the available information.

We have also re-evaluated the epicenters reviewing both macroseismic and instrumental information (Figure 1). We have updated the epicenter of 13 earthquakes with greater variations than 10 km in 4 cases. The largest epicenter modification corresponds to August 11th, 1913 (Imax= VII), earthquake. There is a confusion with the name of the population that suffered the greatest effects, and for this shock its macroseismic epicenter has been moved 41 km to the NW from the IGN epicenter using contemporary sources.

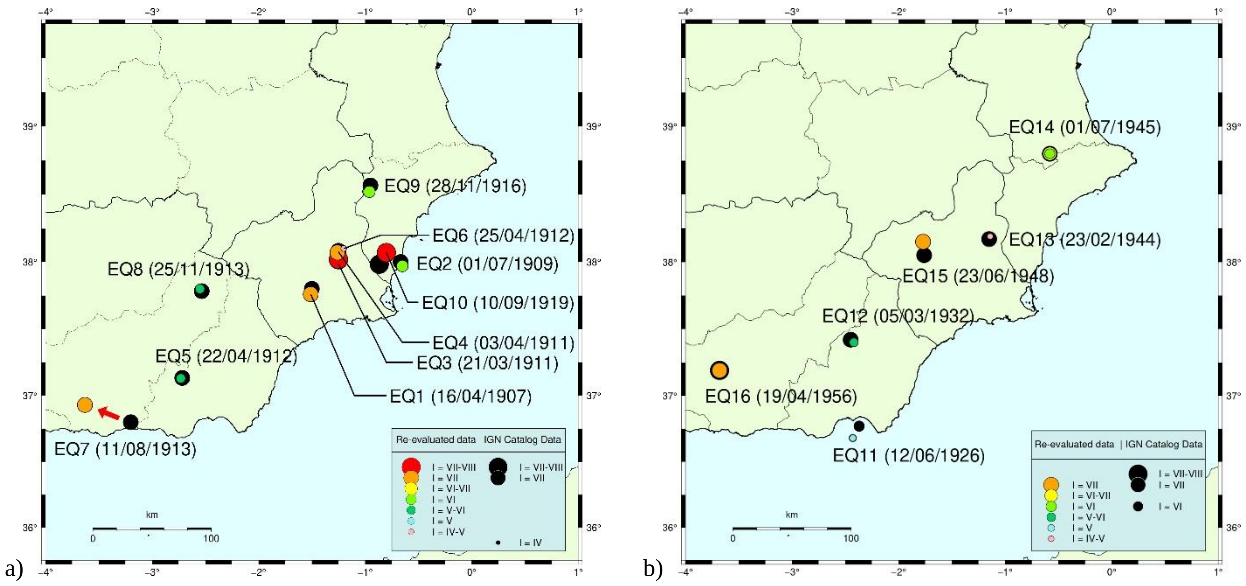

Figure 1. Re-evaluated earthquakes (colored circles) versus IGN epicenters (black circles): a) 1900-1923 period, b) 1924-1962 period.

In this study, we present on one hand, a methodology for the re-evaluation and analysis of earthquakes in the 20th century in Spain, a period that has very inhomogeneous information sources and, on the other hand, we provide a set of earthquakes whose focal parameter have been obtained with homogeneous macroseismic scale, techniques and methods.

Acknowledgements

This work has been partially supported by the Spanish Ministry of Economy and Competitiveness (Project Number PID2021-122662OB-I00) and by the Proyecto de Investigación Santander-UCM (PR44/21-29929).

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17-20 September 2023 - Lixouri, Greece

Bulletin of the Geological Society of Greece, Sp. Publ. 11

Ext. Abs. 00042

Sílex Project: low-cost accelerometers

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Silex is a low-cost accelerograph, developed by the National Geographic Institute (IGN) that provides information on earthquakes, obtained from ground acceleration.

Currently, the IGN has a network of seismometers distributed throughout the national territory that measure the ground velocity, to obtain the focal parameters of every earthquake.

The IGN has also a network of accelerographs installed in the areas of greatest seismic hazard, such as Granada and Murcia (Bravo *et al.*, 2019), which is located in the S-E of Spain the area with most seismic activity. The accelerographs measure the acceleration of the ground, recording strong movements of the ground that occur near the fault that caused it. The calculation of the seismic acceleration also allows to carry out seismic engineering studies.

The aim Silex Project, is to densify the network of accelerographs in an economically way and therefore are located in the most seismic areas of our territory (Figure 1).

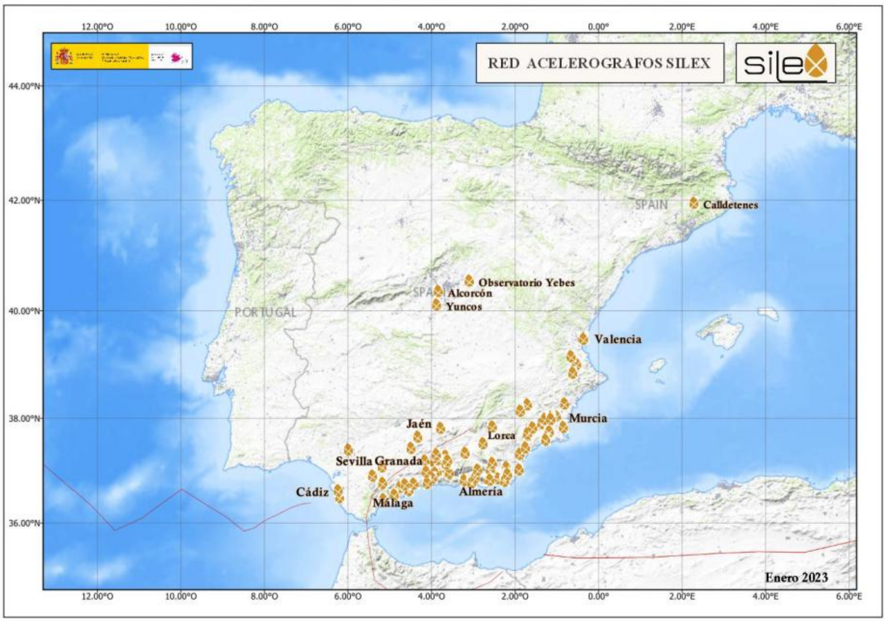

Figure 1. Silex Network in Spain.

Another objective of the Silex Project is to improve both the rapid assessment of the damage of an earthquake and the knowledge of seismicity in the area. All this will help to create data of interest, such as shakemaps.

Shakemaps, can be defined as maps that represent, after the occurrence of an earthquake, different measures of the ground motion, acceleration, velocity or intensity registered in the epicentral zone, in order to show the geographical distribution of the severity of the earthquake (Figure 2).

Silex accelerographs are based on MEMS technology. The term MEMS (Micro Electro Mechanical Systems) refers to the technology of microscopic mechanical devices. Specifically, MEMS accelerometers are capacitive microsensors (Figure 3) where the displacement of a small mass produces a variation in the capacity of a microcapacitor (Martín, 2012). The fields where this technology is used are very diverse, and it is also present in automotive systems (such as the system that activates the airbags when it detects a sudden change in vehicle acceleration) or in the smartphones we use daily.

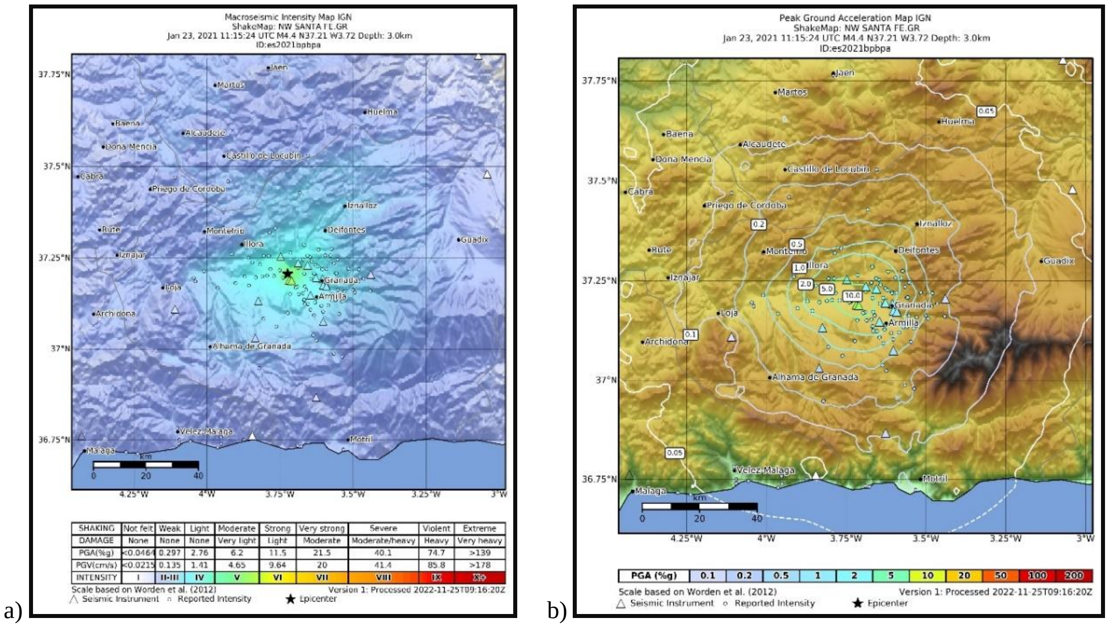

Figure 2. Examples of Shakemaps for 23/01/2021 Granada earthquake in terms of intensity and in terms of Peak Ground acceleration. (Source: Instituto Geográfico Nacional)

The main conditions that the installation must fulfill are as follows:

- Location: In areas where it is common to feel earthquakes and preferably in buildings that are not very tall or bulky. The equipment is installed on the basement that, in contact with the natural terrain, avoiding wooden floors. It should always be covered.
- Fixation: The accelerograph is fixed to the ground with a central screw. Once bolted down and facing to the north, it will not be able to move.
- No disturbance: The place should be quiet and with low traffic, avoiding nearby machinery or appliances that generate vibrations.
- Electricity: Proximity to an electrical outlet (220V) 24 hours a day. The power consumption of the equipment is only 6W, less than a low consumption light bulb.
- GNSS: Currently it is no longer necessary to use the GNSS antenna to obtain time and coordinates. Internet connection is used to get the time by NTP.
- Transmission: For data transmission there are two options: Connect it to a router with 24-hour internet access. The quality of the internet connection will not be affected, or the other option is to connect with a mobile phone SIM card.

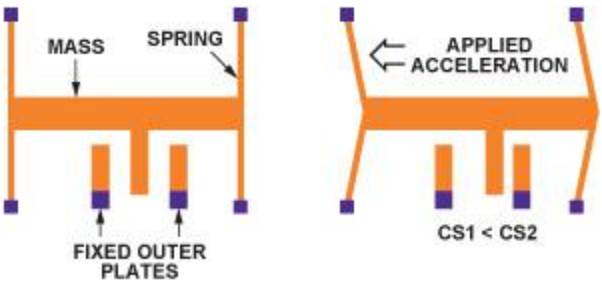

Figure 3. MEMS accelerometer (capacitive microsensor) [Figure obtained from O'Reilly *et al.*, 2009]

A comparison between a Silex with a conventional commercial accelerometer (for example: GeosigGMSPlus) can be observed in Table 1.

Table 1. Comparison between a Silex with a conventional commercial accelerometer.

Accelerometer type	**GeosigGMSPlus**	**Silex**
Precision	$2.6x10^{-7}$ g up to ±2 g [0,00000026-2 g]	3.06 mg up to ±2 g [0,00306-2 g]
Observations	Have a wide measurement range	It is able to take measurements from magnitude 2-3 (that it is roughly when people feel it
Flat Response Range	0-250 Hz	0-100 Hz
Sampling	200 mps (one mesure every 5 msec)	100 mps (one mesure every 10 msec)

Concluding, it is important to mention that a useful and low cost, stable equipment has been developed. Another goal of this project is that with this network we have been able to densify and complement the existing network of conventional accelerographs and to obtain more reliable shake maps, in less time and with more data.

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Ambient Noise H/V Analysis in Lixouri, Kefalonia Island

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The modification of earthquake ground motion, usually amplification within a specific frequency band at a site due to local soil conditions has been identified in early relevant works by e.g., Milne (1898), Takahashi and Hirano (1941) or Gutenberg (1957). Evidence for main control on damage distribution by local geology was established in Japan following the 1923 great Kanto earthquake (Kanai, 1951).

The evaluation of the amplification potential of shaking due to site effects through a detailed characterization of local soil conditions, by determining the soil layering, the resonant frequency and the shallow shear-wave velocity profile, is of great importance. Among the most common methods and techniques for soil characterisation (e.g., Foti et al., 2011) is the analysis of horizontal-to-vertical spectral ratios (HVSR) from single-station ambient-noise records (Molnar et al., 2022), early introduced by Nogoshi and Igarashi (1971) and applied widespread after the revision by Nakamura (1989). Formally, the term ambient-noise includes seismic signals with frequencies above 0.5 Hz called 'microtremors' (i.e., of cultural origin like traffic or industry noise) and those below 0.5 Hz called 'microseisms' or long-period microtremors (i.e., of natural origin like wind or sea waves). HVSR is the most widely used method to perform site characterization and microzonation studies, because its relatively simple approach, the easy, low-cost, and relatively fast development of field surveys and also because of the open source processing software packages developed within the standardization attempt carried out in the framework of the European project SESAME, where a series of guidelines for data acquisition and processing were issued (SESAME, 2004; Bard, 2008; Atakan, 2009).

In the framework of the scientific project "KNETSEISRL (NSRF2014-2020) - Knowledge NETworks SEISmic Risks Lixouri", a detailed HVSR data acquisition, processing and analysis, following the aforementioned guidelines, is being performed. More specifically, in order to determine local soil conditions at sites where seismic stations are installed, 32 ambient-noise measurements of at least 30 minutes duration, mainly concentrated in Lixouri, were conducted during the period July 8th 2022 to October 25th 2022, and are presented in Figure 1. They were obtained using three-component Tromino© recorders, which are ultra-compact and ultra-lightweight instruments specifically developed for ambient-noise surveys.

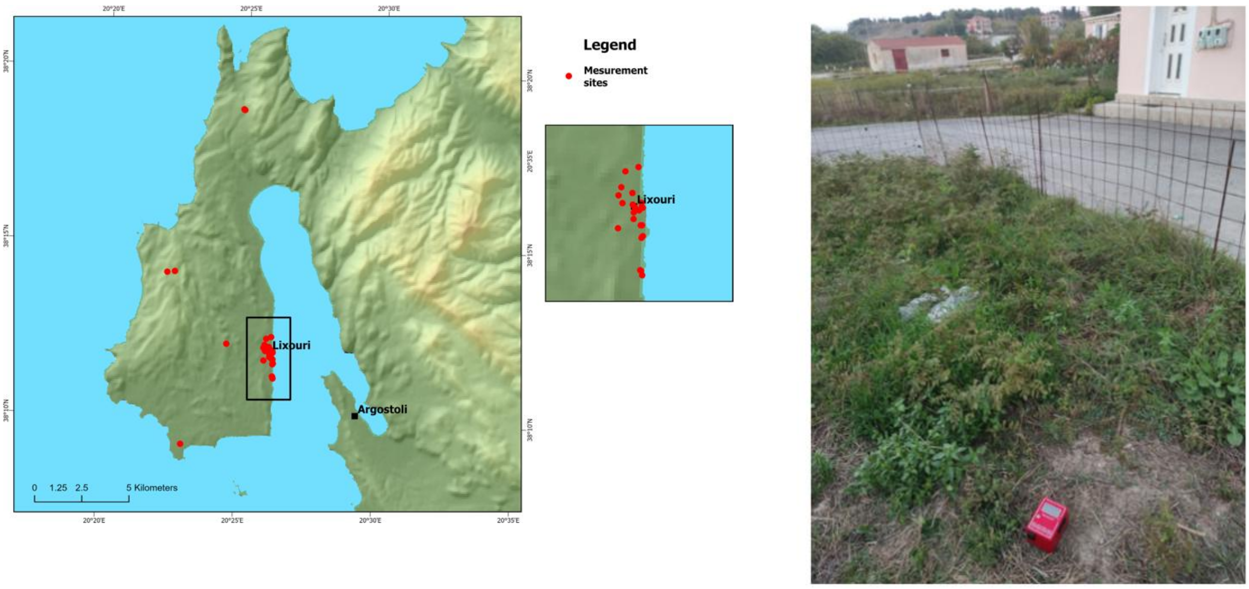

Figure 1. Left: Map showing spatial distribution of ambient noise measurements, at the instruments sites (red circles). Right: Tromino measurement.

Additionally, to determine the extent and thickness of the geological formations in Paliki peninsula, new ambient-noise measurements were carried out in the broader Paliki area during May 2023, delineating specific profiles oriented in E-W direction. In Figure 2, the sites of these measurements are plotted on the regional geological map. In all measurements the sensor was placed directly on the soil/ground to guarantee a good coupling, avoiding pavement, asphalt etc., that could produce surficial inversions of shear-wave velocity.

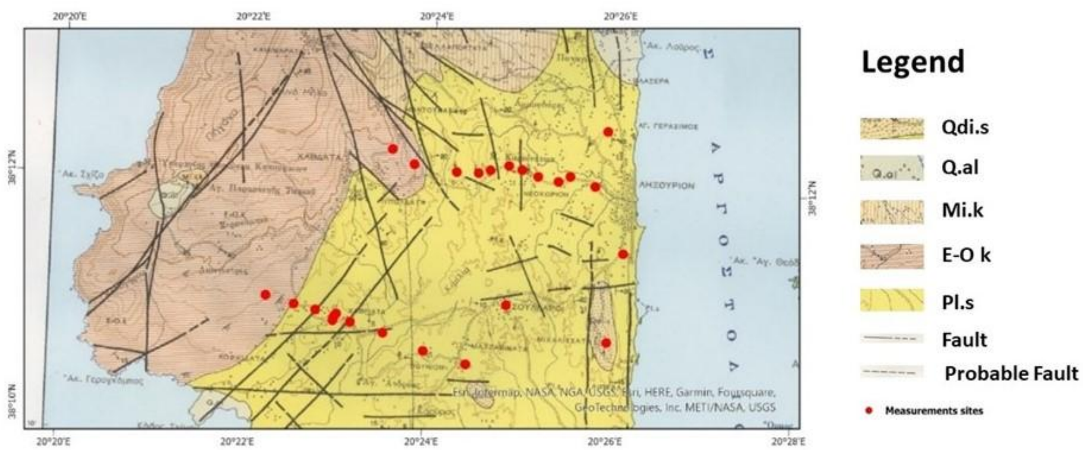

Figure 2. Geological map and specific profiles of ambient noise measurements in Paliki peninsula.

The available geological maps (IGME, 1985) show that the area of Paliki is formed by alluvial deposits (Q.al) of Holocene, sandstones (Qdl.s) with thickness up to 40 m, of Pleistocene age, conglomerates, sandstones, and limestones (Pl.s), ranging from 150 m to 250 m, of Pliocene age, conglomeratic and brecciated limestones (Mi.k) of Messinian and finally massive thick-bedded limestones (E-O k) of Eocene with thickness up to 100 m, which comprise the bedrock (Figure 2).

Ambient-noise recordings were processed using the Grilla© software package, following SESAME standards. When only a single HVSR peak is identified, the corresponding frequency is considered the fundamental resonant frequency at the site; while if more than one peak is found, with higher frequencies, they are associated with shallower layers. The analysis showed that in general, HVSR results can be grouped into four categories: a) peaks at frequencies below 1 Hz, b) peaks between 1.0-4.0 Hz c) peaks in high frequencies and d) no clear peaks (almost flat curves). In general, lower frequencies could be associated with thicker subsurface layers while higher frequencies are with shallower layers and weathered soil. No impedance contrasts in the subsurface layers or rock sites show HVSR flat curves. An example from the preliminary analysis performed is shown in Figure 3.

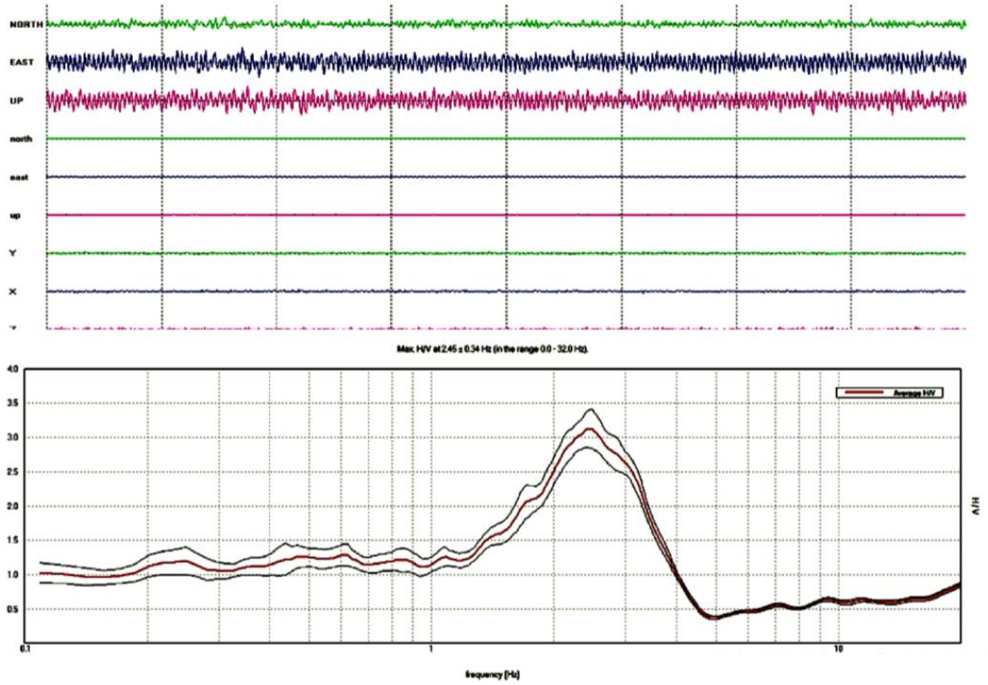

Figure 3. Ambient noise record at ELTA site in Lixouri (top) and HVSR results processed with Grilla© software (bottom).

Further investigations will be performed, with additional free field measurements, as well as within ones in critical infrastructure and buildings, including schools, public services, etc., to determine eigenfrequencies and dynamic characterization for identifying potential of soil-structure resonance.

Acknowledgements

We acknowledge funding by the “New technologies, research and innovation for the creation of poles of attraction” project in the framework of the National Strategic Reference Framework (NSRF) 2014-2020, Regional Operational Programme “Ionian Islands 2014–2020”.

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Large (M_w≥6.0) earthquakes recurrence times and stress evolution in Kefalonia Transform Fault Zone

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Introduction

Large earthquakes (e.g., M_w≥6.0) recurrence behavior on specific fault segments is one of the primary input parameters for developing long-term Earthquake Rupture Forecast (ERF) models. Such models are capable of returning the likelihood of the occurrence of near characteristic magnitude earthquakes in a specific time span and they can be based on either a time-independent or an elastic rebound motivated renewal assumption (Field, 2015). The key parameters of these models are the mean recurrence time, T_r, of large earthquakes and its aperiodicity, α. One important factor to influence T_r on certain fault segments is the interaction among them due to the permanent and transient static stress changes due to stress redistribution caused by earthquakes (Stein et al., 1997; Hardebeck, 2004). This implies that static stress changes between the interacting causative and receiving fault segments are capable of affecting the mean recurrence time, T_r, by moving a given segment towards (promoting) or away (delaying) from failure.

The Kefalonia Transform Fault Zone (KTFZ) is characterized by right-lateral strike slip motion with a minor thrust component (e.g., Papadimitriou, 1993; Louvari et al., 1999) and being the most active seismic zone in the broader Aegean area. KTFZ exhibits the highest crustal deformation rates within the broader Aegean area with slip rates up to 20 mm/yr (Briole et al., 2015), resulting in frequent occurrence of earthquakes with M_w≥6.0 during both instrumental and the historical period (Papazachos and Papazachou, 2003).

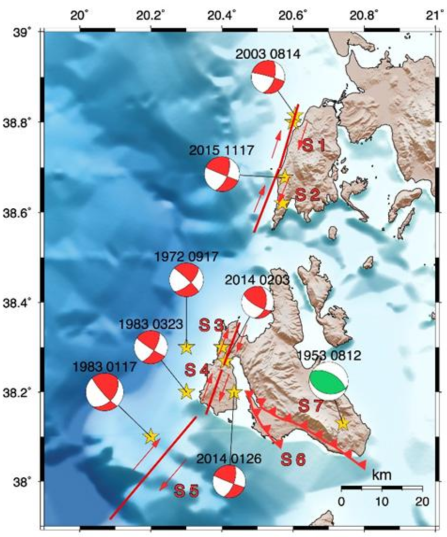

Figure 1. Epicentral distribution of the large earthquakes with M_w≥6.0 since 1948, along with their available fault plane solutions. Red solid lines depict the major fault segments of KTFZ.

The large earthquakes occurred within the study area since 2003 (Figure 1), along with the one occurred offshore southeast of the island of Kefalonia in 1983 with M_w=7.0, attracted the research interest (Scordilis et al., 1985; Karakostas et al., 2004; Karakostas et al., 2015; Papadimitriou et al., 2017) and thus a detailed segmentation model is available. The KTFZ is composed of five major dextral fault segments with strikes ranging from N12°E to N40°E, having lengths of 12–40 km and typical rake values for right-lateral strike slip faulting. The southeastern part of Kefalonia Island is also characterized by the existence of thrust faulting associated with the 1953 series of large earthquakes. The main objectives of the present study are the determination of T_r of large (M_w≥6.0) earthquakes associated with the major fault segments of KTFZ, considering the incorporation of the 74-year (1948-2022) evolutionary stress field.

Methods

The seismic moment rate conservation method (Field et al., 1999) is applied for the computation of T_r of large earthquakes associated with the major fault segments of KTFZ. According to this method, the mean recurrence time in years is given by the equation:

$$T_r = \frac{M_{0max}}{\mu L w V} \quad (1)$$

where M_{0max} is the maximum expected seismic moment of the fault segment calculated by using the maximum observer magnitude of a certain fault segment, μ is the shear modulus, L and w the length and the width of the fault segment, respectively, and V is its long-term slip rate. The computation is made by the application of Equation 1, taking into account their geometrical and kinematic parameters as compiled from the recent studies such the already cited ones. The shear modulus is considered equal to 3.3 GPa (μ=3.3 GPa), while the entire study area is considered as fully coupled (Briole et al., 2021). The maximum expected seismic moment of each fault segment is computed via the relation between the earthquake magnitude and seismic moment of Hanks and Kanamori (1979) using as maximum magnitude the maximum observed one per segment. The variability of T_r is also computed via the method of formal error propagation proposed by Peruzza et al. (2010), taking into account the uncertainties related with the maximum magnitude and slip rate values.

The seismic moment rate conservation method assumes that each fault segment as isolated structure that does not interact with their neighboring segments and does not get affected by the permanent changes of the stress field. In fact, large earthquakes occurrence is controlled by fault interactions through redistribution of stress with a particularly clear example being the Kefalonia Transform Fault Zone (Papadimitriou, 2002). For this reason, the cumulative changes in stress that are assumed to arise from tectonic loading on the major regional fault segments and coseismic displacements associated with large (M_w≥6.0) earthquakes is considered. Interseismic stress accumulation is modeled by introducing "virtual negative displacements" across these faults (Deng and Sykes, 1997).

The large earthquakes mean recurrence time, T_r, is then modeled by both time-independent Poisson model and the Brownian Passage Time (BPT; Matthews et al., 2002) renewal model, aiming at the estimation of the occurrence probabilities of M_w≥6.0 earthquakes on each segment of KTFZ for the next 10, 20, and 30 years since 1/1/2023. For these applications, the mean recurrence time, T_r, and *Cv* values obtained by seismic moment rate conservation method and the incorporation of the state of stress until 2022 is taken into account.

Results

The estimated T_r values, ranging from 33.5 years for the segments of Paliki peninsula (S3 and S4 in Figure 1) up to almost 300 years for the Ainos thrust fault segment (S7 in Figure 1). These variations are obviously related to the dimensions and the slip rate of each fault segment, resulting in different stressing rate values and their maximum observed magnitude, as well. Lefkada North and South fault segments (S1 and S2 in Figure 1) resulting in mean recurrence times equal to T_r= 59.9 years and T_r= 79.6 years, respectively. The shorter mean recurrence time of Lefkada North segment is affected by its larger stressing rate due to its smaller fault dimensions. Concerning the respective *Cv* values it is reported that T_r of Lefkada North fault segment exhibit slightly higher aperiodicity (*Cv*=0.6) than the one of Lefkada South segment (*Cv*=0.4). T_r of the North and South Paliki fault (S3 and S4, respectively) is found equal to T_r= 33.5 years for both, because they have equal dimensions and slip rates and the almost same M_{max_obs}. Their coefficient of variation values indicated a quasi-periodic to slightly aperiodic recurrence behavior (*Cv*=0.6). Mean recurrence time of offshore Kefalonia fault (S5 in Figure 1) is found to be equal to T_r= 210.1 years with an almost quasi-periodic behavior, reporting a coefficient of variation value equal to *Cv*=0.4. For the Argostoli and Ainos thrust fault segments (S6 and S7, respectively) the mean recurrence time values are estimated equal to T_r= 194.6 years and T_r= 298.5 years, respectively. The coefficient of variation for Argostoli fault segment is found to be the largest one, indicating high aperiodic behavior (*Cv*=0.7), whereas the Ainos fault exhibits intermediate periodicity (Cv=0.5).

Coulomb stress changes caused by the 11 $M_w \geq 6.0$ earthquakes since 1948 are calculated, aiming at the identification of the current status of stress onto each fault segment. Coseismic static stress changes (ΔCFF) are computed according to type of faulting of the target fault. The evolved stress field until 2022 is calculated taken into account both tectonic loading and static stress changes caused at the depth of 10 km. The calculation is implemented by considering three mean faulting types, representative for the Lefkada branch of KTFZ (strike:20°, dip:62°, rake:180°; Figure 2a), for the Kefalonia branch of KTFZ (strike:30°, dip:50°, rake:180°; Figure 2b) and the thrust faulting (strike:300°, dip:30°, rake:95°; Figure 2c). The incorporation of the 74-year (1948-2022) evolutionary stress field into the recurrence pattern modeling indicates that the mainly affected fault segments are the Lefkada South and Paliki North ones. On the one hand, the stress accumulation of the Lefkada South fault segment reveals significant time delay, as it is the last ruptured fault segment. On the other hand, the Paliki North fault segment plane was affected by high static stress changes, caused by both the static stress changes of the 2015 earthquake and its high stressing rate. For the other 5 fault segments, either intermediate negative (Lefkada North fault segment) or positive (Paliki South, offshore Kefalonia, Argostoli and Ainos fault segments) static stress changes are observed. The least influence of the evolutionary stress is observed in the offshore Kefalonia and Ainos fault segments, due to their large fault area and the high variable distribution of ΔCFF onto their fault planes. Occurrence probability estimations for the next large earthquake during the next 10, 20 and 30 years, associated with the seven KTFZ fault segments, reveal that the most probable fault segment to be ruptured is the Paliki North fault segment, for an M_w=6.0 earthquake, according to all the four models. For example, the 20-year occurrence probabilities are equal to P_{20}=45% and P_{20}=47%, according to the Poisson and the BPT models. Taking into account the incorporation of static stress changes, these probabilities are significantly increase to 62%, and 78% for the Poisson+ΔCFF and the BPT+ΔCFF models, respectively. Considering the time dependence in the large earthquake occurrence process, significantly increases or decreases the associated seismic hazard. Both time-independent and time-depended modeling results should be equally considered for seismic hazard studies, since there is no statistical evidence of one performing better than the other.

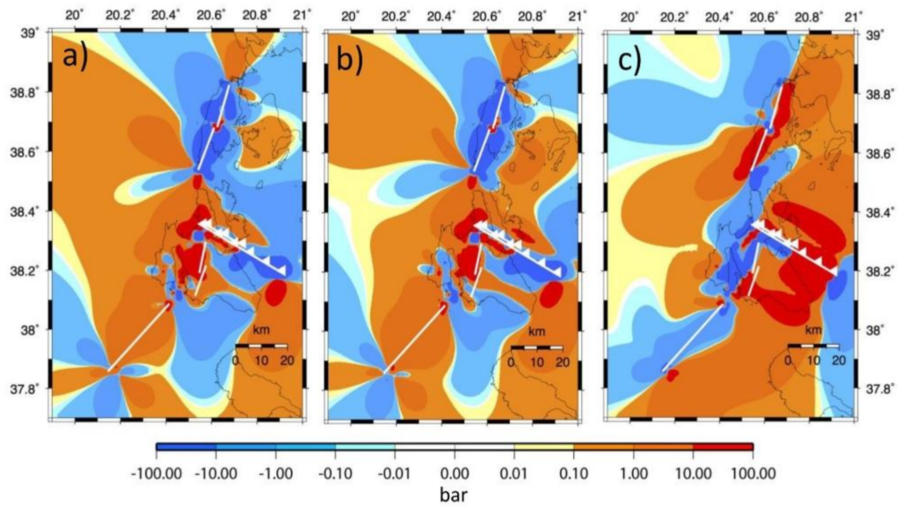

Figure 2. State of stress of KTFZ until 31/12/2022 calculated for (a) a representative dextral strike-slip faulting type of Lefkada North and South fault segments, (b) a representative dextral strike-slip faulting type of Paliki North, Paliki South and offshore Kefalonia fault segments and (c) a representative thrust faulting type of the Argostoli and Ainos fault segments.

Acknowledgements

Funded by the European Union

This study is partially financially supported by artEmis Project funded by the European Union, under Grant Agreement nr 101061712. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Commission–Euratom. Neither the European Union nor the granting authority can be held responsible for them.

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Bulletin of the Geological Society of Greece, Sp. Publ. 11

Ext. Abs. 00045

The 8 September 2022 M_w5.5 earthquake off-shore Kefalonia Island and its aftershock sequence- Preliminary analysis and seismotectonic implications

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Research Highlights

We investigate the properties of a seismic sequence occurred in a relatively high-seismicity area that has not been activated for a period of more than a decade.

Introduction

A moderate (M_w5.5) earthquake occurred on 8 September 2022 at 07:36:27 UTC, in the offshore area SW of Kefalonia Island. Although widely felt, even along the Italian coastline (EMSC felt reports) no major damage was reported to the nearby islands. All available focal mechanism solutions reveal a strike-slip (right-lateral) motion in a fault plane having a SW-NE orientation (strike: N45-50°E) with a slight normal component.

The area hosting the mainshock constitutes the southwestern edge of the Kefalonia Transform Fault Zone (KTFZ) (Figure 1). This major geodynamic feature undergoes relatively high tectonic loading (~30 mm/yr) where stress interactions play a critical role in earthquake occurrences (Papadimitriou, 2002). The KTFZ consists of two major fault branches, namely the Lefkada branch containing its northern part, striking NNE-SSW and the Kefalonia branch to the south with a slightly different NE-SW strike (Figure 1). The southern segment is longer (length ~ 95 km, mean strike N35°E), associated with the stronger earthquakes in the area and with a maximum reported magnitude of M = 7.4 (Papazachos & Papazachou, 2003).

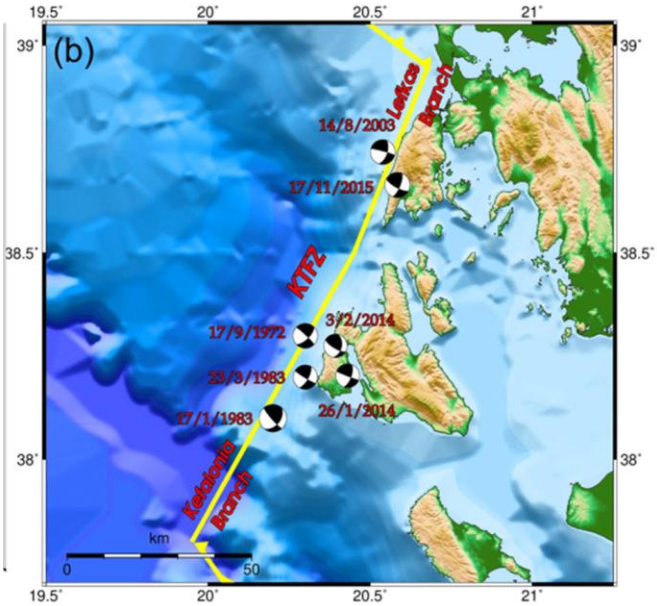

Figure 1: The Kefalonia Transform Fault Zone (KTFZ) with the two distinct Lefkas (to the north) and Kefalonia (to the south) branches and the collision boundary north of Lefkas Island. The black beach balls indicate the fault plane solutions of the most recent strong (M ≥ 6.0) earthquakes in the region.

We aim to identify the seismicity patterns of a precisely relocated earthquake catalog of a low magnitude of completeness in order to reveal the characteristics of the spatiotemporal seismicity evolution.

Methods

An initial earthquake catalog covering the period from 8 September 2022 to 23 February 2023 was compiled by integrating the manually revised solutions of the routine analysis service of the Seismological Station of Thessaloniki ($M_L \geq 2.5$) with the solutions provided by the project "Maintenance and Upgrading of the Seismological Network of Ionian Islands" ($M_L < 2.5$), funded by the Regional Union of Municipalities of Ionian Islands.

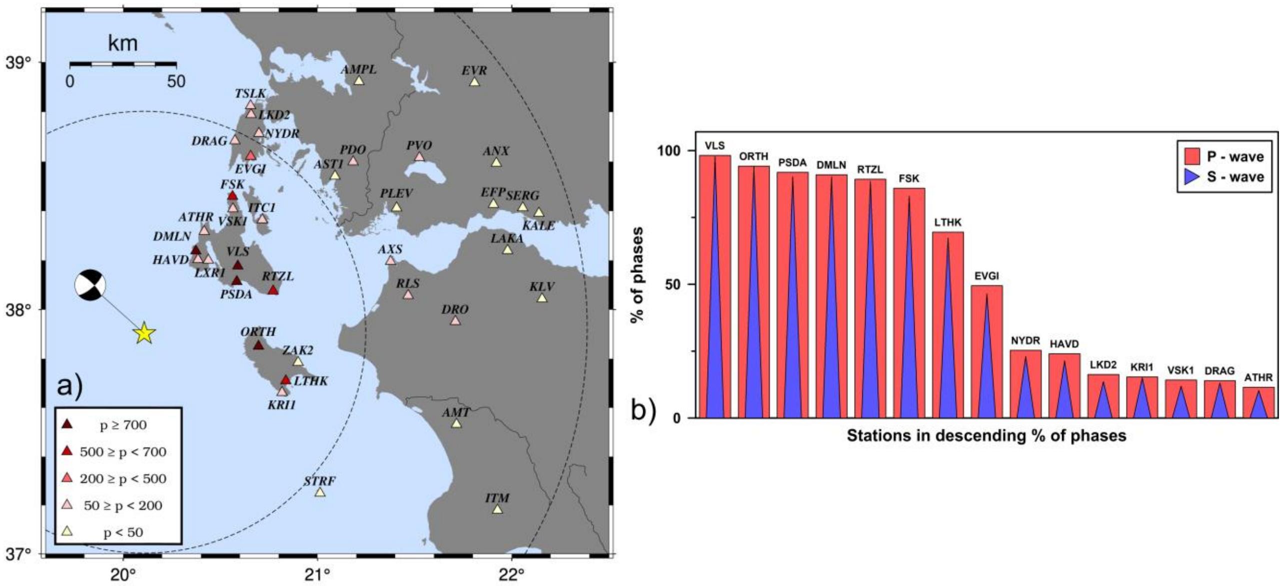

Figure 2: a) Map of the available seismic stations along with the corresponding number of P-phases recorded throughout the aftershock sequence and b) Percentages (%) of p-and s- phases in comparison with the total number of events. The yellow star illustrates the epicenter of the mainshock and the black and white beach ball denotes its focal mechanism.

Manually picked seismic phases (Figure 2) along with a 1D velocity model and a seismic velocity ratio were used to perform an initial location with the use of the Hypoinverse code (Klein, 2002). The estimation of the V_p/V_s ratio was obtained through the Wadati method (Wadati, 1933) by using only the earthquakes having a sufficient number of P- and S- phases. The obtained initial locations were then used as an input to the hypoDD program (Waldhauser, 2001) for the aftershock relocations using the double-difference method.

Results

An initial catalog of 904 earthquakes with magnitudes $0.5 \leq M_L \geq 5.2$ was assembled (Figure 3b). The corresponding double-difference catalog, however, includes a smaller number of events given that some of them are rejected during the relocation process, mainly due to the insufficient number of seismic phases and number of links between them.

Using the relocated epicenters and their spatiotemporal distribution we constrained the spatial dimensions of the aftershock sequence through a detailed analysis of dense cross sections parallel and perpendicular to the dominant strike of the activated structure. The distribution of early aftershocks indicates that the coseismic rupture may have bilateral characteristics. In the course of time, the aftershock zone expanded towards southwest. Using the background rate before the mainshock occurrence, we determine the period in which the overall seismicity is dominated by aftershock activity, thus signifying the end of the aftershock sequence.

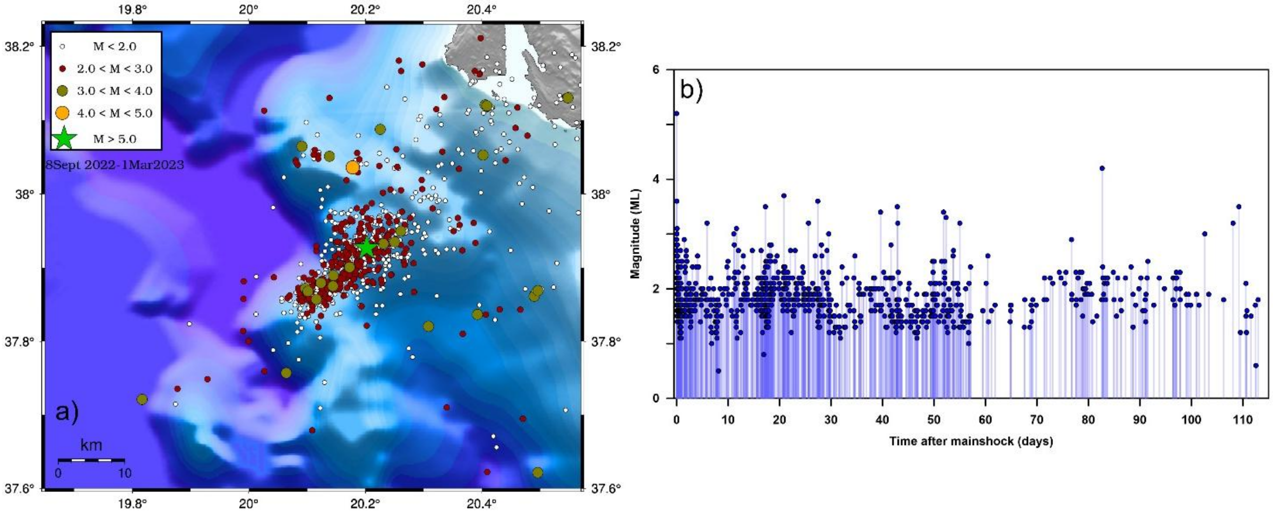

Figure 3: a) Map showing the spatial distribution of relocated aftershocks following the September 8 M_w5.5 event and b) Magnitude versus Time Elapsed (days) from the mainshock occurrence

Conclusions

We collected all the available data for the period under study in order to relocate the aftershock sequence of the moderate (M_w5.5) mainshock that struck the offshore area southwest of Kefalonia Island. Based on the available recordings of the seismological stations of HUSN a double-difference algorithm was used to relocate ~800 aftershocks more than 3 months after the mainshock occurrence. Aftershocks are mostly aligned to a NE-SW orientation forming a ~15 km zone. Combining the aftershock distribution along with the focal mechanisms, we infer the properties of the seismogenic fault (strike, dip) and interpret its activation in connection with nearby fault structures. We also estimate the duration and productivity of the aftershock sequence based on well-established statistical methods.

There are several reasons why it is important to analyze moderate earthquake sequences. We can gain valuable insights into the behavior and characteristics of earthquake occurrence and the underlying processes that drive seismic activity. Furthermore, moderate mainshocks may not cause significant damage compared to stronger earthquakes however they can still contribute significantly to the overall seismic hazard in an area. Incorporating these sequences, we can better evaluate the potential for larger earthquakes and assess the overall seismic hazard in a holistic way.

Acknowledgements

The recordings of the seismological stations used in this study were taken from the Seismological Station of the Aristotle University of Thessaloniki (http://geophysics.geo.auth.gr/ss/station_index_en.html). The software Generic Mapping Tools (Wessel et al., 2013) was used for creating maps and Grapher version 16 for some of the figures.

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8th International Colloquium on Historical Earthquakes, Palaeo- Macroseismology and Seismotectonics

17-20 September 2023 - Lixouri, Greece

Bulletin of the Geological Society of Greece, Sp. Publ. 11

Ext. Abs. 00046

Evaluating the performance of Smoothed Seismicity Models at the Central Ionian Islands

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Research Highlights

It is the first attempt to use a time-independent and spatially varying long-term smoothed seismicity approach to perform earthquake forecasting on a regional basis for Greece.

Introduction

For more than a decade, smoothed seismicity models constitute a powerful tool to forecast spatially varying earthquake occurrence rates. It is a purely data-driven method that takes into account a key assumption that past earthquakes are representative of future seismicity. The implementation of earthquake forecasting models is a crucial process that can be valuable to any seismic hazard analysis. In contrast to fault-based methods, smoothed seismicity models can make important contributions to seismic hazard analysis in cases where knowledge of active faults is not sufficient for use. In the region of the central Ionian Islands, although the main geodynamic features are considered to be well identified (e.g., Scordilis et al., 1985) distributed seismicity can still be found from largely unknown sources, due to the insularity of the area and the absence of surface ruptures (Figure 1).

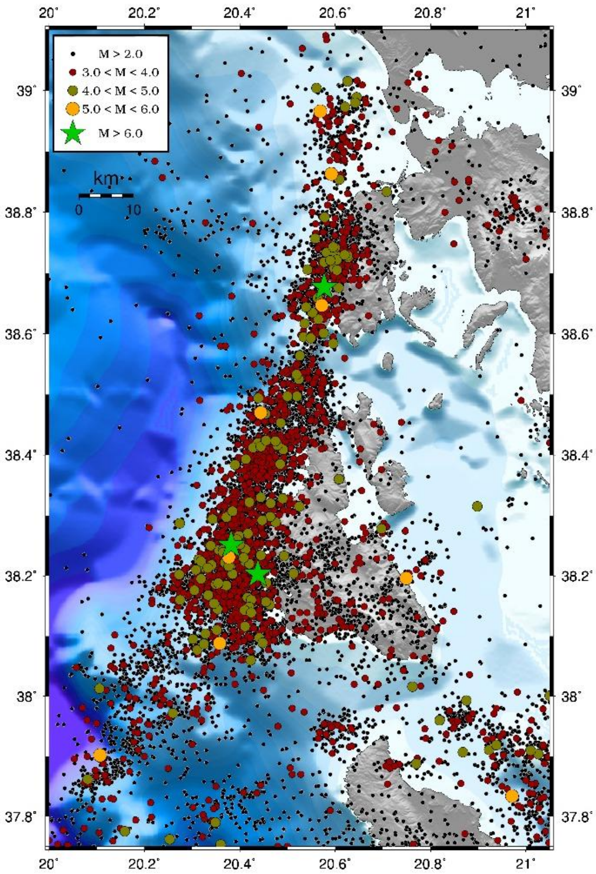

Figure 1: Seismicity (M>2.0) of the central Ionian Islands region from 2010 to 2022

Methods

The employment of a smoothed seismicity model requires a series of steps regarding the treatment of the seismic catalog (i.e., declustering, estimation of seismicity parameters, completeness magnitude estimation) and other critical decisions such as the selection of smoothing parameters.

Our initial catalog covers the period from 1965 to 2022 with magnitudes ranging from less than 0.5 to 6.5. We explored the magnitude of completeness through the Goodness-of-Fit method (Wiemer & Wyss, 2000) for the whole catalog as well as using a moving window approach (Figure 2) to highlight the M_c variations in time. From our analysis, the use of two overlapping subsets of the catalog was deemed appropriate. The first one from 1996 to 2022 and the second one from 2012 to 2022. In parallel, we estimated the b-value over the study area under the assumption that is not highly variable.

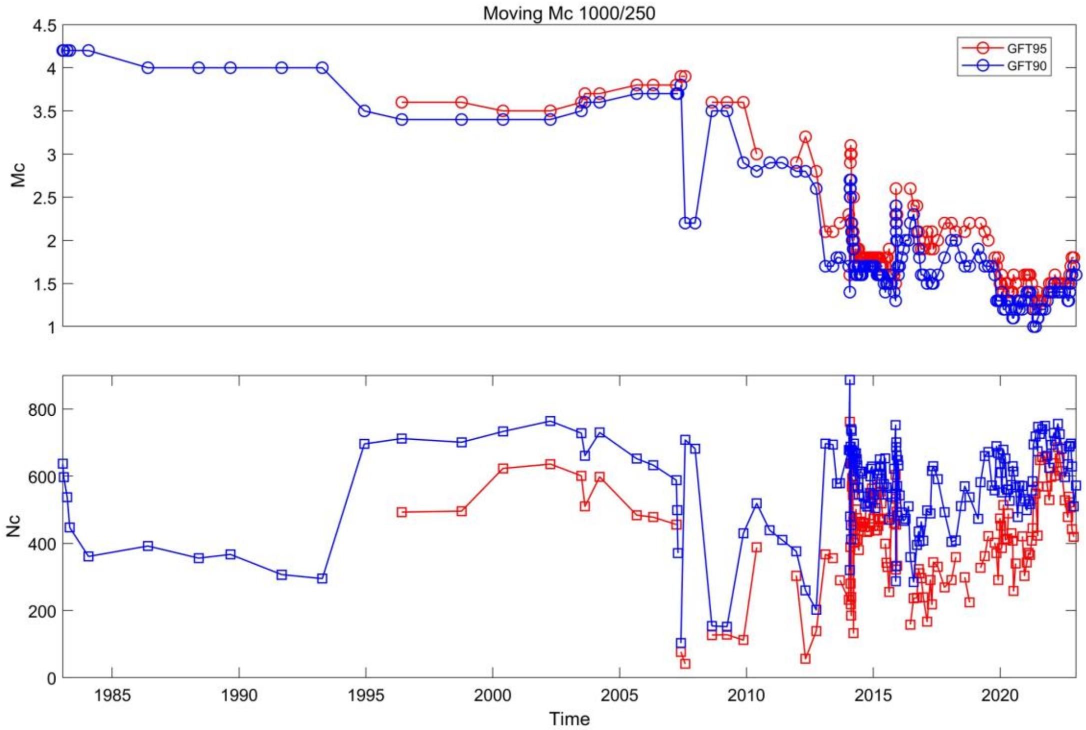

Figure 2: Estimated magnitude of completeness (M_c) and number of events (N_c) as a function of time (1964-2022) at the 90% and 95% of residuals

We employed two different widely used declustering techniques (Gardner & Knopoff, 1974; Zaliapin et al., 2008). Statistical methods (e.g., Lilliefors test) were then performed to evaluate whether the generated declustered catalogs follow a temporally homogeneous Poisson hypothesis. We then calculated the seismicity rates for each declustered catalog using the smoothed seismicity approach as well as for the non-declustered catalog. A training and a validation set were established to determine the best combination of parameters on the one hand, and the performance of the model on the other hand.

A spatial grid of 0.05° by 0.05° was superimposed covering the study area to perform the computations. Then the seismicity rates in each cell of the grid, taking into account the contributions from N events, was estimated following the equation:

$$\lambda_i(m) = \sum_{j=1}^{N} \left(K_{\sigma j}(r_{ij})\right) Q_i\left(\Delta_t, M_{cj}\right),$$

where $K_{\sigma j}$ is the smoothing kernel and $Q_i(\Delta_t, M_{cj})$ is the event rate. Parameters of the kernel are the smoothing distance σj and the distance to the j_{th} earthquake epicenter r_{ij}, whereas the event rates are controlled by the M_c and the completeness times, Δt.

Results

The final smoothed seismicity models were constructed for each learning catalog (Table 1). The results of our analysis are summarized through maps illustrating the annual expected number of M ≥ 4.5 & M ≥ 5.0 events in each cell of the grid for the cases of a) entire, and b) declustered catalogs. The forecasting ability of each different model was evaluated through Likelihood tests.

Table 1: Information on the two different catalogs used. M_c is the completeness magnitude, a & b parameters of the Gutenberg-Richter law, N is the number of events, whereas N_c is the number of events above the M_c.

Subsets of the initial catalog	**Catalog 1**	**Catalog 2**
Time period	1996 - 2022	2012 - 2022
Latitude (°)	[37.75 - 39.10]	
Longitude (°)	[20.00 - 21.05]	
Depth threshold	45 km	
M_c	3.7	2.1
a	8.3	5.8
b	1.38	0.88
N	41973	36437
N_c	1767	10009

Conclusions

A forecast of the probabilities of M ≥ 4.5 & M ≥ 5.0 earthquakes in the region of the central Ionian Islands is attempted by using a smoothed seismicity approach derived from a high-quality seismic catalog. We conclude that the introduction of smoothed seismicity models in the area under study can be proven as a powerful tool to produce seismicity rate forecasts surmounting the subjective nature of areal source zone models as well as the more challenging fault-based ones. Our findings indicate that the use of either declustered or complete catalogs influences the resolution and forecasting skill at a regional level. Removing the foreshocks and aftershocks of our catalog imposes greater weighting on solely the mainshocks, something that may lead to an incomplete view of the spatial distribution of future seismicity. A possible extension in our approach may be the use of a high-quality cross-correlated catalog to extend the model through a 3D approach that considers depth variations. Lastly, a hybrid model that incorporates smoothed historical seismicity combined with geological information on known active faults (e.g., slip rates, maximum magnitude) could constrain the physical assumptions made in a purely catalog-based approach.

Acknowledgements

The initial seismic catalog used in this study was compiled by the bulletins of the Seismological Station of the Aristotle University of Thessaloniki (http://geophysics.geo.auth.gr/ss/station_index_en.html). The software Generic Mapping Tools (Wessel et al., 2013) was used for creating maps.

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8th International Colloquium on Historical Earthquakes, Palaeo- Macroseismology and Seismotectonics

17-20 September 2023 - Lixouri, Greece

Bulletin of the Geological Society of Greece, Sp. Publ. 11

Ext. Abs. 00047

Digitising Analog Seismograms: The Hidden Treasure

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Abstract

This paper is about identifying seismograms in archive collections associated with significant earthquakes in the Greek region prior to the World-Wide Standardized Seismograph Network (WWSSN) for digitization and further analysis. The analysis of analog records of significant earthquakes in Greece is important because such analysis has not been fully undertaken and will open new opportunities for exciting research.

Background

The occurrence and time of early (pre 19th century) earthquakes were recorded by the predecessors of today's seismometers — the so called seismoscopes — for many centuries prior to today. Documenting earthquakes qualitatively began much earlier (Karakaisis et al., 2002). The first instruments recording earthquake ground motions in Europe date to the 18th century, but the most significant contributions to instrumentation were made in the second half of the 18th century (Dewey et al., 1969). Noteworthy contributions are those by Cavalleri, whose instrument with different pendulums was an effort to capture the frequency content of earthquakes, and the *seismografo elettro-magnetico* of Palmieri, who monitored earthquakes in Mt Vesuvius (Dewey et al., 1969 and references therein). The latter are important contributions to today's seismometers because they led to Cecchi's first seismograph (Agamemnone). The National Observatory of Athens obtained such a seismometer which operated in the first quarter of the 20th century. Dewey and Byerly in their 1969 paper provide a very valuable history of early seismometry up to 1900, an excellent resource which does not require reproduction here. Please refer to that paper for additional information on the evolution of instruments which gave birth to what we refer now as seismometers (Dewey et al., 1969).

Working with early seismograms recorded by analog seismometers requires at least some general understanding of the way the early instruments operated. For example, the first instrument at the National Observatory of Athens was an Agamemnone, installed in 1898, but which was then replaced by a more reliable Mainka instrument in 1911 (refer to Figure 2 for a recording made by this instrument). A 2-component Wiechert instrument (recording horizontal motion) was added in 1922 and a vertical Wiechert instrument in 1928 (Karakaisis et al., 2002). Detailed information on the instruments recording earthquakes in the early 20th century in Greece can be found in Karakaisis and Papazachos report (2002).

Introduction

Prior to the adoption of digital earthquake recording methods, ground movements were recorded in analog format, usually on paper. These analog seismograms are at risk of deterioration and inevitably, some may have been lost (Okal, 2015). Preserving such important quantitative information is not an easy task. Digitising these paper seismograms offers an additional layer of preservation while also encouraging further research, as a digital format better facilitates the dissemination and exchange of information.

Many computer programs now exist for the digitization of seismograms (e.g., DigitSeis; Bogiatzis and Ishii, 2016; SeisDig; Bromirski and Chuang, 2003; Wang et al., 2016). Upon testing of one of these applications, the authors believe DigitSeis is a user-friendly program and is relatively easy to learn after the initial training of users. DigitSeis works in both Windows and Mac platforms and has a detailed manual accompanied by videos with explanations.

Analog seismograms associated with past significant earthquakes present new opportunities for research but also many challenges for researchers:

- They are available from a few databases, and only a portion of them has been scanned and is available for download (e.g., INGV, Albini, 2013; Strasbourg, Rivera et al., 2021). Because their preservation requires perfect conditions for the seismogram paper, some may have been lost or destroyed.
- Ensuring a complete set of records for an earthquake is not always straightforward. Records are held by different agencies around the world (e.g., INGV, USGS), with various requirements to obtain such records.
- Fragile seismograms need extra care to be digitised, such as tele-capturing through digital photography or scanning to preserve the record, all of which represent a time-consuming process (Okal, 2015). It is clear therefore that fewer seismograms are scanned than are available.
- An insufficient number of seismograms will not allow for a meaningful analysis of the earthquake of interest.
- Digitisation is a time-consuming process (few hours can be spent in one seismogram depending on user experience and quality of seismogram).
- Due to a large volume of seismograms requiring scanning, some may not be immediately available.
- To digitize seismograms, users must first be trained to work with the software. Often, many researchers do not have experience in this skillset as few work with this type of data.

Objectives

- Identify earthquakes with high quality analog seismogram records for further analysis
- Provide training to new researchers on software for digitizing analog seismograms, the importance of analog seismograms, historical earthquakes and pre-digital records
- Analyse analog records of significant earthquakes in Greece
- Investigate earthquake sources using the analog records of earthquakes which are not well constrained (e.g., depth, location etc.) with implications for estimated seismic risk

Methods

The process of digitizing seismograms is a time-consuming process which includes several steps:

- Identification of earthquakes for analysis in earthquake databases (AHEAD, INGV, etc.),
- Identification of physical location of paper seismograms or online home of scanned seismograms associated with earthquakes of interest,
- Sorting through available records to select those which contain meaningful information,
- Training in digitisation software which includes many steps, such as classification of objects contained in a seismogram (handwritten notes such as time and date; checking for accuracy, etc.),
- Selecting significant earthquakes (pre-1960) with a sufficient number of analog seismograms of high quality

  Analysis of digitised seismograms

Early seismograms

This is a currently ongoing project. Two examples of scanned analog seismograms from INGV (Albini, 2013) of significant past earthquakes from the pre-WWSCN years are shown, along with a digitized seismogram created using DigitSeis. DigitSeis is a relatively easy software to use, even for people without previous such experience; however, even for experienced users, the process of digitizing a seismogram can take several hours.

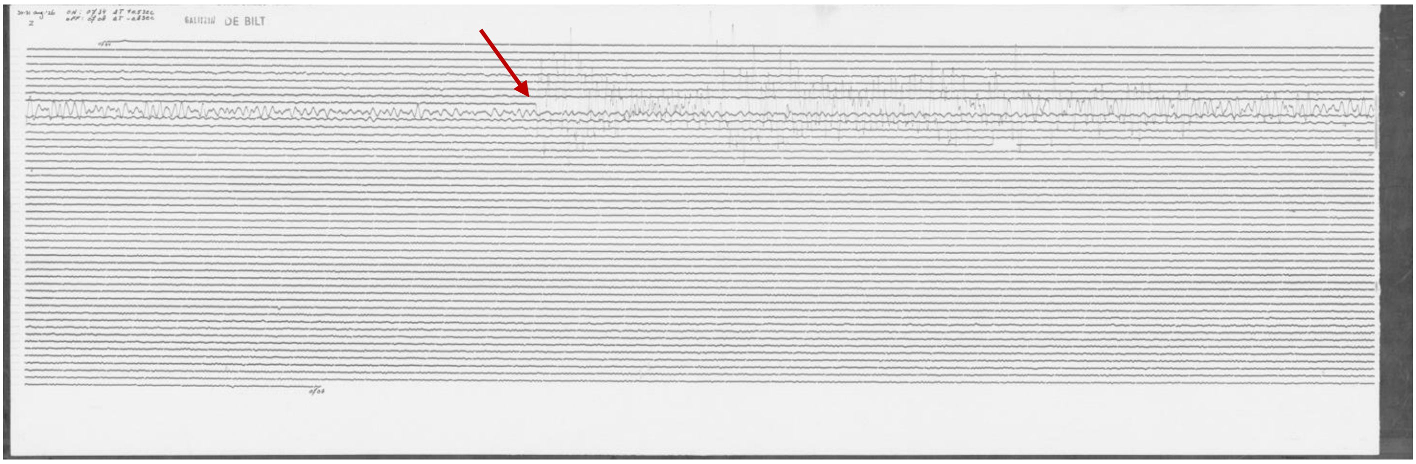

Figure 1. Example of a historical seismogram of a distant earthquake (vertical component) as recorded by De Bilt seismological station in the Netherlands. Red arrow points to first motion (down) in the record. Recording is associated with the 1926-08-30 (11:38 UTC) Sparti earthquake (Barberopoulou et al., 2022). The seismometer location is about 2150 km from the epicenter.

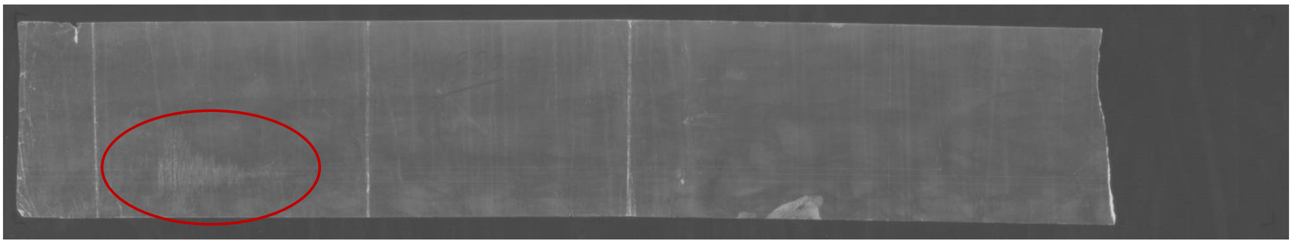

Figure 2. Example of a historical seismogram (EW component) as recorded by Athens (ATH) seismological station in the National Observatory of Athens. A Mainka horizontal pendulum was operating between 1911 and 1963 (NS-EW). The recording is associated with the 1930-02-14 (18:38 UTC) Aitania, Crete earthquake. The seismometer location is about 350 km from the epicenter.

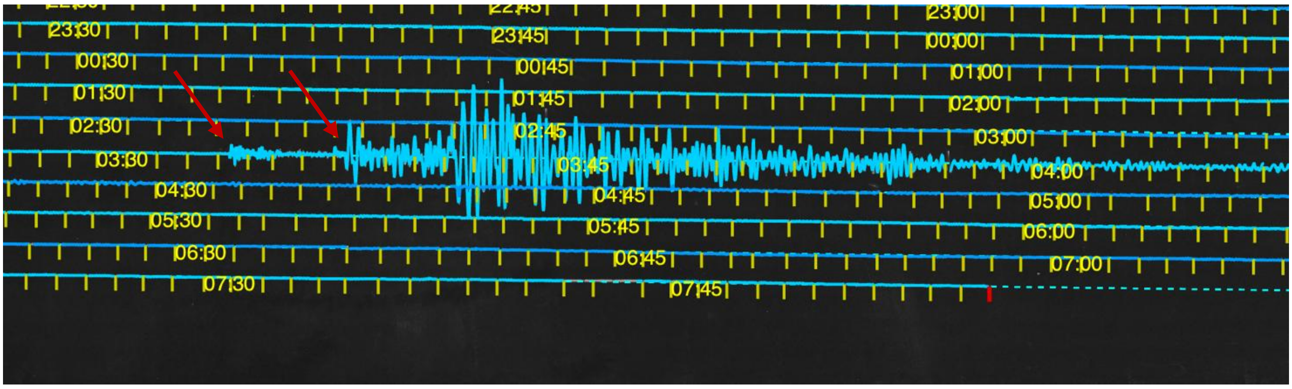

Figure 3. Example of a seismogram in the final stages of digitization as seen from within the DigitSeis interface. Yellow tick marks indicate time marks calculated after absolute times were provided in the program by the user. Seismic waveform is a teleseismic record of the 1953-08-11 (03:32 UTC) Argostoli, Kefalonia earthquake as recorded by the Milne-Shaw instrument operating at the Bidston Observatory (BID) station in the United Kingdom at the time. Red arrows show the arrival of P and S waves in the record.

Acknowledgements

We would like to thank Global Tufts for supporting Sarah Firth.

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Palaeo- Macroseismology and Seismotectonics
17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00048

Is an earthquake scenario compatible with the fall of the 'Grand Menhir Brisé' of Locmariaquer (Brittany, France)?

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Abstract:

The menhir of Locmariaquer lays in four fragments 200 m north of Locmariaquer (Morbihan, Brittany, France). Several hypotheses have been raised over time to explain its fall. This study discusses a potential earthquake origin and investigates the associated ground motion features. The historical seismicity and the current instrumental seismicity support the concept of an active seismic area. Soil and subsurface characterization highlights a complex site response. Several models of the menhir based on archaeological observations are proposed to simulate the dynamic response of the menhir. A ground motion selection from the European Strong Motion database is used as inputs. An earthquake scenario is compatible with the fall of the menhir. The associated Intensity Measures are discussed.

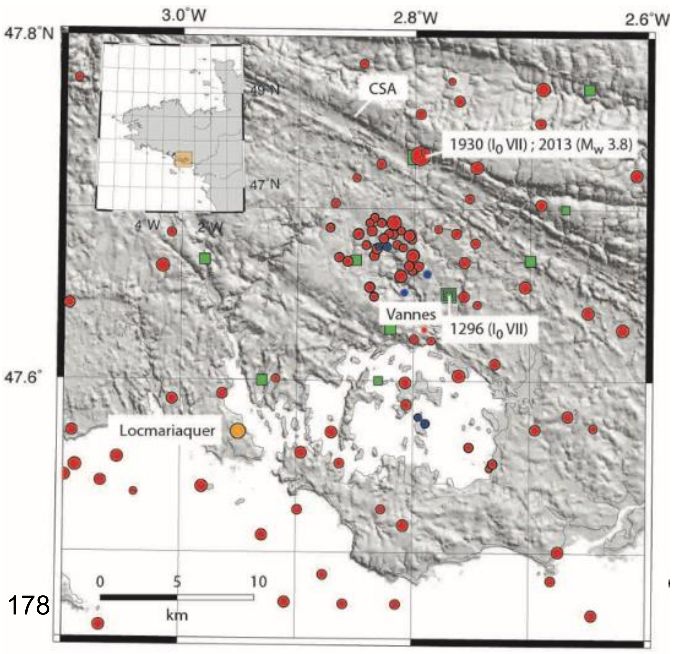
Keywords: Menhir, earthquake, site response, rocking system, Intensity Measures, Archaeoseismology.

Highlights:

- Interdisciplinary research is led to investigate the earthquake hypothesis as an origin to explain the fall of the menhir.
- Rocking systems models are investigated based on archaeological formulation.
- An earthquake is compatible with the fall of the Grand Menhir Brisé of Locmariaquer.

Background:

The 'Grand Menhir Brisé' lays in Locmariaquer in four pieces of orthogneiss. The menhir was more than 20 m in its initial configuration as the largest monolithic bloc erected during the Neolithic period. The origin of its fall is, however, still a matter of debate. L'Helgouach (1983) proposed that the menhir has been voluntarily felled down to reuse the material or for some cultural reasons. Hornsey (1987) defended that the menhir broke during its erection and thus has never been erected again. Hill (1993) proposed a new theory in 1993, assuming that the wind could cause the menhir's fall. Boujot and Cassen (2000) argued that an earthquake could explain its fall Indeed, they identified other megaliths lying in the same direction. Furthermore, the fracture lines of those megaliths do not follow cleavage surfaces which characterize this orthogneiss. Furthermore, no traces of human tools have been found.



Brittany displays a significant intraplate seismic activity mainly distributed along Cadomian (650 – 540 Ma) and Hercynian (370 – 300 Ma) orogenic structures. Historical seismicity is known from the 6th century with the 577 Chinon earthquake (intensity VI MSK-64). Among the most severe historical earthquakes (epicentral intensity of VII-VIII), there are the 1579 Berry, 1711 Loudun, the 1799 Bouin, and the 1930 Vannes events (Jomard et al., 2021). The French modern seismic network RESIF highlights the occurrence of many moderate earthquakes as the Mw 4.3 2002 Hennebont, the Mw 3.8 2013 Vannes, and the Mw 4.0 2019 events (Beucler et al., 2021). Historical and instrumental earthquakes make thus the earthquake a plausible origin to investigate the fall of the menhir of Locmariaquer, located near the South Armorican Shear Zone (CSA in Figure 1).

Figure 1: Location of the 30 historical earthquakes that occurred between 1286 and 1967 (green squares) and instrumental earthquakes (red dots, $M_w \leq 4$).

Objectives:

The study aims to investigate the seismic hypothesis as a potential origin of the fall of the Locmariaquer menhir. Moreover, if so, we aim to test earthquake parameters and characterize ground motion features. Firstly, soil and subsurface characterization will be carried out to study the variability of site response and identify a potential site effect. The response of the menhir is then studied using a simplified rocking system model. The ground motion recorded during the Amatrice and Norcia sequences are used since they provide many records over a wide range of epicentral distances, compatible with those found in Brittany.

Methods

Geological structures are identified using LiDAR and on-site investigation. The two main fault orientations of the Locmariaquer region are N 110 – 120° and N 150 – 160°, respectively associated with the Hercynian orogeny and the opening of the Atlantic ocean. The site response and the subsurface near the menhir are characterized through the deployment of a local seismic network. H/V analysis does not reveal significant site effects, but highlights a strong spatial variability of the site response. Archaeological data reveal the burial of the menhir in a nest, which creates a relationship between the menhir (
Figure **2**-a) and the ground that needs to be considered. To investigate the role played by this burial, two models are proposed: a rectangular block (model 1 in
Figure **2**-b), and a second model taking into account the contact between the menhir and the ground (model 2 in
Figure **2**-c).

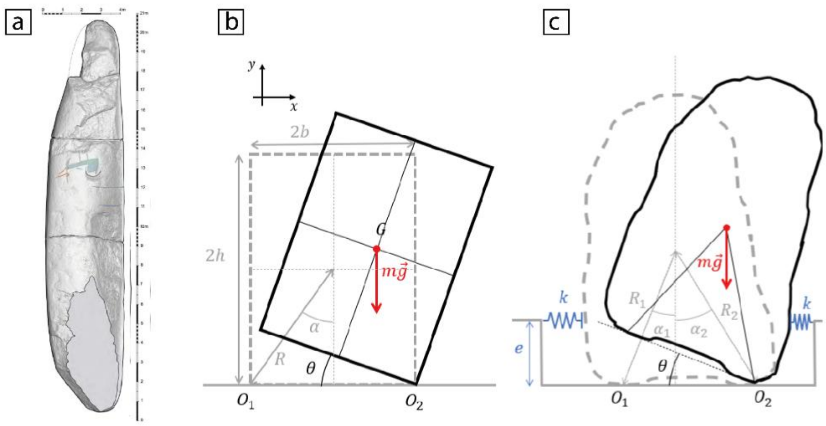


Figure 2: a) Sketch of the 'Grand Menhir Brisé'. b) Model 1: rectangular block model (Housner, 1963). c) Model 2: Buried precarious block model adapted from Shi et al. (1996).

The menhir is modeled as a rocking system. The dimensions of the menhir are extracted from a point cloud (Cassen, 2009; Cassen et al., 2021). The menhir is considered as a rigid block of mass *m*, oscillating on a ground surface, considered a two-dimensional problem. The friction between the menhir and the ground is considered infinite. The ground motion acceleration is noted $a = [A_x(t),\ A_y(t)]$ (

Figure **2**). The menhir is characterized by: its mass *m*, the distance R_1, R_2 between the center of mass G and the points of contact on the ground O_1 and O_2; the angle α_1 and α_2 between (OiG) and the vertical axis; the momentum of inertia I_1 and I_2, around O_1 and O_2 respectively; and the moment of inertia I_0 around the center of mass G. The buried portion of the menhir is modeled by two horizontal unilateral springs of stiffness k representing the stiffness of the soil in compression. They are linked to the menhir at a height e, corresponding to the burial depth (

Figure **2**-c). The equation of motion of the block is different according to the sign of θ. If $\theta \geq 0$, the menhir is turning over 0_1, if not, it is turning around 0_1. The equation of motion around 0_i is expressed:

$$I_i\ddot{\theta} = -sign(\theta).m.\left[g + A_y(t)\right].R_i.\sin(\alpha_i - |\theta|) + m.R_i.A_x(t)\cos(\alpha_i - |\theta|) + k.e^2.\tan(\theta)$$

The block initiates its rocking when the system respects one of the following conditions:

$$A_x(t) > \tan(\alpha_1)\left[g + A_y(t)\right] \; or \; A_y(t) < \tan(\alpha_2)\left[g + A_y(t)\right]$$

The restitution coefficient $r_i = \dot{\theta}_i(t^+)/\dot{\theta}_j(t^-)$ of the block rocking over O_j, and O_i may be expressed as

$$r_i = \frac{I_0 + m.(R_j^2 - R_j.\sin(\alpha_j).R_i.\sin(\alpha_i) - R_j{}^2.\sin^2(\alpha_j))}{I_0 + m.R_i^2}$$

These equations are solved through a Non-Linear Time History Analysis (NLTHA) based on the explicit scheme Runge-Kutta 4. NLTHA starts when the condition of rocking initialization is met, and it stops when θ is out of the bound of stability of the block thus if $\theta > \alpha_1$ or $\theta < -\alpha_2$. The final value of theta allows to identify three states of the menhir: a stable state, a rocking state, and an overturning state.

Seismic records of the Amatrice and Norcia sequences are used from the European Strong Motion database (Luzi et al., 2016). Ground motion is described in terms of nonstructural (Housner Spectrum Intensity, Integral of the Spectral Acceleration, Acceleration Spectral Intensity) and structural dependent Intensity Measures (Peak Ground Acceleration, Peak Ground Velocity, Peak Ground Displacement, Sustained Peak Acceleration 5; Sustained Peak Velocity 5, Cumulative Absolute Velocity, Cumulative Absolute Displacement, Arias intensity, Husid intensity, Root-Mean-Square-Acceleration).

Results

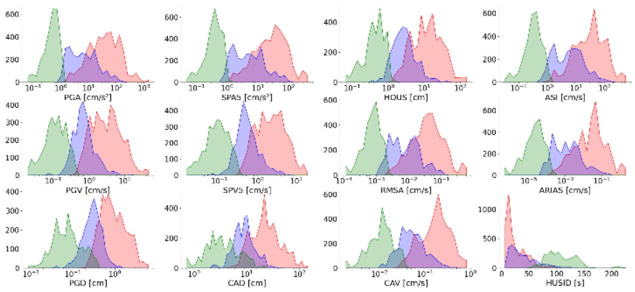


Figure 3: Distribution of the Intensity Measures of the selected ground motion of the Amatrice sequence with respect to the stability of model 1 (Stable in green, rocking in blue, and overturning in red).

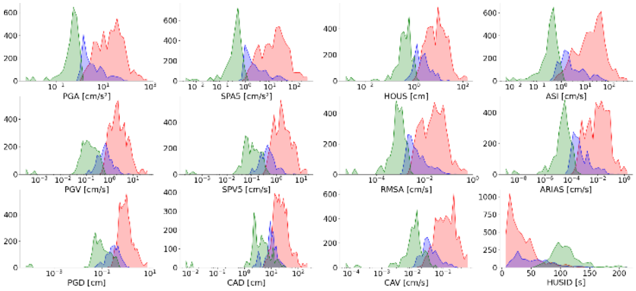


Figure 4: Distribution of the Intensity Measures of the selected ground motion of the Norcia sequence with respect to the stability of model 1 (Stable in green, rocking in blue, and overturning in red).

We considered model 1, 2.29 *m* wide and 20.16 *m* high, for the numerical computation. The impact of the angle of incidence of the earthquake has been studied by rotating the ground motion from 0° to 360° with a simulation every 10°. Figure 3, and Figure 4 shows the distribution of the 12 Intensity Measures calculated for each selected ground motion for the Amatrice and Norcia sequences. All Intensity Measures seem able to discriminate the stable state from the two others (rocking and overturning). However, the Peak Ground Acceleration and the Sustained Peak Acceleration 5 seem to better discriminate the status of stability from the rocking and overturning status. This is consistent with previous equations since it needs to reach a minimal acceleration to start rocking. The Intensity Measures in displacement, such as the Peak Ground Displacements and the Cumulative Absolute Displacement are less accurate to discriminate the stable state from the two others because the distributions of the stable state and the rocking state overlap. The discrimination between the rocking state and the overturning state is more complicated. The Husid, which has the same distribution for the rocking and overturning states for both earthquakes, does not work at all.

Conclusions

This work investigates the earthquake assumption to explain the fall of the menhir of Locmariaquer. Two models with increasing complexity are presented. The last two strongest Italian earthquakes are considered to use ground motions covering a range of moment magnitudes - epicentral distances compatible with the seismogenic area in Brittany. We demonstrate that such an event may induce the fall of the menhir even in a far-field context. The polarization of seismic waves plays an essential role in the seismic response of the menhir. Furthermore, this study shows the impact of ground motion features (IMs) on similar earthquake parameters (Mw-epicentral distance). Among the twelve IMs studied, the PGA and the SPA5 best discriminate the stable state from the rocking state and the overturning state. However, no IM or 2D-vector IM accurately discriminate between the rocking status and the overturning status. Studying vector IM of more dimensions to discriminate between these two states would be interesting.

Acknowledgements

This work (ALEP project) was funded by OSUNA (Nantes University/CNRS). We gratefully thanks the Centre des Monuments Nationaux, in particular O. Agogue, Claire Feuillet, and the staff of Locmariaquer megalithic site, for their help and warm welcome.

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8th International Colloquium on Historical Earthquakes,
Palaeo- Macroseismology and Seismotectonics
17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00049

Revision of moderate Seismicity in Italy during the 1930s. Preliminary results of the year 1930

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Premise

Upon a brief analysis of the Parametric Catalogue of Italian Earthquakes CPTI15 (Rovida *et al.*, 2020, 2022), it becomes evident that the central years of the past century exhibit a significant decrease in seismic activity. This decline in recorded seismic events can be attributed to various factors that affected data collection during crucial periods in history.

The disruption caused by World War II is one such factor that had a profound impact on the seismic data network. The war led to a scarcity of seismic events recorded during that time, as the turmoil and destruction hampered data gathering efforts. Similarly, the subsequent post-war reconstruction years were marked by the loss of essential information.

However, the decrease in seismic activity is not solely confined to the war years. Even in the period preceding World War II, there was a notable reduction in the number of seismic events. The 1930s, in particular, experienced a significant decline in seismic activity, long before the direct impact of the war on Italian territory.

While it is plausible to consider a natural decrease in seismic activity, historical evidence reveals that variations in seismic data were often influenced by social and political circumstances, which significantly impacted data production, dissemination, and preservation. The era of fascist dictatorship, for instance, exerted strict control over the circulation of information, deliberately suppressing certain types of news, including political events and natural disasters like earthquakes (Cannistraro, 1975; Tranfaglia, 2005; Caracciolo, 2021).

Consequently, the Italian seismic catalogue is affected by the human undertaking of recording and interpreting data, which was conditioned by the prevailing political climate. In conclusion, seismic activity is undoubtedly a natural phenomenon, but its documentation and interpretation have been profoundly shaped by the historical context and socio-political influences of each era.

Research aims, methodology and historical sources

The research in question aims to enhance the Italian Macroseismic Database (DBMI, Locati et al., 2022) by incorporating additional earthquake events that were not previously included in the earlier versions of the Italian catalogue (CPTI15). Additionally, the study seeks to update existing records of known earthquakes with new information and macroseismic descriptions.

The research provides macroseismic descriptions of events included in the Italian catalogue (CPTI15), but based only on scanty data from isoseismal maps or drawn from the *Bollettino Sismico*'s appendix "*Macrosismi*" issued by the (Royal) Central Office of Meteorology and Geodynamics (UCMG) (Cavasino, 1928-1936).

The work of reviewing the seismicity of Italy during the 1930s is conducted through the comparison and analysis of three kinds of historical sources:

1st) Newspapers. Actually, this research started collecting news on seismic events from the Italian and some foreign newspapers. Despite being aware of the censorship imposed by the regime, the researchers decided to use newspapers as an alternative source of information. The Italian Seismic Service itself utilized newspapers to gather information on earthquakes. This highlights the importance of newspaper reports as a quite reliable data source. Moreover, to avoid potential censorship, I expanded the sources to include foreign newspapers, particularly those from Austria, France, and Switzerland. These countries' geographic proximity to Italy and the easy online accessibility of their newspapers made them suitable alternatives.

2nd) Administrative Official Documentation. In addition to consulting newspapers, the research also involved the examination of two types of documentation from the Italian Ministry of the Interior, which are stored in the National State Archives in Rome. These two collections provide valuable historical information related to seismic events during the 1930s in Italy. On one hand, telegrams to the Ministry from Local Authorities ("Ufficio Cifra"): This collection consists of telegrams that were sent to the Italian Ministry of the Interior from various local authorities. These telegrams cover a wide range of topics and issues, including information about seismic events. The “Ufficio Cifra” collection is well-known in the field of Historical Seismology. On the other hand, documents stored by a specific administrative office dedicated to earthquake consequences (“Servizi in dipendenza dei terremoti”). This particular collection has not been used in Historical Seismology before, making it a valuable and untapped resource for the current research.

3th) Seismic/macroseismic archive documents. Seismic and macroseismic postcards, along with other documents preserved by the UCMG's Seismic Service and now housed in the INGV's Macroseismic Archive, served as the primary source for the creation of the mentioned appendix “Macrosismi”. However, it is essential to recognize that the relationship between these seismic postcards and the information presented in the Bulletin is not straightforward and linear. It requires a critical reading accompanied by historical analysis tools.

It is not certain that governmental control was exercised over all macroseismic information that reached the Seismic Service from local authorities and other local “observers”.

Nevertheless, it is plausible that in the totalitarian regime's attempt to shape the country's image, there could have been pressure on administrative personnel who provided data to the Seismic Service. While there might not be concrete evidence to confirm this hypothesis, it remains a possibility that cannot be entirely ruled out.

On the contrary, the complaints expressed several times by Cavasino (1928-1936) about the observers who provided information for the bulletins, described as “not very skilled” and their reports as “carelessness” are true.

In any case, the dependence of the UCMG's Seismic Service on external sources, such as mayors and municipal personnel, indeed posed challenges and potential limitations for the accuracy of the collected data, making it particularly vulnerable to political interference that was being experimented in every sector of society at that time. Despite these limitations, the seismic postcards and other documents collected by the Seismic Service remain invaluable for the reconstruction of seismic scenarios during that period.

The methodology employed in this work, which considers almost all events registered in the Italian catalogue (CPTI15) and all events mentioned in different historical sources, is a highly effective approach for understanding Italian seismicity during the specified period. This strategy allows, with a deeper knowledge of the social, cultural and political context, a better and more efficient use of the historical sources. As a result, intertwined data and critical analysis enables to obtain a whole new and comprehensive picture of Italian seismicity of this period.

Some preliminary results: seismicity in the year 1930

In this paper, a summary of the results corresponding to the first year of the mentioned decade, which is 1930, will be presented. According to the CPTI15, a total of twenty-five seismic events are recorded for this year. Out of these events:

- Six have epicenters located outside the Italian territory.
- Five events lack macroseismic data, possibly due to limited reporting or unavailable records.
- Nine events are classified with an intensity level of ≥ 6 MCS, which indicates that these earthquakes caused damages.

With the exception of the two strongest earthquakes, which occurred on July 23rd in Irpinia and October 30th off the Coast of Marche, all other seismic events from the year 1930 have been taken into consideration in this study.

As a result of the research I have compiled sixty-nine files corresponding to almost eighty events (some of them are included in the same file because they belong to a single sequence). That is more than three times the number of events gathered in the Italian catalogue CPTI15 for 1930. Forty-two events are included in the *Bollettino Sismico – Macrosismi*; yet they are now compared and analyzed with the new sources (seismic postcards, newspapers and ministerial documents). All these “new” events do reach the minimum threshold in CPTI15, that is Intensity ≥ 5 MCS. Seven records correspond to events that are not present in the *Bollettino Sismico- Macrosismi*, nor in the PFG catalog (Postpischl, 1985, which condensed older catalogs and it was the support for the newer ones).

Three events with no macroseismic data were provided with macroseismic data points (Carniola Interna 25.02.1930; Tirol, 7.10.1930), while others earthquakes were not perceived, as that of the Adriatic Sea (30.04.1930) or were “fake” as that of the Reggiano (24.09.1930).

Most of the earthquakes recorded in the mentioned Italian catalog for 1930 had only a list of localities with none or very poor macroseismic descriptions. In this revision they were provided with information supplied by the different sources, especially from the macroseismic postcards.

Three cases

In this paper, I will focus on the preliminary results of three events that share a common characteristic – all three are "border" events: Cadore on May 14th, Tirolo on October 10th, and Crete's sea on February 14th. However, these events are quite distinct when viewed from the perspective of the CPTI15 catalogue.

The first event, Cadore, exhibits a well-defined epicenter within the Italian territory and has a set of macroseismic points available. On the other hand, the second event, Tirolo, lacks any macroseismic data in the catalogue, and its epicenter is situated in Tirol, Austria. Interestingly, the third event is absent from the Italian catalogue due to its epicenter falling outside the CPTI15 considered area, yet it resulted in extended macroseismic effects (although no damages reported) in Southeastern Italy. Despite similarities and differences, these three earthquakes show the links between catalogues and seismic historical research fields.

- The first event, known as the Cadore earthquake of 14th May 1930, is recorded in the CPTI15 catalogue with 25 macroseismic data points (MDP), an Imax = 6 MCS, and a moment magnitude (Mw) = 4.89. The location of the epicenter suggests that the earthquake's effects might have been perceived on the other side of the Italian-Austrian border. Austrian newspapers showed indeed that the earthquake shook a large area, and that it causes many damages in a few Austrians towns, few kilometres beyond the Italian border. A first revision of this earthquake (Caracciolo, 2019) showed 82 MDP with an Imax = 7, and a Mw = 5.07.
- The second event is recorded in CPTI15 as the Tirol-Namlos earthquake of 7th October 1930, without any macroseismic information, but with a Mw = 5.33 and an Io = 7-8. In this case, the Austrian newspapers consulted during the research gave most of the data about the event. They mention more than 160 localities, with an Imax = 7.
- The third event was a strong earthquake in the Crete sea. According to the European Earthquake Catalogue (Grüntal et al. 2018), its parameters were: Mw = 6, and an I = 7 and a hypocentre of 91 km. Nevertheless, according to the different newspapers, it caused many damages on the island and it was felt also in the coast of Northern Africa. In Southern Italy, particularly in Sicily, Calabria and Puglia, it was felt in at least 33 localities.

Conclusions

The strategy I adopted for the revision of Italian seismicity during the thirties of the last century has yielded significant results. On one hand, it led to a complete redesign of the Italian seismicity picture for a single year, multiplying the set of data and modifying many of the known information. On the other hand, the three earthquakes I chose as examples demonstrate the potential for improving the knowledge of historical seismicity. These enhancements are the product of a methodology I developed, which aims at an integral review of seismic activity and then building a new picture of Italian seismicity for a given period. It is a strategy that exploits the advantages of a deeper knowledge of the historical conditions and of a more effective use of historical sources. The same methodology turns out useful for the rest of the decade.

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Information About the Macroseismic Field in Cyprus From Antiquity to XX century

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The area of Cyprus is in the Eurasian-Melanesian zone of the continental fracture system and the Cyprus arc is among the characteristic arcs of the system. That is, the area of Cyprus is in the convergence boundary of the Eurasian and the African and Arabian lithospheric plates. This is the main reason of the high tectonic activity in this region. Information on historical earthquakes for Cyprus exist since the 1st century BC. The map in figure 1 gives information on the seismic activity of the area of Cyprus. Different symbols used to represent the instrumental (solid circles) and historical (open circles) events.

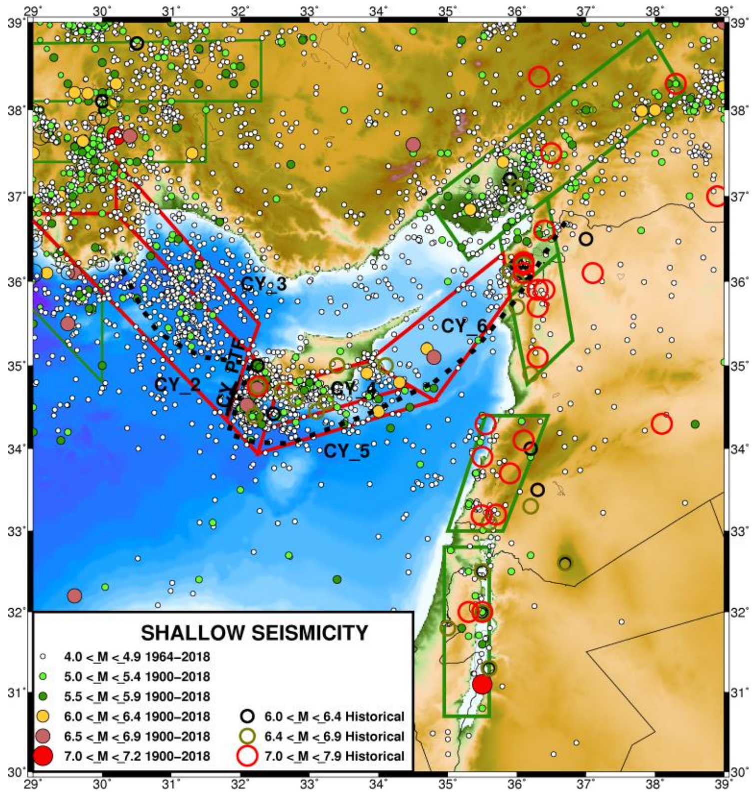


Figure 1. Historical and instrumental seismicity in the broader area of Cyprus. The Paphos fault and the Cypriot arc are also shown.

In the same map (figure 1) the seismic sources model (Papaioannou, 2001) is also shown. The most active seismotectonic unit in the broader region, where the highest seismic activity takes place, is the Paphos Transform Fault (PTF, Papazachos and Papaioannou, 1999).

The high seismicity, combined with the long-standing cultural activity in the island resulted in the compilation of various reports and studies on the effects of earthquakes.

The first known earthquake in the area took place in 15BC, causing damage to the area of Paphos (Ambraseys, 1963; Guidoboni et al, 1994). The map of figure 2 shows the geographical distribution of the localities with reported effects of strong earthquakes. The distribution of the reported intensities in Cyprus is shown in the frequency histogram of figure 3. The maximum macroseismic intensity (X in MM scale) is associated with historical events.

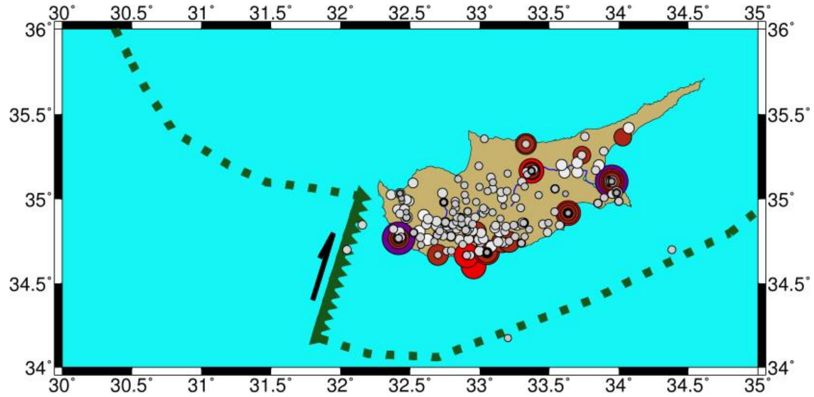


Figure 2. Sites with reported macroseismic observations. Colored circles denote data of historical era, while grey symbols correspond to the instrumental period.

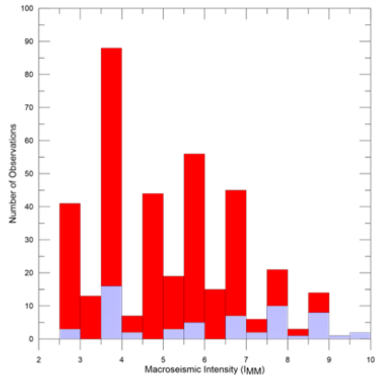
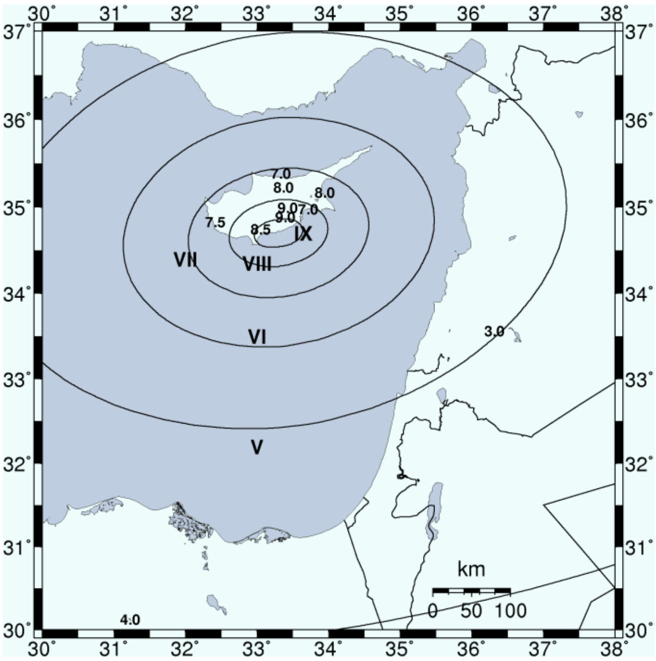


Figure 3. Frequency histogram of the macroseismic intensities. Solid red columns stand for the instrumental era, blue crosshatched represent the historical data.

The intensity data were used for the estimation (approximation) of the main focal parameters (epicentral coordinates, focal depth, magnitude) of the various historical events. In the case of more than 6 Intensity Data Points (IDP) from a given earthquake the focal parameters were determined applying the procedure of Papazachos (1992). This method is based on a model, which assumes anisotropic radiation of the seismic energy at the source as well as geometrical spreading and anelastic attenuation of this energy. The errors in the determination of epicenters of the strong earthquakes, which occurred during the historical period, can be up to 20 km except for the cases when only a few intensity values are available. Even in these cases the errors are usually less than 30 km because the corresponding site of observation is within the rupture zone since $I_O \geq$ VIII.

The application and the results of this methodology for selected strong earthquakes is shown in the maps of figures 4 and 5.



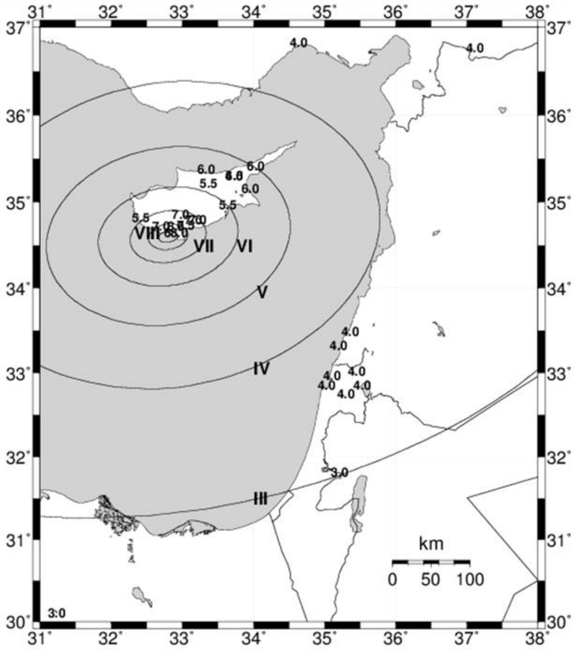


Figure 4. Macroseismic field of the earthquake of April 24, 1491.

Figure 5. Macroseismic field of the earthquake of June 29, 1896.

The statistical treatment of macroseismic data can be used for the validation of probabilistic seismic hazard results and the evaluation of the reliability of the input source models.

The graph in Figure 6 shows the distribution of the cumulative number of the observed macroseismic intensities for the city of Paphos, considering the following completeness criteria: 342 – 2020 $I_{MM} \geq$ IX, 1491 – 2020 $I_{MM} \geq$ VII and 1896 – 2020 $I_{MM} \geq$ VI.

From the graph in figure 6 it is clear that the intensity values follow a hyperbolic distribution as many physical phenomena and, therefore, the seismic hazard curve can be determined. The comparison with PSHA (Probabilistic Seismic Hazard Assessment Fig.7) curve shows deviations not exceeding 0.5 intensity unit, which can be considered as acceptable and within the uncertainties of the macroseismic intensity estimations.

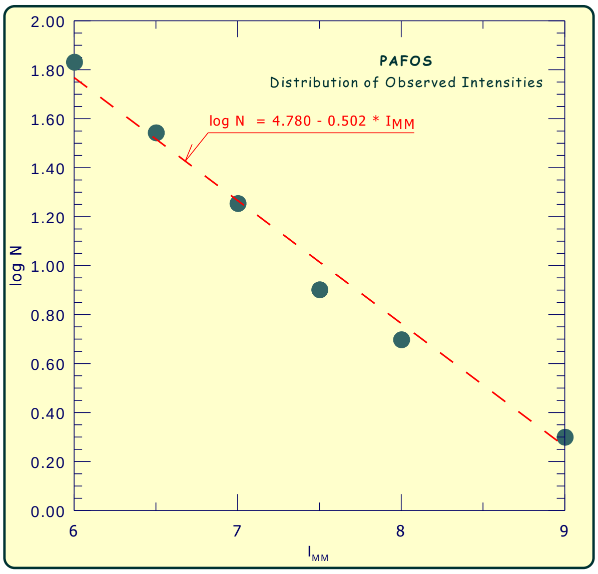


Figure 6. Distribution of observed Macroseismic Intensities for the area of Paphos for the period 342-2020.

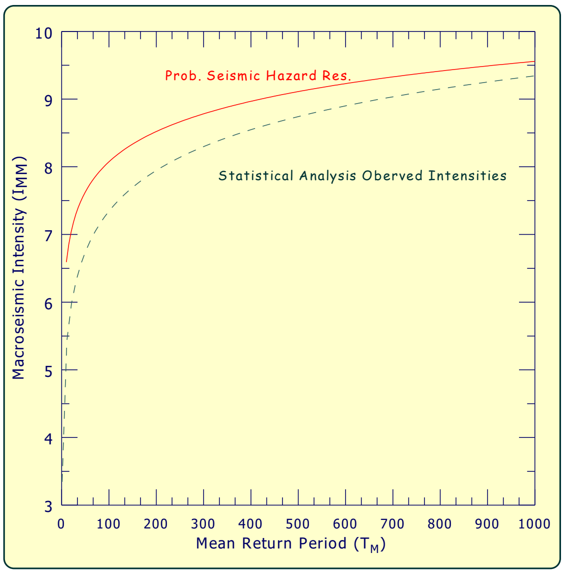


Figure 7. Comparison of the hazard curves based on PSHA and statistical treatment of observed IDP for Paphos area

The available data set of IDP, for the area of Cyprus can be used for the quantification of historical and early instrumental period earthquakes. Complete data of macroseismic observations can be used also for the evaluation of the PSHA results.

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8th International Colloquium on Historical Earthquakes,
Palaeo- Macroseismology and Seismotectonics
17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00051

Coastal changes, the 1953 earthquakes, and palaeoseismic events of Cephalonia

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The 1953 seismic sequence in Cephalonia included a major shock with magnitude M=7.2 and a major foreshock with magnitude 6.8. The overall effect of the seismic sequence was destruction of maximum intensity X: about 80% of the buildings in Cephalonia, Ithaki, and Zakynthos (Zante) Islands which were partly abandoned after the earthquakes, were destroyed. Damage extended also to the mainland (Papazachos and Papazachou, 1997). The geographical scale of destruction was unseen in the history of modern Greece. The instrumental recordings of the 1953 seismic sequence are, however, poor. For this reason, a study of this seismic sequence in the 1990's was based on coastal changes. This study was inspired by a report of Galanopoulos (1955) for seismic uplift at the harbour of Poros, at the eastern of Cephalonia (Fig 1a), as well as along the south coast of the island, east of Argostoli.

This study, summarized in Stiros et al (1994) and Pirazzoli et al (1994) revealed that the central part of Cephalonia was uplifted by 30-70cm (Fig. 1b), and that another major uplift palaeoseismic episode occurred between AD350 and AD700 (AMS dating). This last event cannot be correlated with historical earthquakes, because, in contrast with other parts of Greece, no information for seismicity in the Ionian Islands is available till approximately 1400.

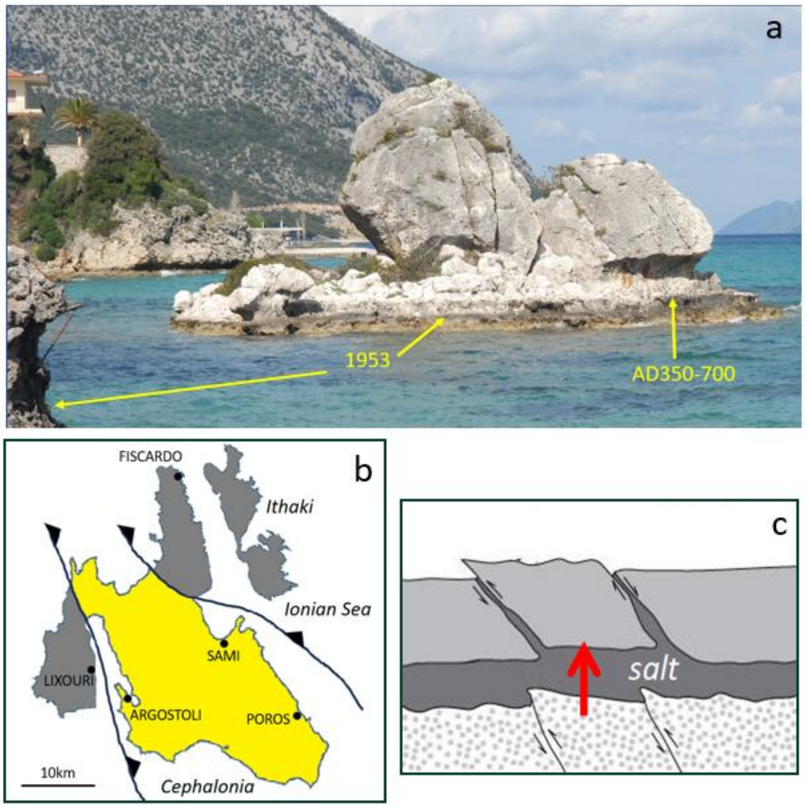

Figure 1. a: A rocky islet in Poros (location in (b)) preserving signs of uplift in 1953; a palaeoseismic event, dated between AD350-700 was also identified. b: Pattern of the 1953 seismic uplift. The uplifted area (in yellow) is bounded by thrusts. c: A conceptual model to explain the 1953 uplift as a result of earthquakes causing

mobilization of evaporites (salt etc.) in a detachment layer and intrusions along faults. Cross section in a nearly SW-NE direction.

Observations of coastal uplift

Observations of coastal uplift were possible only on rigid carbonate coastal rocks, in which geomorphological signs of bio-erosion (notches and micro-benches) and biological remains survive. No signs of biological accretions exist in this region. The tidal range is nearly null. The focus of the study was the identification of the apex (central, deepest point) of bio-erosion notches which correlates with the upper line of specific species, defining a local Biological Mean Sea Level (BMSL). This level was identified in various spots both in living species (active BMSL) and in fossil, uplifted species (fossil BMSL). Their height difference defines the amplitude of a rapid coastal uplift, seismic uplift in our case. AMS dating of selected fossils defines the time of the earthquake. If an uplift is slow, gradual, biological remains are erased because of intense erosion below the BMSL ("mid-littoral zone", the width of which depends on wave energy), while the height of the notch increases. In the case of rapid, co-seismic uplifts exceeding a minimum amplitude, the notch opening is small and biological remains preserved. Hence, micro-morphological and biological observations permit to recognize a rapid, seismic coastal uplift with amplitude higher than 10cm in nearly tideless waters. This was the case with Cephalonia.

Coastal changes during the 1953 earthquakes

The most spectacular cases of the 1953 uplift were found in two sites. In the Poros harbour, where a small rocky islet was uplifted by about 70cm (Fig. 1a); and in the Argostoli sea-mills, where the sea water was flowing into a karstic void generating power for a factory, till the seismic uplift, about 30cm, interrupted the water flow. The detailed study of the coasts based on micro-morphological, biological, and AMS radiometric data, as well as reports just after the earthquakes, revealed that the central part of Cephalonia was uplifted in 1953 (Fig. 1b) by 30-70cm, but with high variability (see Stiros et al., 1994). No uplift was found in the northernmost peninsula and in Ithaki, which tends to subside. In all these areas coasts are marked by hard limestones preserving signs of coastal activity. Because of the type of geological formations, no observations of coastal change were possible along the costs of the western (Lixouri) Paliki peninsula of Cephalonia. At least in the SE part of this area, however, there is stratigraphic evidence of Quaternary uplift. Still, a few harbour sites provided no signs of uplift or of subsidence.

Older coastal change events

In the wider Poros area, above the 1953 shoreline, an older, uplifted shoreline is observed at the height of up to 1.20m (Fig. 1a). This fossil shoreline was dated between AD350 and AD700. Perhaps this shoreline corresponds to undated shorelines found at the depth of 50-60cm in the vicinity of Argostoli and of Sami (for location see Fig. 1b). If this hypothesis is correct, the SE part of Cephalonia was tilted NW-wards during this palaeoseismic event.

Tectonic pattern of the 1953 earthquakes

The part of Cephalonia deformed during the 1953 earthquakes is bounded by major thrusts, but the overall pattern cannot be easily explained as an elastic dislocation, implying uplift and subsidence at the two sides of an activated fault. The variability of the amplitude of the uplift is also hardly consistent with an elastic dislocation.

The explanation for the pattern of seismic uplift should be searched in the geological particularity of the region. The Ionian Sea where Cephalonia is located, is characterized by east-dipping, NNW-trending thrusts, mostly cutting through limestones. There is, however, evidence that a layer of salt and of other evaporites forms a detachment layer at a depth of a few kilometers (Fig. 1c). In some of the faults, evaporites reach the surface (Underhill, 1989).

Evaporites appear as solid rocks. Still, evidence from various regions indicates that, in the long term and at high-strain rates (during strong earthquakes), evaporites are mobilized and they tend to behave as a viscous fluid; they tend to form anticlines above hydrocarbons and to flow through faults till they reach the ground surface.

On these grounds, the fault pattern of the 1953 earthquakes can be schematically summarized in Fig. 1c. This involves possible reactivation of the evaporites at the detachment level and along the faults, the surface of which is "lubricated", enabling a piston type-motion during the strong motion. The overburden is not deformed as a rigid block, and this explains the variability of coastal uplift which is likely to characterize the whole uplifted area. This was an extra reason for seismic damage.

Variability of seismic intensities

A contrast in seismic intensities characterized the 1953 earthquakes: The northernmost peninsula of Cephalonia was left essentially unharmed, while some kilometers to the south, just south of an inferred reactivated fault, and to the east, in Ithaki, destruction was nearly total. Such a contrast does not seem unusual in Cephalonia, as some evidence from historical data indicates. For example, during an earthquake that occurred in 1915, the northern part of Ithaki and a wider area was seriously damaged, but not the northern peninsula of Cephalonia. A possible explanation is the attenuation of seismic waves hitting a fault with evaporitic intrusions from specific directions.

Other implications

Cephalonia represents, among others, a geological laboratory to investigate active diapirism from salt and other evaporites; this is critical, first, for hydrocarbon exploitation, because, with few exceptions, in a global scale, evaporites are confined to tectonically stable areas. Second, for salt mining (mainly cases of bursts).

Evaporites in the Ionian Islands may also have a cultural significance, because Asteris, the only island described by Homer, the location of which is a matter of debate, may be identified with an emerged evaporitic islet not far from Cephalonia (Stiros, 2023).

Acknowledgements

This study was primarily made in cooperation with Paolo Pirazzoli and Jacques Laborel who have passed away.

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8th International Colloquium on Historical Earthquakes,
Palaeo- Macroseismology and Seismotectonics
17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00052

A repository of documentary material dedicated to the earthquakes of Kefalonia

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The idea of developing a repository occurred in the very beginning of establishing a collaboration between the National and Kapodistrian University of Athens research team and the Municipality of Lixouri, in the framework of the NSRF project "KNETSEISRL - Development of Knowledge NETworks for SEISmic disaster Risk, Lixouri". The aim of the project is to create the earthquake archive of Kefalonia, to be hosted in the "Lixouri Centre for the Study of Earthquakes and Risk Reduction due to Natural Phenomena". The information provided in the sources of the archive enables to acquire the best possible knowledge of each earthquake's process, including the seismogenic fault, and its source parameters. This will lead to an updated earthquake catalogue of Kefalonia - Ithaki area and, therefore, its updated seismic hazard assessment.

To accomplish this aim, it was considered necessary to set up an interdisciplinary experienced working group, as such research requires specialized knowledge. The project involves support via networking of regional, national and international experts of research bodies from Italy and Spain and implementation of infrastructure to host international research teams and small scientific conferences.

Discussion and exchange of information between the working group members revealed the existence and potential of a considerable volume of material to be considered when dealing with the earthquakes of the Ionian Islands, specifically of Kefalonia.

The majority of available sources in Lixouri are in Greek, comprising of a large number of local newspapers since 1830, Athens newspapers, an extensive collection of photographs mainly related to the 1953 earthquakes, numerous historical books, geographies, commemorative volumes, monographies and reports dedicated to the 1867 earthquake, manuscripts, old maps, sketches, etc. It is worth noting here that Lixouri has had a long cultural tradition in the last two centuries, apparent in its rich production in literature, history, music, etc. Earthquakes are part of this culture, frequently influencing the local society.

The material in Athens (NKUA) is mainly seismological; collection of modern seismological papers, compilations and catalogs, historical earthquake databases (AHEAD: Albini *et al*., 2013; HMDB.UOA: Kouskouna and Sakkas, 2013), classical seismological catalogs, special volumes on historical earthquakes, historical earthquake sources and related studies, special volumes, geological maps, etc.

The Greek texts of local writers are more detailed, with knowledge of placenames, of the locals who suffered and include information on the local authorities' actions. The texts located in the Italian archives are related to the ruling of Venice (e.g., the Venice state archives) and England in Kefalonia, containing material important for macroseismic intensity assignment, such as damage reports to the central authorities, management of operations, manuscripts, compensation claims, occidental newspapers articles on earthquake effects, etc. The working group is expected to locate more sources related to the Kefalonia historical earthquakes. For example, a rich collection of earthquake information is included in rare textbooks (e.g., "Terra Tremante", the listing of earthquakes written in the 16th and 17th centuries by Bonito, published in 1691), as well as reports compiled or preserved through the centuries by Jesuit monks, are available in Spanish libraries.

A general categorization of the material available is listed in Table 1, following the AHEAD standards. Separate excel sheets are compiled for each one of the three main categories, including the source info, keywords and a more detailed definition of the source (e.g., description of effects, on intensity, scientific interpretations, etc.).

Table 1. Types of sources of Kefalonia historical earthquakes

Source type
Modern scientific papers
Historical and geographical works
Primary and contemporary (to the earthquake) sources

Most major historical earthquakes of Kefalonia – Ithaki area are included in the catalogs of historical earthquakes (SHEEC: Stucchi *et al*., 2013; EPICA: Rovida *et al*., 2022) and in AHEAD and HMBB.UOA databases. However, there are new sources providing detailed information on the date, time, effects at more localities or aftershocks, or simply verifying the event. In what follows, we are presenting two such case studies.

The Kefalonia earthquake of 22 (11) July 1766

This destructive earthquake in the area of Paliki, Kefalonia, is studied in detail by Albini *et al*. (1994), also quoted by Ambraseys (2009). Both studies agree on the event date: 22 (N.S.) July 1766, commenting that the Gazette de France places it on 24 July. We located in Lixouri the English "Pope's Bath Chronicle", dated 25 December 1766, briefly referring to this earthquake (Table 2). The date given is July 24, in agreement with the European press and the number of fatalities is verified. The chronicle mentions that the land was in motion for 50 days, without any reference to the vortex of wind that preceded the earthquake.

Table 2. Two sources of the 22 (11) July 1766 Kefalonia earthquake.

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POPE'S Bath Chronicle
Printed and publish'd by CORNELIUS POPE, in St. James's-Street, BATH.
THURSDAY, DECEMBER 25, 1766.

On the 24th of July (1766) we felt a violent shock of the earth which lasted three minutes and was followed the same day by three other light shocks. The land has continued in motion for 50 days, and we still often feel
</td>
<td>
Albini et al. (1994b)
1766 July (11) 22
A destructive earthquake in Kefalinia. Preceded by a foreshock before dawn, the main shock occurred one hour after sunrise on 11 July 1766 (O.S.) lasting, with intermissions, three minutes. The earthquake was followed by three other shocks during the same day.
The western part of Kefalinia suffered most. A manuscript note from Michalitzata (Vergotis, 1867) says that most of the houses in the district of Paliki were destroyed and those left standing were damaged. It adds, however, that 52 days earlier (20 May 1766 O.S.) the south part of Paliki had suffered from a whirlwind of unprecedented violence which did great damage. Contemporary reports (ASVe, 1766a, b, c) confirm that the damage caused by high winds, which persisted for 13 minutes, was enormous. The combined damage caused by the earthquake and the wind was such that many families left Paliki and settled in the Morea (Peloponnese). The seriousness of the situation in Kefalinia is testified by a petition to the Collegio produced by Niccolò Salomon, tax-farmer of that island (ASVe, 1766g): the Collegio recognized the right of his query and asked to the Senato to approve the diminution of his debt for the year 1766.
Earthquake damage extended to Assos (ASVe, 1766e, f), Lixuri (ASVe, 1766b) and Argostoli where among other buildings the Latin church of San Nicolò in Argostoli (ASVe, 1766d) and a number of manor houses were ruined (Fig. 4). In all about 20 people were killed in the island.
The earthquake was also experienced in Zante: a European traveller who happened to be in quarantine describes the shocks as very strong but he does not mention any damage done in the town (Chandler, 1776). There is some evidence, however, that the earthquake did cause the collapse of a few houses in other parts of Zante (Tsitselis, 1904). It is said that the shock was also felt in Ithaca (Vergotis, 1867). Aftershocks continued more or less for 2 months (Gazette de France, 1766;
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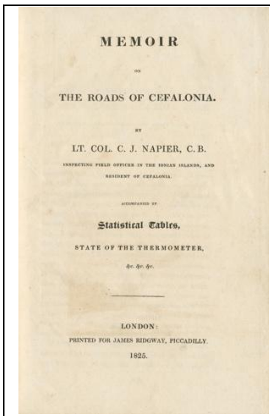
pretty considerable shocks. Many houses have been thrown down, and the rest are nearly all damaged, so that we are obliged to lie in the open fields. The shocks have been general throughout the island, as well in the plains as the mountains; and about 20 persons have perished.	ASVe, 1766b). Some modern writers date this event to 11 May, 11 June and others place it on 24 July (N.S.), which is the date given by the European press (Gazette de France, 1766).

The Kefalonia earthquakes of the period 1822-1824

Charles James Napier's most interesting memorandum concerns Kefalonia's road system. At the end of the text, he provides detailed temperature charts and earthquake information for every trimester. Napier was a British Army officer and politician, who served as governor of Kefalonia for eight years. At least 35 shocks are felt in Kefalonia in the period 29 March 1822 to 28 February 1824, most of which are considered as "new", minor events, although some are described as "smart" shocks. One of them is reported by Albini (2020) in AHEAD as the 19 June 1823 Sagiada (W. Greece) event, therefore one Intensity Data Point from Kefalonia is added. The other case is a series of events in October 1823, also reported by Albini (2020) in AHEAD. These two cases are marked in red in Table 3.

Table 3. Napier's total list of earthquakes and the 3 AHEAD cases.



MEMOIR

ON

THE ROADS OF CEFALONIA.

BY

LT. COL. C. J. NAPIER, C.B.

INSPECTING FIELD OFFICER IN THE IONIAN ISLANDS, AND RESIDENT OF CEFALONIA.

ACCOMPANIED BY

Statistical Tables,

STATE OF THE THERMOMETER,

&c. &c. &c.

LONDON:

PRINTED FOR JAMES RIDGWAY, PICCADILLY.

1825.

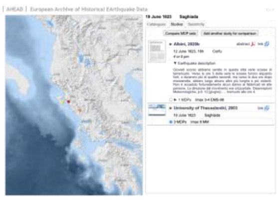
90 THERMOMETER AT ARGOSTOLI.

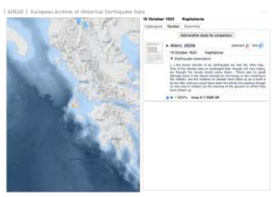
AVERAGE STATE OF THE THERMOMETER AT ARGOSTOLI, In the Island of Cefalonia, during the Quarter ending 20th Dec. 1824.

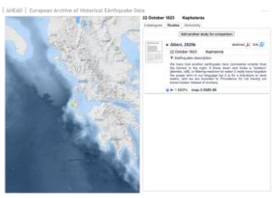
Dates.	Thermometer. Max.	Med.	Min.	Wind.	Weather.
Oct. 20.	82	76½	71¼	S. & S. E.	Cloudy and rainy from 21st September to 27th. 29th and 30th clear: from 1st to 4th October sky dusky, with hot winds from S. E.: clear the remainder of the month, except the 6th, 7th, 11th, and 19th October, which were cloudy and rainy. Six shocks of earthquake were felt during this month.
Nov. 20.	77½	66¼	55¼	N. & S. E.	Clear weather from 21st October to 29th: cloudy and rainy from 30th to 4th November: remainder clear and cloudy, with rain alternately. Some snow fell during this month. Three shocks of earthquake were felt during this month.
Dec. 20.	66	60	54	Northerly	Clear weather from 21st November to 12th December, except the 3d, 4th, and 10th, which were cloudy and rainy: remainder clear. Two shocks of earthquake were felt this month. A quantity of snow fell this month.

QUARTER ENDING 20th MARCH, 1824.

Dates.	Thermometer. Max.	Med.	Min.	Wind.	Weather.
Jan. 20.	63	59½	36	N. & S. E.	Cloudy and rainy, with thunder and lightning, from 21st to 26th December: clear, 27th, 29th, and 30th. Cloudy and rainy, from 31st December to 7th January. Remainder of the month clear weather, except the 16th and 17th, which were cloudy, rainy with thunder and lightning. A slight shock of an earthquake the 1st January at two o'clock P. M.
Feb. 20.	60	56	52	N. & S. E.	Nearly the whole month cloudy and rainy, attended with thunder and lightning, and heavy showers of hail. A great quantity of snow fell this month, on the E. and S. E. mountain.
March 20.	65	62½	57½	S. E. & S. W.	Clear and cloudy alternately, with rain during the cloudy weather, till 6th March: clear till 10th, the remainder cloudy and rainy. A smart shock of an earthquake was felt the 21st February, at twenty minutes before eight o'clock, P. M., and two other slight ones the 27th and 28th. The former at three P. M. and the latter at five A. M.







A shock of an earthquake was felt the 29th of March (1822), Saturday, 3 o'clock P.M.

A shock of an earthquake was felt the 19th of June (1822), at 10 o'clock P.M.

A slight shock of an earthquake was felt the 17th July (1822), at 12 o'clock at night.

A shock of an earthquake was felt the 2nd of August (1822), at half an hour after mid-day

A slight shock of an earthquake was felt the 12th September (1822), at half past six o'clock P.M.; and another the 18th, at half past nine o'clock A.M.

Two shocks of earthquakes were felt this quarter (ending December 20, 1822), the first the 21st September, at half past 4 A.M., the other the 29th November at half past 7 o'clock P.M.

A shock of an earthquake was felt the 26th December (1822), at 8 o'clock A.M.

A shock of an earthquake was felt the 29th January (1823), at 2 o'clock P.M.

Three shocks of earthquakes were felt this month (**1823**), the first the 2nd of **June** at midnight, the second, the 12th at four o'clock P.M. and the third the **19th, at half-past one o'clock, A.M.**

A smart shock of an earthquake was felt the 10th July (1823) at mid-day.

Two shocks of earthquakes were felt the 13th September (1823). On the 18th, 13 or 14 motions of the earth were felt during the day and night.

Several shocks were felt daily, during the 19th, 20th, and 21st September (1823).

Six shocks of earthquakes were felt during this month (October 1823).

Three shocks of earthquakes were felt this month (November 1823).

Two shocks of earthquakes were felt this month (December 1823).

A slight shock of an earthquake the 1st January (1824), at two o'clock P.M.

A smart shock of an earthquake was felt the 21st February (1824), at twenty minutes before eight o'clock, P.M., and two other slight ones the 27th and 28th. The former at three P.M. and the latter at five A.M.

Acknowledgements

We acknowledge funding by the “New technologies, research and innovation for the creation of poles of attraction” project in the framework of the National Strategic Reference Framework (NSRF) 2014-2020, Regional Operational Programme “Ionian Islands 2014–2020”.

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8th International Colloquium on Historical Earthquakes, Palaeo- Macroseismology and Seismotectonics

17-20 September 2023 - Lixouri, Greece

Bulletin of the Geological Society of Greece, Sp. Publl. 11

Ext. Abs. 00054

Macroseismic revisiting the 1953 Kefalonia great earthquakes

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The Ionian Islands Kefalonia, Ithaki, Zakynthos and Lefkada have experienced destructive earthquakes, with considerable damage to infrastructure and population loss. The most significant and destructive event of the broader area occurred on 1953, 12th of August, with magnitude Mw=7.0, preceded by two others, on 9 and 11 of August, with magnitude Mw=5.9 and Mw=6.6, respectively (Makropoulos *et al.*, 2012).

The first shock lasted about 12 seconds and ruined Ithaca, the north part of Kefalonia and south Lefkas. Most of the buildings in Kefalonia collapsed, mainly those situated in the south and south-eastern part of the island, while those situated to the north experienced minor damage. Damage varied from place to place and depended on the vulnerability of the structures and on their foundation conditions: rural houses in the villages which are founded on thin alluvium were totally destroyed while the well-built houses founded on limestone, suffered little or no damage.

The second and largest shock which added to the damage on Ithaca and caused new damage on Kefalonia and on northern Zante. The shock caused serious damage and casualties in Argostoli, where 70 percent of the building stock became uninhabitable, and also at Lixouri and Sami which were almost totally ruined. Damage extended to the south on the island of Zante. In Ithaca, many houses damaged by the first foreshock, collapsed.

The third earthquake of the series in the Ionian islands brought about total destruction. The island of Kefalonia was already heavily damaged by the previous shocks and the fires that followed them, was totally ruined. In the island of Zante only 28 houses were left intact, among them the National Bank and the church of Saint Dionysius, both designed and built to resist earthquakes. Also, the capital of the island was almost totally ruined not only by the shock but also by the fires that followed and which could not be extinguished because of destruction of the water supply system. In Ithaca the cumulative damage left only 400 houses intact. On the island of Lefkas no houses collapsed, but many were heavily damaged or suffered reparable damage. In the provinces of Aitolia and Elis, on the mainland, some houses collapsed. These earthquakes resulted in a great disaster which has been recorded in scientific journals, books and published diaries of survivors.

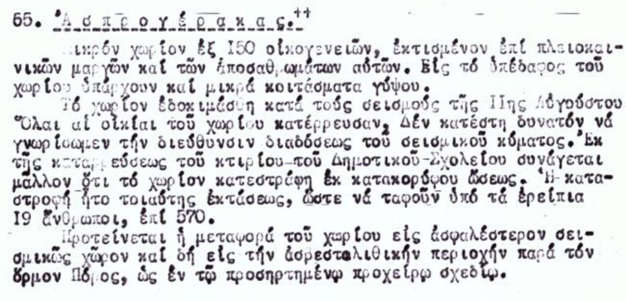
The present study aims to reassess the effects of the August 1953 earthquakes, in terms of macroseismic intensity through collection and analysis of a. published material and b. unpublished or raw material. The available contemporary sources comprise of scientific publications, official reports of post-event surveys, local press, photographic material, etc.

Contemporary published studies, such as those of e.g., Angelopoulos (1954), Beaujeu Garnier (1953), Di Filippo and Marcelli (1954), Galanopoulos (1954), Grandazzi (1953), John (1954), Mueller Miny (1957), Voreadis (1953) provide useful macroseismic information.

Galanopoulos (1953) gives a complete macroseismic intensity list, based on the macroseismic cards collected by the National Observatory of Athens, from which many authors published their isoseismals.

Gradazzi (1954) was one of them. He was spending his summer holidays near Argostoli and witnessed the earthquakes and states for the second event: "…*Le sol trépidait une vitesse folle. A Sami, a Lixouri était le désastre. Partout des ruines des morts des blesses. Et les routes, coupées par les fissures et les éboulis, ne permettaient plus les secour…*". He also gives information on precursory phenomena, especially for the earthquake of 11 August (animals frightened), as well as on the specific characteristics of shaking, noting that in all cases the ground was shaking horizontally, in a direction SE-NW. Critical infrastructure, as well as the houses suffered severe damage. Large fissures were seen on the road network, also directed SE-NW, while electricity, water supply and telecommunication were stopped. The walls of the buildings oscillated and fell outwards, their roofs fell inside. The nearby Hotel Pharao was ruined and only its terrace balcony stood.

A useful source of macroseismic information which has not been analysed so far, is the governmental reports from the autopsies conducted by engineers for the earthquakes of 11th and 12th of August. These accounts, which are considered raw material, are brief reports on each village visited. (Figure 1) shows an example of such a report for the village Asprogerakas.



65. Ἀσπρογέρακας.++

Μικρόν χωρίον ἐξ 150 οἰκογενειῶν, ἐκτισμένον ἐπί πλειοκαινικῶν μαργῶν καί τῶν ἀποσαθρωμάτων αὐτῶν. Εἰς τό ὑπέδαφος τοῦ χωρίου ὑπάρχουν καί μικρά κοιτάσματα γύψου.

Τό χωρίον ἐδοκιμάσθη κατά τούς σεισμούς τῆς 11ης Αὐγούστου. Ὅλαι αἱ οἰκίαι τοῦ χωρίου κατέρρευσαν. Δέν κατέστη δυνατόν νά γνωρίσωμεν τήν διεύθυνσιν διαδόσεως τοῦ σεισμικοῦ κύματος. Ἐκ τῆς καταρρεύσεως τοῦ κτιρίου τοῦ Δημοτικοῦ Σχολείου συνάγεται μᾶλλον ὅτι τό χωρίον κατεστράφη ἐκ κατακορύφου ὤσεως. Ἡ καταστροφή ἦτο τοιαύτης ἐκτάσεως, ὥστε νά ταφοῦν ὑπό τά ἐρείπια 19 ἄνθρωποι, ἐπί 570.

Προτείνεται ἡ μεταφορά τοῦ χωρίου εἰς ἀσφαλέστερον σεισμικῶς χῶρον καί δή εἰς τήν ἀσβεστολιθικήν περιοχήν παρά τόν ὅρμον Πόρος, ὡς ἐν τῷ προσηρτημένῳ προχείρῳ σχεδίῳ.

65. Asprogerakas

A small village consisting of 150 family houses, built on marls aged of Pliocene, lying over small gypsum deposits.

The village suffered severe damage from the 11 August earthquake. All its houses collapsed. We were not able to know the seismic wave propagation direction. From the way the primary school building collapsed, it is inferred that the village was probably destroyed by vertical forces. The destruction was so extensive, that 19 people out of 570 lost their lives, buried under the debris.

Relocation of the village to a safer place is proposed, namely on the limestones next to Poros bay, as seen in the attached design.

Figure 1. Example of damage account from the village Asprogerakas

The accounts analysed in this study are 30 out of a total of 120, concentrated in the southeastern part of Kefalonia. It is noted that such autopsy visits took place in the case of villages that suffered severe structural damage. For the rest of the villages, which were lightly damaged, the community responsibles submitted their own reports.

Each account gives information on the number of houses, local soil conditions, number of damaged buildings, number of life loss, damage degree from the August 11th or 12th event (when possible), macroseismic intensity using the Modified Mercalli Intensity scale (MMI) and finally, a recommendation for relocation of the village, if considered necessary.

The first step was to acquire the list of georeferenced villages. For identified sites, up to date mapping software was exploited in order to obtain their accurate coordinates. However, some sites could not be identified (e.g., Koutrokoi, Petrouli, Ano Valtes, etc.) and all but one were sought in the map compiled by Partsch (1892). We assume that, as these villages were totally destroyed, they were abandoned or rebuilt and merged with nearby villages.

MM intensity is provided for 7 villages due to the August 11th event and for 3 due to the third event. We reassessed intensities for all 30 villages with the European Macroseismic Scale 1998 (EMS98) (Grünthal, 1998). In most cases, the vulnerability of the plethora of houses was classified as “B” (houses) or “B – C” (schools), with few old houses of vulnerability “A”.

Most places were small or medium-sized villages and experienced severe damage (I9 or I9-10), 12 villages experienced intensities between 7 to 8-9, one village had seismogeological effects and one was impossible to visit.

In Table 1, the affected sites are presented, along with the correspondent macroseismic intensity. I (accounts) refers to the intensity reported from the autopsy reports, while I is the intensity assessed in this study. For the villages Markopoulon and Karouza the intensities are one degree higher than those estimated in our study. In Xenopoulon, we assessed higher intensity, while Agia Eirini, Ampela and Kampitsata the intensities are identical. In Figure 2 their spatial distribution is presented, as far as the 2nd event is concerned (August 11). On the left the spatial distribution of MM intensities reported in the accounts are shown and on the right the ones assessed from this study in EMS98.

Table 1. Sites affected by both August 11th and 12th events

Locality	Lat (new)	Long (new)	I_{MM} (accounts) 11/08	I_{MM} (accounts) 12/08	I_{EMS98} (11/08)	I_{EMS98} (12/08)	Nr of Houses
Mavrata	38.073	20.726		9-10	9	9-10	75
Katelios	38.078	20.753			8-9	9-10	Small village
Ratzakli	38.075	20.770	8	9	8	8-9	
Skala	38.074	20.797		10	9	9-10	300
Fanies	38.086	20.772			9	9-10	Small village (8-12 families)
Spathi	38.096	20.772			9	9-10	Small village (8-12 families)
Koutrokoi	38.104	20.770			9	9-10	Small village (9 families)
Markopoulon	38.080	20.731	10-11		9-10		80 families, 300 people(30 died)
Kremmydion	38.088	20.745			9-10		30 families
Petrouli	38.087	20.759			9-10		30 families
Ano Valtes	38.100	20.753			9		15 families
Theodoritsion	38.116	20.751			8-9		8 families
Pastrai, see Pastra	38.094	20.751			9		Small village (30 families, 120 people, 9 died)
Agios Georgios	38.100	20.753			8-9		Small village (30 families)
Asprogerakas	38.111	20.768			9		Small village (150 families, 570 people, 19 died)
Anoinata, see Anninata	38.112	20.781			9-10		200 people, 5 died
Poros	38.154	20.771	Minor damage	Minor damage	7-8	8	Small village
Tzanata	38.142	20.751			9		16 people died
Solomata	38.122	20.752			9-10		Small village (15 families, 2 people died)
Vlachoulata	38.120	20.751			9		Small village (8 families)
Kometnorata					9		Small village (10 families)
Koritsiano, see Agia Eirini	38.123	20.750			8-9		Small village (15 families, 1 death)
Agia Eirini	38.122	20.752	7-8		7-8		Small village (9 families)
Ampela, see Agia Eirini	38.126	20.748	7-8		7-8		35 families, 5 people died
Karouza, see Agia Eirini	38.129	20.748	8-9		8		11 families, 4 people died
Kampitsata	38.136	20.736	7		7		22 families
Xenopoulon	38.136	20.723	7		7-8		48 families
Kapandrition	38.127	20.726			7		52 families, 1 death
Andriolata	38.148	20.727					Not visited
Aphragias	38.150	20.750	SG		SG		Rock falls

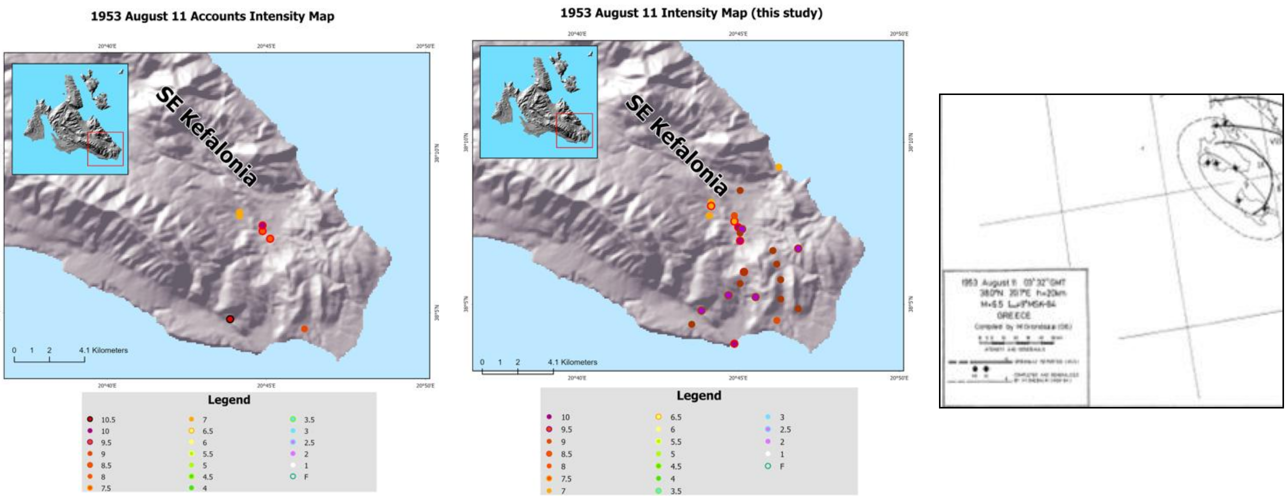


Figure 2. Intensity distribution for the August 11th earthquake from accounts (left) and in this study (middle). The isoseismal map from the atlas of Shebalin et al. (1974b), compiled by Grandazzi (right).

Discussion

Although the 1953 earthquake sequence prevails in the mid 20th century, the sources providing macroseismic information have not yet been exploited adequately. Therefore, it is not clear whether the available intensities refer to one event or they are cumulative, due to the extremely short period of occurrence. One aim of this paper is to examine the inter-relation of information between contemporary local and occidental sources, which need to be re-examined in a comprehensive way.

Furthermore, we study in detail and assess intensity from accounts of autopsies carried out by engineers in 30 villages out of 120 villages of Kefalonia. These places are located in SE Kefalonia, which suffered severe damage and life loss due to the three earthquakes. It is observed that these places are 26 new intensity data points added to the existing ones in the atlas of isoseismals (Shebalin et. al. 1974b). Figure 2 shows that the isoseismal map contains only one intensity value in the studied area.

Acknowledgements

We acknowledge funding by the "New technologies, research and innovation for the creation of poles of attraction" project in the framework of the National Strategic Reference Framework (NSRF) 2014-2020, Regional Operational Programme "Ionian Islands 2014–2020".

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17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00055

The 6 February, 2023 M_w=7.8 and M_w=7.6 Earthquake Doublet in Southeastern Türkiye

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On 6 February, 2023 at 01:17:35 UTC an earthquake of M_w=7.8 occurred in southeastern Türkiye. A second major earthquake of M_w=7.6, triggered by the first one, occurred nine hours later, 90 km north of the first earthquake's epicenter (Figure-1). These major doublet earthquakes devastated eleven provinces in southeastern Türkiye, which occupy about 110,000 km^2 area with a population of 14 million. These earthquakes caused the deaths of more than 57,000 people and more than 107.000 people were injured in Türkiye and Syria.

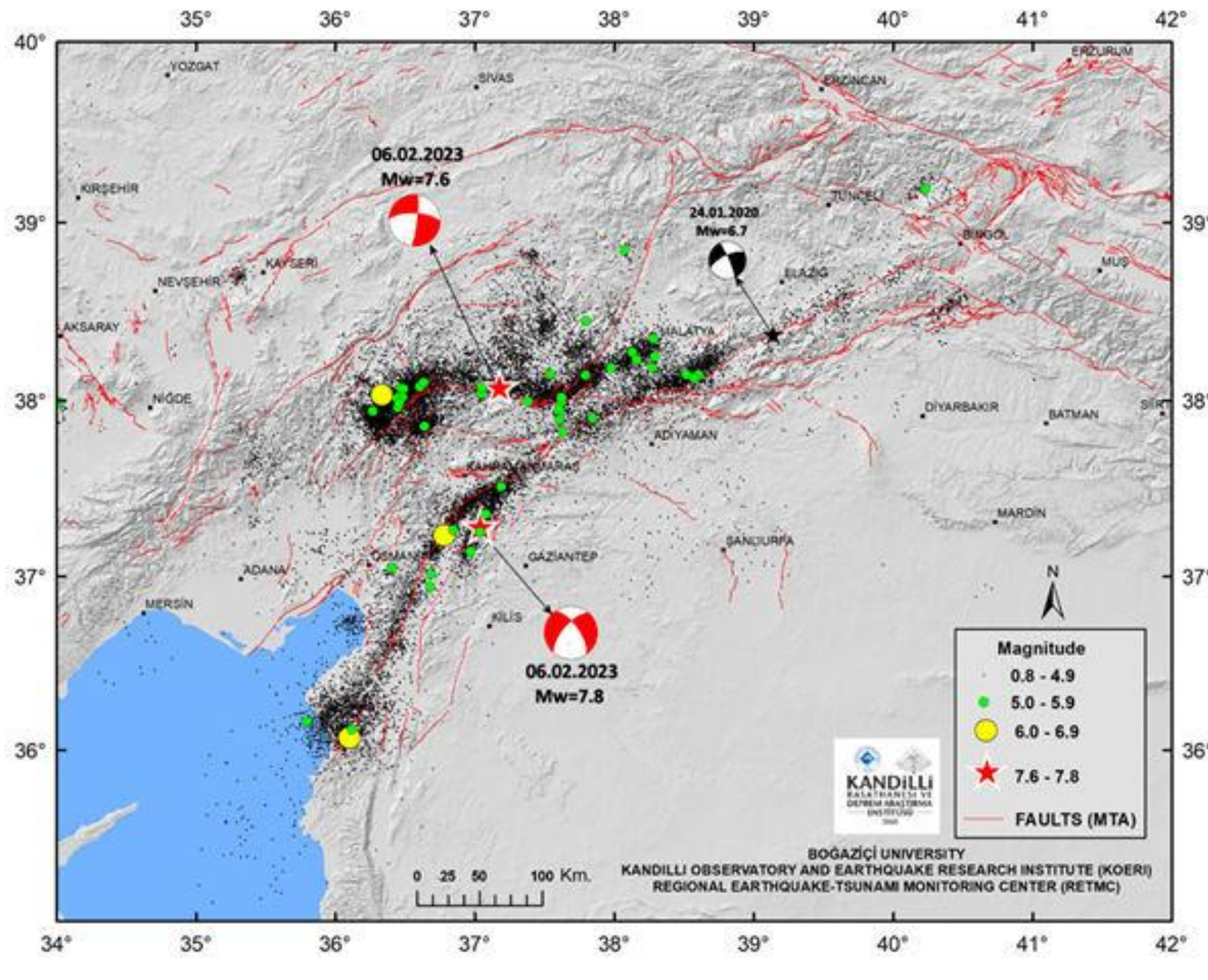

Figure-1. Seismicity map of southeastern Türkiye covering the period from 6 Feb. 2023 to 6 Apr. 2023. The epicenters of the two main shocks that occurred on 6 Feb. 2023 are denoted with red stars and the epicenter of the 24 Jan. 2020 Sivrice Earthquake is denoted with a black star. Red thin lines indicate active faults in the region (Emre et al., 2013). Lower hemisphere projections of focal mechanisms are shown with compressional quadrants shaded red or black. This figure is courtesy of BU-KOERI-RETMC.

These doublet earthquakes occurred in an area where Eurasian, Arabian and African Plates form a triple junction: the Maraş Triple Junction (MTJ). The 580 km long, NE-SW trending, left-lateral strike-slip East Anatolian Fault (EAF) forms the tectonic boundary between the Anatolian Block and the Arabian Plate (Duman and Emre, 2013). The 1.000 km long, N-S trending, left-lateral strike-slip Dead Sea Fault (DSF) forms the tectonic boundary between the African and Arabian Plates. These two major faults intersect at the Maraş Triple Junction.

The first M_w=7.8 earthquake nucleated at the northernmost segment of the DSF. Its Centroid Moment Tensor (CMT) solution gives major left-lateral motion with a minor normal component (Figure-1) When the 42 km long rupture of DSF reached the junction with the EAF (Maraş Triple Junction), 10 seconds after the origin time, three fault segments of the EAF were ruptured bilaterally, with a duration of 70 seconds, creating a 350 km. long fault break (Figure-2). The known last major earthquake on the Pazarcık segment of the East Anatolian Fault Zone was occurred in 1513 (Ambraseys, 1989).

The second M_w=7.6 earthquake, which is triggered by the M_w=7.8 earthquake 9 hours later, nucleated roughly in the middle of an E-W trending Çardak Fault and it ruptured bilaterally creating a 100 km long fault break with a maximum 8.8 m. left-lateral displacement (Figure-2). However, the Çardak fault rupture did not continue along the Sürgü Fault segment to the east, instead it propagated in NE direction rupturing a previously unmapped fault (Çığlık Fault) for 44 km. The known last major earthquake was occurred in 1544 on the Çardak Fault (Ambraseys & Jackson, 1998).

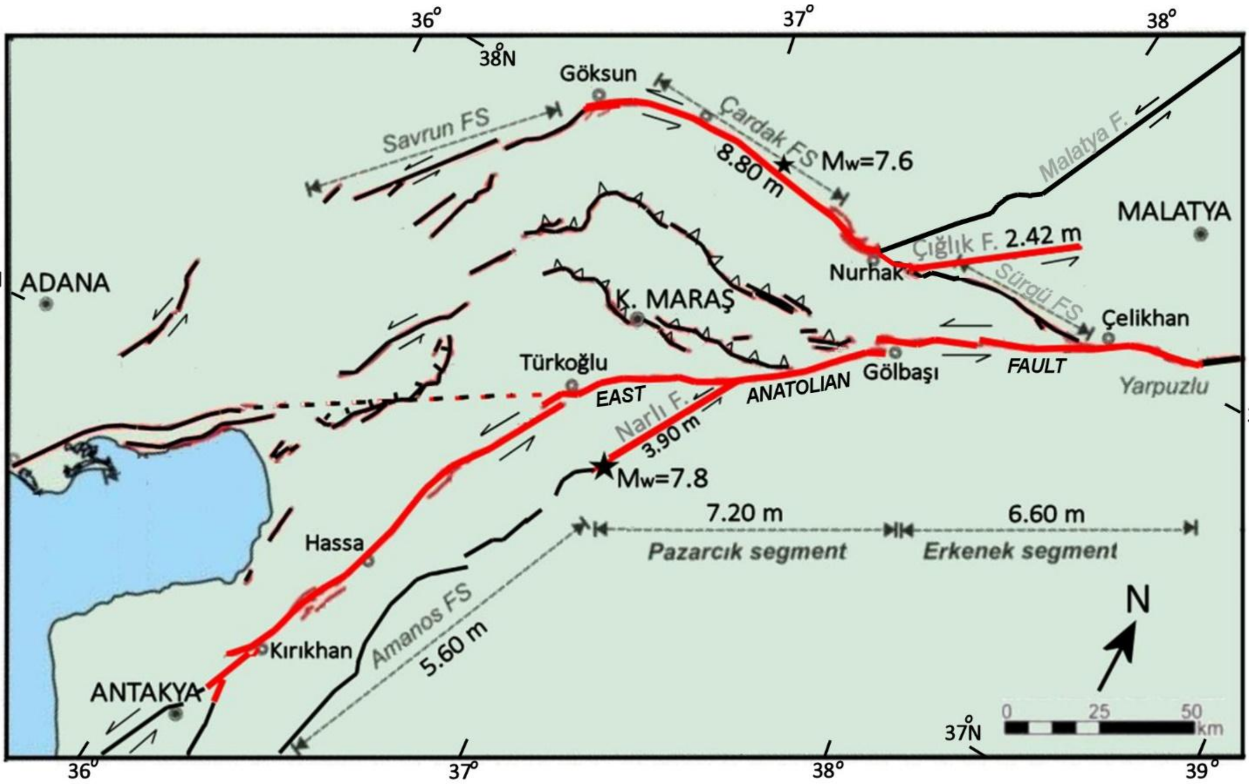

Figure 2. Map of the surface fault breaks created by the 6 Feb. 2023 doublet earthquakes. The measured fault displacements by field studies (Kürçer et al., 2023; Akyüz et al., 2023; Elmacı et al., 2023; Parlak et al., 2023) are shown for different fault segments. . Black lines indicate mapped active faults in the region (Emre et al., 2013).

Several source inversion modelings have been carried out for the 6 February 2023 Pazarcık (Kahramanmaraş) Earthquake using seismic and GNSS inversion (Melgar et al., 2023), potency-density tensor inversion (Okuwaki et al., 2023), seismic, GNSS and InSAR inversion (USGS-NEIC, 2023), InSAR and GNSS inversion (Barbot et al., 2023). These source inversions estimated the seismic moment ranging from 5.40×10^{20} Nm to 9.60×10^{20} Nm with corresponding moment magnitudes ranging from 7.75 to 7.92 (Table-1).

Similarly these inversions estimated the seismic moment ranging from 3.02×10^{20} Nm to 3.64×10^{20} Nm with corresponding moment magnitudes ranging from 7.59 to 7.64 for the Ekinözü (Kahramanmaraş) Earthquake (Table-1).

The seismic moment and moment magnitude estimates based on geological fault rupture data are 7.06x10^{20} Nm and M_w=7.83 for the Pazarcık and 3.63x10^{20} Nm and M_w=7.64 for the Ekinözü (Kahramanmaraş) Earthquakes, respectively (Table-1).

The dense Turkish Strong Motion Instrument Network (AFAD-TADAS) recorded the accelerations created by these earthquakes. Especially in Antakya and Islahiye the recorded horizontal accelerations exceeded 1,000 cm/s^2. These accelerations exceeded the design envelopes of the Turkish Seismic Design Code of 2019 even for critical structures (average 2475 year return period) for periods larger than 0.5 seconds due to alluvial basin magnification and rupture directivity effects and they can partly explain the wide spread damage to buildings and infrastructure.

Table 1. Seismic Moment and Moment Magnitude Estimates obtained by different modeling methods for the 6 February, 2023 Kahramanmaraş, Türkiye Earthquakes

Pazarcık (Kahramanmaraş) Earthquake

M_w=7.8	Seismic Moment	Mw	Total Fault Rupture	Method
Melgar et al., 2023	6.51 x 10^{20} Nm	7.81	350 km	Seismic & GNSS Inversion
Okuwaki et al., 2023	9.60 x 10^{20} Nm	7.92	350 km	Potency-density tensor inversion
USGS-NEIC	7.92 x 10^{20} Nm	7.87	350 km	Seismic, GNSS & InSAR Inversion
Barbot et al., 2023	5.40 x 10^{20} Nm	7.75	292 km	InSAR & GNSS Inversion
This study	7.06 x 10^{20} Nm	7.83	392 km	Geological Fault Rupture Data (Ave. Slip = 2.99 m)

Ekinözü (Kahramanmaraş) Earthquake

M_w=7.6	Seismic Moment	Mw	Total Fault Rupture	Method
Melgar et al., 2023	3.64 x 10^{20} Nm	7.64	160 km	Seismic & GNSS Inversion
Okuwaki et al., 2023	3.02 x 10^{20} Nm	7.59	80 km	Potency-density tensor inversion
Barbot et al., 2023	3.30 x 10^{20} Nm	7.61	186 km	InSAR & GNSS Inversion
This study	3.63 x 10^{20} Nm	7.64	144 km	Geological Fault Rupture Data (Ave. Slip = 4.2 m)

Acknowledgements

I thank Prof. V. Kouskouna and the Organizing Committee for inviting me to the 8th International Colloquium on Historical Earthquakes, Palaeo- Macroseismology and Seismotectonics. I thank Yavuz Güneş and Prof. Doğan Kalafat of BU-KOERİ-RETMC for preparing the Figure-1.

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The Lixouri, Kefalonia, Projects INFRASEPREL, KNETSEISRL ACTCIPROL

V. Kouskouna[1], A. Ganas[2], † I. Kassaras[1] and the Lixouri Projects Group

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Kefalonia, Ionian islands, Western Greece, is known for the highest seismicity and seismic hazard in Greece, due to its complex tectonics, mainly the right-lateral Kefalonia Transform Fault. Lixouri is the capital of the Municipality of Lixouri, which covers the Paliki peninsula in the western part of the island. The town has experienced several damaging earthquakes through the centuries, the most important of which were the 1767, 1867, 1912, 1953, and 2014 events.

Due to its high seismic risk, the Municipality of Lixouri initiated in 2021 a collaboration with the Seismological Laboratory of the National and Kapodistrian University of Athens and a number of collaborating partners through three bilateral projects (Table 1). The aim is the thorough study of the area's past and recent seismicity and tectonic regime by reinforcing its infrastructure towards disaster prevention, enhancing the knowledge of its earthquakes and extending the actions for civil protection and public awareness.

The final target of all three projects is the development of a "Centre of Earthquake Knowledge" in Paliki on earthquake science, civil protection and seismic risk, which will address the scientific community for national and international research activities, as well as the general public for education on civil protection and prevention against earthquakes and related phenomena. The "Earthquake Centre" is planned to host related forums and meetings.

Table 1. Collaborating partners in Lixouri projects and the researchers of the Lixouri Projects Group

Partner	Researchers of the Lixouri Projects Group
Department of Geology and Geoenvironment, National and Kapodistrian University of Athens (NKUA) Greece	V. Kouskouna †I. Kassaras E. Lekkas V. Kapetanidis G. Kaviris F. Vallianatos K. Pavlou N. Sakellariou I. Spingos P. Rallatos N. Galanos
Municipality of Lixouri (ML) Greece	G. Katsivelis G.S. Galanos
Geodynamic Institute - National Observatory of Athens (GEIN-NOA) Greece	A. Ganas V. Tsironi S. Valkaniotis
Earthquake Planning and Protection Organization (EPPO) Greece	E. Lekkas A. Kourou
Center for Security Studies (KEMEA) Greece	G. Sakkas
Museo Nacional de Ciencias Naturales (MNCN) Spain	M.J. Jimenez M. Garcia Fernandez
Istituto Nazionale di Geofisica e Vulcanologia (INGV) Italy	P. Albini

The three projects are interconnected and, in many cases, interdepended: data collected and results obtained from one are used as input to another and researchers participate to more than one project. Therefore, the whole concept may be considered as one general project with three main pillars, i.e. “knowledge”, “research” and “education” (Figure 1), aiming at:

- Enhancing the seismological instrumentation of Paliki, real time recording the local seismicity, assessing the vulnerability of buildings for near real-time shake maps, continuous collecting of macroseismic information from current earthquakes and studying in detail the crustal deformation and the seismotectonic characteristics

- Creating a repository of studies, books and archival material for the thorough study of Paliki’s past seismicity and seismic hazard assessment and

- Promoting public awareness on earthquake and related phenomena issues and educating the various groups of stakeholdres in the area through specialized seminars, tabletop exercises and in person drills.

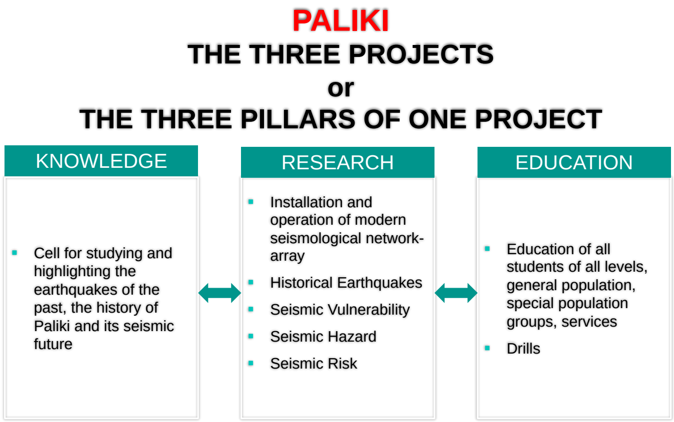

Figure 1. The three pillars of activities of the Paliki projects

1. INFRASEPREL (Reinforcing research INFRAstructure for SEismic disasters PREvention, Lixouri) aims to:

a. create a pioneering research-operational infrastructure in Paliki Peninsula, based on seismic array technology,
b. record the seismic activity in real time,
c. study the seismic risk of the area, for rapid damage assessment and
d. study in depth the seismotectonic characteristics of the area
- Seismic stations (Figure 2): two digital seismometers with a 3-component seismic and a 3-component acceleration sensor, complementing the existing stations of the Hellenic Unified Seismic Network (HUSN) on Kefalonia island (red triangles) and two 1-component seismometers (red squares)

- Accelerographic array (Figure 2): an array of eleven 3-component accelerographs installed in Lixouri, the major town of the peninsula and capital of the Municipality (red circles)

- GNSS station: one instrument installed in Atheras, northern Paliki (Figure 2).

The instruments were installed in 2021, recording a considerable number of local and regional events with magnitudes ranging within $0.3 \le Mw \le 4.5$, contributing to the manual solutions of the Seismological Laboratory. Two platforms were developed for real time seismicity and MMI, PGA, PGV, PSA shaking maps (Seismological Laboratory, dynamic, http://www.geophysics.geol.uoa.gr/stations/gmaps3/kefalonia_map.php) and for seismotectonic and crustal deformation data (Institute of Geodynamics, static).

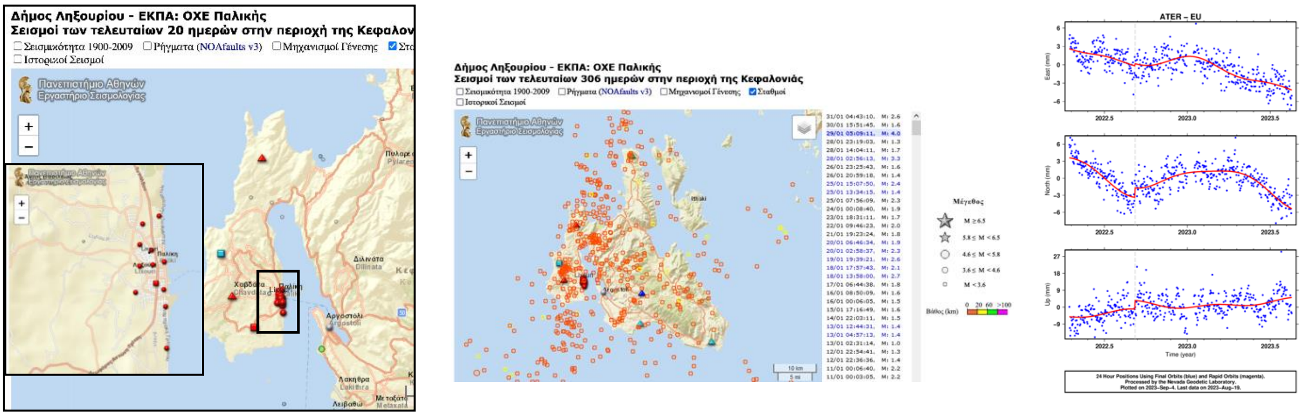

Figure 2. ***Left:*** **Seismic and GNSS stations (red triangles and squares).** ***Inner box*****: Accelerometric array (red circles).** ***Centre*****: Position time series (East, North, Up) of GNSS station ATER with respect to stable Europe. The red line mean trend of the data (motion towards W and S). Data processed by the Nevada Geodetic Laboratory.** ***Right*****: Seismicity recorded in Kefalonia within the period 2021-2023**

2. KNETSEISRL (Development of Knowledge NETworks for SEISmic disaster Risk, Lixouri) aims to:

a. develop a repository of sources related to earthquakes and geodynamic phenomena of Kefalonia
b. compile an updated earthquake catalogue of its earthquakes
c. update the seismic hazard assessment.

A network of researchers contribute to the earthquake archive with archival material and newspapers, books, papers, seismological compilations and modern scientific studies quoting the past earthquakes of Kefalonia. The material is stored in digital and printed form, comprising a database of sources for public use. The database will encompass all available seismological information of each earthquake, providing the seismic picture of Kefalonia, and specifically the various localities of Paliki peninsula.

The contents of the sources for the period before 1900 (historical earthquakes) was thoroughly analysed. The new earthquake catalogue of Kefalonia, extended to previous centuries, is used for its updated seismic hazard assessment.

Site response measurements for HVSR technique were performed at 38 sites (instrument and additional selected sites), using the CSIC, Madrid, Spain, infrastructure as added contribution to the projects.

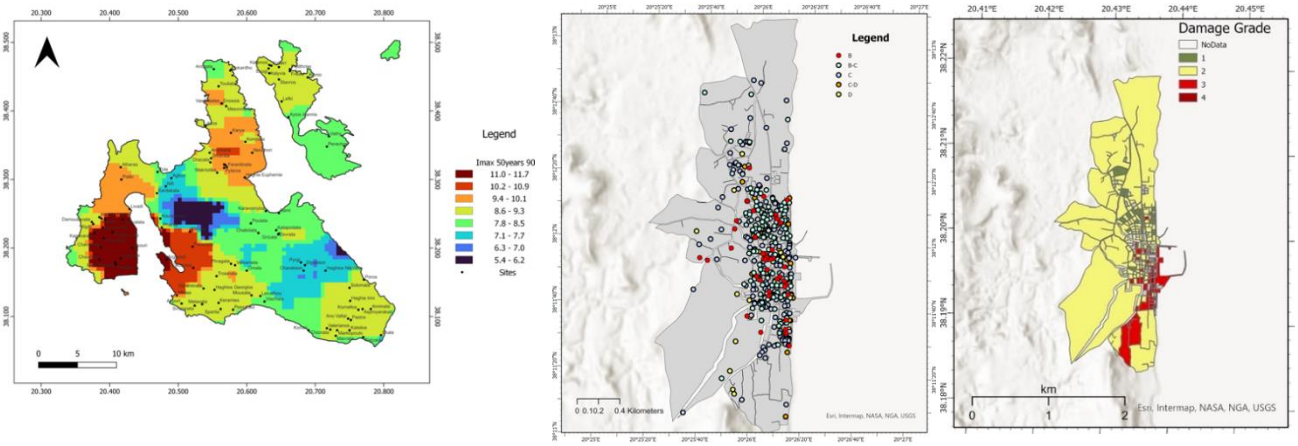

Figure 3. ***Left:*** **Maximum expected EMS98 intensity for Kefalonia and Ithaki with 10% probability of exceedance in the next 50 years (Return Period: 475 years).** ***Centre:*** **EMS98 vulnerability classes of buildings in Lixouri.** ***Right:*** **Spatial distribution of expected damage grade per building block in Lixouri**

3. ACTCIPROL (Information ACTions for CIvil PROtection services, Lixouri) aims to:

a. Mitigate seismic risk in Paliki through continuous education of the population and operational

An updated version of "The earthquake suitcase", a travelling earthquake educational tool is developed to be used in the schools of Paliki. The suitcase includes:

- A portable shaking table with models of buildings with different vulnerability. An accelerometer is attached to the moving platform of the shaking table, recording in real time the simulated earthquake strong motion. The trainees may use the recorded signal for further analysis (e.g. spectral).
- The earthquake emergency kit (e.g. radio, batteries, torch, portable medicine kit, etc.)
- Educational material (e.g. books, leaflets, etc.)

Figure 4. ***Left:*** **Earthquake education in Lixouri.** ***Centre:*** **The earthquake suitcase video.** ***Right*****: The contents of the earthquake suitcase.**

Discussion

The deliverables of all three projects are planned to be hosted in a pioneering Earthquake Centre. Its goal is to support the Municipality of Lixouri through promotion and dissemination activities, organizing conferences, workshops and international forums for exchanging scientific results, specialized training seminars of the involved bodies and public groups and continuous awareness actions of citizens and stakeholders. This space will be an educational centre for the collection, study and promotion of printed, electronic and photographic material regarding the Ionian Islands earthquakes, the revival of the environment and the earthquake effects, as well as for seismic hazard studies. The available dynamic and static seismic data platforms, as well as the database of sources will be available to researchers and the public for further study.

For the promotion of the projects, events open to the general public have been organized in Lixouri and in Athens.

Finally, the **8th International Colloquium on Historical Earthquakes, Palaeo-Macroseismology and Seismotectonics** is organized by the National and Kapodistrian University of Athens and the Municipality of Lixouri, within the framework of the Lixouri projects.

Acknowledgements

We acknowledge funding by the "New technologies, research and innovation for the creation of poles of attraction" project in the framework of the National Strategic Reference Framework (NSRF) 2014-2020, Regional Operational Programme "Ionian Islands 2014–2020".

Discussion

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Bulletin of the Geological Society of Greece, Sp. Publ. 11

Ext. Abs. 00057

Towards the International Macroseismic Scale (IMS-24)

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Probably the most used intensity scale at the moment is the European Macroseismic Scale (EMS-98) which grew from a European Seismological Commission (ESC)-mandated project to update the Medvedev-Sponheur-Karník (MSK) scale (Medvedev et al. 1964). Specific problems to be solved by the Working Group on Macroseismic Scales included the need to include new types of buildings, especially those including earthquake-resistant design features, the need to address a perceived problem of non-linearity in the scale arrangement at the junction of the degrees 6 and 7 (which, after thorough discussion for preparing the EMS-92, as well as for the EMS-98, proved to be illusory); and a general need to generally improve the clarity of the wording of the scale. The revised intensity scale should not only meet the needs of seismologists alone, but which could also meet the needs of civil engineers and other possible users; and should be suitable also for the evaluation of historical earthquakes. It was also agreed that there was a need for a critical revision of the usage of macroseismic effects visible in the ground (rock falls, fissures etc.) and the exposure of underground structures to shakings. One of the main intentions for the revision of the scale was not to change its internal consistency. This would result in intensity evaluations which would be different from earlier applications of the widely used twelve degree scales and which would require a reclassification of all earlier intensity assessments. This would result in a complete confusion in all studies on seismicity and seismic hazard which depend heavily on macroseismic data.

At the first meeting of the WG in 1990 at Zurich it was further agreed that as intensity assignments were often conditioned by practice as much as by the wording of the intensity scale, there was a need for guidelines explaining how the scale should be applied, with the hope that in future, practices in assigning intensity might be to some extent standardized (Musson 1990). To this end, it was agreed that the scale should be an illustrated document, with drawings and photographs that could be used for reference. By the conclusion of the third WG meeting at Walferdange (Luxembourg) the revised scale had so much departed from the look and feel of the MSK scale, that it needed a new appellation, and “European Macroseismic Scale” was at length agreed upon, the adjective “European” reflecting the fact that it was prepared at the request of the ESC.

There was no further meeting of the full WG, and further development towards publication was entrusted to a smaller group of Gottfried Grünthal (GFZ Potsdam), Roger Musson (BGS Edinburgh), Jochen Schwarz (U Weimar), and Max Stucchi (INGV Milano). Serious problems remained regarding the treatment of engineered or antiseismic constructions for intensity evaluation. In fact, even with non-engineered structures, building types previously used in modern intensity scales, there was a general neglect of the quality of workmanship, the structural regularity, the strength of materials, the state of repair, and so on. An essential step for overcoming these problems was the introduction of the Vulnerability Table which provides the possibility to deal in one scheme with different kinds of buildings and the variety of their actual ranges of vulnerability. In former scale versions building types were defined in a rather strict way, by construction type alone. This vulnerability table, as an essential part of the EMS, incorporates engineered and non-engineered buildings into a single frame.

It was clear from the beginning that the EMS-92 version with its adopted compromises had to be understood as an experimental or tentative solution (Grünthal 1993), connected with the commitment to gather more information and experience on this subject, in order to become able to introduce necessary improvements. A period of three years was stipulated for this. At the final stage of the anticipated three years testing period of the EMS-92, and after applications throughout the world, it became clear that the personal judgement used in assigning intensity can be decreased with the new scale. The introduction of the vulnerability table was highly appreciated, as well as the introduction of the new definitions of damage grades and especially the Guide to the Use of the Intensity Scale. Generally, the engineering aspects incorporated into the new scale were appreciated by the engineers. They were the subject of sessions at international conferences on earthquake engineering, and even of a Special Theme Session on the EMS-92 at the World Conference on Earthquake Engineering in Acapulco in 1996, at which time, even if only informally, the idea of developing EMS into an overtly international scale was suggested.

The XXV General Assembly of the ESC in Reykjavik, 1996, passed a resolution recommending the adoption of the new macroseismic scale within the member countries of the European Seismological Commission. The final version (EMS-98) was then published in the Cahier du Centre Européen de Géodynamique et de Séismologie (Grunthal 1998).

Although EMS-98 has been used successfully in many parts of the world outside Europe, it remained the case that it is somewhat Euro-centric. At the prompting of the Scientific Board of GEM (Global Earthquake Model), and with financial help from GEM, a new working group was formed, with the objective of extending the European Macroseismic Scale (EMS-98) and developing it into the International Macroseismic Scale (provisionally labelled IMS-14) to enable it to become more generally applicable to all parts of the globe. Discussions about the development of such a scale began in 2013, when a mini-symposium "Conclusions from 15 years of international experience with the EMS-98" was held at the Vienna Congress on Recent Advances in Earthquake Engineering and Structural Dynamics 2013 (VEESD), Notable contributions included Foulser-Piggot and Spence (2013) and Schwarz et al. (2015). A new WG initially comprised Gottfried Grünthal (GFZ, Potsdam), Roger Musson (BGS Edinburgh), Jochen Schwarz (U Weimar), Robin Spence (Cambridge Architectural Research, UK), Roxane Foulser-Piggott (Cambridge Architectural Research UK), Thomas Wenk (Wenk Erdbebeningenieurwesen und Baudynamik GmbH, Zurich) and with Max Stucchi as advisor.

After VEESD, this WG held a meeting in Cambridge in 2013, and met twice in Potsdam in 2014; a fourth meeting was planned to be held in London, but this never eventuated.

The planned structure of IMS-14 at this point was to be a scale in three parts. The first would be the "core scale", more or less as in EMS-98; part 2 would be the guidelines, again based on EMS-98 with some edits. The third part was envisaged as a web document, covering most of the building types to be encountered worldwide, with descriptions, photos, and remarks on vulnerability. It was clear that this would be a huge undertaking, and the magnitude of the task was perhaps one reason why no further progress was made, although an expanded version of the Guidelines was prepared in draft in October 2014. This draft included a section on Internet microseismology, and included a suggested questionnaire, which had been prepared previously by an ESC working Group on Macroseismology. There were no further WG activities beyond the preliminary draft of the revised Guidelines.

However, the desirability of having an intensity scale that could be looked upon as an international standard was still very clear, and the WG was reconvened in Potsdam in 2023 and continues to be active. The group now includes David Wald (USGS) but without Foulser-Piggott or Stucchi. The chief task is to address the more important building types that were neglected in EMS-98 as being seldom encountered in Europe, but which are essential elsewhere in the world, notably timber-frame buildings. The three-part structure to the scale proposed in 2014 was recognized as being overly ambitious and unrealistic. Also, it was not realistic to attempt to address the seismic behaviour of every building type listed in the GEM Building Taxonomy

(Brzev et al., 2013) based on the limited experience of the members of a small WG. For any given building type found in some national territory, the matters of its behaviour under earthquake loading, the definitive account must be based on the experience of the local engineering and seismological communities.

Thus the WG proposes a structure in which local experts are encouraged to prepare a National Annexe, that, while not being part of IMS-24, can be read alongside it. Such a National Annexe will indicate the typical local buildings and features affecting their seismic performance, and the collection of such National Annexes will grow over time. Such annexes can never be included within the IMS-24, as intellectual property rights (IPR) remain with the National Annexe authors, and are distinct from the IPR of the scale itself.

There is still a need to purge the EMS-98 text of features that reflect its European origin, or which the most important is perhaps the way in which earthquake damage descriptions tend to assume masonry or RC construction, to the neglect of timber or steel, and this is still under discussion. One task is to see the current drawings of damage states extended to include timber and steel-frame structures, and also an update on at least the reinforced concrete drawings in EMS-98.

The plan is now to be able to present the new scale at the 18th World Conference on Earthquake Engineering (WCEE2024) in Milan, Italy, from 30th June to 5th July 2024.

Acknowledgements
This extended abstract was prepared with the help of members of the WG on the International Macroseismic Scale: Gottfried Grünthal, Jochen Schwarz, Robin Spence and Thomas Wenk.

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8th International Colloquium on Historical Earthquakes,
Palaeo- Macroseismology and Seismotectonics
17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00058

A modern view of Statistical Seismology in terms of Tsallis entropy.

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Based on statistical physics and the entropy principle, a unified framework that produces the collective properties of earthquakes and faults from the specification of their microscopic elements and their interactions, has recently been introduced. This framework, called nonextensive statistical mechanics (NESM) was introduced by Tsallis (1988), as a generalization of classic statistical mechanics due to Boltzmann and Gibbs (BG), to describe the macroscopic behaviour of complex systems that present strong correlations among their elements, violating some of the essential properties of BG statistical mechanics (Tsallis, 2009). Such complex systems typically present power-law distributions, enhanced by (multi)fractal geometries, long-range interactions and/or large fluctuations between the various possible states, properties that correspond well to the collective behaviour of earthquakes and faults. Many applications during the last decade have highlighted that NESM is a powerful framework for describing the macroscopic behaviour of earthquakes and faults in a wide range of scales (Vallianatos et al., 2016 and references therein), introducing the field of nonextensive statistical seismology (NESS). The dynamical characteristics that lead to a NESM behaviour were demonstrated by Beck and Cohen (2003). Here, we provide an overview of the fundamental properties and applications of NESS. Initially, we provide an overview of the collective properties of earthquake populations and the main empirical statistical models that have been introduced to describe them. We provide an analytic description of the fundamental theory and the models that have been derived within the NESM framework to describe the collective properties of earthquakes.

Acknowledgements

We acknowledge funding by the "New technologies, research and innovation for the creation of poles of attraction" project in the framework of the National Strategic Reference Framework (NSRF) 2014-2020, Regional Operational Programme "Ionian Islands 2014–2020".

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17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00059

Preliminary Analysis of the scaling laws of the Kefalonia *Mw* 6.1 (January 26, 2014) earthquake aftershock sequence in terms of Non extensive statistical Physics.

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On January 26, 2014 an *Mw* 6.1 earthquake occurred in the western part of the Kefalonia Island that is one of the most seismically active regions in the Eastern Mediterranean region. In the last several years, strong evidence indicates that earthquake generation process can be viewed in terms of the Complexity theory (Sornette, 2004; Sornette and Werner, 2009; Vallianatos et al., 2015; 2016; 2018). It has recently been shown that a wide variety of geodynamic phenomena related to the complexity dynamics reveals interesting features in the framework of new views as that of non-extensive statistical physics (Tsallis, 2009; Vallianatos, 2009; 2011; Vallianatos and Sammonds, 2010; 2013).

Time dynamics characterization of an earthquake sequence gives strong evidence for the existence of an underlying spatiotemporal nonlinear deterministic dynamical process (Telesca et al., 2004). The observed time-space behavior can be mapped by fractal (self-similar) properties such as power laws profiles, long range correlations and space-time clustering (Telesca et al., 2002; Papadakis et al., 2013) that can describe the spatial and temporal distributions of earthquakes (Abe and Suzuki, 2005; Michas et al., 2013).

The goal of this study is to investigate the behavior of the Kefalonia January 26, 2014 earthquake aftershock sequence, using a non-extensive statistical physics (NESP) (Tsallis, 2009) extension of Boltzmann-Gibbs (BG) statistical physics. The NESP method, as proposed by Tsallis entropy (Tsallis, 1988; 2009), has the benefit of being able to represent the spatiotemporal evolution of seismicity using the universal principle of entropy.

The analysis and results indicate that the superstatistical model (Beck and Coen 2003; Beck, 2004) brings forth the *q*-exponential distribution for the interevent times distribution for T<Tc, where Tc a critical interevent time, by a simple mechanism, namely a χ^2-distributed allocated parameter β of the local Poisson process that could describe the distribution of interevent times in Kefalonia aftershock sequence. Using the observed distribution and the *q*-value acquired from our q-statistics fits, we lead to n≈1 or 2, meaning that the number of degrees of freedom (n) influencing the value of β is very low. We note that for T>Tc the observed exponential functions are associated with a significantly higher number of degrees of freedom. The latter implies that in the early aftershock sequence, where the vast majority of interevent times have T values less than Tc, the Tsallis entropic mechanism is predominant in the main part of the aftershock evolution, while as time evolves the characteristics of the aftershock sequence, as that of finite degrees of freedom and long range memory effects related to the NESP, description are not anymore predominant and the Boltzmann-Gibbs (BG) statistical physics is recovered (i.e., q=1).

Acknowledgements

We acknowledge funding by the “New technologies, research and innovation for the creation of poles of attraction” project in the framework of the National Strategic Reference Framework (NSRF) 2014-2020, Regional Operational Programme “Ionian Islands 2014–2020”.

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17-20 September 2023 - Lixouri, Greece
Bulletin of the Geological Society of Greece, Sp. Publ. 11
Ext. Abs. 00061

Using low-cost seismic recording infrastructure for potential evaluation of simulation models on seismic surface waves spatial distribution

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Research Highlights

The paper presents a new methodology that uses low-cost seismic recording infrastructure to study and model via simulation experiments significant variations of the velocity field among different areas of the Paliki peninsula of the Kefalonia Island.

Background

The complexity of understanding crustal processes often needs interdisciplinary contributions and could also demand a vast amount of instrumental and human resources (Hetényi et al., 2018). The continuous and rapid evolution of seismic instrumentation has led to new channels of information and relevantly significant discoveries in the field of seismology (Arrowsmith et al., 2022). Low-cost nodal sensors in dense deployments have been utilized by seismologists to monitor seismicity at a spatial resolution derived by the distribution of the sensors in the examined area (Anthony et al., 2019). Krokidis et al. recently presented a very satisfactory outcome in the performance of a low-cost seismograph which was installed in Evgiros, at Lefkada Island, an area of high seismic activity (Krokidis et al., 2022).

Experimental studies at the geophysical scale validated the effectiveness of seismic metamaterials in attenuation of surface seismic waves (Mu et al., 2020). Colombi et al. showed that natural forests could function as metamaterials where trees act as vertical resonators with locally resonant characteristics (Colombi, 2016). Furthermore, Aravantinos-Zafiris and Sigalas (2021) showed numerically that terraced slopes behave as large scale seismic metasurfaces as they attenuate surface vibrations. It should be mentioned that seismic metamaterials are a recently developed branch of elastic metamaterials, which have gained both scientific and technological attention over the past decades as they constitute a very promising solution on the control of propagation of elastic waves (Deymier, 2013). Evidently, according to literature, as surface seismic waves propagate along the free surface, geomorphology could significantly affect their propagation, thus leading to unexpected wave dispersion.

Objectives

The main objective of the present work is to demonstrate with real experiments the potential combination of two different approaches (low-cost seismic recording infrastructure and of simulation models) in order to model unexpected wave dispersion in specific areas in Paliki peninsula at the Kefalonia island under seismic excitation. For example, in 2014 a sequence of seismic events caused serious damages in public infrastructures and residences (e.g., Karakostas et al., 2014). Although in this seismic sequence, as in plenty of others in the past, there were places where the seismic event caused serious damage and others where the damage was negligible. The increment of the spatial density of seismological instruments could provide very useful information regarding velocity field distribution.

Methods

The installed cost-effective and low-power seismic stations are in depth analyzed by Krokidis et al. (Krokidis et al., 2022). For the needs of this work the recordings of these two stations are presented, as part of the future dense network to be installed in the final setup. The first station is installed in Lixouri and the second station in Chavriata village. Figure 1 shows the installed stations and the relevant places on the map of Kefalonia. On the other hand, all numerical simulations of simplified models of wave propagation in several artificial landforms were performed in a suitable half-space numerical domain by using the Finite Element Method which is implemented in the commercial software COMSOL Multiphysics®.

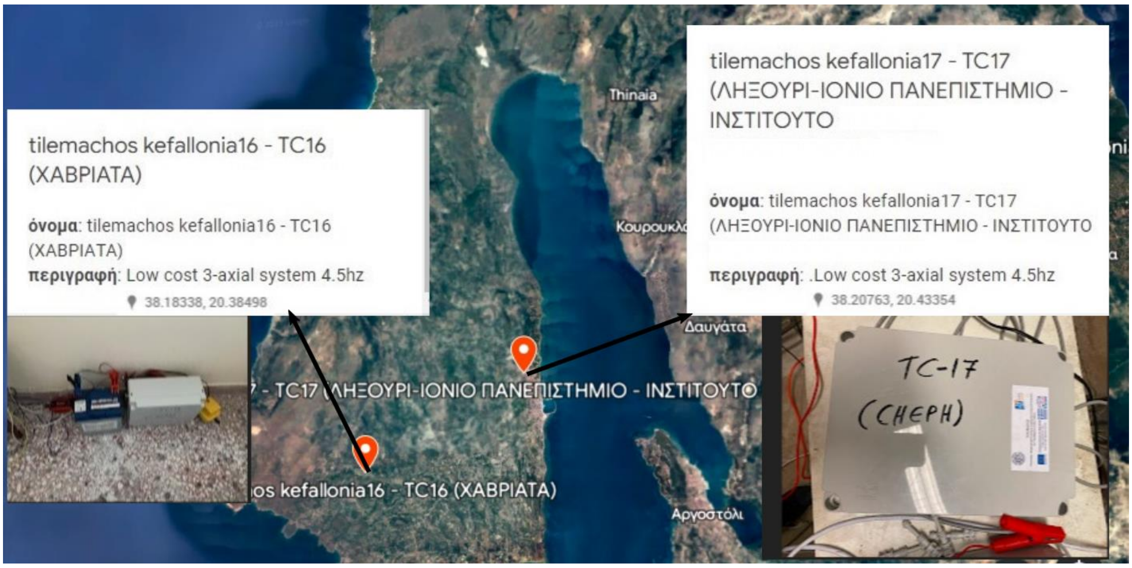

Figure 1. The station which is installed at Lixouri (on the right inset) and the station at Chavriata village (on the left inset) with the relevant position of each place in the map.

Results and Discussion

The results presented here are preliminary results of a seismic event that occurred on 7 July 2023 (12:56:21 GMT, focal depth 10 km) of magnitude M_w 3.6. The presented recordings of the vertical component of the velocity field are from the two stations and are shown in Figure 2. The horizontal distance between these two stations is about 5 km. As the two seismograms indicate, there are notable differences in the measured velocity amplitude.

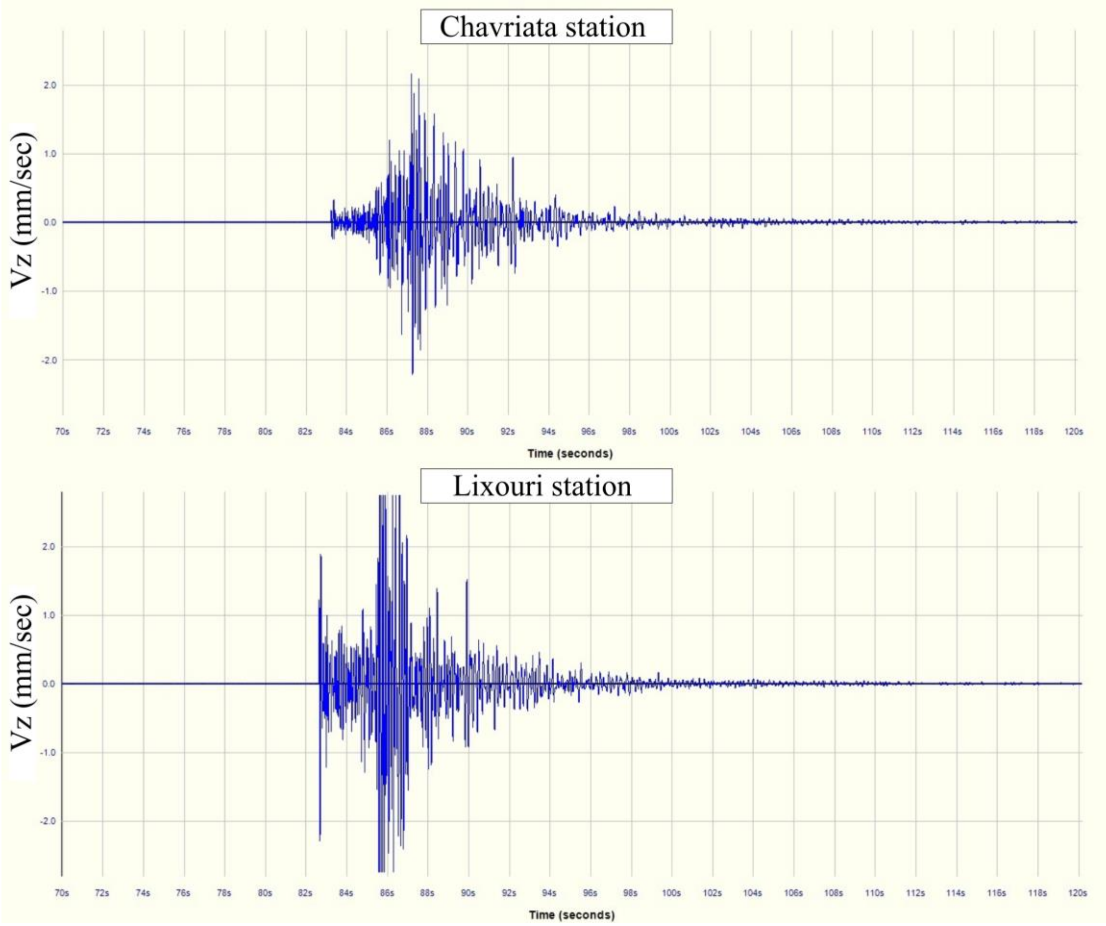

Figure 2. The vertical component (Vz) of the recorded velocity (in mm/sec) of a seismic event on 7 July 2023 of magnitude M_w 3.6 and focal depth 10 km from the station in Chavriata village (top) and the station in Lixouri (bottom)

Experiments in the geophysical scale, and relevant of examined numerical models, provide evidence that the morphology of the surface either naturally as a forest or artificially modifying the ground could provide a metasurface characteristic leading to unexpected ways of wave propagation such as deflection into the bulk (Mu et al., 2020). For a meter scale geometry, it has been numerically shown that terraced slope functionalizes as large scale metasurface (Aravantinos-Zafiris and Sigalas, 2021). As numerical simulations show, the modification of the structure to a non-repeatable sequence of terraces does not significantly affect the functionality of deflecting surface waves. Figure 3 provides the calculated transmission for the simple case with the presence of concrete retaining walls, shown in Figure 3(a), and a relevant where the repeatability of the terraced slope is modified, shown in Figure 3(b). For both cases the Transmission has not been modified significantly as presented in Figure 3(c).

Evidently, it is expected that the creation of a local network of low-cost seismographs will provide more evidence to evaluate the findings of the simplified numerical models. Summarizing, from the analysis of this work it is obvious that, the development of the Paliki low-cost network could stand as a useful channel of information with multiple uses by the community.

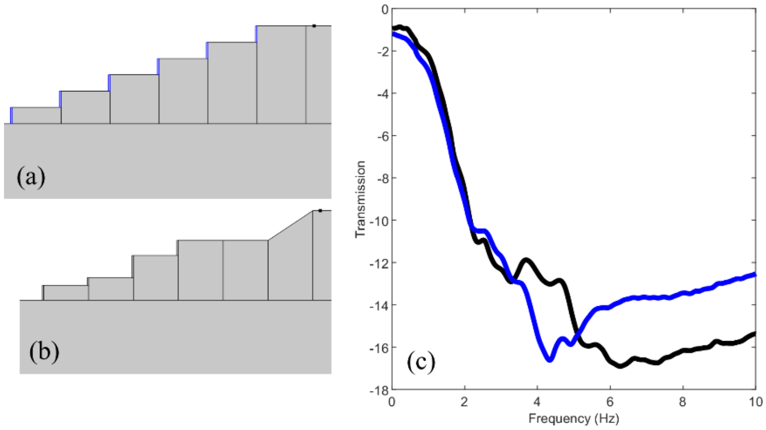

Figure 3. The examined terraced slope with concrete walls (a), the relevant non periodic case (b), and the Transmission for each examined case. Case (a) is represented by the black line, and case (b) is represented by the blue line.

Acknowledgements

The financial support of the European Union and Greece (Partnership Agreement for the Development Framework 2014-2020) under the Regional Operational Programme Ionian Islands 2014-2020 for the project ”Laertis” is gratefully acknowledged.

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8th International Colloquium on Historical Earthquakes, Palaeo- Macroseismology and Seismotectonics

Bulletin of the Geological Society
Special Publication No. 11, 2023
Publisher:
Geological Society of Greece
ISBN: 978-618-86841-1-9
ISSN: 2945-1426