Quaternary earthquakes: geology and palaeoseismology for seismic hazard assessment

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Why does Quaternary geology contribute to seismic hazard assessment?

Strong earthquakes are an essential source of information for research on active tectonics and seismic hazard. For example, large seismic events allow identifying active faults and determining fault kinematics. Teleseismic waveform analyses are used to determine dip and strike of the fault plane and the focal depth (e.g., Hartzell and Heaton, 1983; Jackson and McKenzie, 1984; Maggi et al., 2000). Geodetic techniques like GPS, radar interferometry (InSAR) and pixel matching allow to reveal the surface deformation pattern due to large events and can be used to model the geometry of the causative faults and the amount of slip (e.g., Wald et al., 1996; Talebian et al., 2006; d'Oreye et al., 2011; Elliott et al., 2013, 2016; Fielding et al., 2013; Zhou et al., 2016). Earthquake surface ruptures typically preserved for magnitudes larger than 6.0 tell us much about fault geometry and parameters including slip vector, slip distribution, possible fault interaction, and the landscape response to large tectonic events (e.g., Koto, 1893; Philip and Meghraoui, 1983; Xu et al., 2009; Oskin et al., 2012; Gold et al., 2013). Surface rupture data are thus valuable for piecing together the picture of regional tectonics. In seismic hazard studies, modern large earthquakes do not only reveal capable faults (Azzaro et al., 1998), but also shed light on the ground motion that affects the epicentral area. Studies of large earthquakes are used to estimate the attenuation relationships between earthquake magnitude and the intensity distribution (e.g., Dahle et al., 1990; Sadigh et al., 1997; Bindi et al., 2006). Furthermore, coseismic effects contribute to the overall hazard and can be studied in modern events (Michetti et al., 2007; Porfido et al., 2015).

All these studies have in common that the observation period only covers not more than one hundred years, i.e. the onset of instrumental earthquake detection and modern studies of earthquake geology. However, earthquake recurrence intervals exceed this time span even in the fastest deforming areas of the world. Hence, it is not possible to analyse the entire earthquake cycle with these methods. Often it remains unclear whether or not modern earthquakes represent the worst case scenario, and most active faults in the world did not rupture in the instrumental period at all. Thus, it is essential to gather earthquake data in a longer time scale.

Studies of historical seismicity in written records (Ambraseys, 1971, 1983) and archaeoseismology (Stiros and Jones, 1996; Noller, 2001; Galadini et al., 2006; Rodríguez-Pascua et al., 2011) can extend the earthquake record to several millennia in areas like China, the Mediterranean or the Middle East. However, information in historical sources on active faults and earthquake effects on the environment are frequently incomplete and not homogeneous.

For this reason, collecting meaningful data on fault activity and long-term seismic hazard often requires the integration of information about (palaeo-) earthquake environmental effects (i.e., EEEs; Michetti et al., 2005; Papanikolaou et al., 2015) and results of palaeoseismological studies (e.g., Galli et al., 2008; Reicherter et al., 2009; Grützner et al., 2013). The effects of large earthquakes can be preserved in the geological record for thousands of years and even longer: repeated events of surface faulting and folding create tectonic landforms such as fault scarps, fault-generated mountain fronts, drainage patterns indicative of vertical tectonic motion, etc. (e.g., Wallace, 1978; Blumetti et al, 1993; Bull, 2007; Blumetti and Guerrieri, 2007; McCalpin, 2009). The distribution, variety, and amplitude of such landforms have been used to evaluate the seismic potential of a region employing the concept of the so-called "seismic landscape" (e.g., Serva et al., 2002; Dramis and Blumetti, 2005; Michetti et al., 2005; Michetti et al., 2012). This concept includes the tectonic geomorphology of a region as well as the geological record of past seismic activity. Quaternary science techniques are increasingly employed to investigate the geological record, and interdisciplinary studies have proven necessary and successful to reveal a fault's or region's seismic history. A large variety of tools is available nowadays to the earthquake geologists. Classical on-fault investigations, such as palaeoseismological trenching, coupled with tectonic geomorphology, still form the backbone of palaeo-earthquake research (e.g., Vittori et al., 1991; Dramis and Blumetti, 2005; Bull, 2007; McCalpin, 2009, and many others). The latter takes benefit from recent developments in producing high-resolution digital elevation models (DEM) from data sources such as airborne laser scanning/LiDAR (Haugerud et al., 2003; Arrowsmith and Zielke, 2009), Structure-from-Motion (SfM) photogrammetry (Bemis et al., 2014; Reitman et al., 2015; Elliott et al., 2016), and stereo and tri-stereo satellite imagery (Zielke et al., 2015). Progress in dating techniques such as exposure dating using cosmogenic nuclides, Uranium-Thorium series dating, and luminescence techniques also improved the resolution and reliability of this kind of studies (Benedetti and Van Der Woerd, 2014; Gregory et al., 2014; Rhodes, 2011, 2015; Middleton et al., 2016). Increasing attention is being paid in the last decade to the analysis of EEEs as earthquake proxies and the application of the ESI scale, an intensity scale based only on EEEs developed in the frame of INQUA (Michetti et al., 2007; Serva et al., 2007, 2016; Papanikolaou, 2011; Moreiras and Páez, 2015; Quigley et al., 2016). These studies use earthquake proxies like mass movements, liquefaction, tectonic uplift or subsidence, tsunami, and hydrological anomalies to analyse past seismic events. Related approaches utilise the effects of earthquakes on archaeological sites (Rodríguez-Pascua et al., 2011) and the coastal impact of tsunamis (Lario et al., 2016).

The interaction of different depositional and erosional processes, climate variations, and anthropogenic modifications can lead to a highly complex geological record which complicates the identification of tectonic deformation and secondary earthquake effects in the stratigraphy (Nikonov, 1995). However, the manifold of overlapping and interacting processes also presents a unique opportunity since there are plenty of different ways in which evidence for past seismicity can be recorded. Careful and detailed studies of the Quaternary geological record of earthquakes may include disciplines such as stratigraphy, pedology, limnology, palynology, glaciology, speleology, archaeology, and geoarchaeology, aided by geophysical techniques and Quaternary dating methods.

For example, palaeosols that develop on stable surfaces and which are successively covered by colluvia, as accommodation space has been created by normal faulting, are used as stratigraphic markers in palaeoseismic trenches. However, they are often hard to be identified as younger soil develops on top of them, alterating the older units. This is especially problematic when the sum of coseismic and postseismic offsets is small and only thin layers of colluvium cover the palaeosols.

Groundwater flow, carbonate precipitation, creep, and other mechanisms may also obscure older soils such that the trench stratigraphy is difficult to interpret. Dating palaeosols in the absence of charcoal or preferred radiocarbon material can also be challenging. These problems can often be overcome by detailed palynology, mineralogy, and sedimentology studies. The stratigraphic context of the palaeosols in the first place is the key to unravel the formation and deformation history. Earthquakes with small surface offsets may still leave their geological traces along the fault as open fissures/cracks or in the form of thin anomalous sediment layers due to ponding or mobilisation of slope deposits and dust. The environmental information recorded by old soils can further help to identify phases of soil formation and the response to climatic events. These data can then be used to distinguish sedimentary units that are indicative of seismic activity. Innovative dating techniques with high accuracy and precision can further help to identify the relevant layers in the stratigraphy. In the scenario discussed, integrated work across a number of Quaternary science disciplines would be the key to extract the earthquake information from the geological archives.

As more and more modern examples of earthquakes and earthquake sequences are now available, it becomes increasingly clear that the geological record can be difficult to unravel for other reasons, too. Surface rupture patterns can be highly complex in single events (e.g., Fletcher et al., 2014; DeLong et al., 2016). In earthquake sequences like the one that struck Central Italy in 2016, repeated ruptures of the same fault might occur (Figure 1). These phenomena are obvious issues in palaeoseismological research. While it may never be possible to solve these problems entirely, new techniques and approaches can help to narrow down uncertainties and to better understand past earthquakes.

For the reasons above, Quaternary geology is an essential tool for seismic hazard assessment especially where the surface expression of active faulting is either rapidly obscured by erosion/sedimentation, or the recurrence intervals of surface rupturing earthquakes are very long. This concerns many areas of the world, like stable continental regions such as Central Asia, where earthquake tend to be large but infrequent (e.g. Prentice et al., 2002; Campbell et al., 2015; Grützner et al., 2017), but also regions such as Central Europe (Štěpančíková et al., 2010; Špaček et al., 2015; Grützner et al., 2016). Long recurrence intervals indeed are one of the greatest challenges in earthquake geology research and tectonics, but also in seismic hazard studies (Liu and Stein, 2016). In these cases geomorphological studies on drainage patterns, fluvial and marine terraces, and morphometric analyses can help to identify active faulting. High-resolution geophysical studies can help to identify faults that do not have a surface expression at all and to image their shallow structure.

In the following section we discuss a case study to illustrate how modern earthquakes help to understand the tectonics of Central Italy, and what a sequence of moderate events means for palaeoseismology and seismic hazard research.

An illustrative case study: the Central Apennine Fault Systems

The Central Apennines in Italy are a NW-SE trending mountain range that presently undergoes NE-SW extension in its sectors close to the main water divide. Since the Pliocene, a number of elongated basins bounded by normal faults (i.e., grabens or half-grabens) have formed by repeated cycles of earthquakes (Cinque et al., 1991; Cello et al., 1997). The entire region is thus subject to a moderate-to-high seismic hazard (Galadini and Galli, 2000; Meletti et al., 2016) and in the past ~100 years some of the strongest earthquakes ever recorded in Italy occurred in this region. The analysis of these events from a geological perspective has shaped the understanding of active faulting and seismic hazard in Italy and beyond.

Fucino 1915

On 13 January, 1915, a shallow earthquake with a magnitude of M7 occurred in Fucino Basin. This event caused widespread devastation and left ~30,000 people dead. It took decades for the region to recover and even today the traces of the earthquake are still visible in the epicentral area. The surface rupture pattern was described by Oddone (1915). Blumetti et al. (1988) reconstructed the 1915 surface faulting trace by comparing Oddone‘s report with the impressive tectonic landforms that characterize the Fucino Basin. They also collected original data of coseismic earthquake ground effects through interviews made in 1985 with old locals who had experienced the 1915 event. As a result, among other indicators, they have recognised the occurrence of continuous 1915 surface faulting at the base of a Middle Pleistocene tectonic terrace, testifying that this landform is the result of repeated 1915-like surface faulting events. This large event traced, for Italian geologists, the conceptual model of the seismic landscape of the Central Apennines and laid the groundwork for further studies on earthquake geology in the area. Some years later, palaeoseismological investigations revealed the previous earthquake history of the causative faults and brought to light evidence for historical and pre-historical surface faulting occurrence (Michetti et al., 1996; Galadini and Galli, 1999). Moreover, geodetic studies were used later to investigate the source mechanism of this large event (Ward and Valensise, 1989).

1997 Umbria and Marche

On September-October 1997 a seismic sequence hit the Umbria-Marche region. The epicentres were located in the Colfiorito area. Two main shocks occurred on September 26 (M_W5.7 and M_W6.0) followed by another earthquake on October 14 (M_W5.6). These events were also studied through InSAR modelling (Stramondo et al., 1999): a relatively young innovation in imaging earthquakes back then. At that time the quality of InSAR data was relatively low compared to modern studies. The data did not offer a direct recognition of discrete surface deformation which would allow modelling inversion solutions for fault geometry and slip. Strong motion data and geodetic analysis, however, were used to gather this information. The occurrence and extent of surface faulting in the 1997 earthquakes was debated. Some authors (Cello et al., 1998; Cinti et al., 2000; Vittori et al., 2000) interpreted the surveyed ground ruptures as evidence of coseismic surface faulting ranging between 6 and 12 km in length and between 2 and 10 cm in max displacement, which are typical values for moderate earthquakes (M~6). Conversely, other researchers (e.g. Galli et al., 1998; Messina et al., 2002) interpreted the same features as the result of compaction of debris deposits driven by gravitational motion. Furthermore, a large number of secondary effects were observed (e.g. landslides, ground cracks, liquefactions, etc.) in an area in the order of 1000 km^2 (Guerrieri et al., 2009). Beyond the open debate on the interpretation of ground ruptures, the distribution of coseismic primary and secondary effects is consistent with the “seismic landscape” of the Colfiorito basin that is the result of several 1997-like earthquakes over a long geological time interval (cf., Serva et al., 2002). In this perspective, the 1997 seismic sequence is considered “characteristic” for the area and, therefore, it is indicative of the level of seismic hazard.

L’Aquila 2009

The 2009 L’Aquila, Italy, earthquake was one of the best-studied earthquakes in Europe in the last decades (e.g., Chiarabba et al., 2009; Walters et al., 2009; Cheloni et al., 2010). This event caused a few kilometres of surface faulting (3 to 19 km, according to different authors; i.e. Alessio et al., 2009; Boncio et al., 2010; Vittori et al., 2011) mainly along the Paganica fault, which borders the central section of the L'Aquila basin to the NE. Even though the coseismic throw did not exceed 15 cm, the rupture had broken the Gran Sasso aqueduct, which was providing water to L'Aquila city. This fact has strongly increased the awareness of surface faulting hazard in Italy.

Beyond the fierce debate on earthquake forecasting and risk communication triggered by the "L'Aquila Trial" (Cocco et al., 2015; Stucchi et al., 2016), the L'Aquila event led to a strong nation-wide effort aimed i) at revising the maps of active/capable faults, including additional palaeoseismological studies; and ii) at undertaking microzonation studies at municipality level in the epicentral area. Thanks to these combined efforts much light has been shed on the tectonic structure of the Central Apennines and its earthquake history (e.g., Tertulliani et al., 2009; Galli et al., 2010, 2011; Cinti et al., 2011; Vittori et al., 2011; Chiaraluce, 2012; Giaccio et al., 2012; Blumetti et al., 2013; Galli et al., 2016; Pucci et al., 2016), although the region was in the research focus already before 2009 (Blumetti, 1995; Pantosti et al., 1996; Blumetti and Guerrieri, 2007; Salvi et al., 2003).

Amatrice and Norcia, 2016

The latest insights into the earthquake behaviour of the Central Apennines became possible during the seismic sequence that started in August, 2016, and which was still ongoing in February, 2017 (four earthquakes M_W>5 on 18 February, 2017). Mainshocks between M_W6.0-6.5 struck an area between Campotosto in the south (partially overlapping the N tip of the L'Aquila earthquake sequence) and Norcia in the north. This long-lasting sequence was characterised by successive strong mainshocks, hitting a ca. 80 km long sector of the chain through the repeated re-activation of the same faults (Figure 1) and, contemporarily, a progressive migration of seismicity on adjacent tectonic structures. Research teams from many different institutions surveyed the area soon after the largest events and a great amount of data was collected and readily published on surface faulting and earthquake-induced environmental effects (EMERGEO Working Group, 2016; Livio et al., 2016; Pucci et al., 2017). Previous palaeoseismological studies (e.g., Galadini and Galli, 2003) have found confirmation in the observations related to these events, providing a valuable experimental validation on previous deductions based on palaeoseismic evidence.

One of the main turning points in these events is the availability and increased quality of data on earthquake-induced ground deformation. Thanks to an increased temporal resolution offered by many observation satellite missions (i.e., ESA Sentinel-1, COSMO SkyMed and PALSAR among others) and thanks to continuous GPS network data (Cheloni et al., 2016), scientists had the opportunity to observe the crustal deformation induced by each one of the main shocks composing this sequence, to recognize areas affected by distributed faulting/deformation, and to monitor post-seismic deformation. Inversion of ground deformation data (Lavecchia et al., 2016) together with seismological strong motion datasets and seismicity relocation (Michele et al., 2016) allowed to model the possible seismogenic sources at depth, allowing to better constrain the observations from the surface and the shallow geological record. An intense debate started in the scientific community regarding the role of the seismogenic source in inducing surface faulting, considering also local deep-seated gravitational phenomena (Albano et al., 2016; Aringoli et al., 2016; Huang et al., 2017).

Figure 1: Earthquake environmental effects due to the 2016 earthquake sequence in Central Italy. A) Surface ruptures offset a road in the 24 August, 2016, Amatrice Earthquake (M_W6.2). B) On 26 September, 2016, the road was repaired. C) On 26 October, 2016, the M_W6.6 Norcia Earthquake ruptured the same fault again and offset the re-paved road. T D) Surface ruptures in a road due to the Amatrice Earthquake. E) New surface ruptures were found to offset the road after the Norcia earthquake. This modern example illustrates the pitfalls related to interpreting geological data from palaeo-earthquakes. Looking back a couple of hundreds or even thousands of years, it will be hard or even impossible to distinguish the geological traces of individual moderate earthquakes within a seismogenic zone. Thus, primary offsets used for the reconstruction of palaeo-magnitudes may be misinterpreted. F) Uphill-facing vertical offsets due to the Norcia Earthquake led to ponding in the Castelluccio Plain (photo from 4 November, 2016). In the geological record of palaeo-earthquakes, such features might be preserved as anomalous fine-grained layers in the stratigraphy.

Quaternary geology will have a major opportunity to investigate this issue in the next years, since repeated events like the 2016 ones have left a recognizable footprint in the landscape and in the stratigraphic record. Also, the earthquake series made it possible to observe and distinguish a variety of earthquake environmental effects like primary and secondary ruptures and mass movements. This will provide insights into the distance-magnitude relationships of these EEEs and their occurrence in the case of repeated strong shaking.

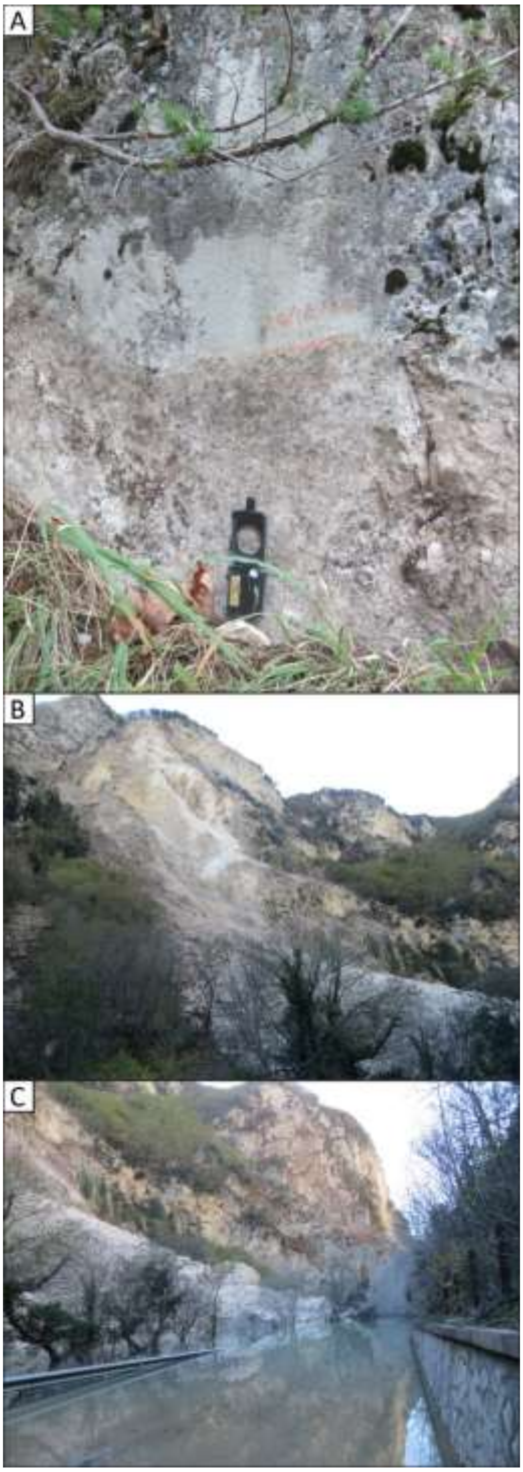

Figure 2: A) The Norcia Earthquake produced offset along limestone fault scarps. B) Secondary earthquake environmental effects of the Norcia Earthquake include, but are not limited to, a number of large mass movements. C) A coseismic landslide blocked a river and led to the formation of a temporal lake (Norcia Earthquake).

The outstanding series of earthquakes in the Central Apennines described above makes clear why novel approaches and interdisciplinary studies on the traces of earthquakes in the Quaternary record are necessary. In fact, they not only allow to understand the tectonic setting of a region - and the Apennines are probably the best example for that in Europe - but they also provide the necessary input data for any evaluation of the seismic hazard (Blumetti and Guerrieri, 2007; IAEA, 2015). The use of palaeoseismological data in seismic hazard assessments can still not be regarded as a matter of course, but it is clear that the instrumental period is too short to serve as a reliable database for a region’s seismicity. Different approaches to seismic hazard assessment exist and they are all subject to intense discussion. Although probabilistic seismic hazard assessment (PSHA) is a common practise, it is technically impossible to evaluate the success of such approaches today due to the short time span of observation (decades) compared to the earthquake occurrence intervals (centuries to tens of thousands of years). However, it is clear that where earthquakes happened in the past, earthquakes will happen in the future. This is what people can and should be prepared for.

Special Issue Quaternary earthquakes: geology and palaeoseismology for seismic hazard assessment

The above described example of the Central Apennines clearly illustrates the need to study the Quaternary earthquake record for understanding the overall tectonics and seismic hazard. In order to discuss about earthquake geology in different tectonic and climatic settings, scientists working on Quaternary earthquakes from all over the world annually organise international conferences in the frame of INQUA (namely International Workshops on Palaeoseismology, Active Tectonics and Archaeoseismology - PATA Days). Each conference is hosted in a different part of the world and accompanied by a number of field trips. Typically, the host scientists introduce the international community to the regional geology and explain the research that has been conducted to unravel the earthquake history and the seismic hazard in each region. One of the learning points is how different methods work in different environments, and which site-specific solutions have been developed to study the Quaternary record of earthquakes.

This Special Issue collects contributions in the field of Earthquake Geology and Palaeoseismology from the 6th INQUA International Workshop on Palaeoseismology, Active Tectonics and Archaeoseismology that was held in Fucino, Italy, in April 2015 (http://www.isprambiente.gov.it/it/fucino-2015). The workshop commemorated the centenary of the 1915 Fucino earthquake and included field trips to the active faults in the Central Apennines and palaeoseismological research sites. The meeting was organized by ISPRA, INGV and University of Insubria and promoted by INQUA TERPRO PALACTE which supported the participation of some ECRs from low-GDP countries. Almost 200 scientists from 25 countries have attended the workshop. The scientific program included four main scientific sessions dealing with Quaternary Geology, Palaeoseismology, Archaeoseismology and Seismic and tsunami hazard. About 150 contributions were presented as oral and poster communications. These contributions have been published as extended abstracts in a Special Volume of INGV Miscellanea and are on-line: http://www.ingv.it/editoria/miscellanea/2015/miscellanea27/.

Fifteen selected studies were invited to this Special Issue. The papers deal with palaeoseismology, detailed studies on stratigraphy, innovative techniques to detect earthquakes in the geological record, EEEs, the ESI 2007 scale, and new methods for seismic hazard assessment such as InSAR. We collected papers from Italy, Greece, Spain, Switzerland, the Czech Republic, Austria, and Mexico to show how different settings require a customised set of Quaternary science techniques (Figure 3). Most of the studies concern regions in Europe where active faulting is abundant and where a strong historical record of past earthquakes is available (Figure 4).

Figure 3: Locations of the studies presented in this Special Volume. Topography and bathymetry are from Etopo1 (Amante and Eakins, 2009). This map is in Mercator projection.

During a microzonation study in San Demetrio ne' Vestini near L'Aquila, an active fault underlying the historical centre was discovered (Working Group MS–AQ, 2010). Whilst the Quaternary evolution of the area was well investigated, an earthquake history based on palaeoseismological data was lacking. The paper by **Blumetti et al.** in this Special Issue closes this gap with a study on the palaeoseismic history of the San Demetrio ne' Vestini fault. In the Quaternary stratigraphy exposed in a very long trench, the authors found evidence for at least five surface faulting events in the past 18 ka and were able to reconstruct the Holocene earthquake record by retrodeforming the sedimentary layers and colluvial wedges.

Livio et al. analysed the L'Aquila earthquake (6 April, 2009, M_W6.3) to study distributed surface faulting. The authors analysed the InSAR-derived deformation field of the main event and were able to correlate these data with the location of distributed surface ruptures and the amount of slip associated. They found a significant correlation between the occurrence of distributed faulting and profile curvature of the dislocation field, in spite of the distance from the primary fault. These findings are important for a correct assessment of surface faulting hazard. They allow exploring the possible triggering of slip on secondary faults induced by a main shock on a primary fault.

Gori et al. investigated a segment of the causative fault of the M7 Fucino event of 1915 and analysed stratigraphic evidence for four earthquakes prior to 1915 in a number of palaeoseismological trenches. In an innovative way they combined classical geological work on the trench stratigraphy with (geo-) archaeological investigations on cultural layers from the Late Neolithic to recent. This enabled the authors to reveal the earthquake history of the past 5,500 years and to reconstruct the interplay between natural and human-induced landscape changes in this region. Their study shows how an interdisciplinary approach encompassing can overcome the limitations of mere palaeoseismological studies.

Figure 4: Seismicity and seismogenic faults in Europe and the Mediterranean area. White dots are earthquakes with M_W>5.5 from the ISC-GEM database, 1900-2012 (Storchak et al., 2013); open circles are historical earthquakes with M_W>6.5 from the SHEEC database (Stucchi et al., 2013); black lines are seismogenic faults from the European Database of Seismogenic Faults (Basili et al., 2013). Topography and bathymetry are from Etopo1 (Amante and Eakins, 2009).

Špaček et al. discuss the recent activity of slow-moving faults in the Bohemian Massif through an integrated geophysical and palaeoseismological approach. In their work they considered the concurrent role played by slope deformation processes and differential denudation, which can eventually lead to a geomorphic scarp that resembles a tectonic one. This paper is not only a contribution to the study of palaeoseismic events in what is often referred to as stable continental region, but also highlights challenges for seismic hazard assessments in such slowly-deforming areas.

Weissl et al. provide multiple field evidence from the Quaternary Gänserndorf Terrace situated north of Vienna. Their researches led to demonstrate the tectonic segmentation of a former much larger river terrace. Luminescence ages (IRSL and OSL) allowed dating the terrace formation as well as the rate of tectonic subsidence. Furthermore, this paper deals with the geomorphology of the terrace surface and the adjacent basins and it discusses dry valleys and large depressions visible in the digital elevation model as a result of permafrost processes. Therefore, this paper demonstrates that both neotectonics and glacial processes have formed the recent landforms of this area.

Assessing the seismogenic potential of active faults in high heat-flow environments can be particularly challenging and needs, as a first step, the characterization of geometry and slip rates of the recognized faults, together with the characterisation of associated geothermal manifestations. **Piccardi et al.** analysed the Tuscany – northern Latium region (Central Italy) by means of DTM analysis, field surveys and the review of a large amount of published literature studies, in order to propose a first systematic characterisation of the structures present in this region.

Ferrater et al. provide a study aimed at defining the seismic potential of the left-lateral strike-slip Alhama de Murcia fault (SE Iberian Peninsula) based on palaeoseismic investigations combined with morphotectonic analyses. Results have shown that the studied fault is one of the most active faults in the Eastern Betics Shear Zone in terms of slip rate. Their integrated approach is recommended especially for faults with scarce evidence of late Holocene slip.

Frigerio et al. present a multidisciplinary field study in the Eastern Monferrato Arc aiming at individuating palaeoseismic evidence of recent strong earthquakes. Through the integration of sedimentological and micropedological data with structural analyses, it has been possible to point out the evidence of several reverse surface faulting and warping events, that allow to state that the Monferrato Arc, similarly to other thrust faults in the Po Plain, is now a seismic gap but it is capable of strong earthquakes (Mmax 6.5) with long recurrence intervals.

Waterside areas can be particularly promising for palaeoseismology since one can benefit also from offshore high-resolution data, including coring, seismic reflection profiles, and bathymetry. **Fabbri et al.** analysed a combined database in the Bernese Alps (Switzerland), close to Lake Thun, including offshore seismic reflection profiles, HR bathymetry, onshore GPR, and field data collection. Their observations confirm a Holocene re-activation of a fault without known historical or instrumental events according to seismic catalogues. This study highlights the value of palaeoseismic investigations in areas with long earthquake recurrence intervals and low seismicity, and it is a great example for the additional power of a multi-method approach.

Four papers are dealing with the ESI07 scale (Michetti et al., 2007; Serva et al., 2015), an intensity scale developed in the frame of INQUA that is based only on the characteristics and size of earthquake environmental effects. This scale has been applied by **Papathanassiou et al.** to the 2014 Jan. 26th and Feb. 3rd Cephalonia earthquakes (Greece). Several coseismic environmental effects were recorded, mainly liquefaction and slope failures, while no significant structural damages occurred. Through the application of the ESI07 scale it was possible to evaluate the 2014 intensity that was comparable with the 1867 earthquake, even if this historical event was lower in terms of magnitude. This result has confirmed the relevance of earthquake environmental effects for a proper seismic hazard assessment since they allow maintaining the consistency with the historical catalogues.

Papanikolau and Melaki have used the ESI07 scale to analyse four events in Greece that occurred recently (1995 M_S6.6 Kozani-Grevena and 1978 M_W6.5 Thessaloniki earthquakes) and in historical times (1894 M6.8 Atalanti and 365AD M_W8.4 Crete earthquakes). A strong record of earthquake environmental effects is available for all these earthquakes, including surface faulting as well as secondary effects. The results have been integrated with other ESI07 applications in Greece and in the Mediterranean with the aim to i) define relationships between magnitude and the ESI07 intensities; ii) offer a preliminary estimate of how the intensity attenuates with distance.

The ESI07 scale has been applied by **Rodríguez-Pascua et al.** to the 1912 Acambay Earthquake (M6.9, Mexico). The authors determined the epicenter of this earthquake analysing earthquake archaeological effects (EAEs) and earthquake environmental effects (EEEs). Moreover, they introduced a new interpretation of the genesis of the earthquake environmental effects. Additionally, they have estimated the total rupture length and the potential seismicity of the Acambay-Tixmadeje fault zone.

Silva et al. applied the ESI07 scale to three earthquakes which occurred in the Betic Cordillera, SE Spain (2011 Lorca, 1863 Huércal-Overa, and 1829 Torrevieja) with the aim to obtain high-resolution ShakeMaps scenarios based on the characteristics and the spatial distribution of EEEs. The resulting maps provide more realistic scenarios than those resulting from damage based EMS macroseismic data, leading to a better definition of the geological parameters of the earthquake (e.g., the characteristics and size of the seismic source).

Two papers presented in this Special Issue deal with spelaeoseismology and evidence for earthquakes from caves. The first contribution, by **Pérez-López et al.,** deals with a classical palaeoseismic analysis of active faulting combined with thermal analysis of the uppermost part of the crust. The authors have used deep caves (300 m depth) to obtain the vertical thermal gradient by direct measurements. They also described the air quality in the caves, seeking for the relationship between gas emission and tectonic activity. The novelty of the methodology is the combination between palaeoseismology and geothermics for the estimation of the Quaternary tectonic slip-rate of active faults. Moreover, the authors dated the last earthquake from the analysis of the remains of bones of Lynx pardinus spelaeus found in the cave.

The second contribution, by **Kagan et al.**, is the study of damaged spelaeothems in Calabrian caves as evidence for earthquakes. The authors found evidence for earthquakes in two caves (Romito and San Paolo caves), that they documented, sampled, and subsequently dated by the state-of-the-art U-Th series method. Their results contribute to the understanding of the recurrence of damaging earthquakes in the Calabrian region. This is finalised to the seismic hazard assessment in the earthquake-prone Apennines region, characterized by a long-term recurrence pattern. Here more than 100,000 people are potentially exposed to earthquake shaking and historical data clearly underestimates the risk. To our knowledge, this is the first report showing this long term, well-dated, palaeoseismic record.

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