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Editorial

Quaternary earthquakes: Geology and palaeoseismology for seismic hazard assessment

1. 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 revealing 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 over 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, 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 palaeoearthquake 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

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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 (Figs. 1 and 2A). 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 when 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.

2. 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.

2.1. 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 recognized 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 prehistorical 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).

2.2. 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).