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Active faulting and seismotectonics in central Italy: Lesson learned from the past 20 years of seismicity. Engineering clues

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ABSTRACT: We present a review of the geological knowledges on the seismogenic faults and fault systems that activated during the last three major seismic sequences in central Italy, since the Colfiorito seismic sequence of 1997. Information describing the Quaternary activity of the causative fault systems have been matched with the geological effects – in terms of surface faulting – caused by the seismic sequences and with moment tensor solutions of a selection earthquakes among the mainshocks, both considering those already published and making new solutions for the mainshock of the 2016 seismic sequence on the Mt. Vettore-Mt. Bove fault and for the major four events occurred on the 18 January 2017 along the Campotosto fault. General considerations in terms of seismotectonics of the central Apennines have been provided, which have implications in terms of defining the effectiveness of neotectonic studies to assess seismogenic potential for a given active fault and to evaluate surface fault displacement hazard.

1 INTRODUCTION

During the past ˜twenty years, three major seismic sequences struck a hundred of square kilometres wide zone in central Italy. Namely, in 1997, a seismic sequence affected the area of Colfiorito, in southern Umbria (mainshock M 5.99, on 26 Sept.; Ekström et al., 1998); in 2009, a M 6.13 (Herrmann et al., 2011) seismic event struck the city L'Aquila, in the Abruzzi region, and surroundings; lastly, the 2016-2017 seismic sequence struck the region in between the two preceding sequences. This has been the most severe and long lasting seismic sequence of the three, characterised by three main shock events, on 24 Aug., 26 Oct. and 30 Oct. 2016, the latter being the largest event of the sequence and in central Italy since the M 7 (Rovida et al., 2016) 1915 Avezzano one.

These sequences gave the opportunity to achieve a large number of data which permitted to refine the geological knowledges of the areas affected and to get to an updated view of the seismotectonic characteristics of the central Apennines of Italy, that was the focus of destructive historical seismic events (M 6.5-7), whose full comprehension still deserves more investigations. We here review the geological knowledges of the areas struck by the sequences as for Quaternary and active faulting, comparing them with information concerning the surface effects caused by the three examined seismic sequences and causative faults. Our aim is to provide the most updated geological view of the seismogenic faults and fault systems and to derive seismotectonic interpretations in terms of relation between activity of the tectonic structures and the major historical and instrumental seismic events. These results allow us to define some general aspects concerning the Apennine active normal faults seismogenic potential and surface faulting hazard.

2 REVIEW OF REGION ACTIVE FAULTS, SEISMOGENIC CHARACTERISTICS AND INTERPRETATIONS

The following sections describe active faults and fault systems in the regions that produced the 1997, 2009 and 2016-2017 seismic sequences (Fig. 1), namely the Colfiorito-Sellano faults, the Norcia fault system, the Upper Aterno Valley fault system, the Mt. Vettore-Mt. Bove fault system, the Amatrice fault and the Campotosto fault. Each sub-section 1) describes geological data that allow to evaluate if a given fault can be considered as the surface expression of a seismogenic source potentially able to generate surface rupturing earthquakes, following the geological criteria proposed by Falcucci et al. (2016) and 2) reviews historical seismicity. Data on the historical earthquakes and the damage distribution are derived from Rovida et al. (2016).

Moment Tensor Solutions (henceforth MTs) of a selection of the main events (M>4.5) for each sequence are provided. As for the 1997 Colfiorito and 2009 L'Aquila seismic sequences, MTs are derived from Ekström et al. (1998) and Herrmann et al. (2011), respectively (Table 1). As for the 30 October 2016 mainshock and the 18 January 2017 events in the Campotosto area, new MTs have been here produced (Munafò et al., 2018; in preparation) (Table 1).

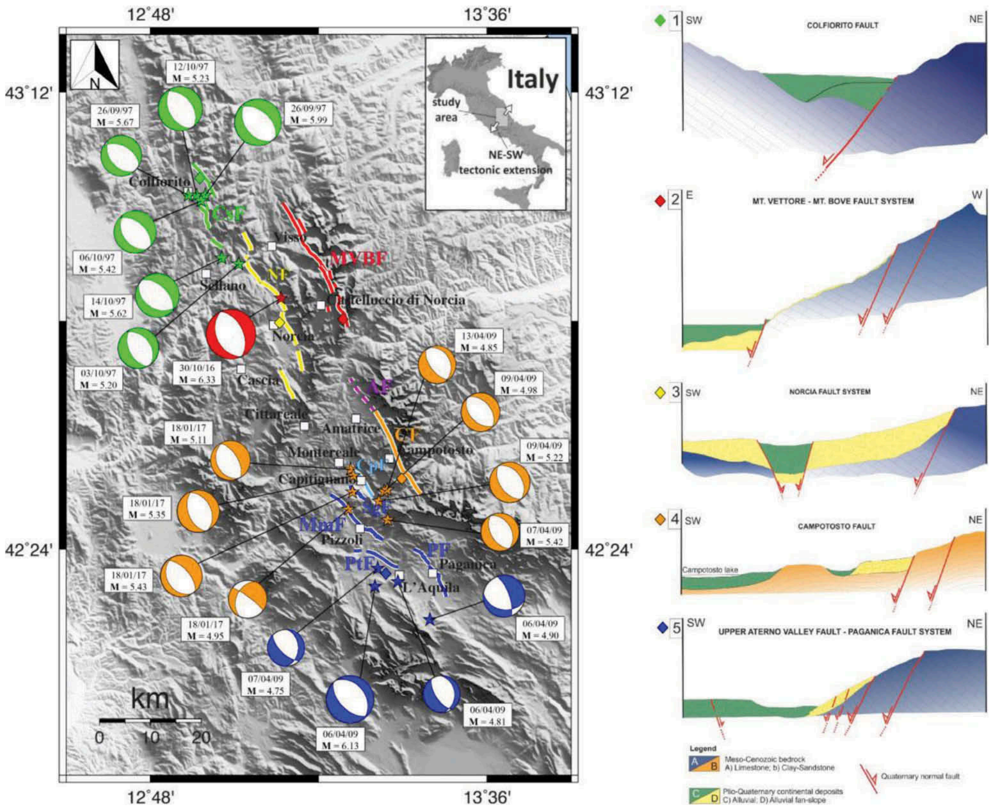

Figure 1. Left panel: DTM with the traces of the active and seismogenic faults, coloured lines (fault strands with the same colour pertain to the same seismogenic fault system). Focal mechanisms are Moment Tensor Solutions (MTs), reported in Table 1. Faults: Colfiorito-Sellano faults, CSF; Norcia fault, NF; Mt. Vettore-Mt. Bove fault system, MVBF; Amatrice fault, AF; Campotosto fault, CF; Capitignano fault, CpF; San Giovanni fault, SgF; Monte Marine fault, MmF; Pettino fault, PtF; Paganica fault, PF. Diamonds correspond to the location of the representative schematic cross-sections reported on the right panel.

Table 1. Source parameters of the moment tensor solutions for the three central Italy seismic sequences. As for the 2016 events, we selected the 30 October mainshock as event representative for the whole sequence.

DATE (yyyy/mm/dd)	TIME (UTC)	LAT. (°N)	LON. (°E)	DEPTH (km)	M (Moment Magnitude)	STK (°N)	DIP (°)	RAKE (°)
1997 Colfiorito								
19970926	003311	43.020	12.910	8.0	5.67	152	46	-83
19970926	094024	43.020	12.930	6.0	5.99	144	42	-80
19971003	085520	43.020	12.890	5.0	5.23	141	43	-74
19971006	232451	43.010	12.920	3.0	5.42	145	40	-80
19971012	110835	42.900	13.010	5.0	5.20	154	51	-82
19971014	152309	42.910	12.970	5.0	5.62	122	38	-100
2009 L'Aquila								
20090406	013239	42.334	13.334	5.0	6.13	135	55	-95
20090406	023704	42.366	13.340	10.0	4.81	0	35	-50
20090406	231537	42.451	13.364	7.0	4.90	330	40	-90
20090407	092628	42.342	13.388	9.0	4.75	355	30	-65
20090407	174737	42.275	13.464	16.0	5.42	340	70	-60
20090409	005259	42.484	13.343	7.0	5.22	145	50	-90
20090409	193816	42.501	13.356	7.0	4.98	135	45	-95
20090413	211424	42.504	13.363	6.0	4.85	335	30	-80
2016-2017 Vettore-Campotosto								
20161030	064017	42.840	13.110	5.0	6.39	155	40	-90
20170118	092540	42.540	13.276	6.0	5.11	155	30	-85
20170118	101409	42.529	13.282	6.0	5.43	160	50	-85
20170118	102523	42.500	13.280	7.0	5.35	150	30	-80
20170118	133336	42.470	13.270	9.0	4.95	205	40	-15

3 COLFIORITO-SELLANO FAULTS

3.1 *Geological evidence of recent activity*

A series of normal faults border to the NE the Colfiorito and Cesi-San Martino basins, and a segment is also present in the Renaro-Mevale area. The structures were responsible for the seismic sequence that struck the Umbria-Marche region in September-October 1997 (e.g. Pantosti et al., 1999; Boncio and Lavecchia, 2000; Cello et al., 2000; Calamita et al., 2000; Cinti et al., 2000; Vittori et al., 2000; Chiaraluce et al., 2005; Barchi e Mirabella, 2009; Ferrarini et al., 2015). The faults display an en-echelon arrangement with dextral step-over, strike about NW-SE and dip towards SW. The Colfiorito fault can be seen for about 8 km in length; the Cesi-San Martino is visible for about 5-7 km in length. Both of the faults display a mainly extensional kinematics (Barchi et al., 2000). This fits the MTs estimated by Ekström et al. (1998) (Table 1), who defined ruptures compatible with the expected normal kinematics of the causative faults.

The Quaternary offset that can be attributed to these faults is on the order of a few hundreds of metres, mostly referable to the Early Pleistocene. Indeed, geological investigations were made after the 1997 seismic sequence by Messina et al. (2002). These investigations consisted in 1) identification and analysis of relict paleo-landsurfaces, 2) field investigations in the Colfiorito and Cesi-San Martino basins aimed at identifying evidence of active faulting of Quaternary deposits, and 3) analysis and interpretation of boreholes and geophysical investigations to reconstruct the deep geometry of the pre-Quaternary top. Flights of paleo-landsurfaces are different and at different elevations across the faults. Such difference defines a landscape evolution controlled by the activity of the faults at least during the late Pliocene-Early Pleistocene. Displacement of the Quaternary successions describes a decreasing activity (at surface) of the main faults since the Middle Pleistocene. Indeed, since then, the effects of extensional tectonics at surface became less prominent in the basins, solely resulting in gentle bending of late Quaternary paleo-landscapes. Importantly, a terrace dated at about 24ka cross-cut the Colfiorito fault trace, resulting not displaced (Messina et al., 2002).

As for the Colfiorito basin, the geological and geophysical information (Messina et al., 2002) suggested that it results from the superimposition of two subsequent stages of evolution of the tectonic depression through the Quaternary: an early stage, during which the basin started to grow much adjacent to the main border fault, followed by a younger stage during which a much deeper depression evolved within the innermost portion of the former basin, with the fault becoming progressively blind. Di Giulio et al. (2003) confirmed that the deep structure of the basin is quite complex and the shape of the basin is hardly associable to a half-graben led by the Colfiorito fault; instead, the structure of the basin seems to have been mostly governed by karstic processes, as well as influenced by pre-Quaternary structural setting and morphology (e.g. Pizzi et al., 2002). Geochemical analyses of soil gas (Lombardi and Voltattorni, 2010) also testified for the presence of a blind fault in the area of the Cesi-San Martino basin, whose tip seems to occur some hundreds of metres in the hanging wall of the fault trace. Hence, the bulk of data describes the tectonic evolution of the area as follows: 1) formation of the Colfiorito and Cesi-San Martino basins in the framework of the central Apennine extensional tectonics; 2) evolution of the two basin as typical half-graben depressions; and 3) reduction of the activity of the normal faults since the Middle Pleistocene (Messina et al., 2002).

The above described neotectonic framework can explain why the coseismic surface ruptures along the fault traces were small, and subtle in places, allowing different authors to propose different interpretations concerning their primary (i.e., tectonic) or secondary (i.e., non-tectonic) origin. Indeed, surface ruptures were interpreted as evidence of surface faulting along the Colfiorito fault by some authors (e.g. Cello et al, 1998; 2000; Vittori et al., 2000; Mildon et al., 2016); conversely, Messina et al. (2002) proposed a non-tectonic origin of the ground fractures based on the above described geological evidence of long-term surface inactivity of the faults along which the coseismic surface evidence have been detected. Moreover, the coseismic reactivation of deep seated gravitational slope deformation during the sequence, detected by Moro et al. (2007) in the epicentral area by means of DInSAR technique, indicates that attention has to be payed when interpreting the surface breaks in this sector as strictly related to faulting.

As for the 14 Oct. 1997 shock (Mw 5.6), surface ruptures were observed along the trace of the activated fault, next to the Rasenna, Renaro and Mevale villages (e.g. Basili et al., 1998). The fractures were characterised by very small vertical offset (cm-scale); they were interpreted as evidence of surface faulting by Pantosti et al. (1999), after paleoseismological investigation, or the effects of gravitational movements by Vittori et al. (2000). Therefore, also in the case of the Renaro-Mevale fault, surface faulting after the 14 Oct. event remained of non-univocal interpretation.

3.2 *Associated seismicity*

30 April 1279 (M 6.2): the earthquake struck a large portion of the Umbria-Marche Apennines, the highest damage degree (Mercalli-Cancani-Sieberg scale, MCS) attributed to Serravalle del Chienti (10 MCS). The event has been felt even in Rome (4 MCS).

26 September 1997 (M 5.99) (Ekstrom et al. 1998): the earthquake affected a large sector of the central-northern Apennines and has had a maximum intensity of 8-9 MCS attributed to Collecurti. High levels of damage were suffered by Annifo Villa, Arvello, Camino, Isola, Molina, Verchiano, Cesi and San Martino. High damage have been suffered by 28 localities, with intensities 7-8 and 8 MCS, while 81 localities suffered intensities 6-7 MCS.

14 October 1997 (M 5.62) (Ekstrom et al. 1998): the earthquake can be considered as a strong aftershock of the 26 Sept. event, even if it can be more correctly attributed to the activation of the Renaro-Mevale fault. Owing to the temporal proximity to the 26 Sept. earthquake, it has not been possible to define the epicentral intensity, as most of the localities were already highly damaged by the preceding shock. The event caused stronger damage to Sellano, Mevale and Montesanto, where intensity reached 8-9 MCS.

3.3 *Seismogenic interpretation*

The above described geological setting, especially as for the Quaternary evolution, suggests that the seismogenic behaviour, in terms of expected magnitudes, is very well represented by the seismic shocks of the 1997 sequence and by the 1279 event. The geological data available to date allow us to exclude the occurrence of much stronger (M>6) earthquakes than the mentioned ones along these faults. Hence, the hypothesis of synchronous activation of three seismogenic sources, represented by the Colfiorito, Cesi-San Martino and Renaro-Mevale fault segments, to generate a single major seismogenic event is quite improbable. This hypothesis is supported by the absence of surface displacements during the late Quaternary and by the long term style of deformation, mainly characterised by continuous bending of the late Quaternary sedimentary successions, that results from the sum of a number of 1997-like preceding seismic events. Within this light, seismological data related to the 1997 seismic sequence (Chiaraluce et al., 2005; Chiarabba and Amato, 2003; Collettini et al., 2005) evidenced the presence of cross-structures in between the ruptured faults that conceivably controlled rupture segmentation and, hence, the maximum expected magnitude.

The length at surface of the three ruptured faults (Colfiorito, Cesi-San Martino, Renaro-Mevale), that is 10 km, 7 km and 5 km, respectively, define maximum expected magnitudes (based on the regressions of Wells and Coppersmith, 1994) of 6, 5.8 and 5.6. This configuration is comparable to that proposed in the DISS database (DISS, Working Group, 2018); instead, it differs from that of Boncio et al. (2004a), who proposed just two seismogenic sources in the area, and from Akinci et al. (2009), who proposed a single potential M 6.3 earthquakes seismic source. Valentini et al. (2017), instead, propose a single seismogenic fault system for these structures, potentially responsible for M 6.6 earthquakes. Basing on the hypothesis that the 1279 seismic event could have been generated by the faults activated in 1997 and that it has had the same characteristics of the 1997 seismic sequence, the recurrence time for these seismogenic sources is of about 700 years. In this perspective, the sum of the magnitudes of the major events of the 1997 sequence basically corresponds to about 6.3.

4 NORCIA FAULT SYSTEM

4.1 *Geological evidence of recent activity*

The Norcia normal fault system is 31 km long (between the villages of Cittareale, to the south and a few km N of Preci, to the north), and strikes NNW-SSE and dips WSW (Fig. 1). It includes four main segments that are visible in the field along carbonate fault scarps on slopes bordering intermontane depressions (e.g. Calamita et al., 1982; 1995; Brozzetti and Lavecchia, 1994; Galadini and Galli, 2000; Pizzi et al., 2002). The Preci, Campi and Norcia Quaternary basins are associated with the northernmost fault segments (Galadini and Galli, 2000). No basin is associated to the southernmost segment, between the villages of Castel Santa Maria and Cittareale (Blumetti et al., 1990).

The clearest evidence of Quaternary activity has been found in the Norcia basin. Similar to other Apennine intermontane depressions, the tectonic evolution of the Norcia basin has been driven by normal faulting along the eastern margin of the basin (Calamita and Pizzi, 1992; Calamita et al., 1999 and 2000; Böhm et al., 2011). The available literature indicates that the western margin of the basin is also a normal fault, in this case with faint geomorphologic evidence of recent activity (Blumetti, 1995; Cello et al., 1998). That fault probably represents the antithetic splay of the main fault emerging along the eastern slope.

The fault has been responsible for the displacement of the Patino alluvial fan deposits (Middle Pleistocene) (Fubelli, 2004) and of slope debris attributed to the Late Pleistocene (Blumetti, 1995). A minimum slip rate of 0.2 mm/yr has been estimated based on topographic offset on a scarp dated 0.1 Ma old and carved into alluvial gravels dated 0.23 Ma old. Recent displacements have also been related to minor fault sections within Norcia (Galli et al., 2005). Paleoseismological investigations identified slip from the 1703 (14 January) M 6.9 earthquake and events between 6th-5th century BC and 3rd-1st BC (likely on 99 BC). As a result, the recurrence interval for large magnitude events can be estimated as 1,700-1,900 years (Galli et al., 2005; 2018). Geomorphologic investigations suggest a total fault displacement between 600 and 900 m over the last 1.1-1.2 Ma (Pizzi and Scisciani, 2000; Pizzi et al., 2002). This estimate is close to that of Gori et al. (2007) based on displacement subsequent to the formation of the so called "top paleolandscape" (i.e. a flat and erosional landscape of Pliocene age carved into the marine substratum) present in the eastern sector of the basin. Uncertainty about the age of this landscape leads to an uncertain slip rate in the range of 0.25-1.15 mm/yr. Evidence of Quaternary activity was also found along the southernmost segment of the Norcia fault, in the area of Mt. Alvagnano (Blumetti, 1995). A bedrock fault scarp is evident along the western slope of this relief and close to the village of Castel Santa Maria. In this case, however, displacement has been influenced also by deep gravitational deformations (Galadini, 2006).

4.2 *Associated seismicity*

1 December 1328 (M 6.5): the damage distribution suggests that this earthquake mainly struck the northernmost sector of the area bordered by the Norcia fault. This may result from the activation of the northernmost segments of this fault (e.g. Galadini et al., 1999). Strong damage has been reported for Preci (10 MCS), close to the macroseismic epicentre, and Norcia (9-10 MCS). Although these near-field effects were severe, it is possible that the magnitude estimate of 6.5 is biased based on the following considerations: no reports of damage in the far-field are available and other large-M events originating in the central Apennines in the Middle Ages have produced notable far-field damage, which makes this event an outlier in this regard.

6 November 1599 (M 6.1): although Norcia suffered damage due to this earthquake (I 8 MCS), the highest intensities (2 localities with I 9 MCS and 6 localities with I 8 MCS) are located about 10 km west of the Norcia plain, in the Cascia area.

14 January 1703 (M 6.9): this earthquake mainly struck the region located on the hanging wall of the Norcia fault system, between Cittareale (I 11 MCS) to the south and Preci (I 8 MCS) to the north. For this reason, it has been suggested that this event activated the entire Norcia fault (Galadini et al., 1999). The impact of this earthquake is demonstrated by reported intensities for several villages: 2 localities with I 11 MCS, 3 with I 10-11 MCS, 36 localities with I 10 MCS. Norcia is among the latter and evidence of the 1703 damage and subsequent changes in building construction practices are still visible in the old town centre.

12 May 1730 (M 6.0): the highest intensity datapoints (I 9 MCS) are located in the Norcia plain and surroundings (11 localities with I 9 MCS). This suggests that only the Norcia section of the fault system may have activated in 1730.

22 August 1859 (M 5.7): damage occurred in a well-defined sector of the Norcia area, specifically a few kilometres north of the main town. For this reason, the event has been proposed to have activated the Campi section of the fault (Galadini et al., 1999). The damage is represented by 5 datapoints reporting a maximum intensity 8-9 MCS.

19 September 1979 (M 5.8): This event has a key role in the local seismic history because it triggered retrofitting of buildings in the old town centres with modern criteria. The effects of the 1979 earthquake are represented by 5 intensity datapoints with I 8-9 MCS and 25 localities with I 8 MCS, mainly located south of Norcia. For this reason, the origin of the earthquake has been attributed to the Cittareale-Mt. Alvagnano section of the Norcia fault.

4.3 *Seismogenic interpretation*

Five historical earthquakes (1328, 14 Jan. 1703, 1730, 1859, 1979) can attributed to the Norcia fault system based on damage distributions (Galadini et al., 1999). The M 6.9 1703 event suggests activation of whole fault system. This is also supported by paleoseismological investigations, which found evidence consistent with the reported magnitude (Galli et al., 2005). The same investigations indicated that a pre-1703 event occurred during the Roman age, possibly 99 BC (i.e. it may coincide with an earthquake known from historical sources).

On the whole, we have likely evidence of "inhomogeneous" seismogenic behaviour, in which single fault segments caused earthquakes with M≤6.5 (note that 6.5 is the magnitude attributed to the 1328 event, magnitude possibly overestimated as noted above) combined with multi-segment ruptures causing earthquakes with magnitudes up to ˜7 (Galadini et al., 1999).

A single 31 km-long (at surface) seismogenic source defines maximum magnitude derived from Wells and Coppersmith (1994) regressions of 6.9-7. Akinci et al. (2009) present a similar view, as well as Valentini et al. (2017). By contrast, Boncio et al. (2004a) define two different sources: 1) the three northernmost segments of the Norcia fault and 2) another source linking the Cascia and the Cittareale-Mt. Alvagnano segments. No individual seismogenic sources are defined in DISS Working Group (2018); the Norcia area is included in a "composite seismogenic source." The composite source into which the Norcia region faults are encompassed ITCS028, with a maximum magnitude of ˜6.5 and a slip rate of 0.1-1.0 mm/year.

5 UPPER ATERNO VALLEY AND PAGANICA FAULT SYSTEM

5.1 *Geological evidence of recent activity*

Quaternary evolution of the upper Aterno valley north of L'Aquila has involved activity of four NW-SE normal fault segments. From the north (Fig. 1), these segments are: the Capitignano and San Giovanni faults, bounding the Montereale basin and 8 and 4 km in length, respectively (Blumetti, 1995; Cacciuni et al., 1995; Galadini and Galli, 2000; Galadini and Messina, 2001; Civico et al., 2016); the Mt. Marine fault, bordering the Arischia basin, 14 km long (Blumetti, 1995; Bagnaia et al., 1996; Basili et al., 1999; Galadini e Galli, 2000; Messina et al., 2003, 2009); the Pettino fault, bordering the L'Aquila basin and adjacent to L'Aquila city, 9 km long (Bagnaia et al., 1996; Blumetti et al., 1996; Galadini and Galli, 2000; Messina et al., 2003, 2009; Nocentini et al., 2017).

The NW portion of the northernmost segment (Capitignano fault) places the clayey-arenaceous Laga flysch in contact with Quaternary deposits related to different orders of alluvial fans (Cacciuni et al., 1995; Chiarini et al., 2014). Tectonic tilting has been identified in the oldest outcropping deposits (Civico et al., 2016), attributed to the Middle Pleistocene. The mountain front east of Capitignano is the geomorphologic evidence of the recent fault activity (Blumetti, 1995; Civico et al., 2016). A 10 km portion of the SE section of the fault can be detected into the Miocene carbonate substratum but does not provide clear evidence of recent tectonic activity. Evidence of lack of recent activity is provided by Plio-Quaternary relict paleo-landsurfaces in this area at the same elevation on the hanging wall and foot wall sides of the fault (Chiarini et al., 2014). In summary, only the NW portion of the Capitignano fault may be recently active (Galadini and Messina, 2001; Chiarini et al., 2014).

The San Giovanni fault presents evidence of Quaternary activity along a scarp south of the Montereale basin, where Early Pleistocene slope derived breccias are tilted (Galadini and Messina, 2001; Civico et al., 2016) and Late Pleistocene-to-late Holocene deposits are displaced (Chiarini et al., 2014; Cinti et al., 2018). Towards the NW, the fault does not displace deposits of the Montereale basin nor the flat and wide paleolandscape carved into the Laga flysch north of the basin (Galadini and Messina, 2001).

The surface expressions of southern segments are characterized by carbonate fault scarps. The fault planes place the marine Meso-Cenozoic substratum in contact with layered slope deposits that date to the Late Pleistocene (radiocarbon ages of 31,710±760 yr BP and 23,330 ±300 yr BP; Galadini and Galli, 2000), confirming a previous chronological attribution by Blumetti (1995). Moreover, an alluvial terrace is vertically displaced by 15-20 m close to the NW tip of the Pettino fault (Galadini and Galli, 2000). Accordingly, a vertical slip rate has been estimated in the order of 0.47-0.86 mm/yr (Galadini and Galli, 2000).

Along the Mt. Marine fault, the aforementioned slope deposits are present both on the hanging wall and foot wall. Topographic profiles across the scarp suggest vertical displacement of 8-10 m and a slip rate of 0.25-0.43 mm/yr (Galadini and Galli, 2000). The total length of the fault is about 14 km, but clear evidence of recent activity is confined to the SE sector, for a length of about 9 km. Here, the fault has generated the Arischia basin and Holocene and historical activity (i.e. activation during the 1703 earthquake; M 6.7) is evident from paleoseismological investigations (Moro et al., 2002; Galli et al., 2011; Moro et al., 2016). The NW portion of this fault, instead, has successions of Plio-Quaternary relict paleolandsurfaces across the fault, indicating lack of significant vertical displacements (Basili et al., 1999).

The Paganica fault is located ESE of L'Aquila. A wide depression between the villages of Tempera, Paganica, Bazzano and Onna is associated with the recent activity of the fault. Different fault splays have vertically displaced an alluvial succession, in which the oldest units (Middle Pleistocene) are exposed at the NE basin margin while more recent units are stacked in the lowest basin sector (Galli et al., 2010).

The Paganica fault generated the 2009 earthquake (**M** 6.13; Herrmann et al., 2011). Surface faulting was observed along the fault after the event (Falcucci et al., 2009; Boncio et al., 2010; Emergeo Working Group, 2010; Galli et al., 2010; Lavecchia et al. 2010; Vittori et al. 2011; Gori et al., 2012). Hypotheses on a possible secondary origin (such as, bending moment faulting) of the coseismic surface ruptures observed in the field after the event were made by Bonini et al. (2014), issuing the Paganica fault to be a blind structure, not directly connected with the fault at surface. Nonetheless, the increase of vertical displacements of the continental sequences spanning the whole Quaternary with the age of the displaced deposits (Galli et al., 2010) indicates rupture propagation from the seismogenic depth up to the surface. Otherwise, if the surface fault would have not been connected with the seismogenic fault at depth, and the surface evidence were just a secondary effect of warping induced by a blind fault, decrease of displacement with depth and hence with the age of the deposits would be expected (see Falcucci et al., 2016 on this topic). Paleoseismological analyses indicate past activation during events larger than that of 2009, based on larger slip per event. In particular, slip from the 2 February 1703 event has been suggested (Galli et al., 2011; Moro et al., 2013), although similar evidence was not found by Cinti et al. (2011). However, the data of Cinti et al. (2011) does not exclude activation of the Paganica fault during an event subsequent to the 1461 earthquake (maybe in 1703). This means that the Paganica fault probably activated together with Mt. Marine to cause the 1703 earthquake. Lastly, ongoing field surveys in the area of the Bagno village (partly described by Maceroni et al., 2018) are revealing the presence of an antithetic structure of the Paganica fault, that brought into contact the siliciclastic bedrock (in the footwall) with alluvial and colluvial deposits (in the hanging wall), as well as with a man-made feature, defining fault activity during the past few millennia.

5.2 *Associated seismicity*

27 November 1461 (M 6.5): this earthquake is considered a "twin" of the 2009 L'Aquila earthquake (Tertulliani et al., 2009). It strongly damaged the same area as in 2009, with the largest intensities in villages south of L'Aquila (Sant'Eusanio Forconese, Poggio Picenze, Onna, Castelnuovo; I 10 MCS in 1461) that were destroyed in 2009.

2 February 1703 (M 6.7): this is the strongest historical earthquake recorded in the L'Aquila area. Interpretation of damage in terms of intensities MCS is complicated by possible damage to villages of the L'Aquila region by the 14 Jan. 1703 Norcia earthquake. However, numerous written sources has permitted to attribute the intensity I 10 MCS to 8 localities. Four villages with 10 MCS (Arischia, Pizzoli, Colle, Barete) are located in the upper Aterno valley, along one of the emerging sections of the causative fault. Evidence of post-event retrofitting in L'Aquila (I 9 MCS) is provided by heavy insertion of the baroque style, numerous inscriptions recalling the damage and the reconstruction, and application of strengthening members such as tie beams. To the Capitignano and San Giovanni fault segments the 16 January shock of the 1703 seismic sequence is tentatively associated by Cinti et al. (2018), and the authors do not rule out a possible sympathetic activation of the San Giovanni fault also during the 2 February 1703 shock.

6 October 1762 (M 5.5): this earthquake struck the same territory damaged in 1461 (and 2009), with significant damage at Castelnuovo (I 9 MCS) and Poggio Picenze (I 8 MCS). It is considered smaller than that event. Possibly, the earthquake did not originate on the Paganica fault but on a still unidentified source to the south, although the 1762 event is attributed to the Paganica fault by Lavecchia et al. (2012).

6 April 2009 (M 6.13) (Herrmann et al., 2011): this earthquake caused destruction and around 300 fatalities in L'Aquila and numerous villages in the Aterno River valley. The macroseismic epicenter is located about 10 km SE of the instrumental epicenter, which is west of L'Aquila (Ameri et al., 2011). Most of the damage occurred on a NW-SE trending belt, about 20 km long (Galli et al., 2009). The maximum intensity (I 9-10 MCS) occurred at Castelnuovo and Onna. Collapses and/or severe damage to a significant percentage of buildings occurred at San Gregorio, Sant'Eusanio Forconese, Tempera and Villa Sant'Angelo (I 9 MCS). Collapse and severe damage rates occurred in the old town centre of L'Aquila, Poggio di Roio and Poggio Picenze (I 8-9 MCS). Collapse and severe damage rates occurred in 21 localities (I between 7-8 and 8 MCS). Lower damage has been attributed to 32 villages with I

between 6-7 and 7 MCS. The pure extensional rupture of the mainshock is consistent with the geometry and location of the Paganica fault at surface.

5.3 *Seismogenic interpretation*

The seismogenic behaviour of the fault segments described above remains an open issue. Paleoseismological and historical data suggest that Mt. Marine fault activated during the 2 Feb. 1703 earthquake (Moro et al., 2002; Galli et al., 2011), while the Paganica fault may have also ruptured during this event based on further paleoseismological studies (Galli et al., 2011; Moro et al., 2013). The Paganica fault also generated the 2009 earthquake and probably the 1461 event.

The northernmost of these segments, i.e. the Capitignano and San Giovanni fault segments, may have generated one of the 1703 events (Jan. 16) (Cinti et al., 2018). Although this event has been reported in the available catalogues (e.g. with M 6.0 in Guidoboni et al., 2007), the real occurrence, the related damage and associated energy is still a matter of debate. Moreover, paleoseismological data on the Capitignano fault are unavailable, nor do historical written sources provide evidence of coseismic activation. Our hypothesis is that at least the northernmost (Capitignano) and southernmost (Paganica) faults are capable of activating as single sources, producing earthquakes of moderate magnitude and related significant damage (1461, 16 Jan 1703, 2009). This interpretation is similar to that proposed by Lavecchia et al. (2012). Since the Paganica fault may have concurred to cause the stronger earthquake of 2 Feb 1703 (together with Mt. Marine fault and, possibly, Pettino fault), we hypothesise that it may exhibit “inhomogeneous” seismogenic behavior whereby it may also activate together with other fault segments of the upper Aterno valley to generate stronger earthquakes (e.g., 1703). This “mixed” behaviour seems to be similar to that of the Norcia fault system.

By merging available historical/paleoseismological information, complete seismogenic source ruptures up to M 6.7 (i.e. of the San Giovanni, Mt. Marine, Pettino and Paganica faults) can be postulated, as well as smaller within-segment earthquakes. The seismogenic behaviour of the San Giovanni fault is still a matter of debate, as it may be a seismogenic source (together with the Capitignano fault) able to rupture individually during M˜6 earthquakes (Cinti et al., 2018) or it rather is part of the upper Aterno valley fault system (Galadini and Galli, 2000) and able to rupture with the other fault segments during M 6.5-7 earthquakes, or both of the things. For the Mt. Marine, Pettino and Paganica segments, we postulate a recurrence time of ˜850-1,200 years for earthquakes with M 6.7 and of ˜300 years for earthquakes with M 6.0-6.2, based on the paleoseismological and historical data. Cinti et al. (2018) postulated recurrence time of the Capitignano-San Giovanni faults shorter than 4,000 years.

The DISS database includes the Capitignano and San Giovanni faults in composite source ITCS028, while two different seismogenic sources have been defined in the L’Aquila area, one comprising the Mt. Marine and Pettino faults (ITIS015), the other in the area of the Paganica fault (ITIS131) (DISS Working Group, 2018). Three different sources, i.e. Montereale (corresponding to the Capitignano fault), Pizzoli-Mt. Pettino (corresponding to Mt. Marine and Pettino faults) and Aquilano (corresponding to the Paganica fault) have been defined by Boncio et al. (2004a). The definition of two seismogenic sources for the L’Aquila area can also be found in Akinci et al. (2009) and two seismogenic sources, related to the Capitignano and Paganica faults have been defined by Lavecchia et al. (2012). Valentini et al. (2017) define three different seismogenic sources, one is the Montereale source comprising the Capitignano fault; one is the Pizzoli-Pettino source, comprising the Mt. Marine and Mt. Pettino fault; and one represented by the Paganica fault.

6 MT. VETTORE-MT. BOVE FAULT SYSTEM, AMATRICE FAULT AND CAMPOTOSTO FAULT

6.1 *Geological evidence of recent activity*

These tectonic structures were involved in the seismic sequence that struck central Italy in 2016-2017, including the M 6.0 mainshock on the 24 August, followed by the M 5.9 shock on the 26

October and, ultimately, by the main event of M 6.5 on the 30 October (http://cnt.rm.ingv.it/). The geological evidence of recent activity of the reactivated faults is summarized and extensively discussed by Galadini et al. (2018) and Falcucci et al. (2018) and references therein. Noteworthy, while the Mt. Vettore-Mt. Bove fault system and the Campotosto fault show evidence of displacement of late Quaterary deposits and landforms all along their traces, thus indicating that these structures are able to produce surface rupturing earthquakes, the Amatrice fault doesn't show evidence of surface displacement during most of the Quaternary. This long-term geological evidence have been verified by the 2016 mainshocks. Indeed, the 24 August event ruptured the Amatrice fault and the southern part of the Mt. Vettore-Mt. Bove fault system, with two separated slip areas on the faults (e.g. Tinti et al., 2016). No surface faulting occurred along the Amatrice fault, whereas clear surface ruptures were observed all along one of the major splays of the Mt. Vettore-Mt. Bove fault system (e.g. Emergeo, 2016). Then, the 26 October and 30 October 2016 mainshocks ruptured the remaining portion of the Mt. Vettore-Mt. Bove fault system both causing surface faulting (the latter of up to about 1.8 m vertical offset) (e.g. Civico et al., 2018; Gori et al., 2018; Villani et al., 2018; Brozzetti et al., 2019). As a whole, the Quaternary activity of the faults involved by the 2016 mainshocks matches with what has occurred during the seismic sequence.

6.2 *Associated seismicity*

Before the 2016-2017 seismic sequence, both the Mt. Vettore-Mt. Bove fault system and the Campotosto fault were considered as dormant, that means active and seismogenic but not responsible for major seismicity (M 6-7) over the past 800-1000 years (Galadini and Galli, 2003). The 30 October 2016 mainshock event ruptured most of the Mt. Vettore-Mt. Bove fault plane that did not activate during the 24 August and 26 October events. Different solutions of the 30 October fault rupture are available in the literature, involving the activation of other structures together with the main Mt. Vettore-Mt. Bove system fault (e.g. Cheloni et al., 2017; Pizzi et al., 2017; Galadini at al., 2018; Scognamiglio et al., 2018; Walters et al., 2018). The MTs indicate pure extensional rupture along a NW-SE (N155°) plane (Table 1), 40° dipping, with source at 5 km depth. Our retrieved depth is rather consistent with other seismological analyses and hypocentral solutions, among which Chiaraluce et al. (2017), who placed the hypocenter at about 7 km, and the solution made by Istituto Nazionale di Geofisica e Vulcanologia (INGV) of Italy, which placed the rupture at 5 km depth (http://cnt.rm.ingv.it/). The sole relevant seismic event known in the seismic catalogues (Rovida et al., 2016) for this area is the 1639 one (M 6.2), which struck the Amatrice village and surroundings. In light of the historical information and of geological, seismological and geodetic evidence related to the 24 August 2016 mainshock, the 1639 event can be considered a "twin" of this event even though, differently from the 24 August 2016 shock, the 17th century event probably ruptured the sole Amatrice fault (Boncio et al., 2004; Galli et al., 2016; Falcucci et al., 2018; Galadini et al., 2018). As for the Campotosto fault, the structure only partially activated during the 2009 L'Aquila seismic sequence and in January 2017, determining a series of seismic events with M not larger than 5.5 (Malagnini and Munafò, 2018). Field surveys we conducted along the fault trace after the major events indicated that the two seismic sequence did not produce surface faulting.

The MTs of the 2009 and 2017 events on the Campotosto fault (Fig. 1; Table 1) are consistent with a normal fault rupture striking parallel to the fault at surface. In particular, the MTs for the largest events on the Campotosto fault of the 2009 and 2017 sequences define a rupture plane striking NW-SE (145° and 160°, respectively) with 50° dip angle, which is highly consistent with the modelled fault geometry retrieved from coseismic deformations (Cheloni et al., 2014; Falcucci et al., 2018).

6.3 *Seismogenic interpretation*

Although historical seismic events cannot be attributed to the Mt. Vettore-Mt. Bove fault system, evidence of recent activity (Galadini and Galli, 2003) and the related seismogenic source geometry (Falcucci et al., 2016; 2018) have led to the interpretation that it represents the superficial expression of a seismogenic source potentially responsible for roughly M 6.5 earthquakes. Indeed, the geologic and geomorphologic features of the Mt. Vettore-Mt. Bove fault are comparable to those of many other well-known active faults in the central Apennines, some of which described above.

The fault is indicated as a “debated source” (ITDS002) in the database DISS (DISS Working Group, 2018), and an individual seismogenic source is lacking in the database to date. Other source models include the Mt. Vettore fault within a map of seismogenic boxes (Boncio et al., 2004a; Valentini et al., 2017) and as an individual source (Akinci et al., 2009).

As for the Campotosto and Amatrice faults, geological data, supported by seismological and geodetic observations made after the 2016-2017 seismic sequence, suggest that they are two separated seismogenic sources; while the former is considered as able to generate M 6.5-7 earthquakes, the latter does not (Falcucci et al., 2018). The Amatrice fault activated during the 24 August 2016 mainshock and very likely during the 1639 seismic event, with M around 6 earthquakes. Hence, the recurrence time of fault activation could be on the order of 350-400 years. On the other hand, no historical seismic event likely occurred on the Campotosto fault. Moreover, as highlighted in Falcucci et al. (2018), the 2009 and 2017 events have been nucleated by the fault but they did not release a significant seismic moment with respect to its overall seismogenic potential, and the remaining maximum expected magnitude of an earthquake generated by the Campotosto fault is still on the order of M 6.4-6.5 (Falcucci et al., 2018). Some authors hypothesised that the Campotosto seismogenic fault at depth might not be connected with the fault at surface (Bigi et al., 2013; Buttinelli et al., 2018). Nonetheless, as in the case of the Paganica fault (see above), the increase of vertical displacement with the age of the displaced deposits, the continuity of the fault trace, and the coincidence of the fault at surface with the updip prolongation of the fault ruptures caused by the 2009 and 2017 sequences (which reached about 1-2 km depth) allow to discard this hypothesis. Boncio et al. (2004b) propose a different interpretation, as the authors consider the Laga Mountain faults, that is the Campotosto and Amatrice faults, as the expression of a single, unsegmented structure. This interpretation is adopted by Valentini et al. (2017). Akinci et al. (2009) consider only the Campotosto fault as a source capable of producing strong earthquakes. Although the DISS database (DISS Working Group 2018) reports a fault in the Laga Mountains area (within the debated seismogenic source ITDS073), individual seismogenic sources is not defined. Nonetheless, the Laga Mountains are partly included in composite source ITCS028.

7 CONCLUSIONS

The present work provides a review of the geological knowledge on the active and seismogenic faults involved in the three main seismic sequences that affected the central Apennine chain since 1997. The seismic sequence showed geological evidence that fully match the Quaternary geological history of each fault, meaning that Quaternary studies aimed at neotectonic assessments have the potential to unravel the seismogenic potential attributable to a given tectonic structure and the fault segmentation. The latter relates to the dimension of the associated seismogenic fault and hence to the maximum expected magnitude. The matching between the evidence provided by the three seismic sequences and the long-term geological data also allows to derive some clues about the surface faulting potential associated to the central Apennine seismogenic faults: the magnitude threshold above which a seismic event can produce primary surface faulting should be considered as >5.5-6, in agreement with the values proposed by Michetti et al. (2000) and Falcucci et al. (2016), that is M>5.5 and M>6±0.2, respectively.

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