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Active faulting, 3-D geological architecture and Plio-Quaternary structural evolution of extensional basins in the central Apennine chain, Italy

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Abstract. The general "basin and range" Apennine topographic characteristic is generally attributed to the presently active normal fault systems, whose long-term activity (throughout the Quaternary) is supposed to have been responsible for the creation of morphological/structural highs and lows. By coupling field geological survey and geophysical investigations, we reconstructed the 3-D geological model of an inner tectonic basin of the central Apennines, the Subequana Valley, bounded to the northeast by the southern segment of one of the major active and seismogenic normal faults of the Apennines, known as the Middle Aterno Valley–Subequana Valley fault system. Our analyses revealed that, since the late Pliocene, the basin evolved in a double half-graben configuration through a polyphase tectonic development. An early phase, Late Pliocene–Early Pleistocene in age, was controlled by the ENE–WSW-striking and SSE-dipping Avezzano–Bussi fault, that determined the formation of an early depocentre towards the N–NW. Subsequently, the main fault became the NW–SE-striking faults, which drove the formation during the Quaternary of a new fault-related depocentre towards the NE. By considering the available geological information, a similar structural evolution has likely involved three close tectonic basins aligned along the Avezzano–Bussi fault, namely the Fucino Basin, the Subequana Valley, and the Sulmona Basin, and it has been probably experienced by other tectonic basins of the chain. The present work therefore points out the role of pre-existing transverse tectonic structures, inherited by previous tectonic phases, in accommodating the ongoing tectonic deformation and, consequently, in influencing the structural characteristics of the major active normal faults. This has implications in terms of earthquake fault rupture propagation and segmentation. Lastly, the morpho-tectonic setting of the Apennine chain results from the superposition of deformation events whose geological legacy must be considered in a wider evolutionary perspective. Our results testify that a large-scale "basin and range" geomorphological feature – often adopted for morpho-tectonic and kinematic evaluations in active extensional contexts, as in the Apennines – just led by range-bounding active normal faults may be actually simplistic, as it could not be applied everywhere, owing to peculiar complexities of the local tectonic histories.

1 Introduction

The presently active normal fault systems are commonly supposed to be the major ones responsible for the recent and present-day regional morpho-tectonic aspect of the central Apennine chain. Indeed, since the late Pliocene, extension took place through normal fault systems presently occurring at the boundary between intermontane basins and mountain ranges (e.g. Cavinato and De Celles, 1999; Galadini and Messina, 2004). The progressive lowering of the fault hanging walls and the relative uplift of the footwalls created alternating morphological/structural highs and lows, that represent the Quaternary geomorphic leitmotiv of the Apennine chain, producing a typical "basin-and-range" physiography. Nonetheless, extensional deformation displaced an inherited thrust-and-fold belt, whose external thrust fronts were still active when regional extension began to affect the inner sectors of the chain (e.g. Carminati and Doglioni, 2012). This resulted in the overprinting of the extensional deformation

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on the compressive one. In addition, an ancient morphogenetic phase, subsequent to the compressive tectonic phase but shortly preceding the onset of extensional deformation, shaped an embryonic central Apennine relief. The related geomorphic signature is represented by the remnants of a low-gradient erosional relict landscape, presently detectable at high elevations along the mountain slopes, carved into the compressively deformed bedrocks and which has been subsequently displaced by the extensional faults (Centamore et al., 2003; Galadini et al., 2003).

Therefore, as pointed out by other authors in the past (Valensise and Pantosti, 2001), the "basin and range" physiography of the Apennine chain, as being ascribable just to the long-term movements of the presently active extensional faults, can be sometimes illusory. In this perspective, the presence of thrust-top basin sediments, deposited during the compressive tectonic phase, at the margins of some present-day intermontane tectonic basins (e.g. Cosentino et al., 2010, and references therein) suggests that those sectors already represented tectonic lows before extension began, and normal faulting has just contributed to enlarge those depressions.

A further element that complicates the structural setting of the central Apennine chain is the recognition of NE–SW-striking, chain-transverse tectonic structures, recognized by different authors in the past, and whose role in both the Pliocene–Quaternary evolution and the current seismotectonics of the belt has been analysed. According to Pizzi and Galadini (2009), NNE–SSW-striking pre-existing structures can act as transfer faults, permitting the propagation of the rupture along adjacent active fault segments, or as structural barriers, halting rupture propagation. Such an opposite role relates to the size of the structure. Specifically, the second case refers to regional basement/crustal oblique pre-existing cross-structures. An example of Apennine chain-transverse fault that can act as barrier to hinder fault rupture propagation has been proposed by Pace et al. (2002), dealing with the source of the M_{S} 5.8 1984 Sangro Valley earthquake. According to Fracassi and Milano (2014), the regional tectonic structure known as the Ortona–Roccamonfina Line allowed soft linkage between active faults across it, as well as the shift of fault dip direction, that is SW-ward and NE-ward, north and south of the Line, respectively.

In the present work, we analyse one of the innermost intermontane basins of the central Apennines, the NW–SE-striking Subequana Valley, which is bounded to the northeast by the southern segment, called the Subequana Valley fault, of a major active and seismogenic 30–35 km long Middle Aterno Valley–Subequana Valley normal fault system (Falcucci et al., 2011), able to rupture during earthquakes with M of up to 6.5–7. Data on the structural framework and evolution of this depression, matched with a 3-D view of the deep geometry of the valley, are gathered to understand the relationship between the activity of the main tectonic structures bounding the basin and, consequently, to decipher the Quaternary evolution of the depression. Moreover, we compare the data obtained in the Subequana Valley with the geological and geophysical information available for other nearby tectonic depressions, namely the Fucino and the Sulmona basins. Our aim is to shed light on the possible occurrence of a common evolutionary path of the three depressions through the Pliocene–Quaternary. In this perspective, we will investigate the role of a regional chain-crossing fault inherited from the compressive tectonic phase in accommodating tectonic deformation through the Pliocene–Quaternary. The analysis of the structural relation between this structure and the active normal faults bounding the Subequana Valley, and the Fucino and Sulmona basins can allow us to make inferences on the role of such pre-existing structural features in the evolutionary path of the Apennine chain and in its seismotectonic characteristics, in terms of fault segmentation, possibly applicable to many other sectors of the Apennine chain.

To fulfil the objective of the work we adopt a multi-methodological approach that combines geological and geophysical data. Then, general aspects of the Apennine chain evolution are illustrated, followed by more detailed geological information concerning the Subequana Valley. The results of our investigation are then illustrated and discussed. We examine the implications in terms of Quaternary structural evolution of the basin as well as of a wider portion of the chain, proposing an evolutionary structural model. In the concluding remarks, a summary of the obtained results is provided and general considerations on their meaning in terms of active tectonic setting of this portion of the belt are made.

2 Geological background

2.1 Tectonic evolution of the central Apennines

Since the Miocene, the tectonic history of the central Apennines has involved the occurrence of two kinematically opposite tectonic phases. The first phase was compressional, in response to the Africa, Eurasia, and Adria plates' convergence and subduction of the Ionian lithosphere (e.g. Faccenna et al., 2004; Carminati et al., 2004), and it has been characterized by development of NW–SE-oriented, E–NE-verging thrust-and-fold systems at the expenses of the Meso-Cenozoic carbonate and siliciclastic marine sequences (e.g. Ciarapica and Passeri, 1998; Centamore et al., 1991; Patacca et al., 1990, 2008, and references therein). This phase built the main structural edifice of the chain, through subsequent episodes of migration of the compressive front, with in-sequence and out-of-sequence thrusting events (e.g. Ghisetti and Vezzani, 1991; Cipollari et al., 1997, 1999; Scrocca, 2006; Cosentino et al., 2010, and references therein).

Since the Pliocene, the compressive front progressively migrated towards the east and the northeast, affecting the Adriatic sectors, while extension began to affect the inner sector of the chain (e.g. Malinverno and Ryan, 1986; Patacca et al., 1990; Doglioni, 1991, 1995), with a progressive migra-

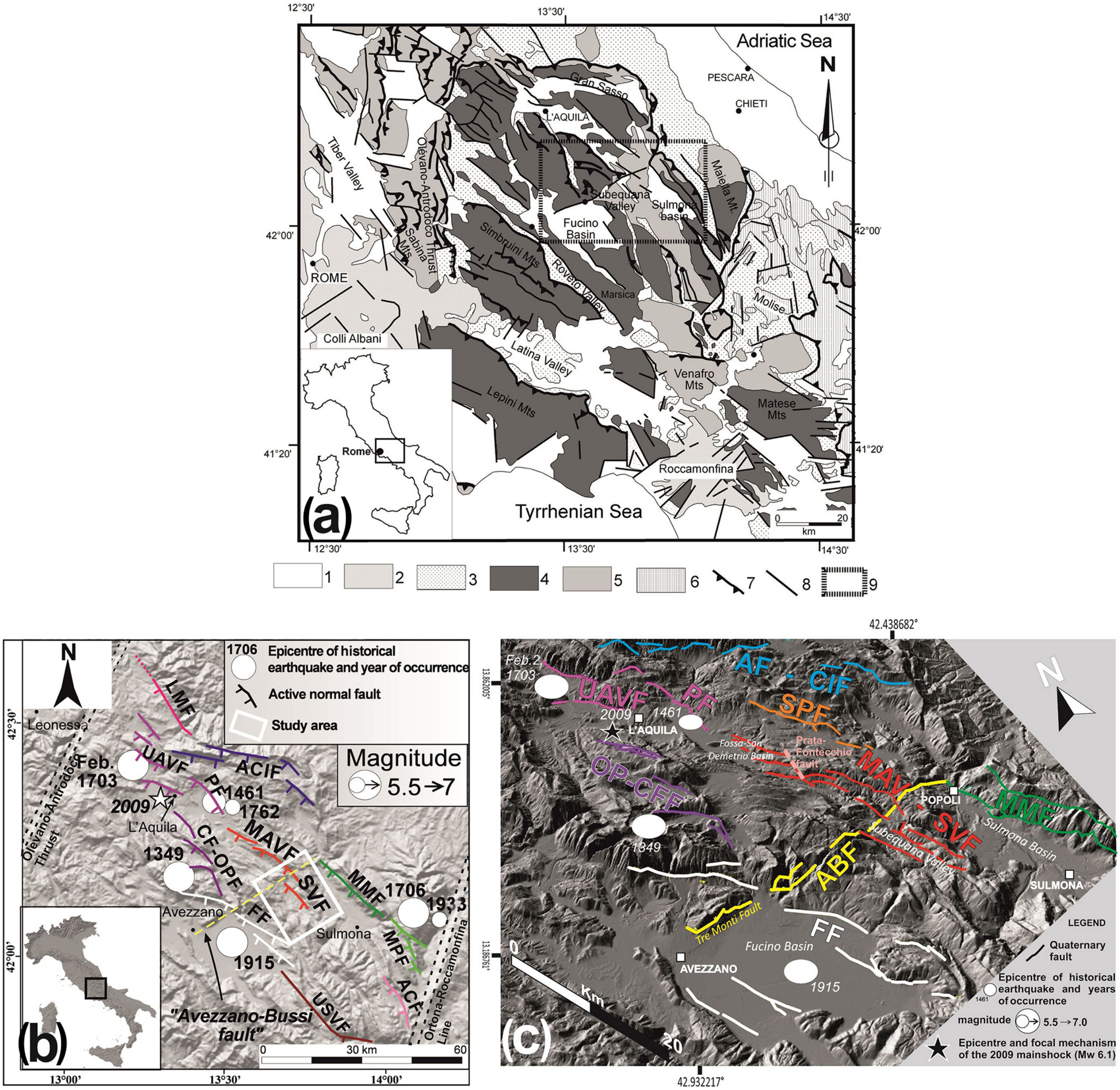

Figure 1. **(a)** Geological–structural scheme of the central Apennines. (1) Marine and continental clastic deposits (Pliocene–Quaternary); (2) volcanic deposits (Pleistocene); (3) synorogenic hemipelagic and turbiditic sequences (Tortonian–Pliocene); (4) carbonate platform deposits (Triassic–Miocene); (5) slope and pelagic deposits (Lias–Miocene); (6) Molise–Sannio pelagic deposits (Cretaceous–Miocene); (7) main thrust fault; (8) main normal and/or strike–slip fault; (9) study area. **(b)** Seismotectonic framework of the central Apennines (shaded relief); faults (colours indicate splays and segments comprised in the same fault system): MAV-SVF, Middle Aterno Valley–Subequana Valley fault system; ABF, Avezzano–Bussi fault; FF, Fucino fault; MMF, Mt Morrone fault; OP-CFF, Ovindoli–Pezza–Campo Felice fault, SPF, San Pio fault; AF-CIF, Assergi–Campo Imperatore fault system; UAVF, Upper Aterno Valley fault system; PF, Paganica fault. **(c)** Shaded relief in perspective view of the seismotectonic setting of the area under investigation.

tion towards the external sectors of the chain (e.g. Cavinato and De Celles, 1999; Galadini and Messina, 2004; Fubelli et al., 2009, and references therein). The eastward migration of compression–extension pair (e.g. Carminati and Doglioni, 2012) occurred contemporaneously to regional uplift (e.g. D'Agostino et al., 2001; Galadini et al., 2003; Pizzi, 2003). Specifically, uplift seems to have temporally occurred at the compression–extension transition, and a range of evidence indicates that mantle played a role in chain doming and consequent localization of major extension at crest of the topographic bulge (e.g. D'Agostino et al., 2001). Hence, topography of the chain derives from competition of chain uplift and extensional faulting along major normal fault systems, paralleling the axis of the chain. According to D'Agostino et al. (2014), active extensional deformation within the chain would be driven by lateral variation in the gravitational potential energy of the lithosphere. These faults offset the thrust-and-fold-related structures and caused the development of mainly half-graben tectonic depressions, with the main basin-boundary faults on their eastern side, mostly NW–SE-striking and dipping southwestwards. The depressions became traps for continental sedimentary sequences (e.g. Bosi et al., 2003). Many of the extensional faults located in the innermost sector of the chain are presently active (Fig. 1) and responsible for large-magnitude, surface-rupturing seismic events (M_w of up to 7; Galadini and Galli, 2000; Basili et al., 2008; Galli et al., 2008). One of the active normal faults is the NW–SE Paganica fault, activated during the M_w 6.2 2009 L'Aquila earthquake (Falcucci et al., 2009; Boncio et al., 2010; Emergeo, 2010; Chiaraluce et al., 2011; Cinti et al., 2011; Galli et al., 2010; Vittori et al., 2011; Gori et al., 2012; Moro et al., 2013).

Also the extensional faults get younger towards the east pursuing the compressive front (e.g. Cavinato and De Celles, 1999; Fubelli et al., 2009). An early phase of local tectonic extension has been recognized within some of the central Apennine intermontane tectonic basins, such as the Fucino Basin (Galadini and Messina, 2001) and the L'Aquila Basin (Nocentini, 2016), during the late Pliocene–early Quaternary. This phase seems to have not been accommodated along the presently active basin bounding normal faults, but along pre-Quaternary structures. One of these structures is a major fault system that cuts across the central sector of the chain and it is known as the Avezzano–Bussi fault system (hereafter ABF; Fig. 1). As will be shown below, the available literature agrees in attributing to the ABF a significant role in leading to the first phase of formation of the Fucino Basin. Other major chain-transverse faults are also known, among which the so-called Olevano–Antrodoco Line and the Ortona–Roccamonfina Line, which are considered as the northern Apennines–central Apennines and central Apennines–southern Apennines structural boundaries, respectively. These structures, that probably re-activated older faults that separated different Meso-Cenozoic palaeogeographic marine domains, are defined to have accommodated differential migration velocities of thrust fronts during the compressive tectonic phase, also leading to out-of-sequence compressive tectonic events (e.g. Satolli and Calamita, 2008; Cosentino et al., 2010).

2.2 The Subequana Valley

The Subequana Valley is located in the inner sector of the central Apennine chain. The Aterno River currently drains the valley and hydrologically connects the L'Aquila Basin to the Sulmona Basin (Fig. 2a). The Subequana Valley is one of the less known intermontane depressions of the central Apennines as for the Quaternary continental morpho-stratigraphic evolution. Little information about the Quaternary geological evolution can be derived from the studies of Bosi and Bertini (1970) and Miccadei et al. (1997), who identified a thick outcropping lacustrine sequence attributed to the Early Pleistocene by the former authors and to the Middle Pleistocene by the latter (Fig. 2a). In particular, Bosi and Bertini (1970) proposed the presence of an Early Pleistocene single lacustrine basin encompassing the Subequana Valley, the Middle Aterno River valley, and the Fossa–San Demetrio–L'Aquila Basin, from south to north. Miccadei et al. (1997) also identified alluvial fan bodies, attributed to the late Middle Pleistocene and to the Late Pleistocene, embedded within the lacustrine succession (Fig. 2a).

The formation of the Subequana Valley is due to the activity of a ∼ 10 km long normal fault, known as the Subequana Valley fault (hereafter SVF), that bounds the depression to the NE, striking NW–SE and dipping towards SW (Miccadei et al., 1997; Fig. 2a). Recent field investigations permitted Falcucci et al. (2011) to provide a detailed mapping of the fault, which is made of two main parallel fault splays affecting the southwestern slope of Mt Urano, some minor synthetic splays and a major antithetic fault on the western side of the valley (Fig. 2a).

The SVF is the southern segment of a 30–35 km long active fault system, the Middle Aterno Valley–Subequana fault (hereafter MAVFSVF; Falcucci et al., 2011, 2015; Fig. 1). Recent palaeoseismological investigations carried out along the MAVF–SVF system documented that the fault system ruptured twice during the late Holocene, with minimum 0.8 m surface offset per event (Falcucci et al., 2011, 2015).

2.3 The Avezzano–Bussi fault system

The ABF is a complex structure striking about ENE–WSW that bounds the Fucino Basin, the Subequana Valley, and the Sulmona Basin to the north (Fig. 1). According to Ghisetti and Vezzani (1997), who first made extensive structural analyses along the fault system, the ABF is made of two main segments, an eastern segment and a western segment. These are characterized by 1000 m dip slip displacement. The horizontal throw was the prevailing one, with about 5 km right lateral offset. The authors defined a polyphase kinematic history of the ABF – including transtensional to extensional kinematics – and hypothesized it to be a tear fault that absorbed differential velocities of thrust fronts' propagation during the compressive tectonic phase.

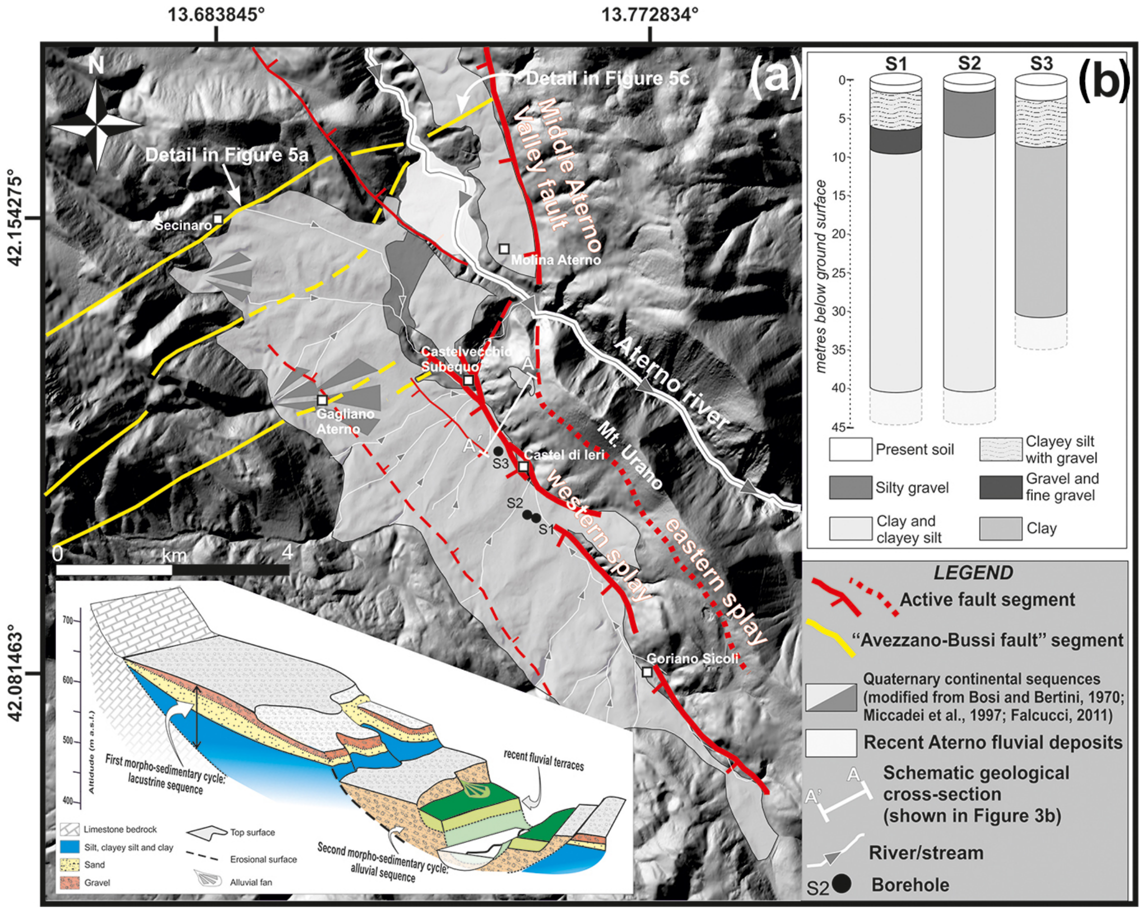

Figure 2. **(a)** Shaded relief of the Subequana Valley (plan view) on which simplified geological map (modified after Bosi and Bertini, 1970; Miccadei, 1997; Falcucci, 2011) is reported; morpho-stratigraphic reconstruction of the Quaternary succession of the Subequana Valley (Falcucci et al., 2011), inset. **(b)** Stratigraphy of boreholes drilled in the Subequana Valley during the 1970s.

Galadini and Messina (2001) deduced that the ABF has been active during the late Pliocene, controlling the earliest stages of formation of the Fucino Basin. The fault would have been active up to uppermost part of the late Pliocene–beginning of the Early Pleistocene, when the progressive spreading of the Fucino Basin has been driven by the NW–SE-striking and SW-dipping normal fault system on the eastern border of the depression (e.g. Michetti et al., 1996; Galadini et al., 1997; Galadini and Galli, 1999; Gori et al., 2007, 2015a), in relation to regional kinematic changes in the central Apennines tectonics during the Early Pleistocene (Galadini, 1999). The presently active Fucino fault is ∼ 35 km long and has been responsible for high magnitude seismic events, e.g. the M_{w} 7, 1915 Avezzano earthquake (e.g. Galadini et al., 1997). Based on geological and geophysical (reflection seismic lines) observations, Cavinato et al. (2002) confirmed that ENE–WSW faults had a major activity during the Pliocene, and they progressively stopped (or slowed down) during the Quaternary. The NW–SE faults remained active during the Pleistocene and they are currently active.

Overall, this led to a complex 3-D basin architecture, related to the activity of fault systems having almost perpendicular trend. Galadini and Messina (2001) defined that the ENE–WSW-trending Tre Monti fault, a sub-segment of the ABF in the Fucino Basin, strongly reduced its activity since the early Quaternary, being responsible for only few-metres offset of Early Pleistocene slope deposits. According to the mentioned authors, this fault would presently just play the role of minor releasing fault (Destro, 1995), which only accommodates movements along the active NW–SE-trending Fucino fault system.

Galadini and Messina (2001) also made some inferences on the ABF activity in the Subequana Valley. They proposed fault activity during the Pliocene, comparably to the Fucino Basin, that ended before the Early Pleistocene, as early Quaternary land surfaces crosscut the fault. Nonetheless, differently from the Fucino Basin, data about the deep geometry of the Subequana Valley were not available at that time and this prevented the authors from verifying their hypothesis. As will be shown later, our data partly confirm the Galadini and Messina hypothesis but also modify it to some extent.

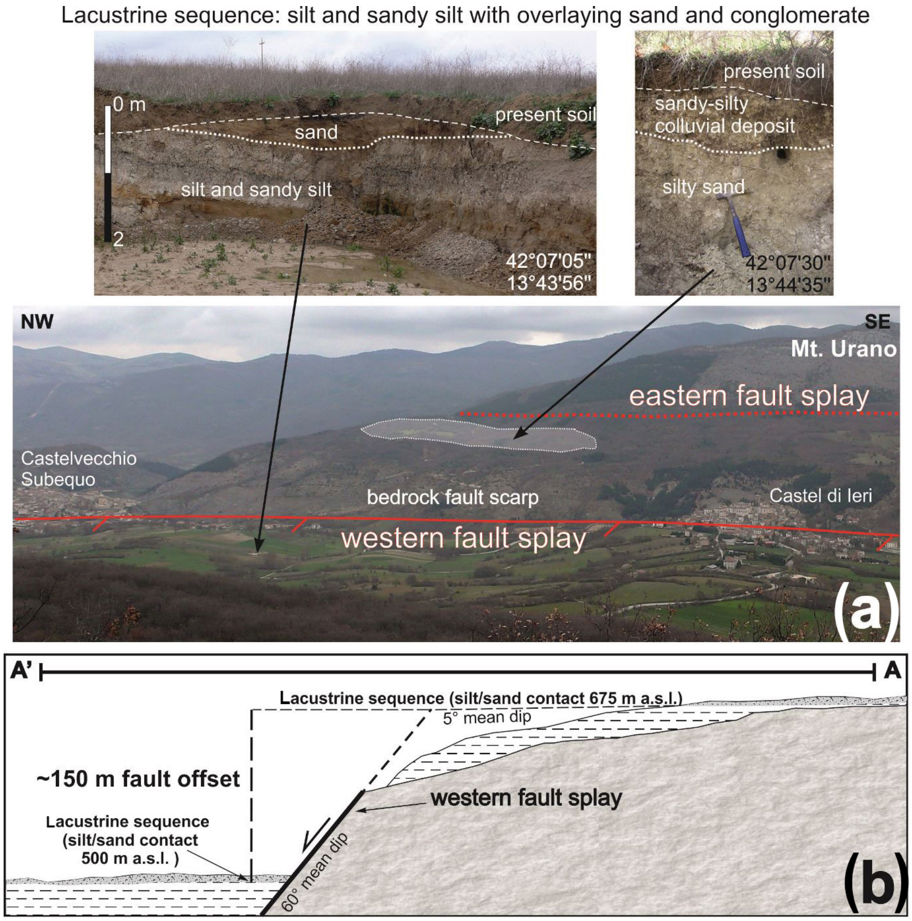

Figure 3. **(a)** Panoramic view of the southwestern slope of Mt Urano; major normal fault splay of the Subequana Valley fault, red lines; outcrops of the upper lacustrine sequence of the Subequana Valley are pointed by arrows and shown in insets. **(b)** Schematic geological cross section showing the displacement of the Subequana Valley lacustrine deposits across the western splay of the fault (see Fig. 2 for the section trace).

3 Geological field data

3.1 Morpho-stratigraphic investigation

Extensive field surveys and the analysis of the continental sequence hosted within the Subequana Valley allow us to recognize two main Quaternary morpho-sedimentary cycles (Falcucci, 2011; Gori et al., 2015b; Fig. 2a, inset). The former consists is a lacustrine sequence made of whitish-greyish silt and clayey silt that grades upwards to sand a few metres thick with sparse conglomerate interbedded layers. The sequence crops out all along the valley. Palaeomagnetic analyses made on the lake sediments and *U* series dating of two tephra layers found within the uppermost portion of the silt sequence mainly provided an Early Pleistocene age, with the sandy and conglomerate unit deposited across and shortly after the Matuyama–Brunhes palaeomagnetic reversal (Falcucci, 2011). This morpho-stratigraphic setting testifies for a mainly Early Pleistocene Subequana Lake basin – in agreement with Bosi and Bertini (1970) – that has been progressively filled by alluvial deposition sourced from the surrounding reliefs just after the Early–Middle Pleistocene transition.

Afterward, a major erosional phase took place, as testified by an erosional surface deeply cut into the described lacustrine sequence, related to a significant drop of the base level. The second morpho-sedimentary cycle, Middle Pleistocene in age, lies onto this erosional surface, and is represented by fluvial/alluvial deposits cropping out along the northern portion of the valley, of the order of tens of metres thick. These merge to northerly fluvial sediments, that flowed from the Middle Aterno River valley. This suggests that the formerly closed hydrographic system of the Subequana Valley opened at the beginning of the Middle Pleistocene, after the lake basin infill; then, erosion took place and a palaeo-Aterno River system established. The second cycle is presently suspended over the Aterno River thalweg, owing to successive river entrenchment. Comparable morpho-stratigraphic evolution has been observed in many other central Apennines

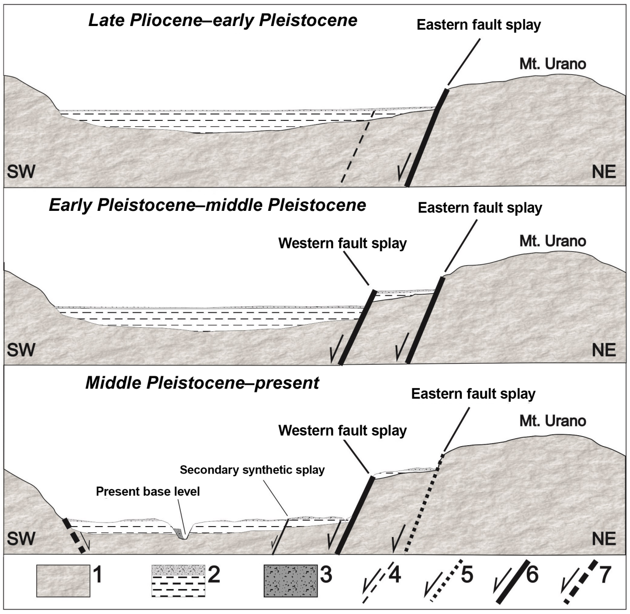

Figure 4. Scheme of the Quaternary structural evolution of the Subequana Valley fault and of Mt Urano southwestern slope. (1) Carbonate bedrock, (2) lacustrine sequence, (3) fluvial-alluvial deposits, (4) incipient normal fault, (5) inactive normal fault or normal fault whose current activity is presently uncertain, (6) active normal fault, and (7) supposed antithetic normal fault.

intermontane basins (e.g. Bosi et al., 2003), most of which hosted lakes during the early phase of formation. These ancient lakes have been subsequently cut by headward erosion of rivers, coming from outside the basins. This processes has been related to the increase of chain uplift which occurred at the Early–Middle Pleistocene transition (e.g. Centamore et al., 2003).

River incision, as well as minor streams, produced exposed thickness of the lacustrine sequence of several tens of metres. We also collected stratigraphic and sedimentological data from boreholes made some 40 years ago for water extraction (Fig. 2b) in the central sector of the basin, near Castel di Ieri. The deepest ones (about 40 m depth from the ground surface) cored the lake silt unit. None of the boreholes reached the bedrock. As will be shown later, this is in agreement with the attitude of the buried basin bottom defined by means of geophysical survey. Moreover, borehole S2 provided evidence of alluvial deposits (gravel and fine gravel) overlying the lake silt unit. This corroborates the stratigraphic setting above described, that is, the presence of the Early Pleistocene lake that has been progressively filled, grading upward into an alluvial environment. The bedrock progressively crops out in places at the northern portion of the basin at the base of the lake sequence (Fig. 2a), thus testifying to a quite articulated geometry of the basin bottom underneath the sedimentary cover.

3.2 Evidence for Quaternary activity of the SVF

The above-described morpho-sedimentary sequence mainly crops out on the hanging wall of the SVF. Nevertheless, remnants of the lake sequence are also seen in the sector comprised between the eastern and western splays of the structure, lying onto the carbonate substratum (Fig. 3a). Here, the sequence is suspended above the basin bottom, from which it is separated by the scarp of the western fault splay (Fig. 3a). This indicates that after the lake basin infill, the sedimentary sequence has been truncated by the western fault splay, which left the deposits hanging on the fault hanging wall. The difference in elevation of the contact between the sand-and-conglomerate body and the underlying silt at the footwall defines a post-Early Pleistocene fault offset of the order of some 150 m across the western fault splay (Fig. 3b).

The following lines of evidence allow us to hypothesize that the fault splay nucleation may have not been synchronous, that is, the eastern splay activated before the western splay or that the activity of the western splay strongly increased after the lake basin infill: (i) the lacustrine sequence occurs solely in the footwall of the western splay (it has never been found in the footwall of the eastern one); (ii) the geometric relation between the lake sediments and the eastern fault scarp seems to indicate that the scarp probably represented the border of the lake; (iii) the sub-horizontal attitude of the stratigraphic contact between the lacustrine unit and the overlying alluvial unit across the western fault suggests that the latter deposited in a palaeo-landscape still in the proximity of the local base level, i.e. the landscape evolved before the formation of the slope (and related topographic gradient) associated with the western fault or the western fault scarp was still too small to significantly influence the alluvial deposition (Fig. 4). The subsequent activation of the western fault or a significant increase of the fault slip would have definitively left the lake sequence hanging over the valley bottom. Such a structural evolution has been observed in other central Apennine active normal fault systems (e.g. Gori et al., 2007, 2014; Falcucci et al., 2015).

3.3 New data from the Avezzano–Bussi fault

As formerly defined by Galadini and Messina (2001), the ABF bounds the Subequana Valley to the northwest. The fault is here represented by discrete parallel splays, that define a roughly 2 km wide fault zone in the bedrock. From a geomorphic point of view, the presence of this tectonic structure is attested by a rather straight trend of the slopes, and by incisions in the carbonate bedrock that are aligned along the ABF; these incisions probably are probably localized along zones of weakness in the limestone rocks determined by fault shearing.

Field survey conducted along the ABF defined that in the sector comprised between the Fucino Basin and the Subequana Valley the tectonic structure is barely visible in the local slope morphology. In agreement with Galadini and Messina (2001), neither evident fault scarps are here visible nor any other morpho-tectonic features that can be related to the recent activity of the ABF. Geomorphic hints of the Quaternary ABF activity seem to end within the Fucino Basin.

The geomorphic and structural evidence of the ABF become again detectable within the Subequana Valley. More in detail, in the area of Secinaro, we found a high angle ENE–WSW-striking fault surface at the base of the slope, aligned along the ABF. Slope-derived breccias are displaced by a few metres and dragged, compatible with dip slip along the fault plane (Figs. 2a, 5a), defining a roughly normal-to-oblique (extensional) sense of motion. Structural observations related to the tectonic structure are shown in Fig. 5a.

The displaced deposits can be related by lithology – that is, angular-to-subangular carbonate clasts in a pink-orange cement – to those deposits widely distributed in the central Apennines, known as the Early Pleistocene "second sedimentary cycle breccias" of Bosi et al. (2003). This chronostratigraphic correlation is corroborated by the fact that they are hanging above the present bottom of local incisions, and their attitude progressively flattens (as moving away from the fault zone) at elevations comparable to the above-described lacustrine sequence. This suggests that the breccias refer to a base level higher than the present one, comparable to that of the Early Pleistocene lake. The slight displacement of the breccias indicates that the activity of minor tectonic features related to the ABF within the Subequana Valley may have lasted until the Early Pleistocene, or even later.

Furthermore, along the northeastern far end of the Subequana Valley, at the overlapping zone between the SVF and the MAVF, another high-angle ENE–WSW-striking fault plane is seen, aligned along the ABF. Here, slope deposits referable to the Middle Pleistocene (Falcucci et al., 2015) are displaced along the fault and affected by minor fault surfaces (Figs. 2a, 5b). The sense of displacement of the Middle Pleistocene slope deposits and structural features, as reconstructed from fault population analysis (Fig. 5b), indicate dominant normal dip-slip kinematics of the fault, but with very small offset. Therefore, together with the above-described faulted breccias, this evidence testifies to a post-Early/Middle Pleistocene activity of secondary faults that can be associated to the ABF within the Subequana Valley.

Moving to the E–NE, having crossed the MAVF, the geomorphic traces of the ABF disappear again along the reliefs that separate the Subequana Valley from the Sulmona Basin. Indeed, comparably to the sector comprised between the Fucino Basin from the Subequana Valley, no fault scarp or any other morpho-tectonic feature that may suggest Quaternary activity of the ABF is here seen. Entering the Sulmona Basin, instead, the northern border of the depression displays a quite rectilinear trend (about ENE–WSW oriented) and a discontinuous and altered bedrock scarp aligned along the ABF is seen at the base of the slopes (Fig. 6a). This geomorphic feature abuts the northern tip of the active normal fault that bounds the Sulmona Basin to the NE, the Mt Morrone fault, a 23 km long structure active since the Early Pleistocene (e.g. Gori et al., 2011). Other ENE–WSW-striking faults are seen along the northern sector of Mt Morrone. One of these fault splays whose bedrock fault plane is seen in the Sant'Anna Valley, presently accommodates lateral movements of large-scale gravitational mass movements (Gori et al., 2014). Interestingly, sets of ENE–WSW- to NE–SW-striking sub-vertical fault planes are seen in the northernmost portion of the basin (Fig. 6b), just southwest of Popoli, affecting the Early Pleistocene lacustrine sequence (Giaccio et al., 2009; Gori et al., 2011), whose activity is possibly attributable to the Middle Pleistocene owing to stratigraphic similarities with the sequence described by Regattieri et al. (2016). The mainly normal sense of displacement of the lacustrine deposits, the almost vertical and often anastomosed, undulated and wavy attitude and geometry of the majority of the shear planes (lithons of the lake silty deposits are locally distinguished), and the variations of thickness of the same displaced layers across them (Fig. 6b) suggest a major normal kinematics with local normal–oblique component.

4 Geophysical survey in the Subequana Valley

4.1 Methods

In order to achieve information about the geological framework of the Subequana Valley, we combine data from field surveying of the Quaternary stratigraphic sequence filling the valley with data derived from the analysis of unpublished well logs of boreholes made after the 2009 L'Aquila earthquake for emergency housing projects.

To enlighten the deep structure of the Subequana Valley, a campaign of ambient seismic noise measurements was performed between July 2009 and February 2010 (Marzorati et al., 2010; Ladina et al., 2017). Ambient seismic noise is always present and it can provide information about the characteristics of the ground. The analysis of the seismic signals allowed the identification of the resonance frequency of the interface between the bedrock and the continental sedimentary fill. For this purpose, we performed extensive measurements all along the valley. Most of the measurements were performed with good weather condition, as weather can influence the quality of the measurements. However, to mitigate the possible effects of wind and rain, as well as of presence of vegetation on the ground, the sensors were protected by a cap and buried in the soil, where high vegetation could interact with the sensor due to the wind.

Microtremors were recorded through portable seismic stations equipped with Lennartz 5s (www.lennartz-electronic.de) velocimetric sensors and 24 bit Reftek 130 (www.reftek.com) digital acquisition systems (DASs). The stations were connected with a battery of 12 V/12 Ah and GPS antenna to precisely locate each measurement point. The gain was set

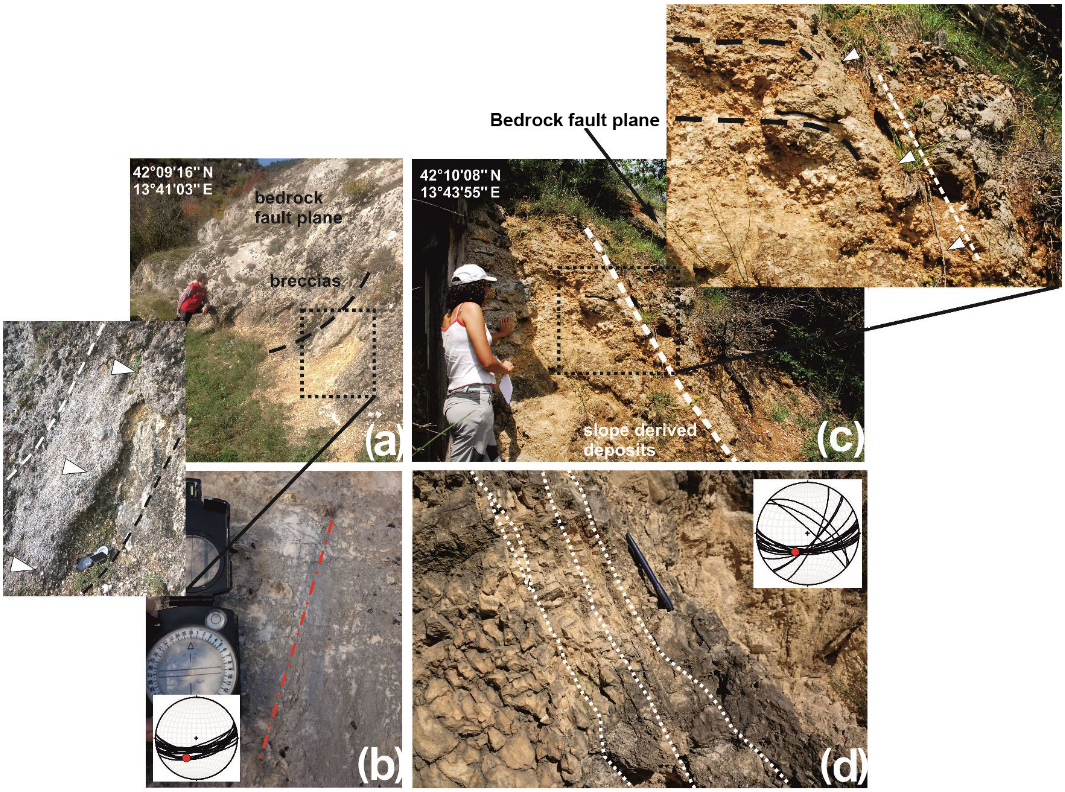

Figure 5. (a) Early Pleistocene breccias dragged along a secondary fault splay parallel to the Avezzano–Bussi fault (see Fig. 2 for location); a detail in inset, where white triangles indicate a fault plane affecting the breccias and dashed lines mark the dragging of the deposits. **(b)** Bedrock fault plane along which the breccias are dragged; slickenlines, red dashed line. on the Schmidt net diagram (inset), the synthetic shear planes detected in the fault zone (black great circles) and the pitch of the slickenlines, derived from statistical analysis of seven measurements (red dots) are plotted. **(c)** Middle Pleistocene slope deposits affected by extensional faults (white dashed line) parallel to the Avezzano–Bussi fault (see Fig. 2 for location); a detail in inset, where black dashed lines mark the attitude of the deposits in the fault zone, and the white dashed line and triangles mark a fault plane affecting the deposits. **(d)** Shear zone related to the fault plane in **(c)**; white dotted lines, synthetic shear planes; the synthetic shear planes detected in the fault zone (black great circles) and the pitch of the slickenlines (red dots) are plotted on the Schmidt net diagram (inset).

high in the digital acquisition to obtain the maximum resolution and the possibility to record the seismic noise vibrations. The acquisitions were set with rate of 100 sps and the length of measurement was at least 30 min each. The three acquisition channels (one for each component) were recorded on memory compact flash.

The ambient seismic noise recordings were manually selected in order to remove the possible traces of signal affected by disturbances and artificial transients (Marzorati et al., 2010). The waveforms of the three components of the signal were windowed in 120 s long time series. Then, a cosine taper 10 % and a bandpass Butterworth four-pole filter between 0.2 and 30 Hz were applied to compute the power spectral density (PSD) of each selected window. Each PSD was smoothed using the Konno and Ohmachi (1998) technique (with smoothing parameter $b = 40$) and used to compute the noise horizontal to vertical spectral ratio – NHVSR (Nogoshi and Igarashi, 1971; Nakamura, 1989, 2000).

4.2 Reconstruction of the deep geometry of the bedrock

Ambient seismic noise measurements provide a 1-D response of the basin at each measure point (Fig. 7a). By interpolating each measure, a 3-D picture of the deep morphology of the bedrock–sedimentary fill interface can be obtained, as illustrated in the following.

Generally, the resonance frequency f_0 of a sedimentary cover is described as the maximum of the ellipticity curve of Rayleigh waves, obtained by the mean of the horizontal-to-vertical (H/V) ratio of spectral amplitudes of noise components (Lachet and Bard, 1994; Tokimatsu, 1997; Bard, 1999; Nakamura, 2000; Fäh et al., 2001; SESAME, 2005). Modelling the resonant frequency by the 1-D quarter-wavelength approximation, the f_0 is given by the following equation:

$$f_0 = \frac{V_S}{4H}, \tag{1}$$

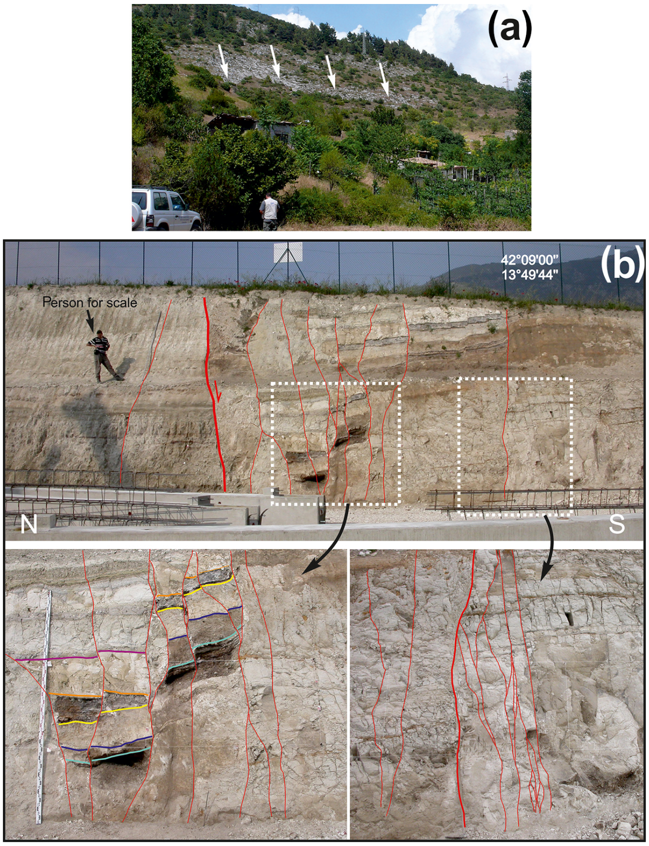

Figure 6. **(a)** Discontinuous bedrock fault scarp of the Avezzano–Bussi fault along the northern border of the Sulmona Basin. **(b)** Transtensional faults in the Sulmona Basin, aligned along one of the splays of the Avezzano Bussi fault, displacing Early Pleistocene lacustrine sequence.

where V_S is the shear wave velocity and H is the depth of the sediments. This relationship is used to infer thickness of sedimentary cover over a rigid bedrock in the presence of an impedance contrast (Yamanaka et al., 1994; Ibs-von Seht and Wohlenberg, 1999; Nakamura, 2000). From data processing, a set of 65 NHVSR curves resulted as reliable (see Supplement). The f_0 of each site was evaluated averaging all frequencies calculated from analysis windows selected from whole seismic traces (see Supplement). All the curves with no significant peak were considered as flat (SESAME, 2005).

In general, at the edges of the basin, frequencies were between 1 and 5 Hz, with the exception of the area in front of Castelvecchio Subequo, where a series of NHVSR curves were flat, indicating the presence of bedrock close to the ground surface (Fig. S1, Table S1; see Marzorati et al., 2011, and Pagliaroli et al., 2015, for details on the local seismic response in the Castelvecchio Subequo and Castel di Ieri areas). This is in agreement with the above-described geological observations. Also, the northern portion of the basin indicates frequencies around and greater than 1 Hz. The smaller f_0 (between 0.48 and 1 Hz) were founded in the central–northern part of the basin and they were also present along the longitudinal axis of the basin towards the southeast.

Taking advantage of Eq. (1), it is possible to estimate the depth of the bedrock–sediments interface below each measuring point, using the average values of V_S of the sedimentary layers. Neither geological or geotechnical data are available for the deepest portion of the Subequana Valley. Nonetheless, the described geological setting of the basin and of other surrounding depressions – such as the L'Aquila Basin, the Middle Aterno River valley, and the Sulmona Basin, and the few borehole data available define that the majority of the sediments infilling the Subequana Valley is conceivably represented by the lacustrine sequence, which has geotechnical characteristics similar to those of the mentioned neighbouring basins.

After the 2009 L'Aquila earthquake, a campaign of seismic microzonation was conducted in the epicentral and mesoseismal areas (Gruppo di Lavoro MS-AQ, 2010). A geotechnical model of the lacustrine white carbonate silt was built to estimate the value of V_S in relation to the thickness of the sediments. A set of down-hole (DH) test measurements explored the maximum depth of 50 m. At higher depth, the V_S estimate was defined by measuring the variation of the small shear strain stiffness, G0, and the mean effective stress, p', by resonant column (RC) tests (Lanzo et al., 2011). The V_S value extrapolated to a depth of 200 m reaches 600 m s^{-1}. In the Sulmona Basin, the V_S of deepest lacustrine deposits estimated with joint inversion of seismic array techniques was also about 600 m s^{-1} (Di Giulio et al., 2016).

The piecewise linear function of V_S was interpolated by the following power law (Gruppo di Lavoro MS-AQ, 2010):

$$V_S = 230H^{0.17}. \tag{2}$$

The V_S model of Eq. (2) provides velocity of deep lacustrine deposits comparable to that estimated for the L'Aquila and Sulmona basins by Lanzo et al. (2011) and Di Giulio et al. (2016), respectively. For the shallow layers (up to 40 m depth), V_S ranges between 300 and 400 m s^{-1}. This shallow V_S agrees with value estimated by means of the multichannel analysis of surface waves (MASW) technique in the Castelvecchio Subequo and Castel di Ieri areas (Salucci, 2010a, b), where the shallow layers are made of silt covered by sand and sandy gravel a few metres thick (Salucci, 2010a, b). Such lithology fits the class of "lacustrine white carbonate silts" as defined by geotechnical model in MZS Working Group (2011), which comprises silt, sand, and gravel layers.

In this perspective, the assumption that the Subequana Valley is mainly filled with the lacustrine sequence can be acceptable, considering the lithologies comprised within the class of "lacustrine white carbonate silts" defined by MZS Working Group (2011). Indeed, if a sand or gravel layer occurs in the deepest portions of the basin, it is lithologically included in the assumed sedimentary class.

Hence, to obtain an estimate of the thickness of the sediments above the bedrock in correspondence with seismic

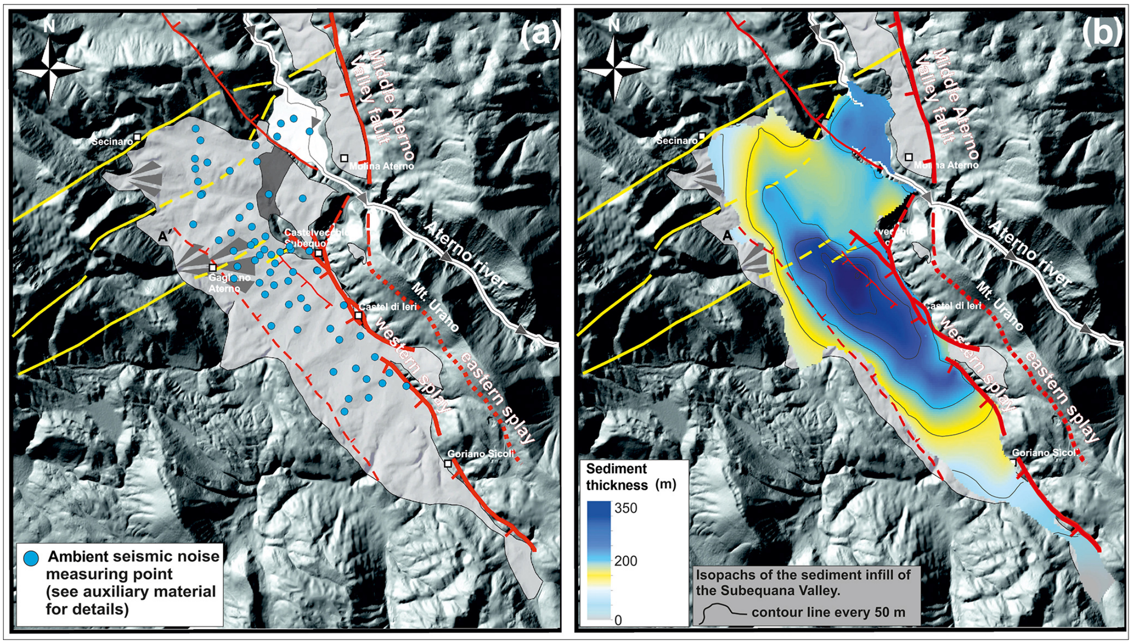

Figure 7. **(a)** Simplified geological map of the Subequana Valley (legend as in Fig. 2); location of the ambient seismic noise measuring points, blue circles. **(b)** Reconstruction of the deep geometry of the Subequana Valley (legend as in Fig. 2), defined by the sedimentary infill thickness.

noise measurement points, it is possible to derive the following equation, which describes the sediment thickness (H) as a function of the soil resonance frequency (f_0) from Eqs. (1) and (2):

$$H = (0.0174 f_0)^{-\left(\frac{1}{0.83}\right)}. \tag{3}$$

Figure 7b shows the sediment thickness obtained by seismic noise measurements (Fig. S2). The estimation points were interpolated by natural neighbour algorithm, and matched with the geological characteristics at surface, getting a 3-D view of the morphology of the bedrock/sediment infill interface (see Supplement). Specifically, the depth of the interface is obtained by subtracting the sediment thickness from the topographic height of each measurement point. As a result, the obtained reconstruction of the deep basin geometry defines the deepest zone in the central–northern part of the basin, where the estimate of the thickness of the sedimentary layers reaches values of up to 300–350 m (Supplement).

North of the deepest part of the basin, the bedrock gets progressively shallower approaching the ABF shear zone (Fig. 7b). To the east, instead, the bedrock abruptly rises at surface, indicating the presence of a high-angle buried scarp west of Castelvecchio Subequo, which coincides with a secondary synthetic splay of the SVF (Fig. 7b).

5 Discussion

5.1 Morpho-structural evolution of the Subequana Valley and of other basins aligned along the ABF

Geological and geophysical data describe a complex morpho-structural picture of the Subequana Valley. A comparison with the surrounding areas can help to decipher it in evolutionary terms and, consequently, to make hypotheses on the structural evolution of a wider sector of the Apennine chain.

The setting described for the Subequana Valley appears highly comparable to that of the Fucino Basin (Giraudi, 1988; Galadini and Messina, 2001; Cavinato et al., 2002). In detail:

1. The major active faults on the eastern border of both of the depressions active since the late Pliocene–Early Pleistocene are responsible for hundred-metres offset of deposits spanning the Quaternary – as documented in Sect. 3.2 – and determine significant surface offset (up to about 1 m) per event of activation.

2. The two basins are bounded to the north by the ABF that displays evidence of small displacements of early to Middle Pleistocene deposits along some of its strands. In this perspective, Falcucci et al. (2011) have defined that small portions of the ABF are presently used solely as connecting/transfer faults between two main segments of the SVF. Consistently, no evidence of Quaternary activity is seen along the portions of the ABF

in the mountainous sectors between the Subequana Valley and the Fucino Basin, to the west, and between the Subequana Valley and the Sulmona Basin, to the east.

3. Geomorphic/structural features that can be related to the ABF (such as rectilinear slopes and bedrock fault planes aligned along the structure) and evidence of Quaternary deposits displaced by fault planes aligned along the ABF are confined within the Fucino, Subequana Valley, and Sulmona basins, which are bounded by active normal faults. In the areas in between the depressions, instead, no geomorphic imprint of the ABF on the landscape is seen, and it is just geologically detectable for the lateral juxtaposition of different bedrock units.

4. The available geophysical data document an overall half-graben geometry for both the tectonic depressions, with maximum thickness of the infilling deposits – both buried underneath the plains and outcropping – not strictly centred with respect to the presently active faults, as would be expected, but occurring in the northeastern portion of the basins (Fig. 8).

As described earlier in this work, Galadini and Messina (2001) attributed these geological–structural features of the Fucino Basin to a double, superposed half-graben style of extension, firstly controlled by the ABF – mostly during the late Pliocene – and then by the NW–SE-trending and presently active Fucino fault during the whole Quaternary. As a result, the described similarities between the geological and structural characteristics, and between the 3-D deep geometry of the Fucino Basin and Subequana Valley indicate that a very similar evolution for both of the tectonic depression can be plausible.

Furthermore, interestingly, gravimetric investigations made by Di Filippo and Miccadei (1997) depicted a deep geometry of the Sulmona Basin markedly similar to that of the Fucino Basin and the Subequana Valley. Indeed, the authors defined a maximum depth of the depression in the northeastern portion of the basin, i.e. not centred with respect to the major active normal fault of the basin, the above mentioned Mt Morrone active normal fault (Fig. 8). The deep geometry of the Sulmona Basin defined by gravimetric data has been recently confirmed by Di Giulio et al. (2016) through ambient seismic noise measurements – that is, the same technique we adopted to investigate the Subequana Valley deep architecture. The authors defined the frequency of resonance of the bedrock–sedimentary fill interface, and imaged its trend beneath the sedimentary cover.

Therefore, the structural evolution defined for the Fucino Basin can be likely ascribed not only to the Subequana Valley but also to the Sulmona Basin. As for the ABF, in agreement with Galadini and Messina (2001), our observations indicate that, as in the Fucino Basin, it likely played during the Quaternary – and may still play – the role of releasing fault also in the Subequana Valley and the Sulmona Basin, with the difference that in the Fucino Basin and the Subequana Valley, the active fault systems cut across the ABF, while in the Sulmona Basin, the Mt Morrone fault ends against the ABF. A scheme of the proposed structural evolution of the depression is shown in Fig. 9.

Hence, to sum up, the three basins would have experienced a comparable structural evolution, with an early phase of nucleation during the late Pliocene ruled by the activity of the ABF and, likely, of the former strands of the NW–SE-trending and presently active normal faults. This phase resulted in the formation of early depocentres mostly located in the northern sectors of the present basins, at the intersection of the two almost perpendicular fault systems. Then, since the Early Pleistocene, the NW–SE-trending normal faults became the leading structures, and determined the formation of new depocentres centred on the major active faults, partly superposed on the older ones. Since then, the ABF has acted just as a local release fault (Destro, 1995) of the NW–SE-trending normal faults.

It must be discussed whether the very similar deep asymmetric shape displayed by the three basins could be related to an along-strike non-symmetric slip (i.e. slip that is maximum at the centre of the fault and that symmetrically tapers towards the tips) along the NW–SE faults. Along-strike asymmetric fault slip, indeed, would result in an asymmetric basin geometry, with the maximum thickness of the deposits located where the fault displacement is maximum, i.e. not centred to the fault. This can be ruled out for the following considerations. (1) In the Subequana Valley, the contact between the Quaternary infill and the bedrock reaches the surface at the tips of the SVF, with a certain asymmetry towards the north. However, in the northern part of the Valley, several hundred metres north of the fault tip – that is, where the long-term SVF offset is expected to be very low – a relevant thickness of lake/alluvial deposits is present at the hanging wall of the ABF, lying onto the outcropping bedrock, both on the hanging wall and on the footwall of the SVF. Here, the sedimentary sequence ends against the ABF, near Secinaro (Figs. 2, 5a). This implies that the basin depocentre can be only partly attributed to the Subequana Valley fault movements or only to interaction of the two orthogonal fault systems; otherwise, we should have found early Quaternary deposits only where the downthrown blocks of the two intersecting structures overlap. (2) If basin asymmetry was related just to a non-symmetric slip along the basin bounding active faults, this would imply that similar kinematic behaviour would have characterized all of the three faults, and for a very long time period, likely the whole Quaternary; and this is quite improbable. (3) Asymmetry of the deep geometry of the Sulmona Basin (with the deepest part located in the central-northern portion of the depression), comparable by shape with that of the Subequana Valley and Fucino Basin, does not fit the throw rate estimate in different sector of the Sulmona–Mt Morrone fault. Indeed, fault slip rate estimates, defined through the displacement of Early to Late Pleistocene

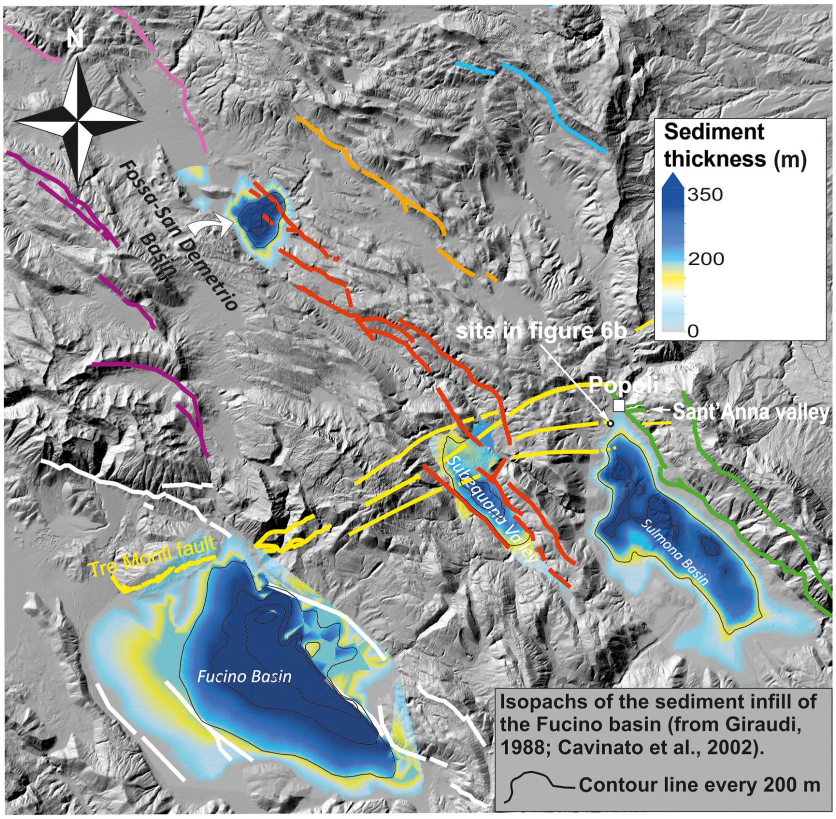

Figure 8. Shaded relief on which the reconstruction of the isopachs of the Fucino Basin, Subequana Valley, and Sulmona Basin sedimentary infill are reported, as well as that of the Fossa–San Demetrio depression, derived by crossing data from Bosi and Bertini (1970), Cesi et al. (2010), Linee Guida MZS (2010), Di Nezza et al. (2010), Di Filippo et al. (2011), Civico et al. (2015), and Pucci et al. (2016); legend of the fault systems as in Fig. 2.

continental deposits (e.g. Gori et al., 2011), defined very similar estimates in the central and southern sectors of the fault; conversely, slip rate values strongly decrease in the northern sector of the fault. This would be not consistent with the deep geometry of the Sulmona Basin. This implies that asymmetry of the Sulmona Basin does not relate solely to the long-term activity of the Mt Morrone fault.

5.2 Tectonic implications at regional and wider scale

In a wider perspective, further sectors of the central Apennine may have undergone a similar structural evolution, with chain-transverse tectonic structures active during the early phases of basin formation and presently acting just as secondary faults. For instance, the available literature suggests that one of these structures may have determined the early nucleation of the Fossa–San Demetrio depression, at the southern sector of the L'Aquila Basin. There, refined gravimetric prospection (Cesi et al., 2010; Di Nezza et al., 2010; Di Filippo et al., 2011), supported by further geophysical investigations (Civico et al., 2015; Pucci et al., 2016), document a gravimetric narrow low, roughly NE–SW oriented, that testifies for a deep bedrock–sedimentary fill interface, buried by the Quaternary continental sequences. This low shows very steep, quite linear and sharp boundaries towards the north and south (Fig. 8). These boundaries coincide with an abrupt deepening of the carbonate bedrock (which sharply sinks into the basin) and seem to align with local NE–SW-trending cross-basin faults. As proposed by Falcucci et al. (2015), NE–SW-trending faults (such as the Prata–Fontecchio fault) at the northern sector of the active MAVF have been no more active as primary/major faults during the Quaternary, but they locally act only as secondary/transfer faults between the northern major segments of the active MAVF–SVF system. Hence, similarly to the cases of the Fucino Basin, and Subequana Valley and Sulmona basins, it is possible to hypothesize that the early phases of formation of the Fossa–San Demetrio depression have been led by cross-basin structures that have been subsequently cut by the Quaternary NW–SE-trending normal fault occurring in the area (e.g. Bosi and Bertini, 1970; Falcucci et al., 2015). The older structure may presently play only the role of fault segment boundary between the Paganica fault, to the northeast, and the MAVF-SVF system, to the southeast, hindering fault rupture propagation as they are structurally and kinematically separated (Gori et al., 2012; Fig. 8).

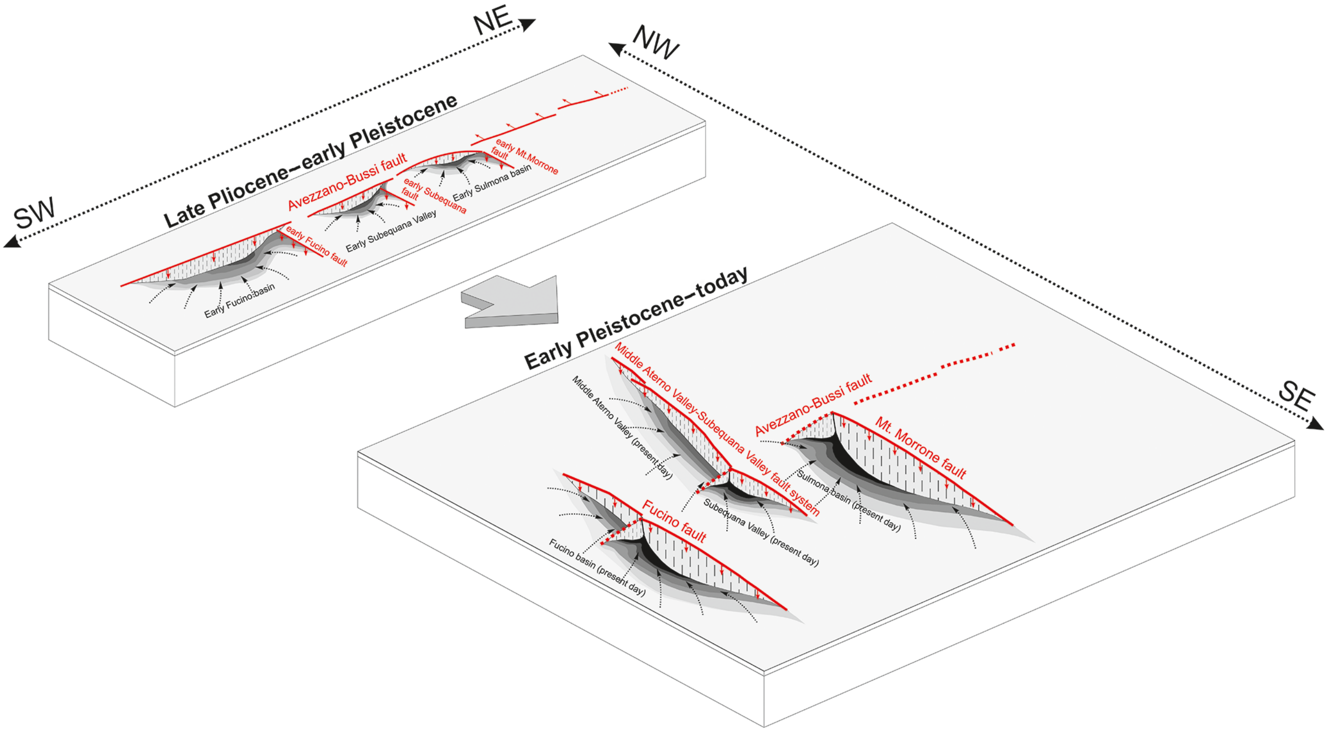

Figure 9. Scheme of the late Pliocene-to-present structural evolution of the Fucino Basin, Subequana Valley, and Sulmona Basin.

The results of our analysis also have important implications on some major seismotectonic aspects of the Apennine chain. The defined secondary role of the ABF in the recent tectonic activity is in agreement with the structural observation made by Roberts and Michetti (2004). Interestingly, the authors defined that the Tre Monti fault is probably not a major fault, owing to a number of structural and geomorphic features exhibited by the structure. Moreover, at a wider scale, the authors proposed an age of 2.5–3.3 Ma for the initiation of NW–SE-trending fault activity in the central Apennines, which is roughly consistent with the age that we propose for the onset of the Fucino, Subequana Valley, and Sulmona faults activity, when the ABF was still leading the formation of the early basins.

Our results, conversely, contrast with the hypothesis of Benedetti et al. (2013) regarding the recent kinematic behaviour of the Fucino fault system. The authors described the ENE–WSW-trending Tre Monti fault, a segment of the ABF, as a 20 km long active fault (actually being just 15 km long, as mapped by the authors) able to rupture primarily. Although the authors defined it as a minor fault, they attributed a high seismic potential to the structure ($M_{\mathrm{w}} > 6.4$ earthquakes originated along the fault, with some 0.7 m offset per event) and a high earthquake probability (probable rupture in the next ~ 0.2 ka). This hypothesis is based on cosmogenic nuclide ^{36}Cl dating of the fault plane exhumation, suggesting that the fault plane has been exposed only for tectonic slip. However, besides being not geometrically coherent with the present-day NE–SW-trending extensional stress regime (as the fault trends parallel to the main extensional axis), they do not discuss any other non-tectonic cause that may contribute to or even determine fault plane exposition, such as landsliding and/or erosion of the debris accumulated at the base of the fault scarp (e.g. Fubelli et a., 2009; Kastelic et al., 2015, 2017). Moreover, the secondary role we defined for the whole ABF implies that the Tre Monti fault is unlikely to nucleate primarily seismic events that strongly. This is in agreement with what Galadini and Messina (2001) already defined for the Tre Monti fault, i.e. the few-metre fault offset of early Quaternary deposits along the fault trace, comparably to what we observed along the ABF in the Subequana Valley. This would be therefore consistent with solely secondary movements of the structure to accommodate slip on the presently NW–SE-trending major active Fucino and Subequana Valley faults. Even if minor seismic events along the ABF cannot be completely ruled out, the 0.7 m slip per event defined by Benedetti et al. (2013) – that is consistent with a $M > 6.5$ earthquake, according to the regressions of Wells and Coppersmith (1994) – can actually incorporate contribution of the above-mentioned non-tectonic processes.

Other extensional tectonic contexts worldwide show interaction between orthogonal (or quasi-orthogonal) fault systems similar to that we describe. For instance, Şengör (1987) described cross-faults in western Turkey, which are controlled by zones of weakness that may be related to older structures and which trend perpendicular to the strike of the major extensional faults, that act as tear faults separating different downthrown blocks. In more detail, the author pointed out the importance of correct identification of different types of cross (or transverse) faults as this can result in incorrect assessments of the tectonic history of a given extensional tectonic setting. This is in agreement with the role of transverse faults in the central Apennines in accommodating tectonic extension, as Pizzi and Galadini (2009) pointed out and we attest for the ABF, and the importance of differentiating transverse structures for correctly assessing the role that they play in accommodating the ongoing tectonic regime as segment boundary or transfer faults. Morley et al. (2004) described oblique alignment of secondary faults and jogs in major faults of Thailand along oblique trends that indicates the structural influence of passive basement transverse fabrics. In particular, they concluded that pre-existing oblique fabrics (faults) can cause the oblique orientation of superposing faults, or can influence the location, geometry, and style of transfer zones, fault linkage, and displacement patterns. In the case we investigated, accordingly, the presence of the transverse ABF influenced the location of transfer faults between major active fault segments, as in the cases of the Fucino and Middle Aterno Valley–Subequana Valley fault systems, and the en-echelon arrangement between the segments.

Wilkins and Shultz (2003) described re-activation as extensional faults of pre-existing faults striking perpendicular to major extensional faults even on Mars, in response to stress changes related to slip change along the border faults.

6 Concluding remarks

Integrated geological and geophysical investigations in the Subequana Valley allowed us to get a 3-D view of the tectonic basin, that we framed in the Quaternary morphostratigraphic evolution of the depression.

Our analyses revealed an asymmetric deep geometry of the basin, characterized by maximum depth in the northeastern sector. The comparison with the structural evolution and setting of the nearby Fucino and Sulmona basins suggests that the three depressions experienced a similar double polarity nucleation, with two subsequent phases: an early phase, probably late Pliocene in age, led by the activity the regional chain-crossing, ENE–WSW-trending Avezzano–Bussi fault (ABF), contemporaneously to the early activation of the former strands of the NW–SE-trending normal faults. Afterwards, since the Early Pleistocene, the NW–SE basin bounding extensional faults took on the opening of the depressions, with the ABF just playing the role of release fault to accommodate slip on the major faults since then. A similar evolution may have been experienced by other basins of the Apennine chain.

We observed that the ABF is cut by the Fucino fault and, even more evidently, by the Middle Aterno Valley–Subequana Valley fault system. Conversely, the Sulmona–Mt Morrone active normal fault ends against the ABF. Hence, following Pizzi and Galadini (2009), the about 40 km long ABF may be a chain-crossing structure at threshold size between acting as transfer fault or as structural barrier. This could have implications in terms of definition of the role of other chain-crossing faults in the seismotectonics of the central Apennines.

As for the cause of the shift in the trend of the extensional deformation – firstly led by chain-crossing faults and then by chain-parallel faults – we can hypothesize that the early phase might be associated to the formation of extensional basins at the bending or stepping of tear faults of the thrust fronts, as releasing bend zones (or pull-apart depressions), following the model proposed by Doglioni (1995). Subsequently, NE–SW-trending Quaternary regional extensional tectonics, related to the E and NE migration of the chain and slab retreat (Carminati and Doglioni, 2012) and, as exposed above, to chain doming caused by mantle dynamics (e.g. D'Agostino et al., 2001; Aoudia et al., 2007), operated accordingly through NW–SE fault systems.

We highlight that where deformation phases quickly follow one another, the tectonic evolution of a region frames within a progressive and continuous process, which implies morpho-structural heritage and interference that must be understood and considered in kinematic assessments of the presently active tectonic regime. In this perspective, a basic morpho-tectonic fault-bounded basin model in which the tectonic depressions are strictly ruled by just the long-term activity of the presently active bounding faults, cannot be applied tout court to the Apennines and, likely, to other extensional settings. In this perspective, the "basin and range" geomorphic setting of the central Apennine chain, where the relief evolution is strictly ruled by the activity of the major normal fault systems during the Quaternary, has to be viewed with great caution, and, in light of this, any tectonic analyses or kinematic evaluations in the central Apennine chain cannot be based on simply assuming a flat landscape preceding the currently active extensional tectonic regime. Instead, studies on the long-term morpho-tectonic evolution in whichever tectonically active region have to take into consideration any possible geological legacy over a time span of interest for neotectonics, which lies at the base of the definition of the term given by Bosi (1992) for the Italian case.

Data availability. In Ladina et al. (2017) the dataset of the ambient seismic noise measurements performed in the Subequana Valley can be found, archived in SAC format.

The Supplement related to this article is available online at doi:10.5194/se-8-319-2017-supplement.

Author contributions. Stefano Gori and Emanuela Falcucci performed geological field investigations, manuscript writing, and

tectonic interpretation of the geophysical survey and modelling carried out by Chiara Ladina and Simone Marzorati. General tectonic/structural aspects were discussed and shared with Fabrizio Galadini.

Competing interests. The authors declare that they have no conflict of interest.

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