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Active faulting, 3-D basin architecture and Plio-Quaternary structural evolution of extensional basins: a 4-D perspective on the central Apennine chain evolution, Italy

Stefano Gori[1], Emanuela Falcucci[1], Chiara Ladina[1], Simone Marzorati[1], Fabrizio Galadini[1]

[1]Istituto Nazionale di Geofisica e Vulcanologia, Roma, Via di Vigna Murata 605, 00143, Italy

Correspondence to: Stefano Gori (stefano.gori@ingv.it)

Abstract. The general "basin and range" aspect of the Apennine relief is generally attributed to the presently active normal fault systems, whose activity throughout the Quaternary is supposed to have created alternating morphological/structural highs and lows. By coupling field geological survey and geophysical investigations, we reconstructed the 3-D geometry of one of the innermost tectonic basins of the central Apennines, the Subequana Valley, bounded to the north-east by an active and seismogenic normal fault. Our analyses revealed that, since the Late Pliocene, the depression experienced a double polarity, half graben-mode nucleation. An early phase, Late Pliocene-Early Pleistocene in age, was led by the ENE-WSW trending 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 trending, SW dipping and presently active normal fault system, that led 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 that the morpho-tectonic setting of the Apennine chain results from the superposition of deformation events whose "legacy" must be considered in a wider evolutionary perspective. Within this light, our results testify that a simple "basin and range" model – often adopted for morpho-tectonic and kinematic evaluations in active extensional contexts, as in the Apennines – may be actually simplistic, as it could not be applied everywhere, owing to peculiar complexities of the local tectonic histories.

Keywords. Active normal faulting, geological surveying, ambient seismic noise, 3-D basin structure, central Apennines

1 Introduction

The presently active normal fault systems are commonly supposed to be the major 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 slopes. The progressive lowering of the fault hanging walls and the relative uplift of the footwalls – together with regional uplift – created alternating morphological/structural highs and lows, that represent the Quaternary geomorphic *leitmotiv* of the Apennine relief. And this gives the chain the general appearance of a "basin and range" type belt. Nonetheless, extensional deformation displaced an inherited structural edifice, that was just built by the compressive tectonic regime, whose external thrust fronts were still active when extension began to affect the inner sectors of the chain. This resulted in the superposition of subsequent tectonic deformations led by structures in kinematic "antiphase" relation. 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 belt. The related geomorphic signature is represented by the remnants of a low gradient erosional paleo-landscape, presently detectable at high elevations along the montane slopes, carved into the compressively deformed bedrocks and that 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" structure of the Apennine chain, as being just ascribable 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 were already tectonic "lows" before extension began, and normal faulting has contributed to enlarge those depression.

In the present work, we analyse one of the innermost intermontane basins of the central Apennines, the Subequana Valley, which is bounded to the north-east by an active and seismogenic normal fault system (Falcucci et al., 2011). 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. As will be shown, a basic morpho-tectonic fault-bounded basin model in which the basin structure is strictly ruled by just the long term activity of the presently active bounding faults, cannot be applied *tout court* to the central Apennines and, likely, to other extensional settings. In a general perspective, our work points out that where deformation phases follow shortly one another, the tectonic evolution of a region – the Apennine chain in our case – frames within a progressive and continuous process, that implies morpho-structural "heritage" that must be understood and considered in kinematic assessments of the presently active tectonic regime.

To fulfil the objective of the work we adopt a multi-methodological approach, explained in the following paragraph, 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 Methods

In order to achieve information about the geological framework of the Subequana Valley, we cross data from field surveying carried out *ad hoc* for this work and from the Ph.D. project of Falcucci (2011). Survey of the Quaternary stratigraphic sequence filling the valley is carried out. The data obtained are then enriched by stratigraphic information derived from the analysis of unpublished well logs of boreholes made during the seventies of the past century and of others 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 has been performed between July, 2009 and February, 2010 (Marzorati et al., 2010). 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. At 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, for mitigating the possible effects of wind and rain, as well as of presence of vegetation on the ground, the sensors have been repaired 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 (url: www.lennartz-electronic.de. last check of availability June 2016) velocimetric sensors and 24-bit Reftek 130 (url: www.reftek.com. last check of availability June 2016) Digital Acquisition Systems (DAS). The stations were connected with battery of 12V/12Ah and with GPS antenna to precisely locate each measurement point. The gain was set 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 of at least 30 minutes 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 4 poles 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; Nakamura, 2000).

3 Geological background

3.1 Tectonic evolution of the central Apennines

The tectonic history of the central Apennines saw, since the Miocene, the occurrence of two subsequent, kinematically opposite tectonic phases. Namely, the first phase was compressional, in response to the Africa, Eurasia and Adria plates convergence. Systems of roughly NW-SE trending thrusts (mainly dipping to the SW) and folds displaced Meso-Cenozoic carbonate and siliciclastic marine sequences (e.g. Patacca et al., 2008, and references therein). This phase built the main structural edifice of the chain, through subsequent episodes of migration of the compressive front (e.g. Cosentino et al., 2010 and references therein), with in-sequence and out-of-sequence thrusting events. These are testified by subsequent foredeep and thrust-top basins interposed to thrust fronts.

As the compressive front progressively migrated towards the east and the northeast, extension began to affect the innermost portion of the chain, since the Pliocene (e.g. Cavinato and De Celles, 1999). This new tectonic phase manifested itself through the formation of normal fault systems, mostly paralleling the axis of the chain. These faults offset the thrust-and-fold related structures and spread mainly half graben tectonic depressions, with the main faults on their eastern side, mostly NW-SE trending and dipping SW-wards . 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 (Mw of up to 7) (Galadini and Galli, 2000; Basili et al., 2008; Galli et al., 2008). One of these, namely the Paganica fault, activated during the Mw 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).

Comparably to the compressive deformation, extension seems to have migrated towards the outer sectors of the chain (e.g. Cavinato and De Celles, 1999; Fubelli et al., 2009), with normal fault systems progressively younger west to east, in a sort of "pursuit" of the compressive front. An early phase of local extension has been recognised within some of the central Apennine intermontane tectonic basins, such as the Fucino (Galadini and Messina, 2001) and the L'Aquila (Nocentini, 2016) basins, occurred during the Late Pliocene-Early Quaternary. This phase seems to have not been occurred 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 the first phase of formation of the Fucino basin.

3.2 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 derive 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, trending NW-SE and dipping towards SW (Miccadei et al., 1997) (Fig. 2a). Recent field investigations permitted Falcucci et al. (2011) detailed mapping of the fault, which is made of two main parallel fault splays affecting the south-western 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 together with the Middle Aterno Valley fault (hereafter MAVF) (Falcucci et al., 2011; Falcucci et al., 2015) (Fig. 1). Recent paleoseismological investigations made along the MAVF-SVF system defined that the structure ruptured as a whole twice during the late Holocene, with minimum 0.8 m surface offset per event (Falcucci et al., 2011; 2015).

3.3 The Avezzano-Bussi fault system

The ABF is a complex structure trending 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 characterised 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 hypothesised it to be a tear fault that absorbed differential velocities of thrust fronts propagation during the compressive tectonic phase.

Galadini and Messina (2001) defined that the ABF has been active during the Late Pliocene, leading 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 taken by the NW-SE trending 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; Gori et al., 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 Mw 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 fault remained active during the Pleistocene and they are currently active.

Overall, this led to a complex three-dimensional 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 authors, this fault would presently just play the role of minor releasing fault (Destro, 1995), that only accommodates movements along the active NW-SE trending Fucino fault system.

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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 basins, that ended before the Early Pleistocene, as early Quaternary landsurfaces 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 to verify their hypothesis. As it will be shown later on, our data partly confirm the Galadini and Messina's hypothesis but they also revise it to some extent.

4 Geological field data

4.1 Morpho-stratigraphic investigation

Extensive field surveying and analysis of the continental sequence hosted within the Subequana valley were recently carried out in the framework of the Ph.D project of Falcucci (2011). Two main Quaternary morpho-sedimentary cycles were recognised (Falcucci, 2011; Gori et al., 2015b) (Fig. 2a, inset). The former is represented by the above mentioned lacustrine sequence, made of whitish-grayish silt and clayey silt, that grades upwards to a few metres-thick sand with sparse conglomerate layers interbedded. The sequence crops out all along the valley. Paleomagnetic analyses made on the lake sediments and U-series dating of two tephra layers found at the uppermost portion of the silt sequence defined a mainly Early Pleistocene age, with the sandy and conglomerate unit deposited across and shortly after the Matuyama-Brunhes paleomagnetic reversal (Falcucci, 2011). This morpho-stratigraphic setting testifies to a mainly Early Pleistocene Subequana lake basin – in agreement with Bosi and Bertini (1970) – that has been progressively filled by the clastic deposition sourced from the surrounding reliefs just after the Early-Middle Pleistocene transition.

Afterward, the basin experienced a major erosional phase, testified by an erosional surface deeply cut into the described lacustrine sequence. The second morpho-sedimentary cycle lays onto this erosional surface. This phase, Middle Pleistocene in age, is represented by alluvial deposits cropping out along the northern portion of the valley. 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 paleo-Aterno river system established. The second cycle, that testifies to this phase, is presently suspended over the Aterno river thalweg, owing to successive river entrenchment.

River incision, as well as minor streams, defined several tens-of-metres exposed thickness of the lacustrine sequence, that is the most prominent sedimentary body of the basin. The second sedimentary cycle, instead, is on the order of ten of metres thick. We also collected data derived from boreholes made some forty years ago for water (Fig. 2b). The deepest reaching ones (about 40 m depth from the ground surface) cored the lake silt body in different parts of the basin, and they did not reach the bedrock. The substratum 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.

4.2 Evidence for the long term (Quaternary) activity of the SVF

The above described morpho-sedimentary sequence mainly crops out at 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, resting onto the carbonate substratum (Fig. 3a). Here, the sequence is suspended over 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 hanged on the fault footwall. 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 in the order of some 150 m across the western fault splay (Fig. 3b).

Moreover, the fact that the lacustrine sequence occurs in the footwall of the western splay and in the hanging wall of the eastern one suggests that splay nucleation has not been synchronous, that is, the eastern splay activated before the western splay (Fig. 4). Such structural evolution has been observed in other central Apennine active normal fault systems (e.g. Gori et al., 2007; 2014; Falcucci et al., 2015).

4.3 New data from the Avezzano-Bussi fault

As formerly defined by Galadini and Messina (2001), the ABF bounds the Subequana Valley to the northeast. From a structural viewpoint, it has been responsible for structural features (such as high angle fault planes, joints, cleavage) trending about ENE-WSW that affect the carbonate bedrock exposed along the basin bounding reliefs. The fault is here represented by different parallel splays, that define a roughly 2 km-wide shear zone in the bedrock. From a geomorphic point of view, the presence of this tectonic lineament is testified by a rather straight trend of the slopes, and by incisions in the carbonate bedrock that align along the ABF; these incisions probably set 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 feature 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, as we described before. More in detail, in the area of Secinaro, we found a high angle ENE-WSW trending fault plane at the base of the slope, aligned along the ABF. Slope derived breccias underwent few metres displacement and dragging along the fault plane (Figs. 2a; 5a), defining a dip slip (extensional) sense of motion.

The displaced deposits can be related by lithology – that is, angular-to-subangular carbonate clasts in a pink-orange cement – to those widespread in the central Apennines, known as the Early Pleistocene “second sedimentary cycle breccias” of Bosi et al. (2003). Here, this chronological association is corroborated by the fact that they are suspended over 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 little 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 north-eastern far end of the Subequana Valley, at the overlapping zone between the SVF and the MAVF, another a high angle ENE-WSW trending 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 shear planes (Figs. 2a; 5b). The sense of displacement of the Middle Pleistocene slope deposits suggests extensional movements of the fault, but with very reduced offset. Therefore, together with the above described faulted breccias, this evidence testifies to a post-Early/Middle Pleistocene activity of secondary shear planes that can be associated to the ABF within the Subequana Valley.

Moving farther to the E-NE, once 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 are 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 ends against 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 trending faults are seen along the northern sector of Mt. Morrone. One of these structures, whose bedrock fault plane is seen in the Sant'Anna valley, that opens on Popoli, presently accommodates lateral movements of large scale gravitational mass movements (Gori et al., 2014). Interestingly, sets of ENE-WSW to NE-SW trending sub-vertical fault planes, roughly aligned with this fault, are seen in the northernmost portion of the basin (Fig. 6b), just south-west of Popoli, affecting the Early-to-Middle Pleistocene lacustrine sequence (Giaccio et al.., 2009; 2013; Gori et al., 2011). The sense of displacement of the lacustrine deposits, the often anastomosed and wavy geometry of the majority of the shear planes ("lithons" of the lake silty deposits are locally distinguished), and the varying thickness of some layers across them (Fig. 6b) suggest a transtensive kinematics.

Overall, our observations indicate that 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 imprints of the ABF on the landscape is seen, and it is just "geologically" detectable for the lateral juxtaposition of different bedrock units.

5 Geophysical surveying in the Subequana Valley

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 interface bedrock-sedimentary cover can be obtained, as shown in the following.

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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 following equation:

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

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 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 supplementary material). In the cases where only a single peak was found, f_0 was considered the fundamental frequency of the site. All the curves with no significant peak were considered as "flat" (Sesame, 2005).

In general, at the edges of the basin, frequencies were comprised 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 the bedrock close to ground surface (Figure F1) (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 south-east.

Taking advantage of equation (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, of the middle Aterno river valley and of the Sulmona basi –, and the few borehole data available define that the majority of the sediments infilling the Subequana Valley is conceivably represented by the lacustrine sequence, that 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 (MZS Working Group, 2011). 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 strain shear stiffness, G_0, 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. Also in the Sulmona basin, V_S of deepest lacustrine deposits estimated with joint inversion of seismic array techniques resulted of about 600 m/s (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):

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

The V_S model of equation (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. This superficial V_S agrees with value estimated by means of Multichannel Analisys of Surface Waves (MASW) technique in the Castelvecchio Subequo and Castel di Ieri areas (Salucci, 2010a; b), where the shallow layers are composed by silt covered by few metres-thick sand and sandy gravel (Salucci, 2010a; b). Such lithology clearly 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 considered as acceptable, considering the lithologies comprised within the class of "lacustrine white carbonate silts" defined by MZS Working Group (2011). Indeed, if any sand or gravel layers occurs in the deepest portions of the basin, it is lithologically "contained" within the assumed sedimentary class.

Hence, to obtain an estimate of the relative thickness of the sediments above the bedrock in correspondence with seismic 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 equations (1) and (2):

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

Figure 7b shows estimate of the bedrock/sediment infill interface, derived from the sediment thickness obtained by seismic noise measurements. 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. 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 obtain 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 300-350 m. 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 to the surface, indicating the presence of an high angle buried cliff west of Castelvecchio Subequo, that coincides with a secondary synthetic splay of the SVF (Fig. 7b).

It is worth noting that the three boreholes available for the Subequana Valley are consistent with the estimated deposits thickness (Figs. 2a, b), that is, they did not reach the bedrock (they reached about 40 m depth in the lacustrine silt) in an area where our data would indicate a bedrock/sediment infill interface about 100 m deep.

6 Discussion

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 an evolutionary perspective 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 two basins are bounded to the north by the ABF, which displays evidence of small displacements of Early-to-Middle Pleistocene deposits along some of its strands. In this perspective, Falcucci et al. (2011) already defined that small portions of the ABF are presently used solely as connecting/transfer faults between two main segments of the SVF. On the other hand, no evidence of Quaternary activity are seen along the portions of the ABF between the Subequana Valley and the Fucino basin, to the west, and the Sulmona basin, to the east.

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

3) Geophysical data available define an asymmetric deep geometry of both of the depressions, with maximum depths of bedrock-sedimentary fill interface not strictly centred with respect to the presently active faults, as would be expected, but located in the north-eastern 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 polarity nucleation of the depression, firstly led by the ABF – mostly during the Late Pliocene – and then driven 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 evolutionary route for both of the tectonic depression can be plausible.

We now consider the available information regarding the Sulmona basin. 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 north-eastern 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 figure 9.

In a wider perspective, further sectors of the central Apennine may have undergone a similar structural evolution, with chain-crossing tectonic structures active during the early phases of formation of basins 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), showed here a gravimetric narrow "low", roughly NE-SW oriented, that testifies to 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 primary active 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, Subequana Valley and Sulmona basins, it is possible to hypothesise 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 "structural boundary" between the Paganica fault, to the northeast, and the MAVF-SVF system, to the southeast, that are structurally and kinematically separated (Gori et al., 2012) (Fig. 8).

7 Concluding remarks

Entwined geological and geophysical investigations in the Subequana Valley revealed a complex 3-D basin architecture, with an asymmetric deep geometry characterised by maximum depth in the northeastern sector. The comparison with the structural evolution and setting of the nearby Fucino and Sulmona basins suggest 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), inherited by the compressive tectonic phase. Afterwards, since the Early Pleistocene, the presently active 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. Such a structural evolution could have been also experienced by other basins of the central Apennines, such as the Fossa-San Demetrio depression, south of L'Aquila.

The results of our investigations have a twofold implication, one local, in terms of seismotectonic characteristics of the central Apennine, and one general, in terms of evolution of the Apennine chain and of a broader methodological approach. First, the defined secondary role of the ABF during the whole Quaternary, in agreement with Galadini and Messina (2001), contrasts 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. They attributed a high seismic potential to this structure (Mw>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), based on cosmogenic nuclide ^{36}Cl dating of the fault plane exhumation.

They assumed 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, the secondary role we defined for the whole ABF implies that the Tre Monti fault is unlikely to nucleate primarily seismic events that strong. Furthermore, as already defined by Galadini and Messina (2001), the very small offset of early Quaternary deposits along the Tre Monti fault, comparably to what we observed along the ABF in the Subequana Valley, has to be referred solely to secondary movements of the structure to accommodate major slip on the presently NW-SE trending active 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 earthquakes, according to the regressions of Wells and Coppersmith (1994) – can actually incorporate the contribution of other non-tectonic processes, such as landsliding or erosion of the debris accumulated at the base of the bedrock fault scarp.
On a wider perspective, we can make an hypothesis on the cause of this shift in the trend of the extensional deformation – firstly led by chain-crossing faults and then by chain-parallel faults –: 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). Subsequently, NE-SW trending Quaternary regional extensional tectonics operated accordingly through NW-SE fault systems. But much more work is need to verify this hypothesis.
Lastly, the present study reinforces the concept that a simple “basin and range” type morpho-structural model for 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 taken with great caution. Indeed, the Quaternary extensional tectonic phase inherited a complex morpho-structural “landscape” from the compressive tectonic phase and the subsequent Pliocene morphogenetic phase (paleo-landscape), preceding or just at the onset of extension. The consequence is that any tectonic analyses or kinematic evaluations in the central Apennine chain cannot be based under the assumption of a “flat landscape” preceding the currently active 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”, adopting the farsighted definition of the term given by Bosi (1992) for the Italian case.

Author contribution

Stefano Gori and Emanuela Falcucci performed geological field investigations, as well as tectonic interpretation in the light of geophysical survey and modelling carried out by Chiara Ladina and Simone Marzorati,. General tectonic/structural aspects have been discussed and shared with Fabrizio Galadini.

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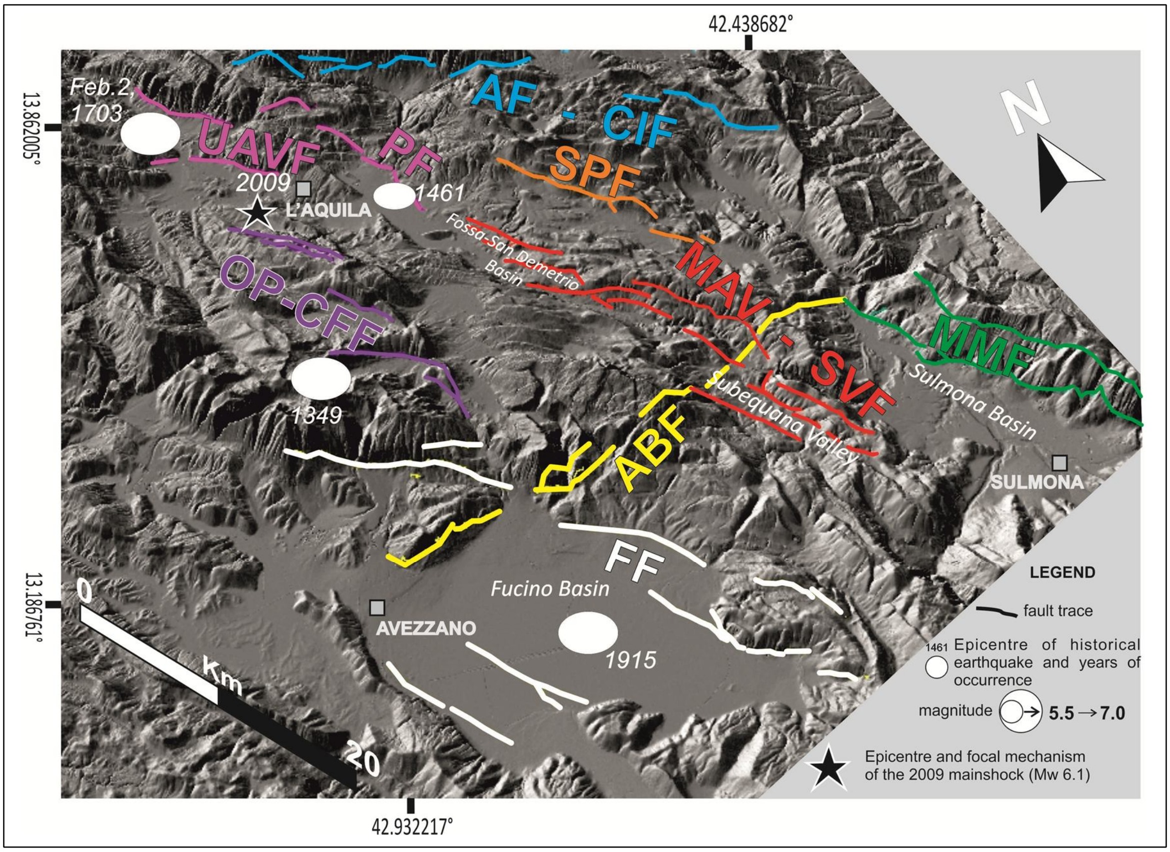

Figure 1: Seismotectonic scheme of the central Apennines (shaded relief in perspective view). Faults (colours indicate splays and segments comprised in the same fault system): MAV-SVF, Middle Aterno Valley-Subequana Valley fault system; ABF, Avezzano-Bussi fault; FF, Fucino fault; MMF, Mt. Morrone fault; 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.

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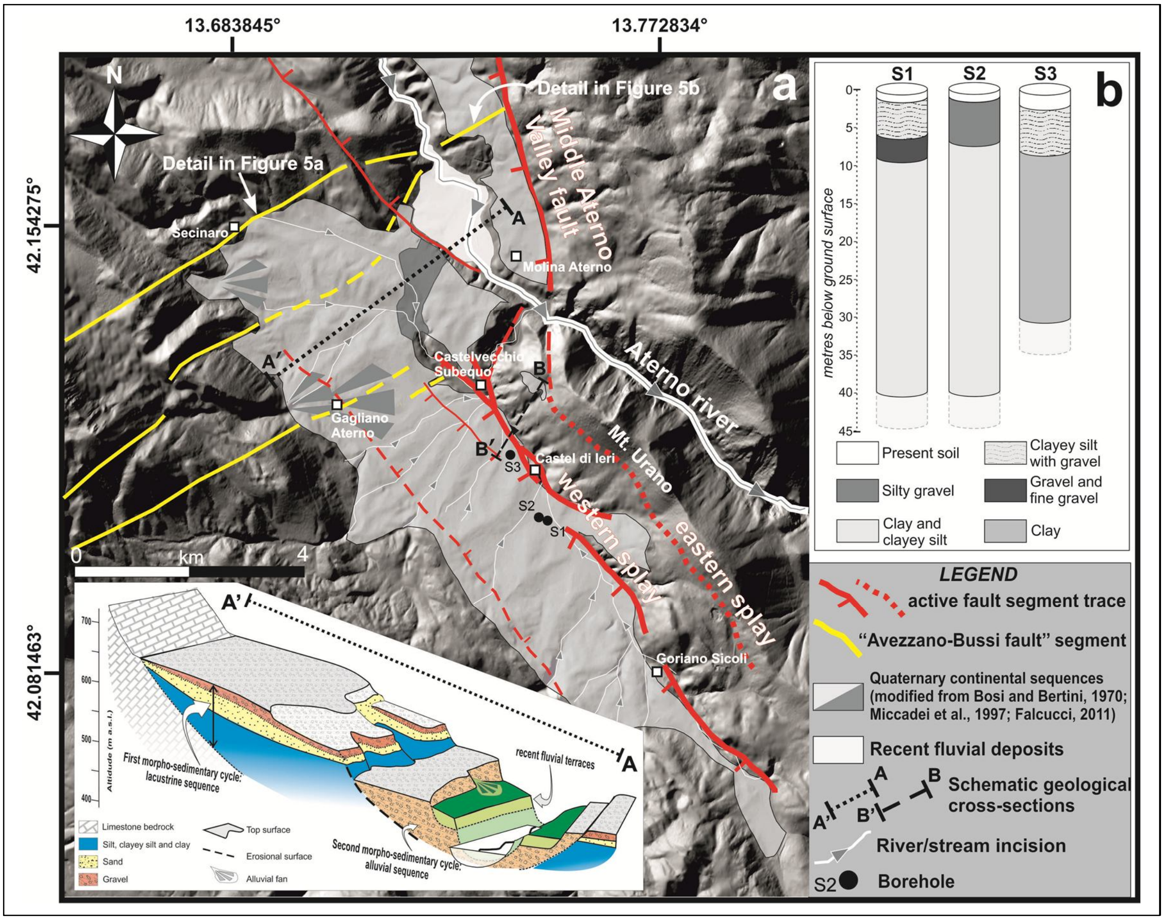

Figure 2: a) Shaded relief of the Subequana Valley (plan view) on which simplified geological map (modified after Bosi and Bertini, 1970; Miccadei et al., 1997; Falcucci, 2011) is reported; morpho-stratigraphic reconstruction of the Quaternary succession of the Subequana Valley, inset. b) Stratigraphy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

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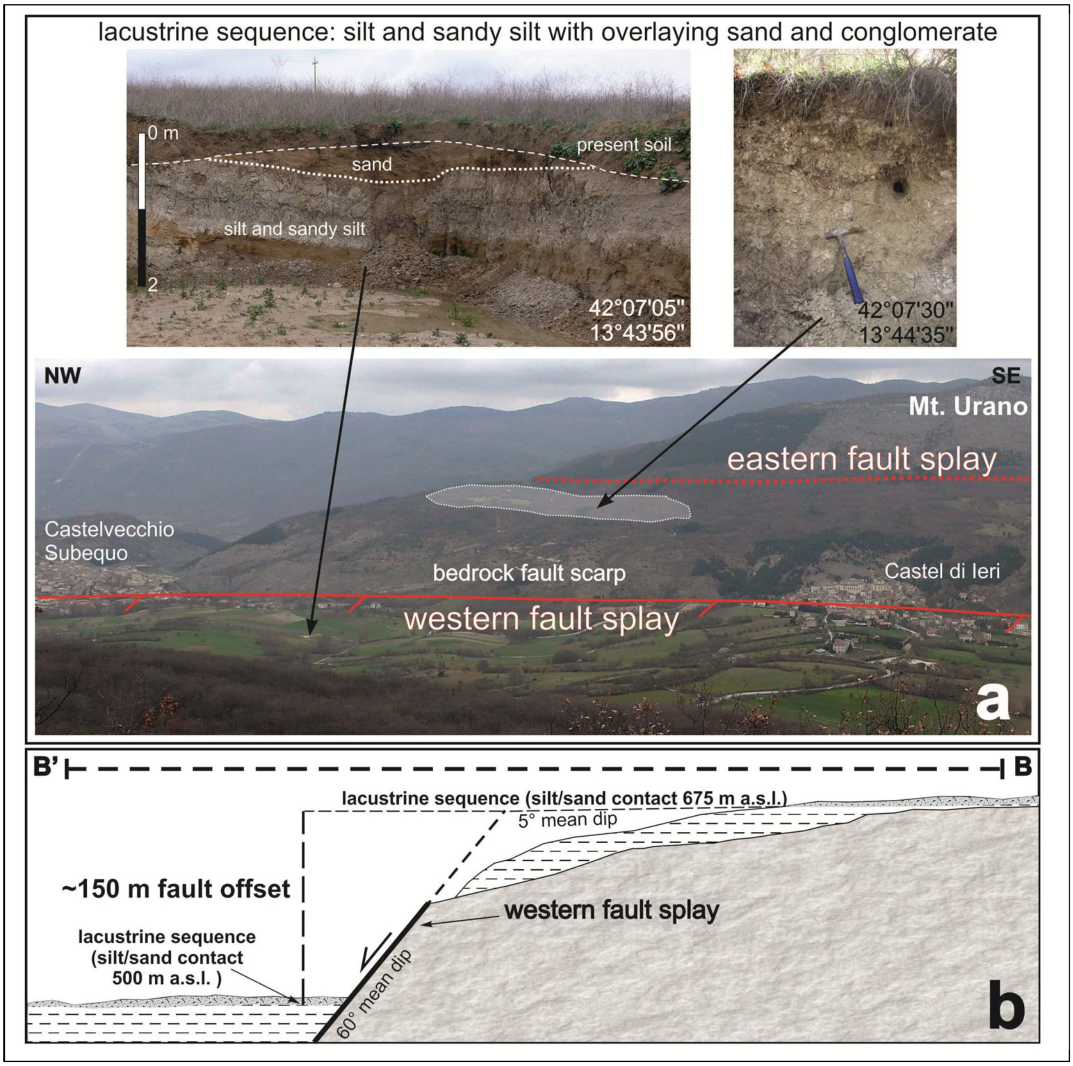

Figure 3: a) Panoramic view of the southwestern slope of Mt. Urano; major normal fault splay of the Subequana Valley fault, red lines; outcrops of the upper lacustrine sequence of the Subequana Valley are pointed by arrows and shown in insets. b) schematic geological cross-section showing the displacement of the Subequana Valley lacustrine across the western splay of the fault.

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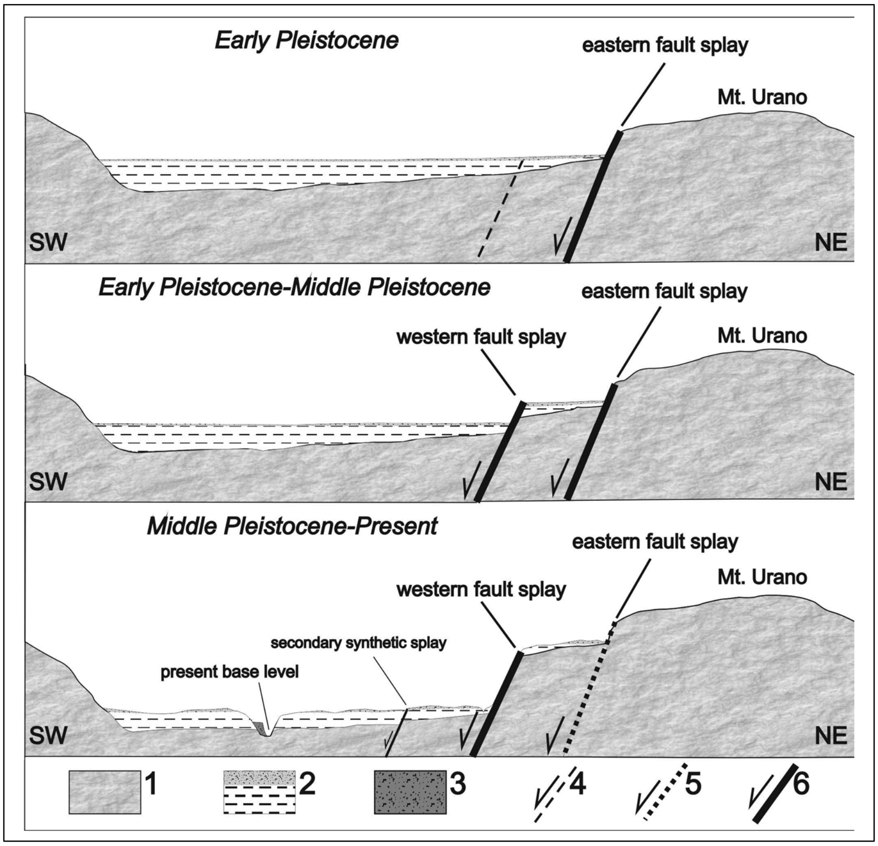

Figure 4: Scheme of the Quaternary structural evolution of the Subequana Valley fault and of Mt. Urano southwestern slope. 1) carbonate bedrock, 2) lacustrine sequence, fluvial-alluvial deposits, 4) incipient normal fault, 5) inactive normal fault or normal fault whose current activity is presently uncertain,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

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Figure 5: a) Early Pleistocene breccias dragged along a secondary fault splay parallel to the Avezzano-Bussi fault, see figure 2 for location. b) Middle Pleistocene slope derived deposits affected by extensional faults (white dashed line) parallel to the Avezzano-Bussi fault, see figure 2 for location.

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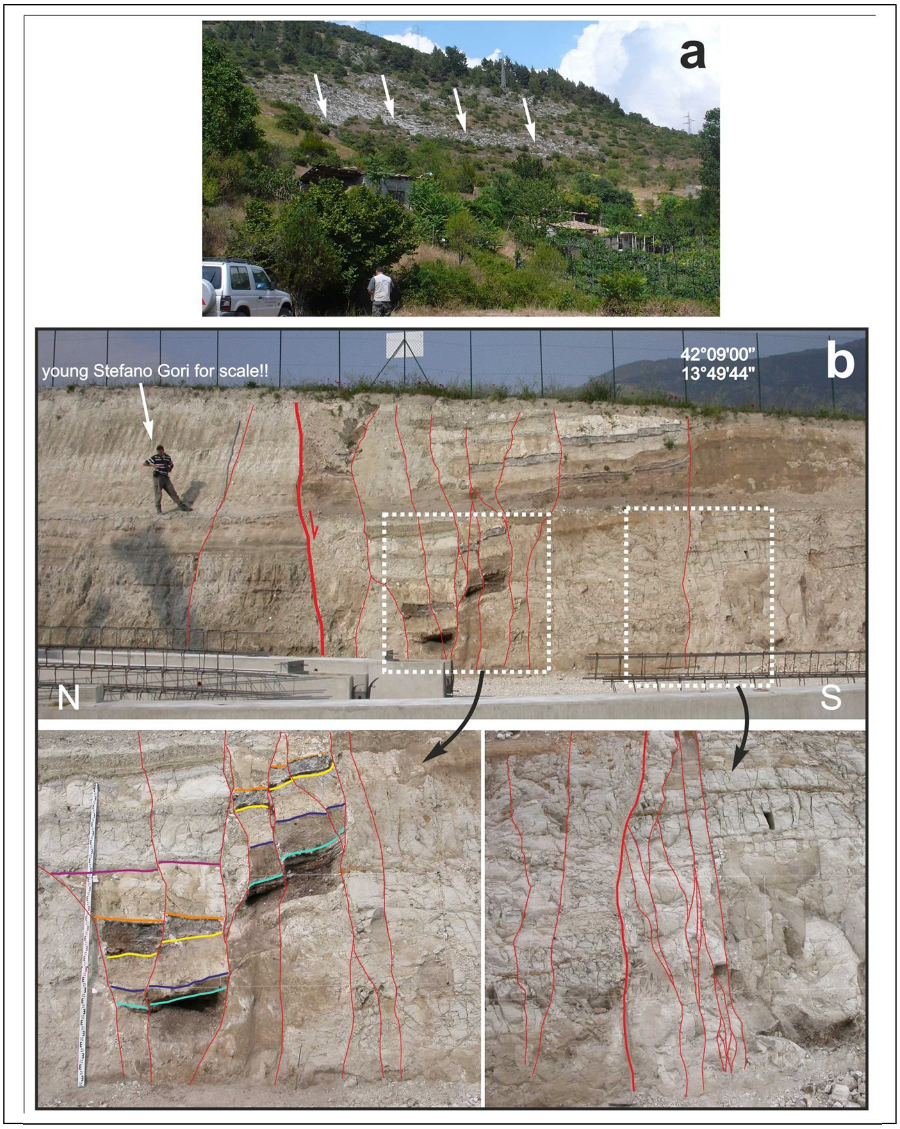

Figure 6: a) Discontinuous bedrock fault scarp of the Avezzano-Bussi fault along the northern border of the Sulmona basin. b) Transtensional faults in the Sulmona basin, aligned along one of the splays of the Avezzano Bussi fault, displacing Early Pleistocene lacustrine sequence.

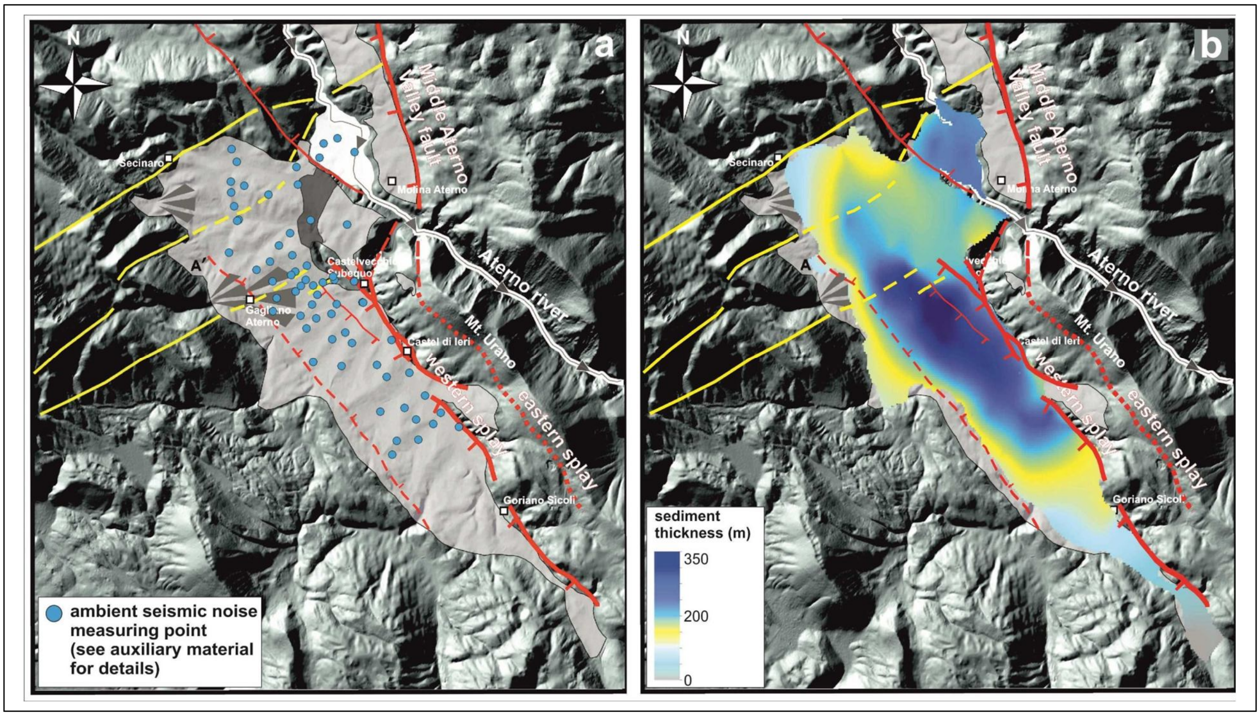

Figure 7: a) Simplified geological map of the Subequana Valley (legend as in figure 2); location of the ambient seismic noise measuring points, blue circles. b) Reconstruction of the deep geometry of the Subequana Valley (legend as in figure 2), defined by the sedimentary fill thickness.

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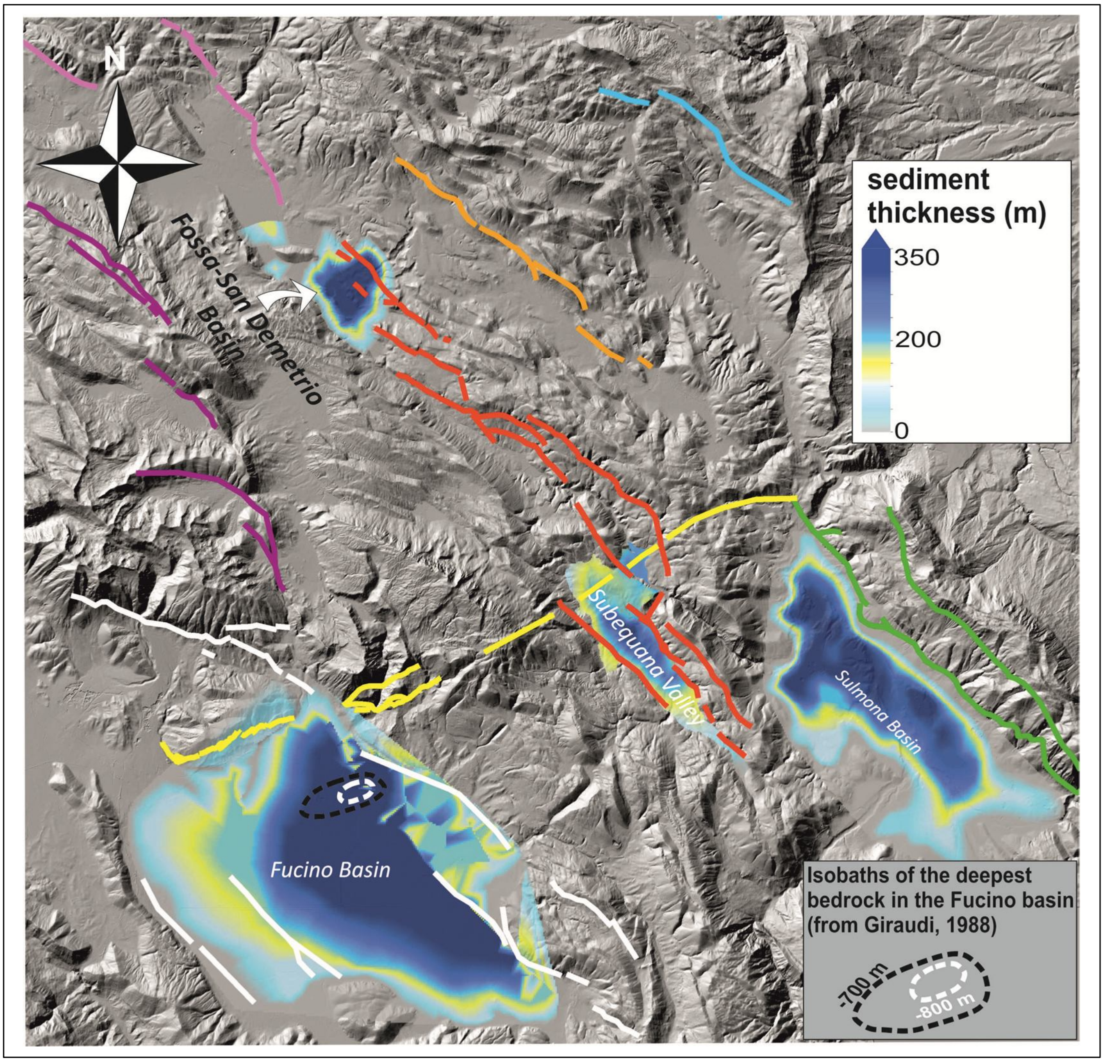

Figure 8: Shaded relief on which the reconstruction of the deep architectures of the Fucino basin, Subequana Valley and Sulmona basin are reported, as well as that of the Fossa-San Demetrio depression (legend of the fault systems as in figure 2).

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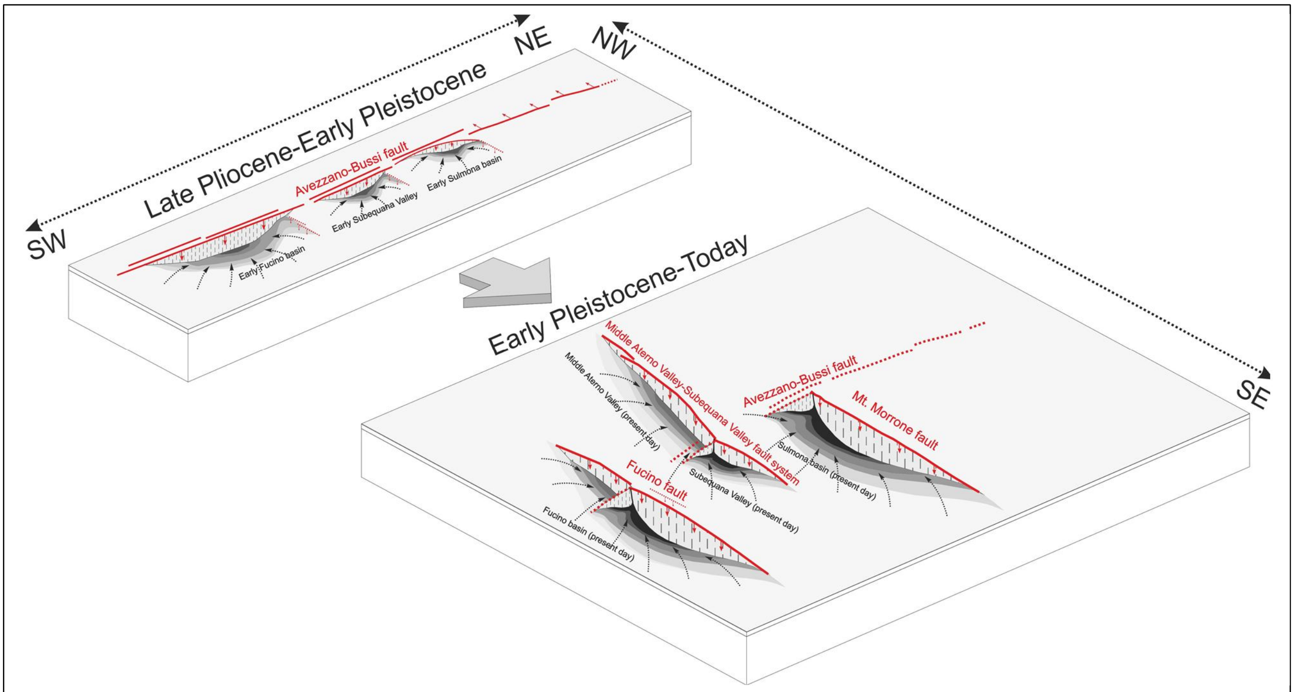

Figure 9: Scheme of the Late Pliocene-to-present structural evolution of the Fucino basin, Subequana Valley and Sulmona basin.