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Assessing active and capable faulting as best practice for post-earthquake reconstruction activities: the Sant'Eutizio Abbey case study, in the epicentral area of the 2016 central Italy seismic sequence

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Abstract

Surface faulting is, together with strong ground shaking, a hazard associated with major earthquake faults. Assessing surface faulting potential of a given active tectonic structure is a fundamental prerequisite to adequately plan the use of territories and to perform new constructions, in order to act practices aimed to mitigate the associated risk. Assessing the surface faulting potential represents also ground for correctly performing re-construction and retrofitting of buildings and infrastructures during post-earthquake activities. We investigated a branch of a major seismogenic normal fault in the central Apennines of Italy, the Campi-Preci fault, along which the monumental Sant'Eutizio Abbey is located. The medieval Abbey is one of the most important cultural/religious edifices of the central Apennines, heavily damaged by the M_W 6.5 October 30, 2016, earthquake, focused a few km to the south. Our study, based on field geological, geomorphological and structural survey and trenching investigations revealed that I) the trace of the Campi-Preci active fault branch is not actually located where presently reported in the available literature, II) the supposed morpho-tectonic features (basically, some km-long scarp carved on the Meso-Cenozoic carbonate bedrock), that suggested the presence of the fault segment in the area of the Sant'Eutizio Abbey, are not related to the active fault but are probably associated to a presently inactive reverse fault and III) the Sant'Eutizio Abbey is likely not potentially affected by primary surface faulting. Our work highlights that only a comprehensive multidisciplinary approach allows to correctly assess surface faulting potential in both seismotectonic and engineering perspectives.

Keywords: Post-earthquake reconstruction; Active and capable faulting; 2016 seismic sequence; Sant'Eutizio Abbey; Central Italy.

1. Introduction

The 2016-2017 seismic sequence in central Italy, whose largest event of M_W 6.5 occurred on the 30th of October 2016, severely struck many towns and villages, causing widespread destruction to buildings and infrastructures. Besides strong ground shaking, constructions and lifelines have been damaged by earthquake-induced landslides and by surface breaks occurred along the earthquake fault, the Mt. Vettore-Mt. Bove normal fault (hereafter MVBF). For instance, the occurrence of surface faulting ruptured the San Benedetto gallery, which crosses one of the antithetic branches of the MVBF [e.g. Galli et al., 2019; Cheloni et al., 2019].

Some important historical monumental buildings have been severely damaged by the quake, such as the San Benedetto Basilica in the town of Norcia, that almost completely collapsed, and the Sant'Eutizio Abbey (hereafter SEA), near Preci, which underwent partial collapse owing to shaking and seismically triggered landfall (Figure 1). The Abbey is one of the most relevant medieval religious buildings of the central Apennines, being considered the place of origin of the Benedictine Catholic Order.

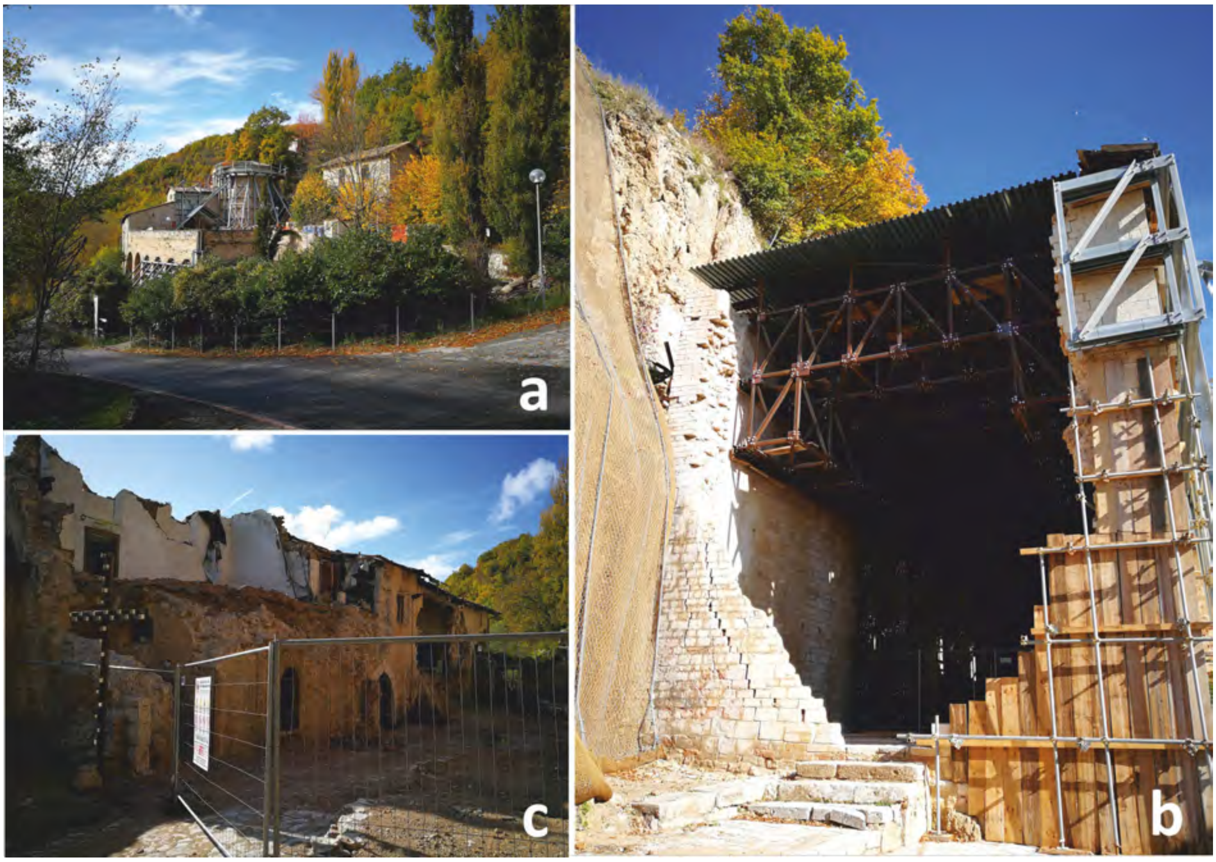

Figure 1. (a) View of the Sant'Eutizio Abbey partially collapsed owing to shaking and seismically triggered landfall; The figures (b) and (c) show the church and building severely damaged, respectively.

Following the 2016 heavy damage, plans for reconstruction and seismic retrofitting of the SEA included the identification of all the possible geological criticalities that would potentially affect the site, in order to act practices aimed to mitigate the related risk. Surface faulting is one of the hazards that, based on the current knowledge, can affect the SEA. Indeed, the Abbey is located along the possible trace of an active normal fault, known as the Campi-Preci fault segment (henceforth CPFs), which is the northernmost branch of the Norcia active normal fault (henceforth NF). The NF is commonly considered as the expression at surface of a major seismogenic source, activated over the past few centuries with earthquakes of up to M_W 6.5-7 [Blumetti, 1995; Galli et al., 2005, 2018], from which metre-scale surface faulting is expected.

In particular, the trace of the CPFs is indicated, in the SEA area, in the available geological literature as well as in the microzonation studies of the Preci village area. Nonetheless, no clear geological evidence of the recent activity of the CPFs are currently available. The aim of the present work is to investigate the area of the SEA and surroundings to find geological information that can cast light on the activity of the tectonic structure and to define its trace in detail, in order to verify the presence of the fault in the SEA area. These data can thus represent the ground for the retrofitting procedures of the historical buildings.

The work firstly presents the geological background of the region, focusing on the structural and seismotectonic characteristics of the Norcia and Campi-Preci areas. Then, the bulk of the geological, geomorphological and structural investigations are shown, together with the results of paleoseismological analyses (by means of trenching) carried out in the SEA site.

In the discussion, we examine the outcomes of our analyses and the possible implications on the definition of kinematic history of the CPFs, on the related surface faulting potential and on the definition of its actual trace. The conclusions sum up the results of our study, highlighting the effectiveness of the adopted approach in the SEA case study for surface faulting hazard assessment.

2. Geological background

2.1 Geological and structural setting

The study area is located within the central Apennines, in southern Umbria, and is part of the 2016 epicentral area. In particular, the epicenter of the largest event of the sequence, the M_W 6.5 earthquake occurred on the 30^{th} of October, locates at a planar distance of ca. 5-6 km to the SE of the SEA. The Apennine chain reliefs are made of marine limestone, marly-limestone and marly-clay sequences, deposited between the Early Jurassic and Early Miocene. The present geological and structural setting of the area is due to the superposition of two tectonic phases, the former compressive and the latter extensional. The compressive tectonic phase folded the Meso-Cenozoic marine sequences through thrust systems E- and NE verging and W- and SW dipping. The Sibillini Mts. thrust front is the major reverse regional tectonic feature that structured this part of the chain [e.g. Calamita et al., 1982; Blumetti and Dramis, 1992; Cipollari and Cosentino, 1995; Cosentino et al., 2010] during the Late Miocene-Early Pliocene. The subsequent extensional tectonic regime began to affect this sector in the late Pliocene-Early Pleistocene, contemporaneously to the overall chain uplift [e.g. Parotto e Praturlon, 1975; Cavinato et al., 1993]. While the active compressive thrust fronts migrated towards the Adriatic sectors, series of mainly NW-SE trending and SW dipping normal fault systems began to activate in the inner domains of the chain, displacing and/or negatively inverting the pre-existing compressive tectonic structures. Extensional tectonics contributed to the formation and Quaternary evolution of intermontane tectonic depressions (as half-grabens structures) that characterise the inner sector of the chain, among which the Norcia, Campi, Castelluccio di Norcia, Cascia, Colfiorito and L'Aquila basins [e.g. Cavinato and Miccadei, 1995; Galadini et al., 2003; Galadini and Messina, 2004].

The activity of some of the normal fault systems continued through the Quaternary and some of them are currently active, as demonstrated by geological and geomorphological evidence of Late Pleistocene-Holocene activity [e.g. Galadini and Galli, 2000]. The activation of these normal faults caused the largest earthquakes that struck this sector of the central Apennines in historical times, up to the past decades, such as those occurred in 13^{th} January 1915 (Fucino area, M_W 7.08), 14^{th} January 1703 (Norcia basin, M_W 6.92), 2^{nd} February 1703 (L'Aquila basin, M_W 6.67) [e.g. Rovida et al., 2020]. The 2016 seismic sequence is an example of this. It has been generated by the activation of the MVBF, located E of the area investigated by the present study (Figure 2a), which is one of the major normal faults of the central Apennines, defined as potentially responsible for about M 6.5 seismic events prior to its 2016 activation [Galadini and Galli, 2003]. Moreover, normal fault activity coupled to the chain uplift contributed to the increase of the local relief over the Quaternary, determining gravitational instability of mountain slopes and leading to the onset of deep-seated gravitational slope movements, widespread in this part of the mountain belt [e.g. Dramis et al., 2002; Galadini, 2006].

The study area is located along another major active normal fault system of southern Umbria, the so-called NF (Figure 2b), discussed in the next section.

2.2 Seismotectonic framework of the Norcia basin and surrounding areas

The available literature defined the NF as comprising several segments and branches, with evidence of Quaternary and Late Quaternary activity along most of them. Overall, the NF is considered as about 30 km-long expression at surface of a seismogenic source potentially responsible for M_W 6.5-7 earthquakes. The central segment of the fault bounds the Norcia basin to the E, with synthetic and antithetic branches affecting the area of the Norcia town. To the S, some fault splays bound Mt. Alvagnano to the SW and affect the Castel Santa Maria village area. The northern segment of the NF is represented by the CPFs (Figure 2c). It displays an en-echelon arrangement (dextral step-over) with the main fault segment of the Norcia basin, being separated less than one kilometer from each other (Figure 2a, b).

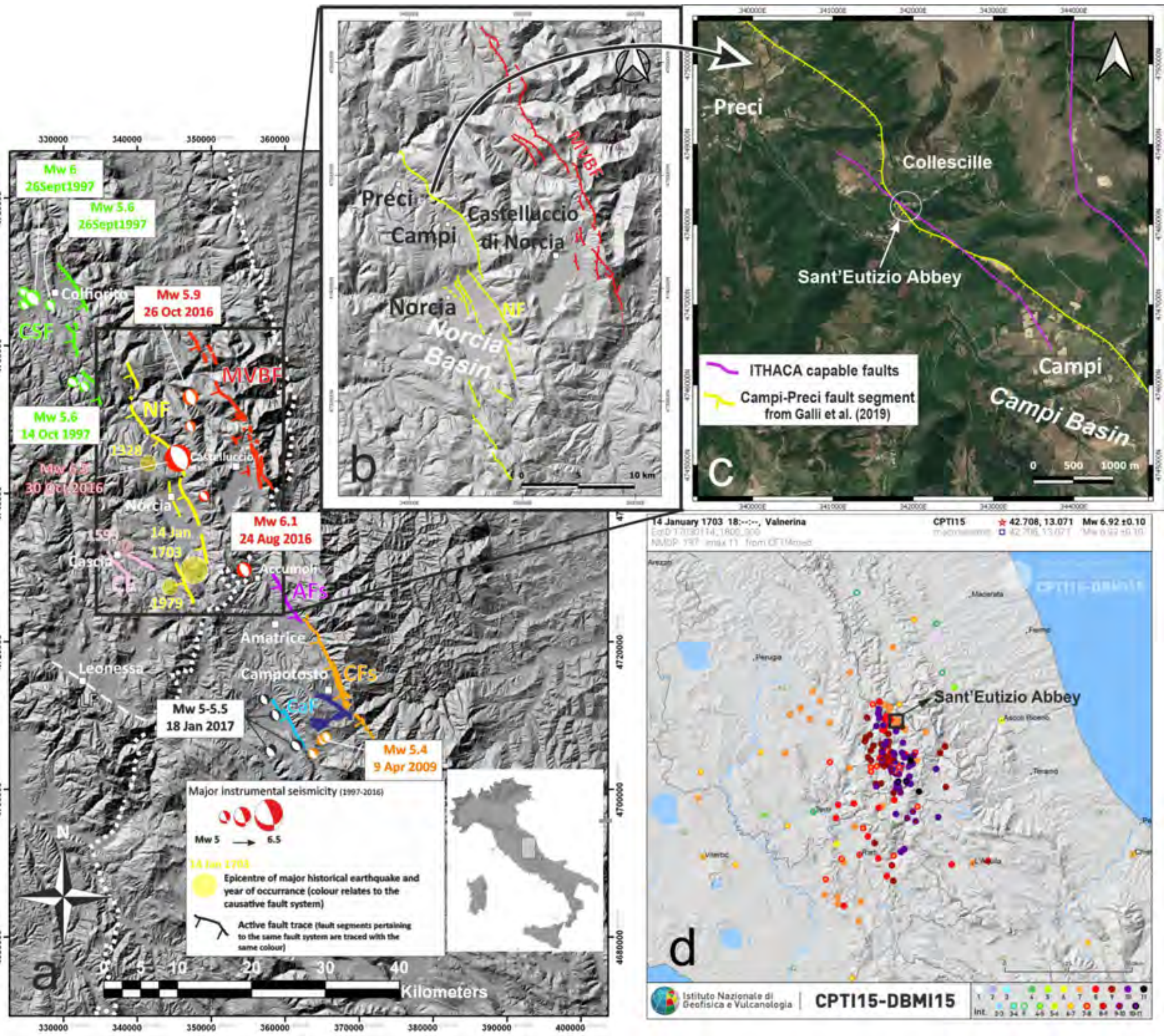

Figure 2. (a) Map (shaded relief model) showing the seismotectonic setting of the central Apennines [modified from Galadini et al., 2018]. The coloured circles represent the epicenter of major historical earthquakes that affected the area since the 1979 Valnerina seismic event. Coloured lines represent the trace of the major active normal faults. The dotted white line represents the Sibillini-Olevano-Antrodoco thrust front. Faults: CFS, Colfiorito-Sellano fault; MVBF, Monte Vettore-Monte Bove fault; NF, Norcia fault; CF, Cascia fault; AFs Amatrice fault; CFs Campotosto fault; CaF; Capitignano fault; LF, Leonessa Fault. (b) Detail with the major segments and branches of the Norcia fault (NF) and Mt. Vettore-Mt. Bove fault (MVBF); (c) Map (satellite imagery) of the study area with the trace of the Campi-Preci fault segment according to the ITHACA database, marked with purple line, and according to Galli et al. [2019, and references therein], marked with red line; (d) Macroseismic intensities distribution of the 14th of January, 1703, seismic event [Rovida et al., 2020].

Geological evidence of Quaternary and late Quaternary activity of the NF, represented by displaced alluvial and slope sedimentary sequences, has been found in the Norcia basin [e.g. Blumetti et al., 1990; 1993; Blumetti, 1995; Cello et al., 1998], defining a fault slip rate in the range 0.25-1.15 mm/yr [Gori et al., 2007]. Paleoseismological investigations made along synthetic and antithetic splays in the Norcia basin [Galli et al., 2005, 2018] also showed the occurrence of surface faulting events over the past millennia. Paleoseismological analyses and the damage distribution of the M_W 6.92 14th January, 1703, seismic shock defined the NF as causative of this event (Figure 2d). Indeed, evidence of surface ruptures chronologically consistent with the 1703 earthquake has been detected by trenching the fault splays in the Norcia town area. The event also activated (or determined an abrupt acceleration of movements) of deep-seated, large-scale gravitational instabilities located in the area [e.g. Blumetti et al., 1990; Blumetti, 1995; Galadini, 2006]. As for the CPFs, few preliminary geological observations support the recent activity of the fault segment [Maceroni et al., 2018]. Nonetheless, analysis of the recent movements of the CPFs and detailed mapping of the fault trace are currently lacking and activity of this structure has been suggested also by the proximity with the active fault segment in the Norcia basin.

In terms of historical seismicity [e.g. Rovida et al., 2020], the Norcia and Campi basins area and surroundings have been struck by several moderate-to-large magnitude earthquakes, probably with the highest seismicity rate of the central Apennines:

The 1st of December, 1328, M_W 6.49±0.28 earthquake struck the area north of the Norcia and Campi basins with damage estimated with Intensity (hereafter I) 10 of the Mercalli-Cancani-Sieberg (hereafter MCS) scale in Preci, Montesanto and Norcia.

The 6th of November, 1599, M_W 6.07±0.24 affected the area of Cascia, a few km W and SW of Norcia, with damage of up to 8-9 MCS.

The 14th of January, 1703, M_W 6.92±0.10 earthquake is to be considered the most significant seismic event in the study area, with damage of up to 11 MCS attributed to two localities, and widespread destruction throughout a wide area, within the Norcia basin and surroundings. The entire Norcia active faults system is considered as the causative seismogenic source of this event.

The 12th of May, 1730, M_W 6.04±0.10 earthquake caused damage concentrated mainly around Campi, estimated with I up to 9 MCS.

The 22nd of August, 1859, M_W 5.73±0.29 earthquake was responsible for damage of up to 8-9 MCS, striking the sector of the Norcia and Campi basins.

The 19th of September, 1979, M_W 5.83±0.10 seismic event caused significant damage in the southern sector of the Norcia area, between Norcia and Leonessa, with damage of up to 9 MCS.

The events with M_W<6.5 are probably related to the activation of individual segments of the NF or to minor faults in the surrounding, whereas events with M_W>6.5 (namely the 1703 one) have been determined by the rupture of the entire seismogenic structure [Galadini et al., 1999]. As for the 1328 event, specifically, the M_W of this event is likely overestimated, owing to the lack of reported damage in the far-field and considering that other large Magnitude earthquakes that struck the central Apennines during the Middle Ages have caused significant far-field damage, which would make this event an “exception” in these terms.

2.3 The Campi-Preci fault segment

The CPFs represents the northernmost branch of the NF. The trace, kinematic characteristics and recent movements of the structure are still roughly defined in the available literature. In the Geological Map of Italy, Sheet 132 “Norcia” (scale 1:100,000) (Figure 3a), there is a fault with undefined kinematics that crosses the area under investigation. The same fault is also mapped in the Geological Map of Umbria, section No. 325090 “Preci” (scale 1:10,000), but defined as a normal fault. The Geological Map of Umbria indicates that this fault is traced in correspondence to a SW-facing escarpment just W of the Acquaro village (Figure 3b). There, the fault is reported to have brought into contact different formations of the Umbria-Marche marine Meso-Cenozoic sequence: in particular, the Jurassic limestone of the “Maiolica Formation” with marly-clay Cretaceous-Cenozoic formations (Figure 4). North of Acquaro and of the SEA, the fault is mapped along an escarpment located W of the Collescille village, but with an uncertain trace, as it would be buried by landslide deposits.

According to the mentioned maps, the Sant'Eutizio Abbey would be located along the supposed fault trace. The maps indicate that the Abbey is built onto calcareous tufa, located where the fault is supposed to place into contact the aforementioned bedrock formations.

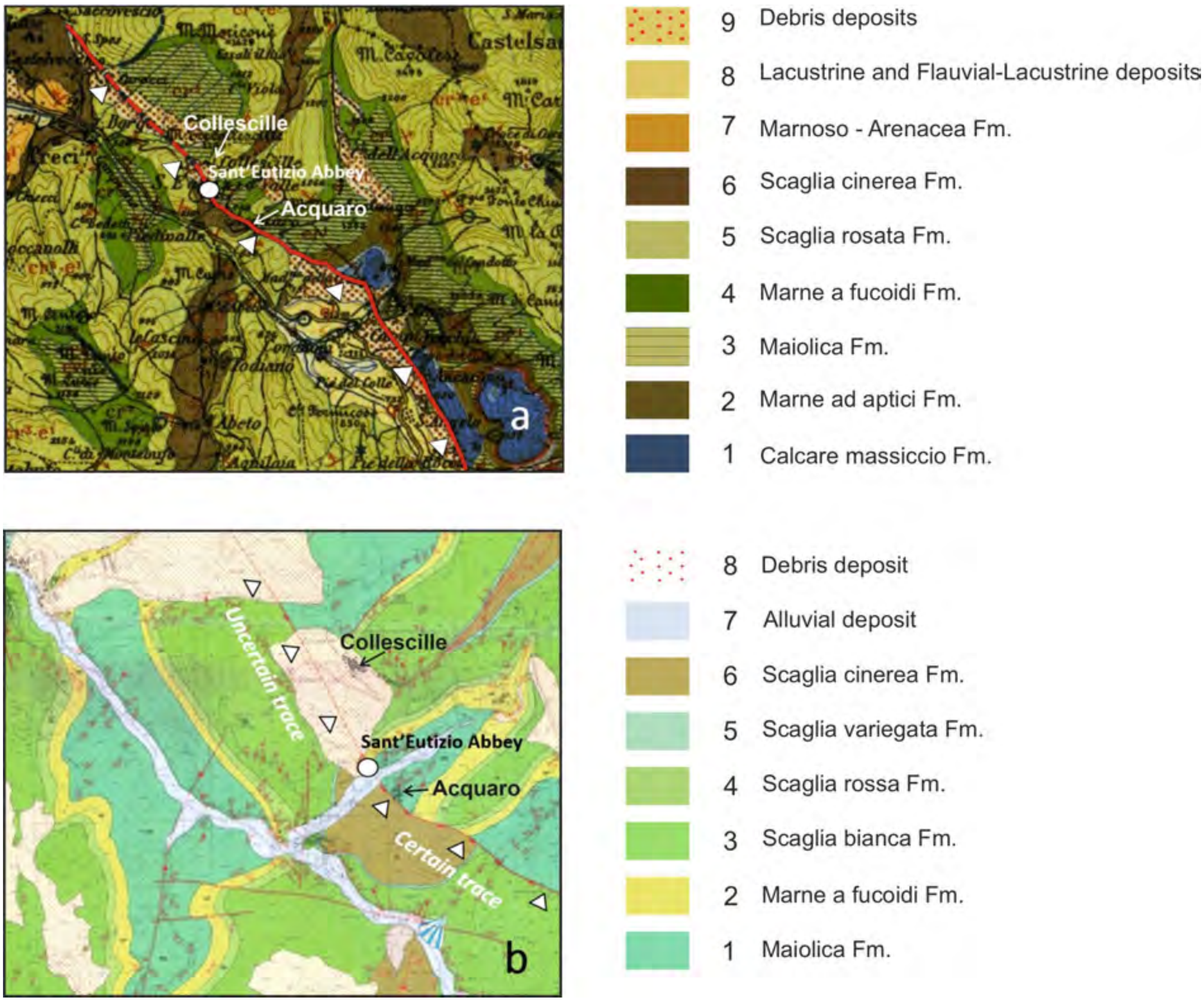

Figure 3. (a) Detail of Geological Map of Italy, Sheet 132 "Norcia" (scale 1: 100,000), where the Campi-Preci fault segment trace is marked by red line and indicated by white triangles; (b) Detail of Geological Map of Umbria, section No. 325090 "Preci" (scale 1:10,000), where the Campi-Preci fault segment trace is marked by white triangles.

The trace of a NW-SE trending and SW dipping normal fault in the SEA area is also reported in the "Geological-Technical map" of seismic microzonation studies of this area (Figure 5a). According to the Guidelines for Microzonation Studies in force in Italy [Commissione Tecnica per la Microzonazione Sismica, 2015], a fault is defined as Active and Capable if it shows evidence of activity at surface over the last 40kyr BP, whereas a fault is defined as Potentially Active and Capable if it shows evidence of activity during the Middle-Late Pleistocene, but not necessarily over the past 40kyr BP. The Geological-Technical map reports the fault in the SEA as a "Potentially Active and Capable Fault", with uncertain or presumed trace. The associated geological section that crosses the trace of the fault shows the tectonic contact between the formations of the carbonate bedrock across the supposed normal fault, but no information about the activity of this fault in recent times is shown (Figure 5b).

The traces of capable faults in the Campi and SEA areas are also reported in the database of Capable Faults of Italy (ITaly HAzard from CApable faults "ITHACA") [ITHACA Working Group, 2019] (Figure 5c), made by the Istituto Superiore per la Protezione Ambientale of Italy. In this area, indeed, the ITHACA database reports two capable fault segments, one N-S to NNW-SSE trending, affecting the slopes E and N of Campi, the other NW-SE trending, which affects the SEA area. The two structures are defined as active in the Holocene (namely defined as after

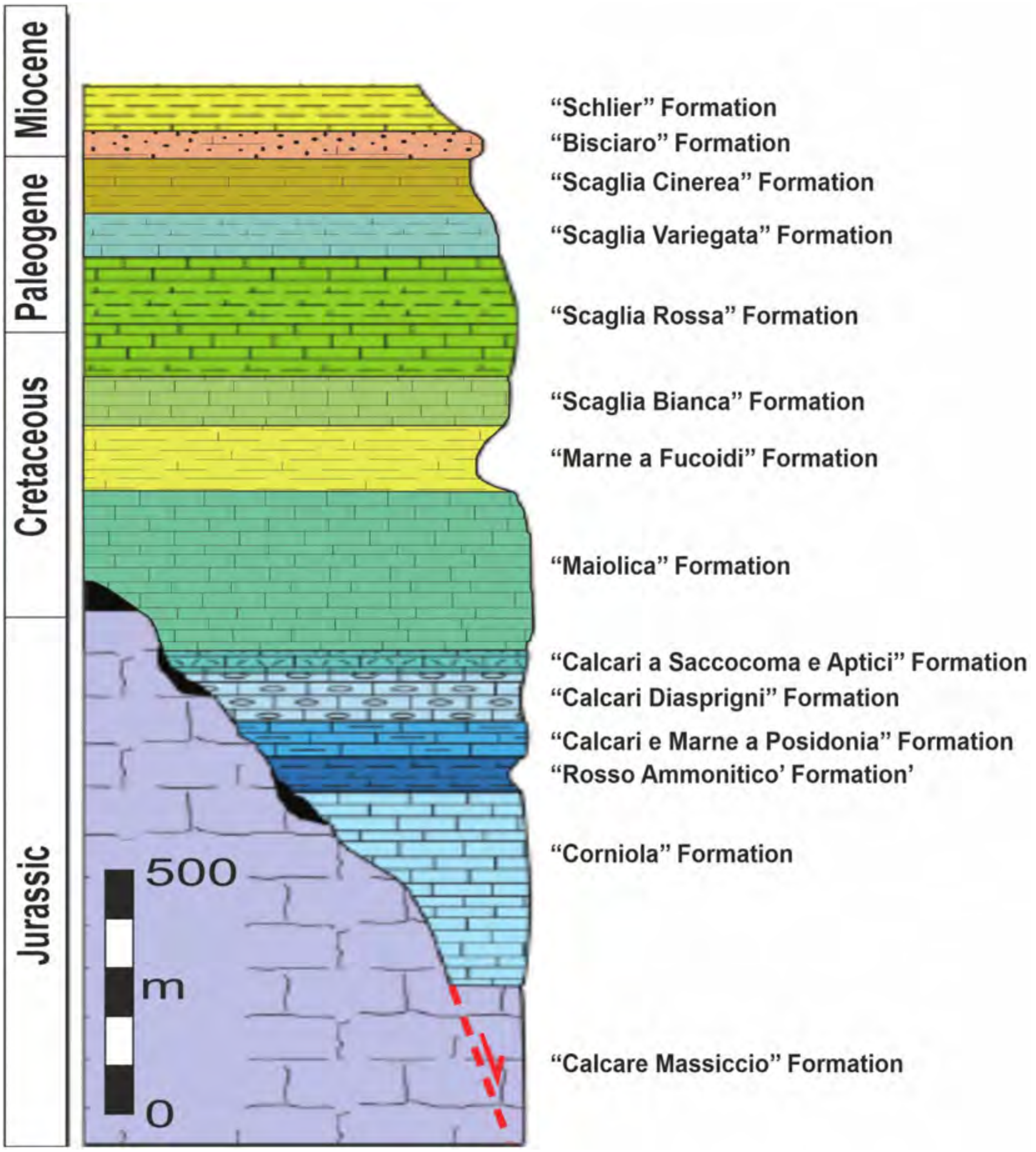

Figure 4. Simplified stratigraphic scheme of the Umbria-Marche marine Meso-Cenozoic sequence.

10kyr BP) and associated to the seismogenic structure responsible for the above-mentioned January 14, 1703, and September 19, 1979, earthquakes, likely owing to the possible structural relation with the NF. However, no direct evidence of this activation is provided for the two fault segments in the ITHACA database.

Therefore, as regards the trace of the capable fault reported in ITHACA, that affects the SEA site, it is conceivably based on a possible structural continuity with the normal faults in the Norcia basin and on potentially morphotectonic hints, represented by the presence of escarpments, supposed to be normal fault-related scarps, between the villages of Acquaro and Collescille.

Recently, in order to investigate the late Quaternary activity of the CPFs, geological field analyses have been conducted by Maceroni et al. [2019] along the eastern margin of the Campi basin. Preliminary observations revealed the presence of an extensional fault zone in a sector located some hundred metres E of the supposed trace of the CPFs, reported in the available literature. In fact, a bedrock fault plane has been identified near the Piè La Rocca (Figure 6) village and along the slopes bounding the Campi basin to the E and NE. Along the prolongation to the N of this structural feature, the shear zone affects likely late Quaternary slope deposits [Maceroni et al., 2019].

Lastly, Galli et al. [2019] indicated the CPFs as a segment of the NF. The trace of the fault reported by the authors in the SEA area is very similar to the fault trace reported in ITHACA.

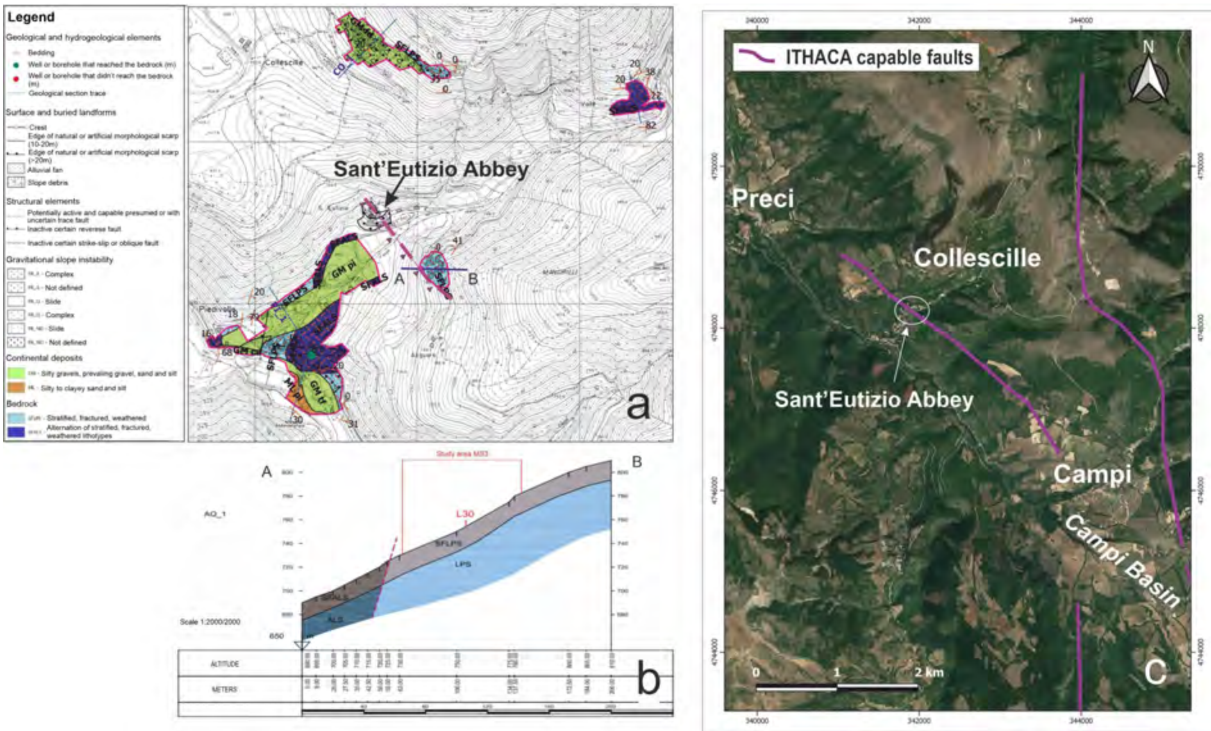

Figure 5. (a) "Geological-Technical map" of seismic microzonation study of the Sant'Eutizio Abbey area (https://www.regione.umbria.it/paesaggio-urbanistica/area-terremoto-2016/2017). The normal fault supposedly affecting the Sant'Eutizio Abbey area is marked by purple dashed line and indicated by purple triangles; (b) Geological cross-section of the Acquaro village area from seismic microzonation (blue line, cross-section trace in "a") that shows the tectonic contact between the formations of the carbonate bedrock across the supposed normal fault; (c) Map (satellite imagery) of the study area on which the traces of the capable faults reported in the ITHACA database [ITHACA Working Group, 2019] (http://sgi2.isprambiente.it/ithacaweb/viewer/) are indicated by purple lines.

3. Field observations

3.1 New geological data from the Campi-Preci active fault segment

As described above, geologic evidence of late Quaternary activity of the CPFs has been first documented by Maceroni et al. [2019]. Based on these preliminary observations, we performed field investigations, supported by aerial photographs analysis along the fault trace, in order to identify further evidence that corroborates the recent fault activity and to perform detailed mapping of its entire trace (Figure 6).

Geologic survey allowed us to identify the fault scarp (Figure 7a) in the central-southern sector of the Campi basin, i.e. a small depression located south of the SEA, in the area of the Campi village. The scarp is carved onto the limestone bedrock and the fault plane is very often exposed at its base. In the area of the Piè La Rocca locality, the fault places in contact the carbonate substratum, in the fault footwall, with slope debris, in the fault hanging wall (Figure 7a). The layers of the debris show a general attitude slightly dipping towards the basin but, approaching the fault, the deposit appears clearly dragged along its plane, and the layers get parallel to the slickenside. Minor shear planes also affect the slope debris (Figure 7b). As for the age of the faulted deposits, no direct chronological constraints have been found to date. Nonetheless, the fact that the debris attitude refers to a slope very similar to the present one (that is, the layers become progressively sub-horizontal approaching the Campi basin bottom) and its lithological features (i.e. almost loose carbonate clasts in a coarse sandy yellowish-brownish matrix) suggest a late Quaternary age (likely referable to the "éboulis ordonné", related to Late Pleistocene-Holocene) [Coltorti & Dramis, 1988].

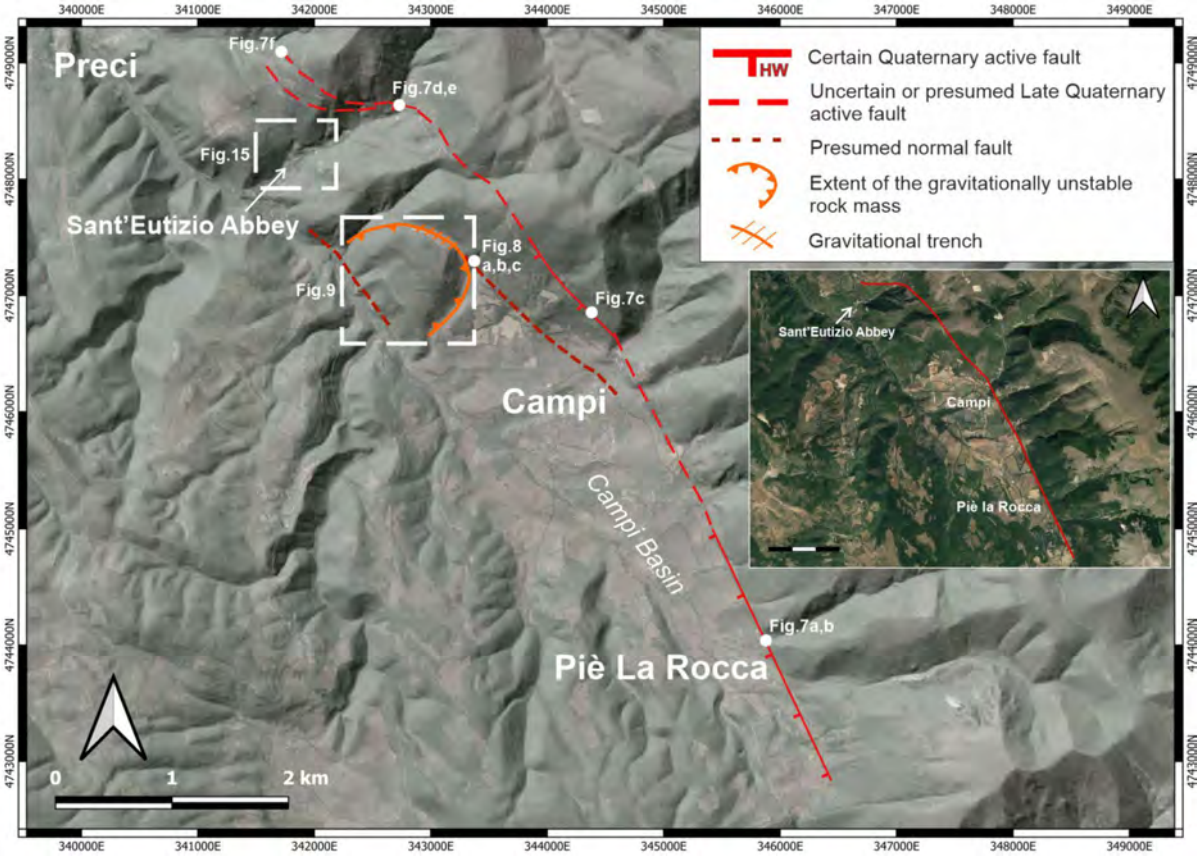

Figure 6. Hill-shade digital terrain model and satellite image of the study area showing main geomorphic and morphotectonic elements that affect the Sant'Eutizio Abbey area and the Campi basin. The inset shows the Campi-Preci fault traced by Maceroni et al. [2019]. The red short lines indicate the hangingwall of the Campi-Preci fault in the present study.

Moving toward the NNW, the bedrock fault plane is clearly visible along the basal portion of the slope (Figure 7c). Further to the NNW, the shear zone related to the CPFs reaches the zone described by Maceroni et al. [2019], where further displaced slope debris has been seen (Figure 7d, e). Considering the shear zone orientation described above and the presence of some bedrock fault planes trending roughly E-W (N 110°) (Figure 7f) north of Collescille, it is possible to hypothesize a fault trace roughly parallel to the slope on which the Collescille is located.

In the Campi basin area we found further slope debris affected by shear planes, showing extensional sense of motion (Figure 8a, b, c,). Noteworthy, they did not occur along the trace of the CPFs but in the central-southern sector of a NW-SE trending small trough, that affects the slopes bounding the Campi basin to the north. These slope debris are similar by lithology and sedimentological characteristics to those described by Maceroni et al. [2019], thus suggesting a late Quaternary age. Importantly, as described above, the displaced debris occurred within a small trough.

This feature occurs on top of a large portion of the carbonate slope characterised by a bulged morphology at its toe and bounded to the NW and SE by stream incisions having curvilinear pattern in plan view. These geomorphic characteristics suggest that the trough locates on top of a large-scale gravitation mass movement, whose formation is probably to relate to the increase of the local relief caused by the stream incision located at the base of the slopes in this area (Figure 9).

As a result, the shear planes affecting the slope debris at the border of the gravitational trench may represent the evidence of recent movements of the large-scale gravitational mass movement. Further elements that support this interpretation will be provide below, in terms of tectonic features located north of the gravitational trench, in the SEA area. Our observations indicate that the mass movement does not reach the SEA area but represents, however, a further element of surface instability in the area.

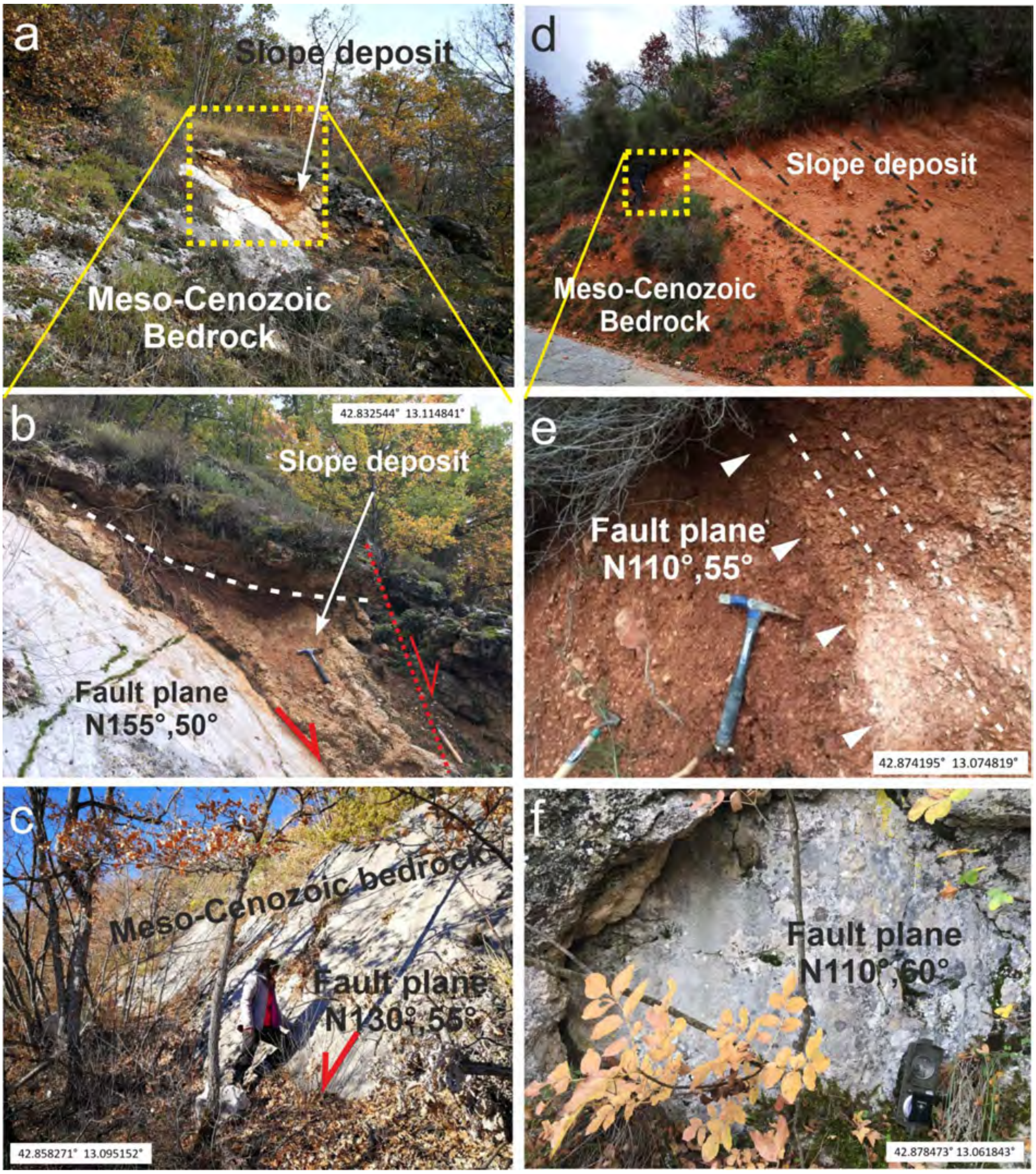

Figure 7. (a) Tectonic contact between meso-cenozoic bedrock and slope deposits; (b) Close-up image of "a" showing the main and secondary shear planes (indicated by the red dashed line) affecting the slope deposits. Dragging of the slope deposits along the fault plane is indicated by the white dashed line; (c) Slickenside outcropping at the base of the fault scarp seen North of the Campi village; (d) Tectonic contact between meso-cenozoic bedrock and probably Late Pleistocene slope deposits [modified from Maceroni et al., 2019] owing to normal fault activity; the black dashed lines represent the attitude of the displaced slope deposits; (e) Detail of the shear zone in "d"; the white triangles mark a shear plane that affects the slope deposits; the white dashed lines mark secondary shear planes that affect the slope deposits. (f) Bedrock fault plane outcropping at North of Collescille.

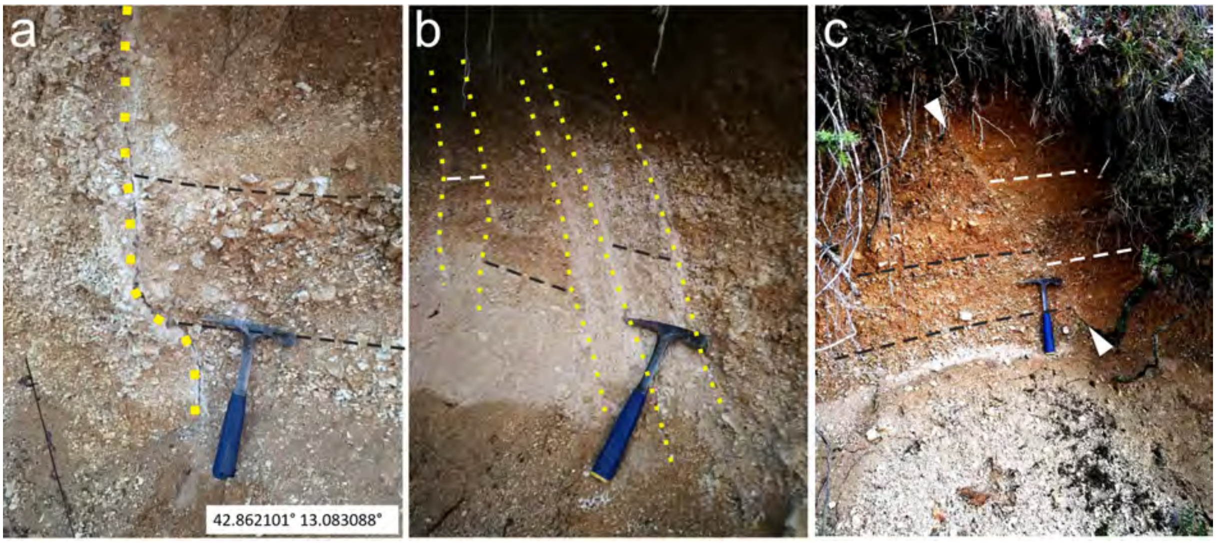

Figure 8. (a) Shear plane (marked by yellow dotted line) affecting probably Late Pleistocene-Holocene slope deposits (attitude is marked by black dashed lines) along the gravitational trench. (b) Shear planes (marked by yellow dotted line) affecting probably Late Pleistocene-Holocene slope deposits (attitude is marked by black and white lines) along the gravitational trench. (c) Shear plane (indicated by white triangles) affecting probably Late Pleistocene-Holocene slope deposits (attitude is marked by black and white lines).

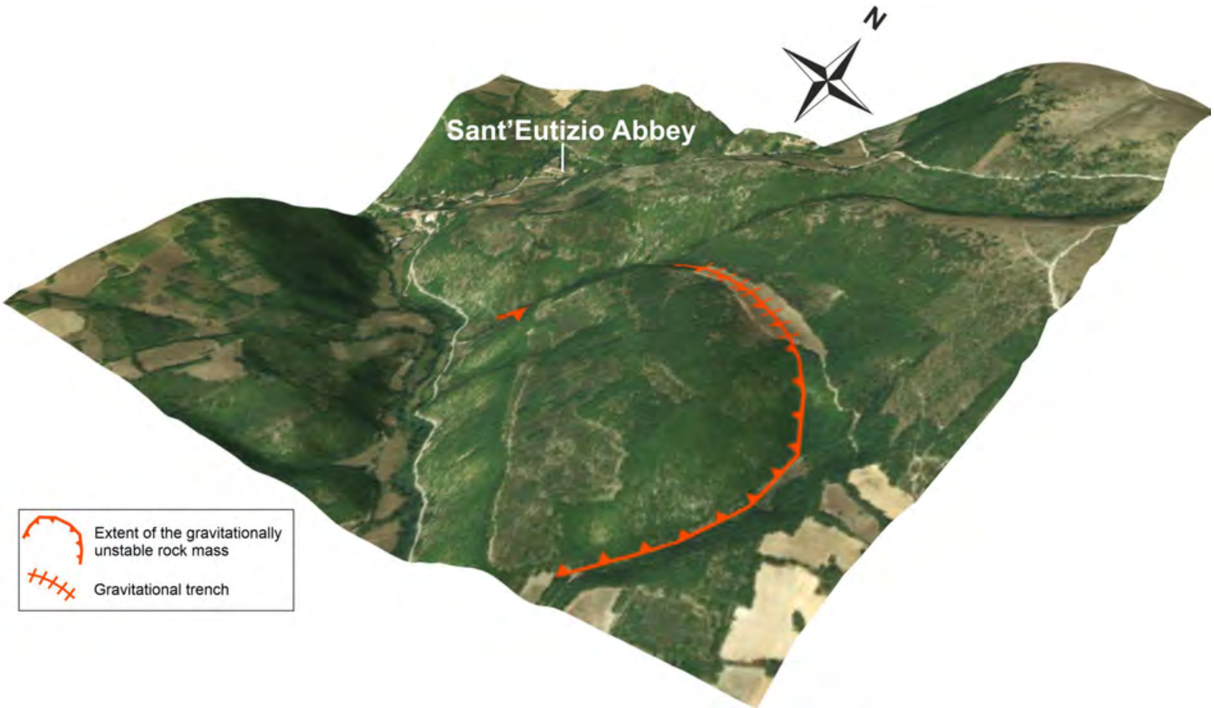

Figure 9. Satellite image (from Google Earth) in perspective view (towards the North) that shows the gravitationally unstable rock mass located SE of Piedivalle; the gravitational trench seen on top of the large-scale mass movement is coincident with limit of gravitationally unstable rock mass.

3.2 Investigating the previously mapped Campi-Preci fault branch in the Sant'Eutizio Abbey area

Considering the above-described evidence of displacement of slope deposits along the fault branch, likely late Quaternary in age, we investigated in more detail the fault branch supposed to cross the area of the SEA and reported in literature. Particularly, we carried out geologic field surveys along the supposed fault scarp in order to verify the presence of structural features relatable to an extensional shear zone and, if so, to identify evidence of recent activity. Our observations revealed that just north of SEA, along the scarp, the Jurassic limestone "Maiolica Formation" crops out, in the footwall of the supposed fault as reported in the available geological maps and scientific literature. However, the limestone displays deformation relatable to compressive tectonics, represented by overturned and recumbent folds, with almost sub-horizontal axial planes, verging towards the W and SW (Figure 10a, b; the attitude of the bedrock layers, fold limbs, fold axis and all of the other structural data refers to Right Hand Rule notation, henceforth RHR). In correspondence with the supposed extensional shear zone, the "Maiolica Formation" is intensely deformed, showing tight folds and being affected by reverse shear planes; moreover, it overthrusted the Jurassic marly "Marne a Fucoidi Formation" (Figure 10c, d). No evidence of extensional deformation is seen here, neither cutting nor inverting the compression-related structures.

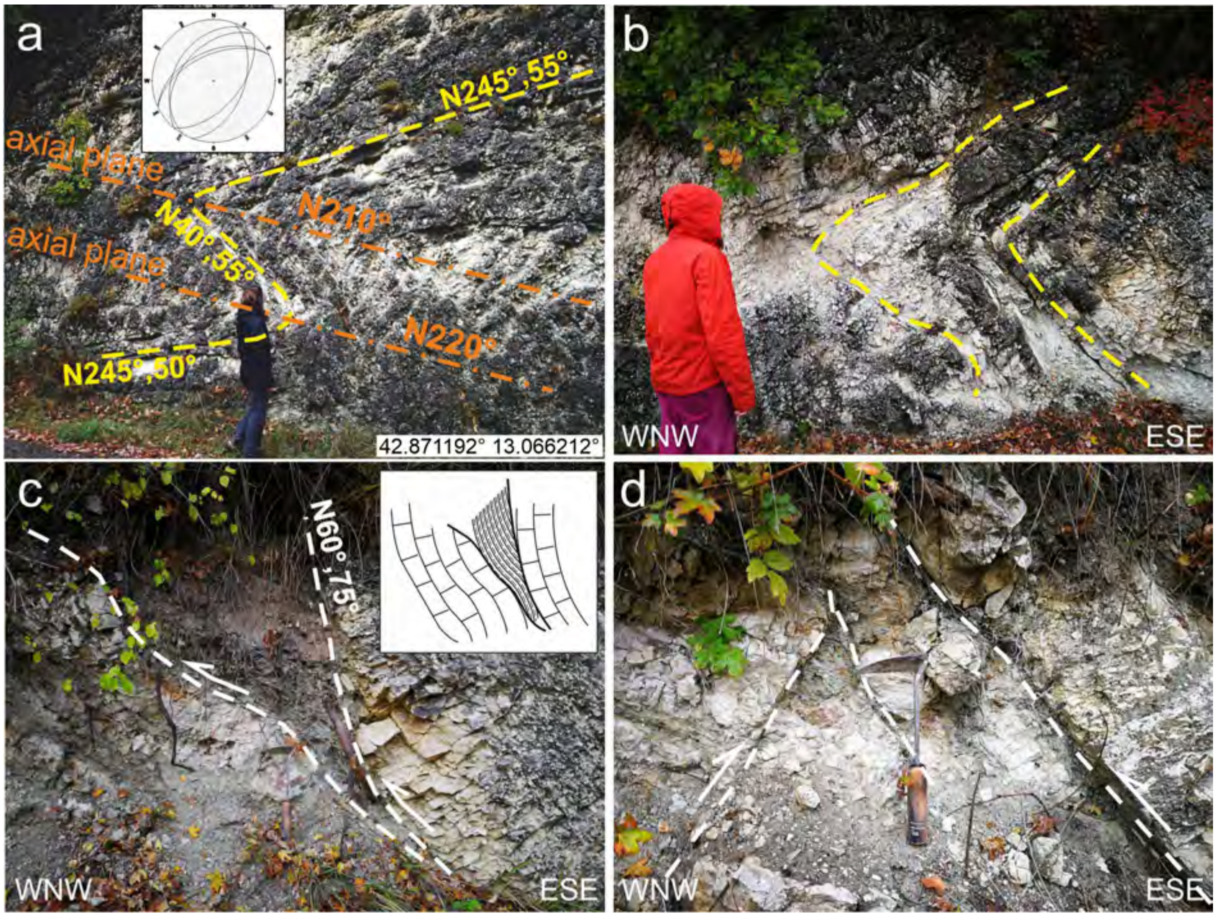

Figure 10. (a) Overturned and recumbent folds with almost sub-horizontal axial planes, verging towards the W and SW, that affects the Jurassic limestone "Maiolica Formation" outcropping North of Sant'Eutizio Abbey. The fold limbs are marked by yellow dashed line (the structural data of the fold limbs are represented by the stereoplot in inset of "a"), whereas the fold axial planes are marked with orange dash-dot lines; the attitude of the fold limbs and of the axial planes are also reported; (b) Evidence of chevron recumbent fold (the limbs are marked with the yellow line) outcropping North of the Sant'Eutizio Abbey; (c) and (d) Inverse shear planes (marked by white dashed lines) affecting the "Maiolica Formation", with a scheme of the meso-scale structural setting (in inset of "c").

Moving further to the W and SW, the Cenozoic marly-clayey "Scaglia Cinerea Formation" crops out, thus placed in lateral contact with the Jurassic formations. The described deformation features suggest that the contact between the Jurassic and Cenozoic bedrock formations is not ascribable to extensional lowering of the younger formations, but to rising of the older ones, owing to a reverse shear zone.

Few tens of metres to the S, in the western margin of the SEA area, further evidence of compressive deformation of the bedrock formations are seen. Here, the "Scaglia Cinerea Formation" displays an almost horizontal attitude, trending N200°. Some low angle shear planes affect the formation, showing slickenlines and calcite fibers compatible with compressive shear. Slickenlines and calcite fibers have been also seen in between some layers of the "Scaglia Cinerea Formation", conceivably resulting from shearing and flexural folding (Figure 11) [see e.g. Perrit and Roberts, 2007, on the issue].

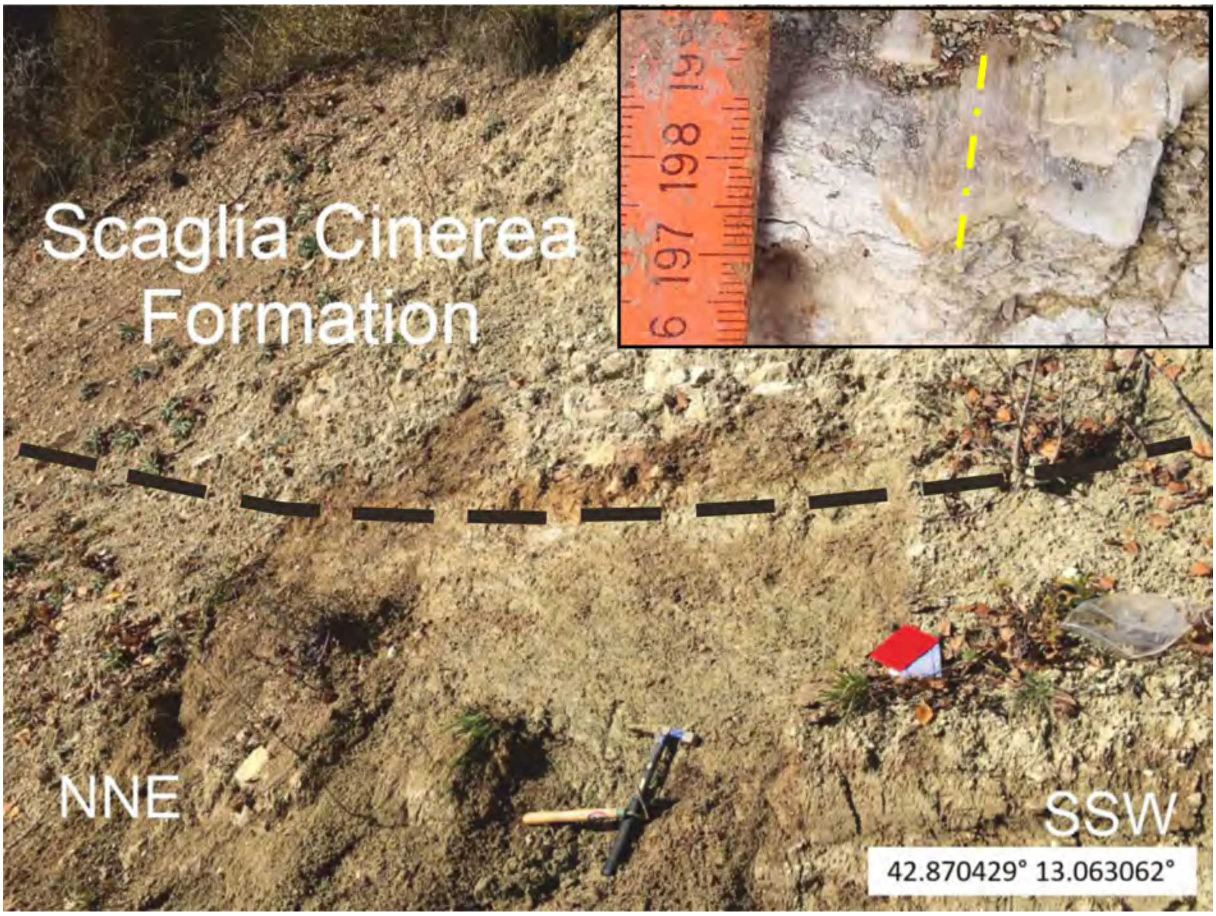

Figure 11. "Scaglia Cinerea Formation" outcropping in the western margin of Sant'Eutizio Abbey; the sub-horizontal attitude is marked by the black dashed line. The inset shows a detail of slickenlines (the direction is marked by the yellow dashed-dot line) and calcite fibers resulting from shearing and flexural folding.

Moving to the N and NE, at the NE edge of the SEA (Figure 12a, b), vertical-to-subvertical shear planes, with E-W to NE-SW trend (N100°, N68°, N70°, N54°) affect the "Scaglia Cinerea Formation" (Figure 12c, d, e). Sub-horizontal slickenlines (10° pitch angle) and calcite fibers have been observed along these shear planes (Figure 12f), testifying to dextral strike-slip kinematics. These features can represent minor tear faults that allowed differential motion of portions of the compressive shear zone. Indeed, the contact between the "Maiolica Formation" and the "Scaglia Cinerea Formation" underneath the SEA seems to occur more to the W, i.e. right-laterally dislocated, with respect to the above described site (Figure 10).

Within this light, four boreholes drilled within the SEA site and the bedrock outcropping just E of the Abbey (Figure 13a) show that the Abbey is located onto the bedrock pertaining to the "Maiolica Formation" and to the "Marne a Fucoidi Formation". In particular, S1, S3 and S4 boreholes (Figure 13b) crossed the deposits related to the

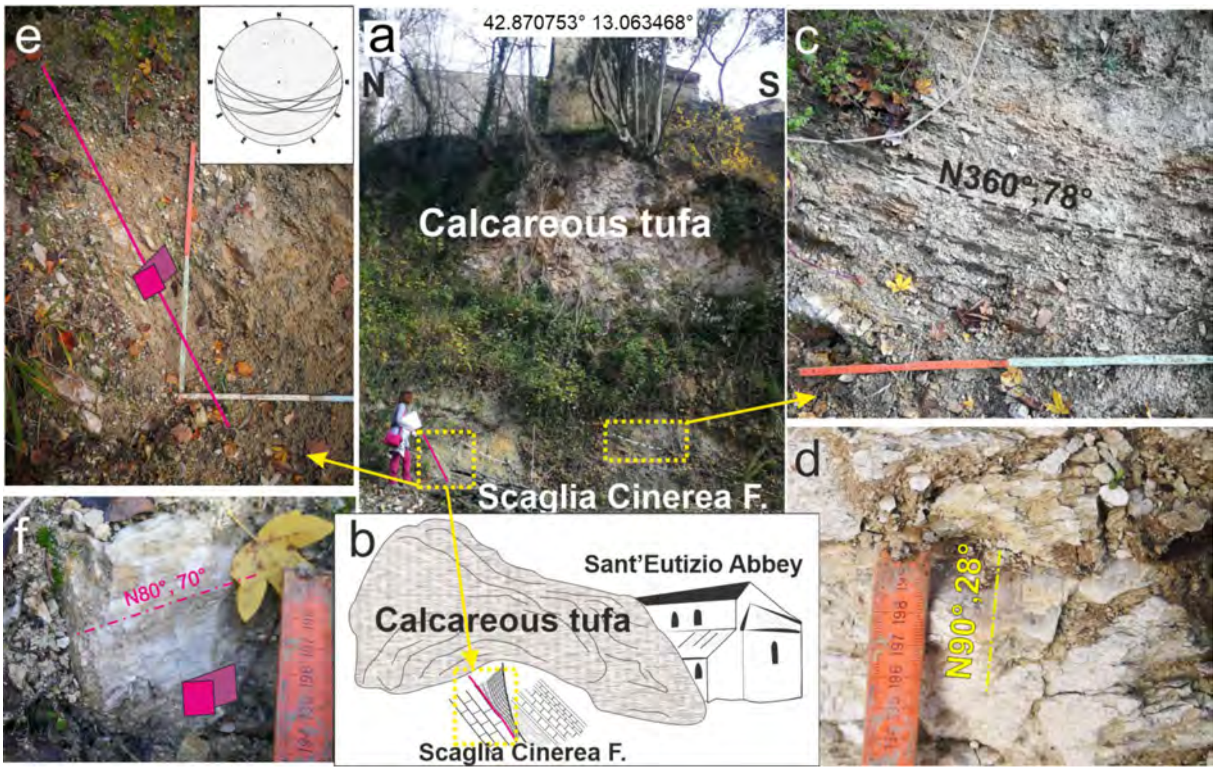

Figure 12. (a) Photograph of the northern sector of the Sant'Eutizio Abbey (view to the East) showing the overlap of calcareous tufa onto Cenozoic marly-clay of the "Scaglia Cinerea Formation", whose attitude is marked by white dashed lines; the red line marks the strike-slip fault showed in "e". (b) Morpho-stratigraphic scheme of "a". (c) Detail of the "Scaglia Cinerea Formation"; the attitude is marked by the black dashed line. (d) Close-up photograph of the "Scaglia Cinerea Formation" affected by a reverse very low dip angle shear plane; the slickenlines observed along calcite steps occurring on the reverse shear plane are marked by the yellow dash-dot line. (e) Close-up view of the high angle shear zone (indicated by the red line), that refers to the yellow dashed box in a, affecting the "Scaglia Cinerea Formation", associated with a strike-slip tectonic structure; the pink arrow indicates the sense of motion. The inset shows the stereoplot of the shear planes affecting the "Scaglia Cinerea Formation". (f) Slickenlines in calcite steps (the direction is marked by the pink dash-dot line) observed along one of the high angle shear planes associated with the strike-slip fault; the pink arrow indicates the sense of motion.

calcareous tufa, outcropping in the Abbey site to the E, and reached down to the "Maiolica Formation" bedrock. The limestone was found at depth ranging between 6-7 m depth in S1, to about 9-10 m depth in S3 and to 12-13 m depth in S4. This describes a basal contact surface with the overlying calcareous tufa that gently dips towards the S, with no evidence of displacement. Borehole S2, instead, found marly-clayey bedrock underneath the calcareous tufa, represented by the "Marne a Fucoidi Formation". Hence, the lateral contact between the "Maiolica Formation"-"Marne a Fucoidi Formation" and the "Scaglia Cinerea Formation" occurs in the westernmost sector of the Abbey area.

To the S and SE of the SEA, further evidence of compressive deformation is seen along the scarp of the supposed extensional fault, at the base of the slope onto which the Acquaro village is located. Here, indeed, in the hanging wall of the supposed extensional fault, the "Maiolica Formation" is affected by overturned and recumbent folds verging towards the W and SW (Figure 14a), similarly to those observed N of the SEA, and by a reverse fault plane verging W- and SW-ward at the base of the scarp (Figure 14b). Again, the "Scaglia Cinerea Formation" crops out W of the reverse shear zone. No evidence of extensional features, that might have cut or invert the compressive structures, has been seen also in the area. Therefore, comparably to what described above, this suggests that the lateral contact between the "Maiolica Formation" and the "Scaglia Cinerea Formation" is likely to relate to a W- and SW-verging reverse shear zone.

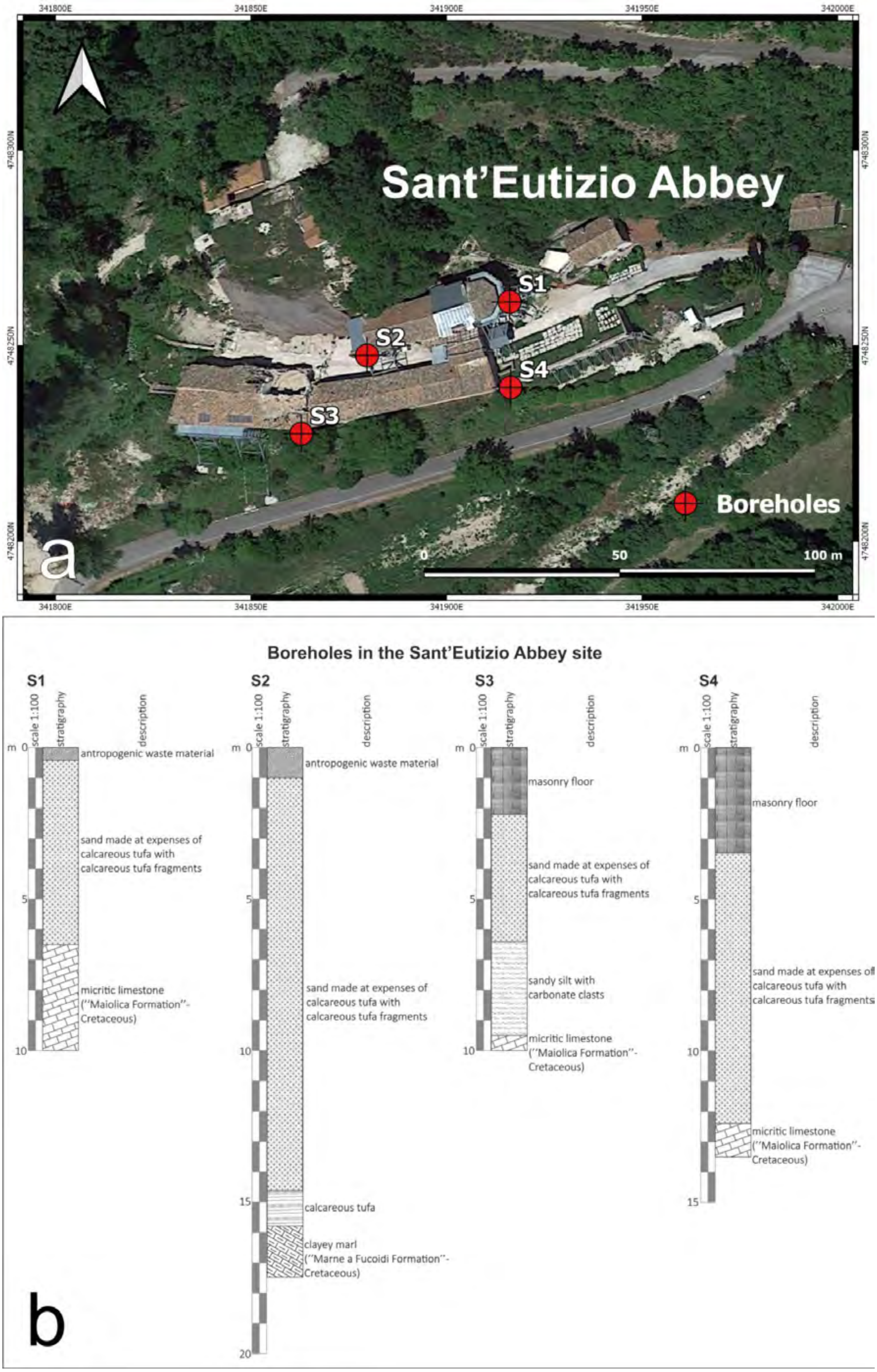

Figure 13. (a) Satellite image (in plan view) of the Sant'Eutizio Abbey area where the four boreholes described in the text are located. (b) Stratigraphy sequence observed in the four boreholes.

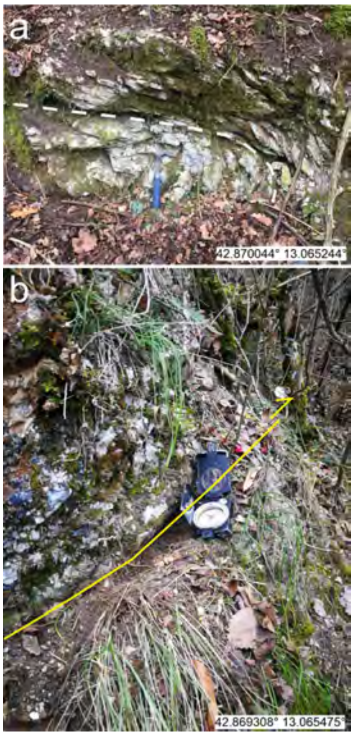

Figure 14. (a) Fold (marked by the white dashed line) affecting the "Maiolica Formation". (b) West-verging reverse shear plane, (indicated with the yellow line) affecting the "Maiolica Formation"; the arrow indicates the sense of motion.

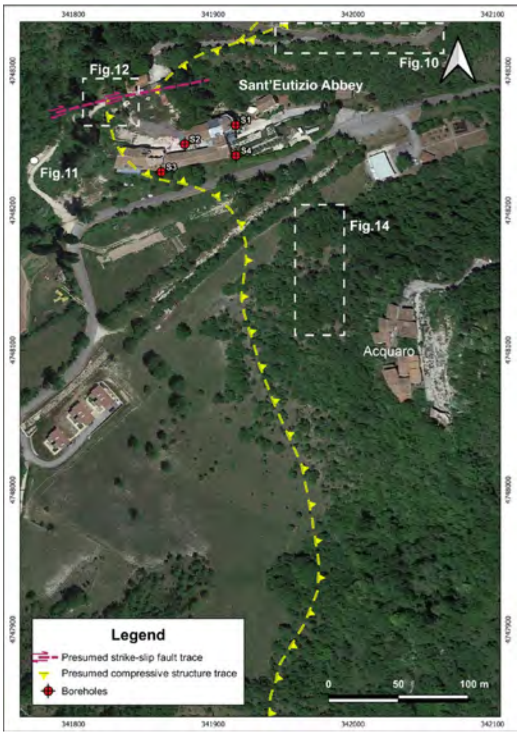

Figure 15. Satellite image (in plan view) of the Sant'Eutizio Abbey area on which the hypothesised thrust front trace (marked by the yellow dashed line) is shown; the yellow triangles represent the hanging wall of the compressive structure. The purple dashed line marks the strike-slip fault trace that locally displaced the compressive structure.

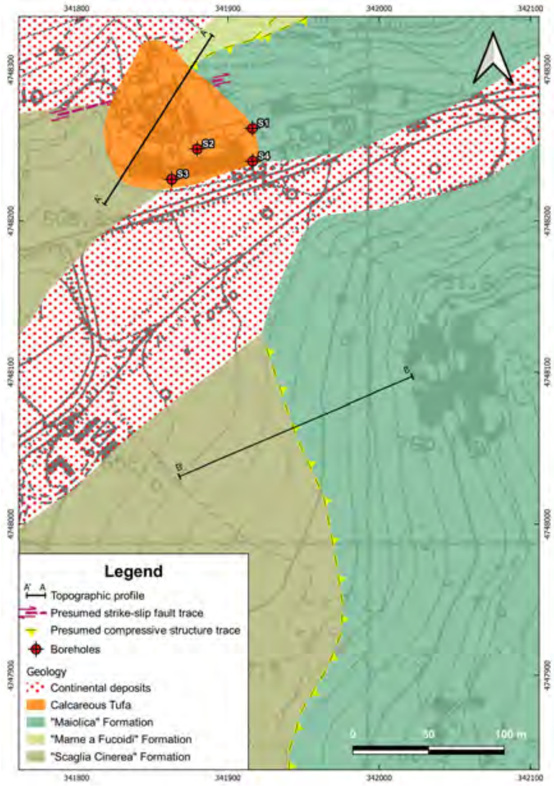

Figure 16. Geological Map (modified from Geological Map of Umbria, section No. 325090 "Preci") of the Sant'Eutizio Abbey area, that displays the tectonic contact between "Maiolica Formation" and "Scaglia Cinerea Formation" due to the identified compressive structure.

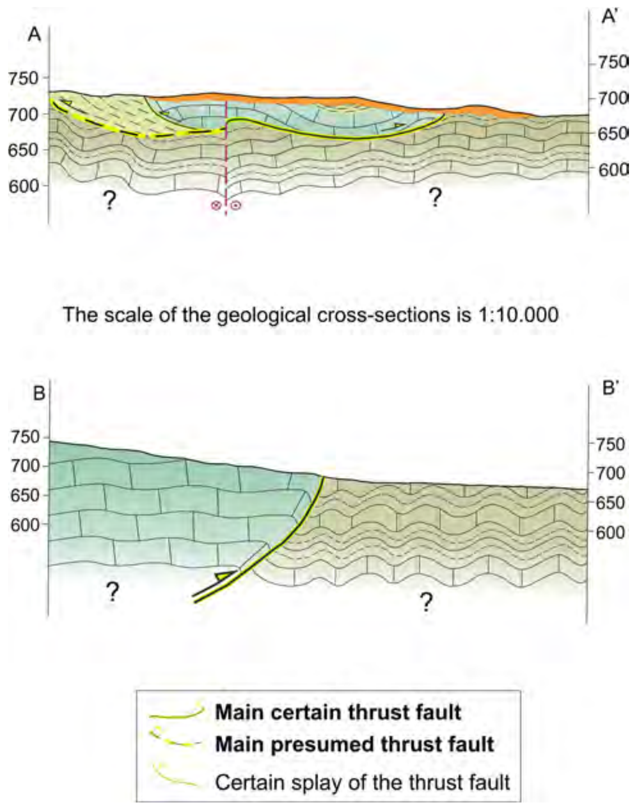

Figure 17. Geological cross-sections in the SEA area, that refer to topographic profiles in Figure 16.

As a whole, the described pieces of evidence strongly suggest that, in the SEA area, are likely ascribable to a reverse shear zone, with the older formations of the bedrock overthrusted onto the younger ones (Figures 15, 16 and 17). This corroborates the observations that the branch of the CPFs does not affect the SEA area but it is located more to the E.

3.3 Trench analysis in the Sant'Eutizio Abbey site

Based on the above observations, we carried more detailed analysis in the Abbey site, by performing an excavation all along the building area, to explore the possible presence of a shear zone (supposedly extensional) right underneath the historical edifice. The trench, about 120 m long, 2 metres deep and large, has been dug about NE-SW trending, that is, perpendicular to the supposed fault trace (Figure 18). The excavation exposed a sedimentary sequence made of colluvial and alluvial sedimentary units, derived from the erosional and depositional processes within the valley adjacent to the Abbey (Figure 19) (Figures S1-S15 as supplementary material).

Figure 18. Drone-derived orthophoto of the Sant'Eutizio Abbey area. The yellow dashed rectangle represents the trenching area.

Figure 19. Photomosaic of the central part of the northern wall of the paleoseismological trench.

We distinguished four main sedimentary units, here described from the lowermost one (the older unit exposed by the trench) to the uppermost one.

Unit 4: clast-supported alluvial gravel, made of cm-size to decimeter-size sub-rounded carbonate pebbles, sub-horizontally layered, slightly dipping SE-ward. Locally channel-type structures are present. The overall sedimentological characteristics of the unit suggest mixed alluvial and debris flow-type deposition. The gravel contained abundant pottery fragments, brick and tiles fragments and shards (Figure 20a).

Unit 3: it unconformably overlaid Unit 4 through an erosional surface gently dipping towards the SW. The sedimentological features of Unit 3 are very similar to Unit 4. It consists in layered alluvial gravel, made of cm-size to decimeter-size sub-rounded carbonate pebbles, with almost sub-horizontal attitude gently dipping SW-ward. A large number of pottery fragments, brick and tiles fragments and shards have been found within the unit.

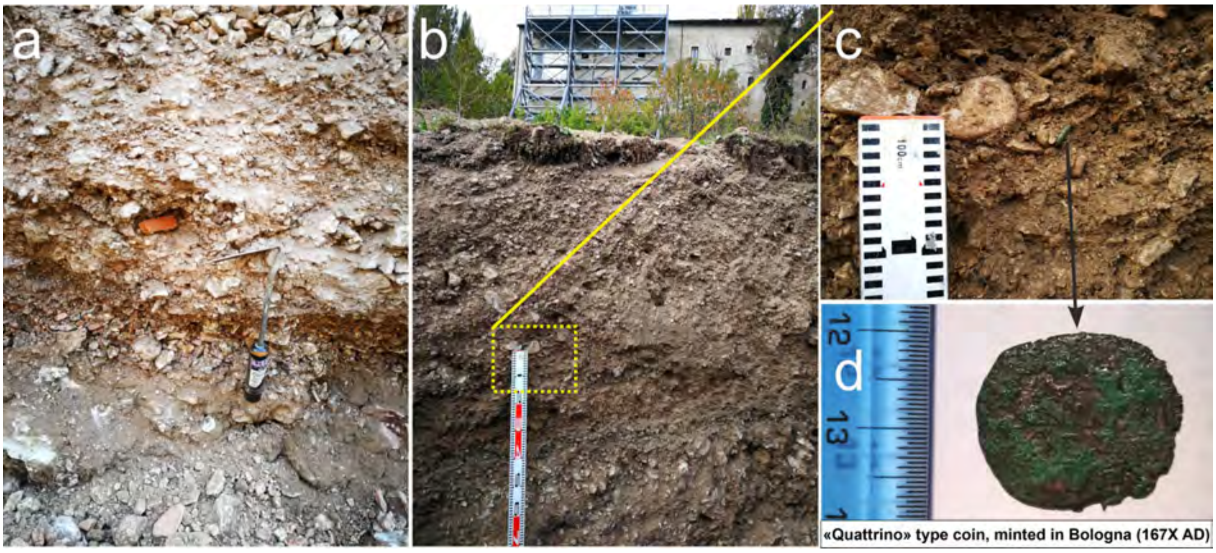

Figure 20. (a) Photograph detail of Unit 4 showing a tile or brick fragment (indicated by the yellow arrow) embedded within the carbonate gravel. (b) Section of Unit 1 in which the coin, shown in "c" and "d" was found. (c) and (d) Detail of the "Quattrino" coin found within Unit 1.

Unit 2: it consists in a thin silty-clayey brownish layer that showed an almost constant thickness (about 5-10 cm), not affected by erosional surfaces, overlying the lower units. Abundant charcoal fragments were found with the unit, the largest ones have been collected for radiocarbon dating (three samples), and gave ages very similar to each other, i.e. 1404-1450 cal. A.D. (radiocarbon age 490±30 BP), 1426-1516 cal. A.D. (radiocarbon age 420±30 BP) and 1445-1524 cal. A.D. (radiocarbon age 380±30 BP). The sedimentological characteristics, the abundance of charcoals, the relation with the underlying units and the constant thickness suggest that Unit 2 resulted from incipient pedogenic process affecting alluvial deposits.

Unit 1: it represents a colluvial-alluvial deposit. Towards the SW, it consisted of a colluvial body, made of angular, up-to-cm size carbonate clasts in a sandy matrix, containing abundant pottery fragments, and showing an overall sub-horizontal attitude. A coin has been found in the uppermost portion of the unit (Figure 20b, c, d). It has been archaeologically determined as a "Quattrino" type coin, minted in Bologna (northern Italy) during the seventies of the 17th century AD. (i.e. 167x AD). Towards the NE, the colluvial deposits graded into alluvial sediment that showed sub-rounded carbonate pebbles and channel-type structures.

In terms of possible occurrence of tectonic deformation, the analysis of the trench walls revealed no shear planes displacing the exposed units, which appeared laterally continuous, not being affected by any discontinuity attributable to faulting (Figure 21).

Moreover, the attitude of the units is consistent with primary sedimentary layering, that is, they units did not appear tilted or locally bent owing the movements of any local tectonic structure. The sole discontinuities in the stratigraphic succession were represented by erosional surfaces or by very local recent man-made excavations (and fill). The calcareous tufa onto which the SEA is partly built does not seem to be affected by any tectonic deformation as well.

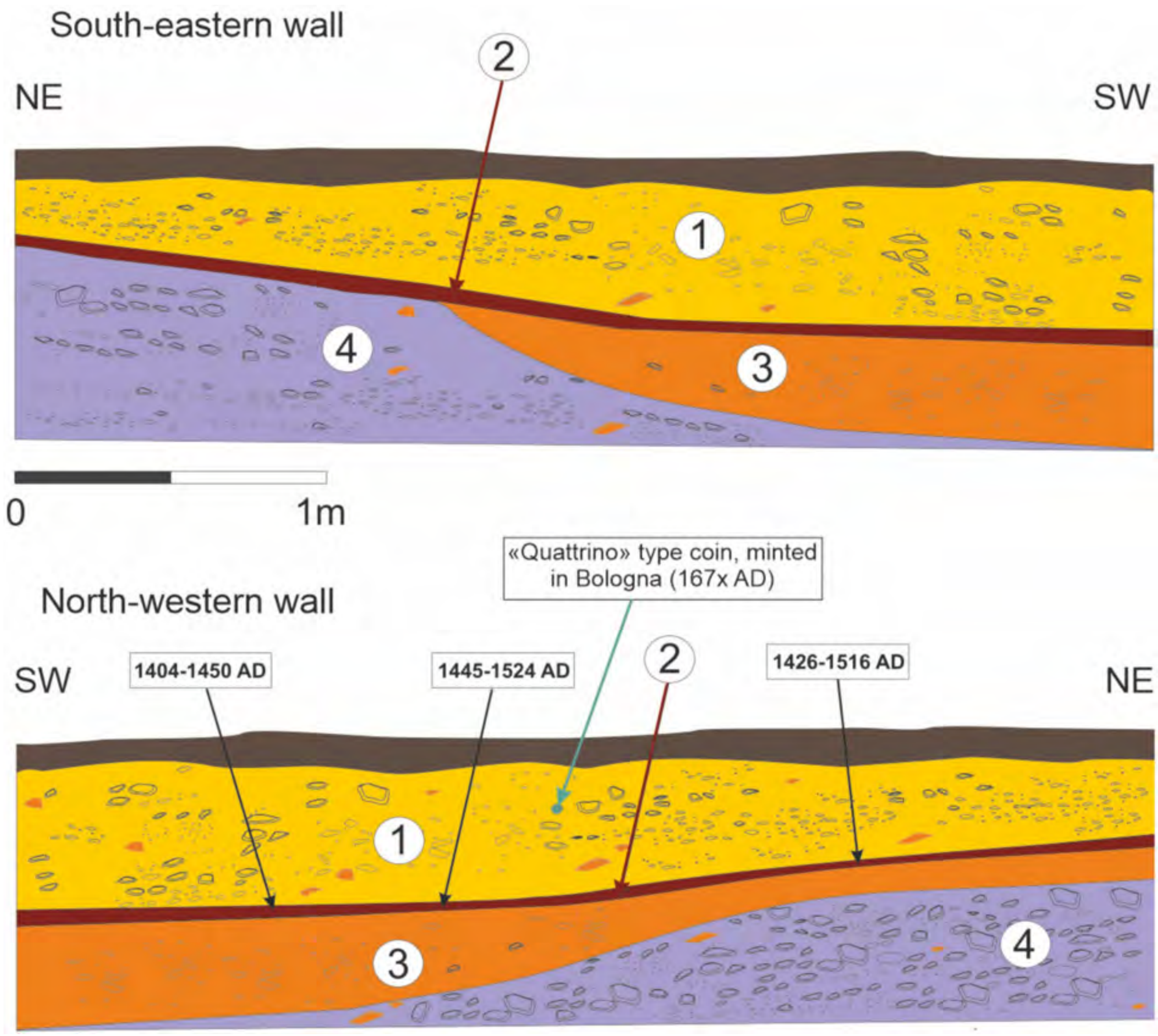

Figure 21. Stratigraphic schemes of the paleoseismological trench walls. The numbers indicate the stratigraphic units identified; the black arrows indicate the location of the charcoal fragments found within the stratigraphic units and collected for radiocarbon age determination; the obtained ages are indicated.

Hence, no evidence of recent normal faulting appears in the SEA area. The only tectonic feature of the Abbey site relates to the described compressive deformation that only affects the carbonate bedrock. It must be underlined that the compressive tectonic phase was active in this portion of the Apennines up to the Pliocene and then it became inactive. In this framework, the observed W- and SW-verging reverse shear zone is likely to be considered as an inactive back-thrust.

4. Discussion

4.1 Tracing the Campi-Preci fault segment

Field surveys carried out along the CPFs permitted us to identify new evidence of recent activity of the fault, confirming the preliminary observations made by Maceroni et al. [2019]. The morpho-stratigraphic relation with the present slopes and the sedimentological characteristics of the detected faulted deposits suggest that they can be likely referred to the slope deposits widespread in the Apennines and related to the Late Pleistocene, conceivably to the Last Glacial Maximum [Coltorti and Dramis, 1995]. Therefore, it implies that the CPFs can be considered as active and capable, according 1) to the Guidelines for microzonation studies in Italy, made by the National Department of Civil Protection in 2008, that define the last 40kyr as the time interval in which a fault has to show (or has not to show) evidence of repeated faulting to be considered as active and capable (or inactive, on the contrary), and 2) to Galadini et al. [2012] who define a fault as active and capable if it shows evidence of activity after the Middle Pleistocene, unless the fault is sealed by deposits or landforms younger than the Last Glacial Maximum (25-15 ka).

Moreover, the fact that the fault branch occurs along the northern prolongation of the active fault strands that affect the Norcia basin, to the SE, and the very close spacing between these structures corroborates (as hypothesised by other authors) that the CPFs is part of the major active NF system. In light of this, considering that the NF activated (and ruptured the ground surface) during the M_W 6.9, 14th of January 1703 seismic shock, the activation of the CPFs during this seismic event, together with all of the other strands of the earthquake fault, is likely, as well as the probable occurrence of surface faulting along the CPFs trace during the earthquake.

As far as the presence of the CPFs in the SEA area is concerned, geological-structural field observations indicate that the structure affects a sector located some hundred metres far from the Abbey to the E. Moreover, investigations made along the supposed trace of the CPFs, as mapped in previous works, revealed that the lateral contact between different formations of the carbonate bedrock is likely to relate to a compressive tectonic structure (a back-thrust related to the E-verging Sibillini Mts. thrust front) [e.g. Cosentino et al., 2010] presently inactive (associated to pre-Quaternary compressive tectonic regime). This back-thrust placed the older “Maiolica Formation” on the younger “Scaglia Cinerea Formation”. This setting can be also responsible for the presence of the W-facing scarp along the slopes, supposed to be normal fault-related by previous works. As a matter of fact, our observations suggest that the scarp may simply result from different erodibility (i.e. differential erosion) of the laterally juxtaposed formations of the bedrock, being the marly-clayey “Scaglia Cinerea Formation” more erodible than the limestone “Maiolica Formation”, located at the footwall and hanging wall of the back-thrust, respectively.

The identification of the thrust and the absence of any normal fault in the SEA area corroborate our interpretation of the origin of the shear planes seen just south of the Abbey, affecting late Quaternary slope debris and related to the movement of a gravitationally unstable rock mass located just north of the Campi basin. The distance from the trace of the CPFs and, as described above, the presence of the inactive compressive tectonic structure and the absence of normal faults along the prolongation towards the NE of the shear planes permit to likely associate these features to the movement of the gravitationally unstable rock mass.

4.2 Assessing surface faulting in the Sant’Eutizio Abbey site

As described in paragraph 3.3, no evidence of tectonic displacements has been found within the trench excavated next to the Abbey site. Nonetheless, some considerations must be made based on the chrono-stratigraphic elements we found within the exposed units.

In detail, dating obtained by means of 14C method applied on charcoals and numismatic determination of the coin define a very recent age for the trenched sedimentary units. In particular, Unit 2 deposited during and after the 15th-16th century and Unit 1 after the 17th century. The chronological constraints and the sedimentological characteristics suggest units deposition as the response to climatic oscillations that characterised the so-called “Little Ice Age”, which took place during the 16th-19th century. In particular, according to Giraudi [2005], the late Holocene continental stratigraphy of the Apennines is characterised by alternating soils and alluvial, colluvial, and periglacial deposits, associated to climatic oscillation occurred during this period, that the author distinguished into two subsequent phases. The first and older phase refers to glacial advance, reduction of vegetation on mountain slopes and onset of periglacial geomorphic processes. This determined the onset of slope debris production and transportation, with large amounts of surficial waters. The second phase relates to glacial retreat, temperature increase and consequent development of soils.

The first phase is sedimentologically and chronologically consistent with Units 3 and 4. Specifically, the clast-supported texture and the high-energy sedimentation (i.e. debris flow) that characterise these units suggest deposition when the feeding stream was strongly active and efficient in terms of clast transportation. The presence of brick and tile shards within these units is indicative of a very recent age of deposition, compatible with the Little Ice Age.

Unit 2 can be referred to the second phase described by Giraudi [2005], as its sedimentological characteristics suggest to be an incipient pedogenetic unit. In particular, the constant thickness of the unit is indicative of primary deposition and in-situ formation, in response to warm climatic conditions suitable for soil development. This interpretation is corroborated by the abundant large size charcoal fragments, indicative of the presence of dense wood;

furthermore, angularity of the charcoal fragments indicates the lack of transportation and consequent smoothing. Therefore, the obtained 14C ages are indicative of the actual age of Unit 2 deposition. Hence, the ages obtained are well framed within the Little Ice Age. Unit 1, lastly, is an alluvial-colluvial deposit that covers Unit 2, comparably to what Giraudi [2005] observed in other sites of the Apennines, where the author detected soils dated at the same age of Unit 2 covered by scree, glacial debris and periglacial features, likely referable to a new cold phase.

Hence, the foregoing indicates that the Units uncovered by the trench and, hence, the absence of faulting refer to only the last few hundred years. Taking into consideration the 1500-2500 years mean activation recurrence time defined for the central Apennine major active normal faults [e.g. Galadini and Galli, 2000; Galli et al., 2008], the last few hundred years could appear a too short time span to completely rule out future fault ruptures, as the fault might be only buried (blind) underneath the very recent sedimentary cover. Also taking into account the above-mentioned Guidelines for Microzonation studies, the last few hundred years are a too short time span, with respect to the last 40kyr, to rule out fault capability. Nonetheless, our field observations allow to make some inferences for ruling out the presence of a capable fault in the SEA area, that can be summed up:

- the presence of just reverse faulting affecting the bedrock indicates the absence of extensional faulting (Figure 22);
- the CPFs is conceivably the northern segment of the NF, which entirely ruptured during the M_W 6.9 14th January, 1703, seismic event. The trenched stratigraphic sequence in the SEA site chronologically encompasses the year of the earthquake occurrence. Therefore, significant surface rupture along a normal fault supposedly located in the Abbey area during this event would be expected. Indeed, evidence of metre-scale surface faulting related to the 1703 seismic event has been paleoseismologically detected along the other branches and segments of the NF, referred to the 1703 seismic event [Blumetti, 1995; Galli et al., 2005; 2018];
- the apparent upward convex limit between units 4 and 3, that may suggest deformation associated with blind fault, is instead an erosional surface, dipping to the SW, whose formation only relates to the local morphology of the area, to the nature of the deposits themselves and to the depositional mechanism. If the up-ward convex

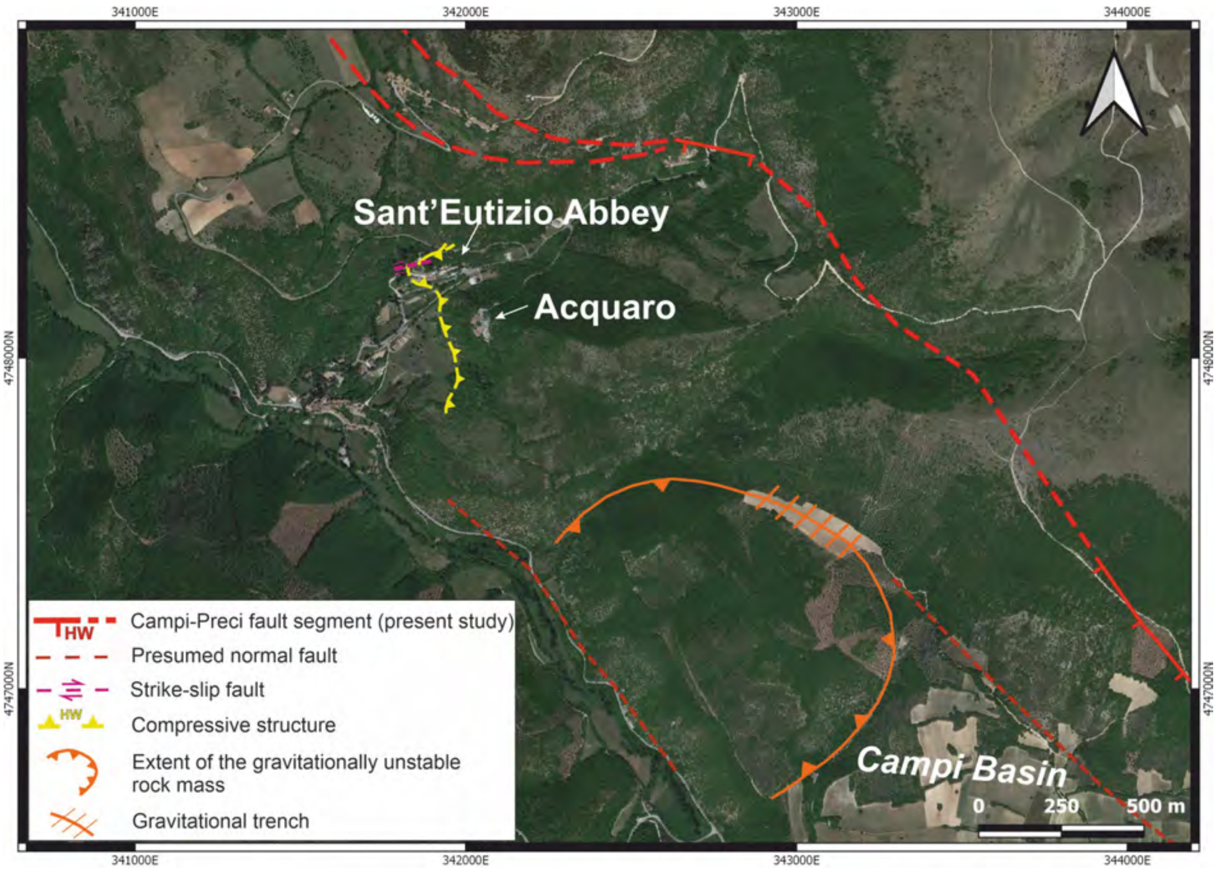

Figure 22. Satellite image (in plan view) of the Sant'Eutizio Abbey area showing the structural and morpho-tectonic setting defined in the present study. Each structural and geomorphic feature is provided as supplementary material (online resources).

limit was due to deformation associated with a blind fault, such a deformation should necessarily have affected units 4 and 3, and hence the gravel layers should show an at least comparable bending. However, the gravel layers of unit 4 are sub-horizontal and they are only truncated by the erosional surface itself.

Therefore, the bulk of long-term geological information, considerations of the seismotectonic framework of the area, and a detailed analysis of paleoseismological data allow to conceivably rule out the presence of a primary capable fault in the SEA area.

5. Conclusions

The Sant'Eutizio Abbey, one the most important cultural/religious medieval settlements of central Italy, suffered severe damage owing to the M_W 6.5 earthquake that struck this region on the 30th of October 2016. Activities aimed at restoring the buildings required specific investigations about the presence in the Abbey site of a potentially active and capable fault, in order to plan interventions aimed to reduce future surface faulting effects to the settlement. The literature defined that the Sant'Eutizio Abbey sector is indeed located along the trace of the northern segment of the major active and seismogenic Norcia fault, namely the Campi-Preci fault segment. However, information about the actual location of the fault trace in this area and of its recent activity are currently incomplete.

Geological field investigations we carried out in this area revealed that, on the one hand, the fault segment affects late Quaternary slope deposits, thus corroborating fault activity; on the other hand, the fault trace locates some hundred metres E of the Sant'Eutizio Abbey site, differently to where is traced in the available literature. Moreover, we observed that the lateral contact between Meso-Cenozoic bedrock formations occurring in the Abbey site is not related to normal faulting (as hypothesised in previous studies), but to a currently inactive reverse tectonic structure. The differential erodibility of the bedrock formations, placed into contact by the reverse tectonic structures (mainly carbonate in the reverse fault hanging wall and marly-clayey in the footwall), determined the formation of the escarpment that was formerly supposed to be related to a normal fault.

We also dug an excavation on the side of the Sant'Eutizio Abbey. The trench exposed alluvial-colluvial units not affected by any shear plane or tectonic deformation, but the very recent age of the stratigraphic units (i.e. spanning only the past four-five centuries) would not allowed to completely rule out the presence of a possible capable fault in the SEA area. However, the geological evidence of the absence of extensional features, affecting the bedrock, and the lack of fault planes associated to surface faulting caused by the M_W 6.9 14th January 1703 earthquake generated by the Norcia fault, allowed to conceivably rule out any active and capable primary tectonic structure underneath the Abbey site. It must be underlined that the SEA is located in the area affected by the NF, which is causative of $M_W\sim 7$ earthquakes, whose main trace occurs few hundred metres far from the Abbey site, to the E. This implies that the Abbey might be affected by strong ground shaking caused by the activation of the NF (and/or by other major seismogenic sources of the region). In light of this, minor surface offset in the Abbey site associated to ground shaking (owing to differential mechanical behavior of the bedrock formations onto which the Abbey is built), or to sympathetic/triggered movements of the reverse shear plane, or to landsliding cannot be completely ruled out.

From an epistemological point of view, our work highlights that the sole presence of morpho-tectonic features (such as supposed active fault-related scarps), the sole the identification of a exposed bedrock fault planes, and/or the lateral contact of terrains of very different ages and nature are not sufficient elements for claiming to active and capable faulting [e.g. Fubelli et al., 2009; Falcucci and Gori, 2014; Falcucci et al., 2016; Kastelic et al., 2017]; in addition, the sole paleoseismological investigations may not always be sufficient to assess the presence or absence of a primary active and capable fault in a given area if they are not framed within a comprehensive multidisciplinary approach.

The geological, morpho-lito-stratigraphic and structural analysis, in a neotectonic perspective, thus represent the prerequisite for correctly planning engineering practices aimed to mitigate the risk associated with active faults, both for ground shaking and for surface faulting.

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Statements and Declarations. The authors state that the transparency of data and proposed material and that no customized software and/or codes were used in this work.

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