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A Normal Faults System in the Monte Nerone area and its significance in the recent seismo-tectonic setting of the Northern Umbria-Marche Apennines (Italy).

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Abstract. The faults system mapped in the northern Marche Apennines, the NW sector of Monte Nerone, Italy, shows many indications of recent activity. This area has been affected by some strong historical earthquakes, such as the Cagli earthquake of 1781, similar to seismic events close by affecting the southern Marche, Umbria, Lazio, and Abruzzi areas in recent years, we focused our investigation on this sector.

The original field mapping work integrated with seismic and subsurface data suggests very similar genesis and kinematics to those of the recent seismic events in the south of Marche region. In addition, this interpretation could also attest the extensional tectonic activity affecting the whole Adriatic side of the watershed backbone of this sector of the Apennines, with probable inversion of involved previous compressional features, such as thrust ramps.

1 Introduction and Aims

The study of the recent tectonic evolution of the Umbrian–Marchean–Romagnan Apennines is essential for understanding seismicity and the related risk in a very active chain sector (ISIDe Working Group, 2007; Mantovani et al., 2014). The knowledge of the areas related to the recent events in central Italy in L'Aquila (2009) and Amatrice (2016) has been considerably furthered thanks to the strong research activities of numerous researchers and institutions. Much progress has subsequently been made in these areas where surface and deep geological knowledge has been reviewed and reinterpreted (Buttinelli et al., 2018; Scognamiglio et al., 2018; Bignami et al., 2019; Improta et al., 2019; Ercoli et al., 2020).

Historical data also give indications of a high risk in the northern areas of the Umbrian–Marchean Apennines close to those affected by the events in 2016 due to the possibility of a reactivation of the seismogenic structures with disastrous consequences.

According to historical sources (Presciutti et al., 2017), one of the main events known in this region is the Cagli earthquake of 1781, for which a magnitude of 6.5 Mw was estimated (Baratta, 1896; Monachesi, 1987; Rovida et al., 2019), very similar to those measured in central Italy.

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The aim of this study was to contribute to define tectonic structures by recognizing and mapping the faults that are most likely the most evident surface indications of historical earthquakes. We mapped a system of faults in the NW area of the Monte Nerone anticline (northern Marche region), which, due to the geometry, kinematics, and influence on the morphology of the territory, is a source of superficial evidence of known historical events. For this purpose, faults, in part already known by official cartography (Regione Marche, Carta geologica regionale 1:10000, 2020), were re-mapped and reinterpreted in their geometry and kinematics with integration with recent subsurface and seismological data. Then, they were compared with the models newly proposed for the interpretation of recent events in the more southern areas.

2 Tectonic Setting

The outermost part of the ~~northern Apennines,~~ the Umbrian–Marchean Apennines (Fig. 1), is a fold-and-thrust orogenic chain formed by the rotation of the Sardinia–Corsica block towards the Adriatic foreland (Barchi et al., 1998; Lavecchia et al., 1988; Butler et al., 2000). Deformation migrated from WSW to ENE, from the Tyrrhenian to the Adriatic, and from the Oligocene to the Pliocene–Quaternary ages, involving the pre-orogeny carbonate succession and syn-tectonic terrigenous deposits (Lavecchia et al., 1988; Barchi et al., 1998).

Shortening of the orogenic chain was then followed by a progressive extensional tectonic, always in the same SW–NE direction (Malinverno and Ryan, 1986).

The shortening structures are cut by successive normal faults in the Tyrrhenian Tosco–Umbrian area, while, beyond the Apennine watershed, toward the Adriatic side, a ~~compression~~ regime persists (Signorini, 1946; Petricca et al., 2019).

This hypothesis is questioned by various authors who believe that the extensional regime is no longer limited to the Tyrrhenian sector, but that even eastward, beyond the Apennine watershed, there are indications of recent extensional tectonics (Barchi et al., 1996; Savelli et al., 2002; Borraccini et al., 2004; Anderlini et al., 2016; Chiaraluce et al., 2017). In an extensional deformation framework, a low angle, east dipping normal fault (LANF) (Collettini et al., 2006; Mirabella et al., 2011) was interpreted by crustal seismic profiles (Barchi et al., 1998). Therefore, the seismic events recorded in this tectonically active area (Chiarabba et al., 2005; De Luca et al., 2009; Mantovani et al., 2014) could be related to this extensional context, such as the recent events in the sectors of the southern Umbrian–Marchean Apennines (Chiaraluce et al., 2007; Carannante et al., 2013).

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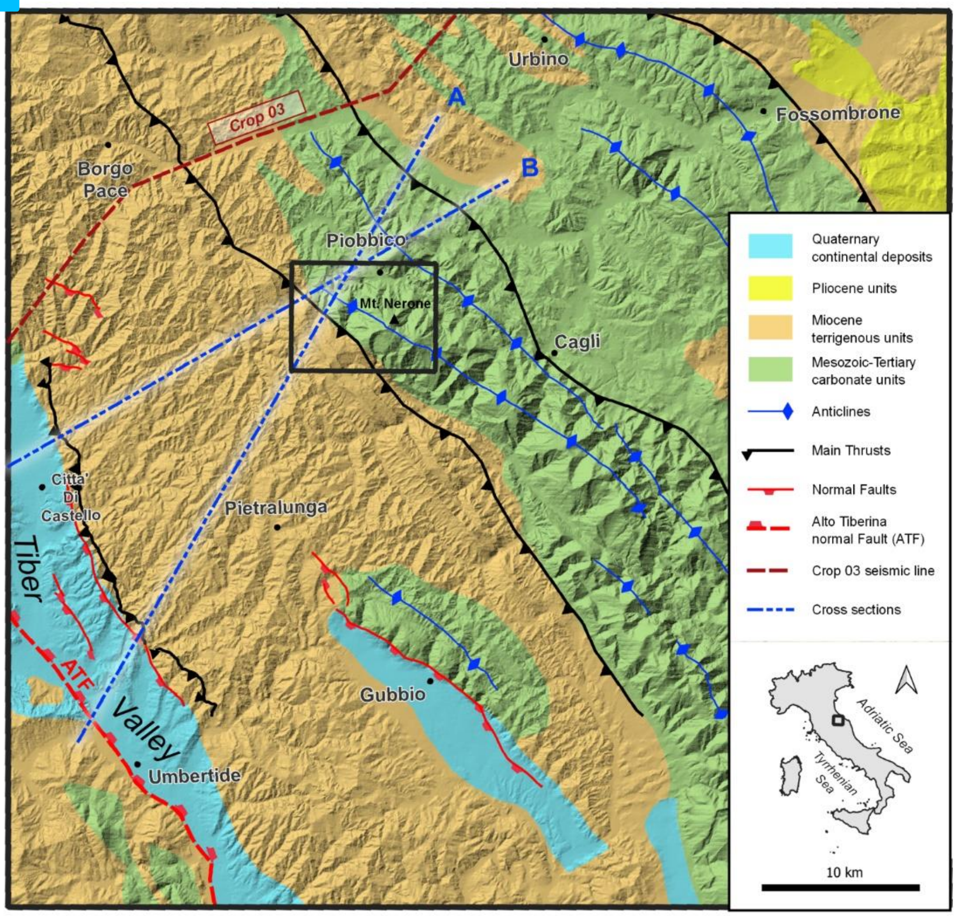

Fig. 1: Schematic tectonic map of the northern sector of the Umbria–Marche Apennines (northern Apennines), showing the study area ~~by~~ the black rectangle (Fig. 2) and the traces of the cross-sections (Fig. 10).

3 ~~Geological Features~~ of the Study Area

The study area is an internal sector of the ~~Umbrian–Marchigiano~~ Apennines (Province of Pesaro–Urbino, northern Marche) which includes the north-western tip of the anticline of Monte Nerone and the neighboring areas of the Biscubio River valley and its tributaries. The stratigraphy can be summarized as a carbonate sequence of Jurassic to Oligocene ages; for a more detailed definition, refer to the literature (Centamore et al., 1991). This succession sedimented on the edge of the African platform, during the Liassic rifting became a passive margin (Alvarez, 2009). The gradual increase in the terrigenous content of the Scaglie Group indicates the transition to a turbidite complex of a Miocene foredeep, represented in this region by the Marnoso–Arenacea Formation (Ricci Lucchi, 2003).

The main local tectonic structure consists of a NW–SE-oriented anticlinorium, consistent with the regional Apennine trend, with a longitudinal extension of about 30 km and a wavelength of 5–6 km. In the study area, this structure has a periclinal

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termination overlain by the most recent terrigenous units, due to out-of-sequence thrusts (Corsi and De Feyter, 1991). In addition, WSW–ENE transcurrent faults dissect the whole structure.

Recent and minor normal faults, with a length of a few kilometers and a WNW–ESE trend, cut the structure without clear evidences of being connected in larger faults.

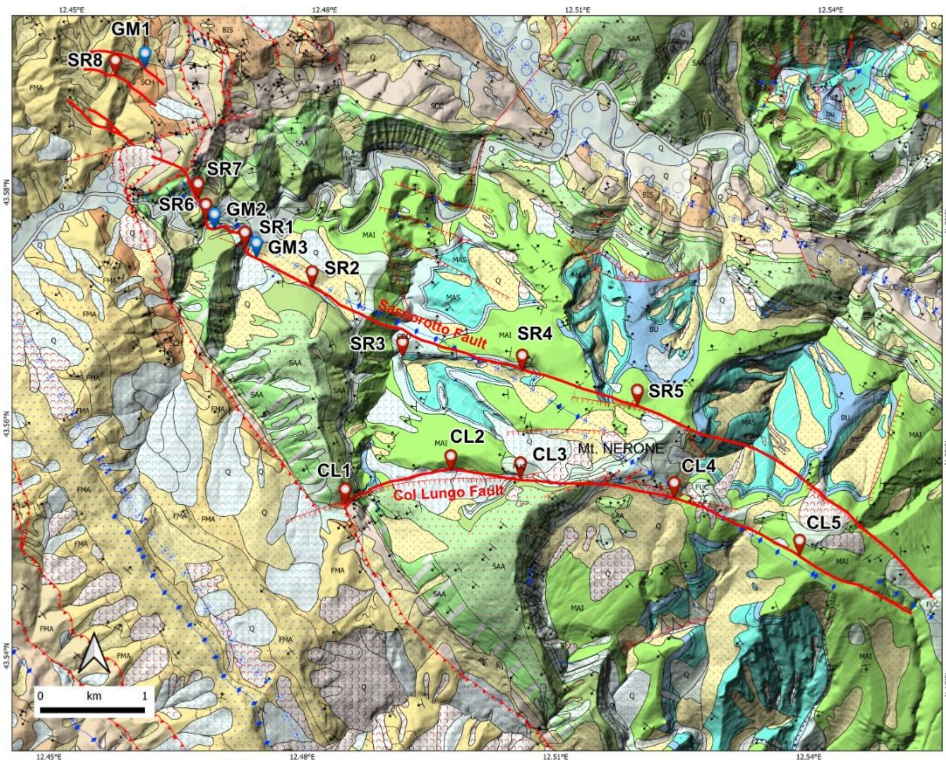

Figure 2: ~~Simplified~~ geological map of the study area from a geological map of the Marche region at a scale of 1:10,000 (Regione Marche, Carta geologica regionale 1:10000, 2020). The thick red lines are the fault traces mapped in this study. SR (Sassorotto), CL (Col Lungo) and GM (~~Geomorphology~~) are the observation sites. Geological units: MAS, Calcare Massiccio Formation; BU, Bugarone Group; COI, Corniola Formation; RSA, Rosso Ammonitico Formation; POD, Posidonia Formation; CDU, Calcari diasprini; MAI, Maiolica Formation; FUC, Fucoidi Marls Formation; SBI, Scaglia Bianca Formation; SAA, Scaglia Rossa Formation; VAS, Scaglia Variegata Formation; SCC, Scaglia Cinerea Formation; BIS, Bisciaro Formation; SCH, Schlier Formation; FMA, Marnoso Arenacea Formation; Q, Quaternary deposits.

4 Methods and Tools

The methods and tools used in this work were largely discussed in a previous paper to which we refer the reader for more detailed information (De Donatis et al., 2020). Several digital methods and procedures were applied from field to laboratory operations in an iterative way.

Ground-based digital mapping was integrated with drone surveys to allow us to capture a large amount of data and observations, in order to detail the geometry of the fault system and interpret its kinematics.

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The field-derived map and subsurface data were imported in GIS and 3D modeling environments, enabling us to synthesize a geological model.

The hardware used in the field were as follows: a tablet PC (Windows operating system) with a stylus, a GPS Bluetooth antenna (NMEA protocol), an Android smartphone and camera, and a commercial UAV equipped with a 12-megapixel camera.

The software consists of different programs: an open-source GIS (QGIS ver. 3.10 with QT designer for customization (QGIS Development Team, 2019)), a drone fly planner (Pix4D (Professional photogrammetry and drone mapping software, 2020) and Ground Station Software | UgCS PC Mission Planning, 2020)), drone photogrammetry (Agisoft LLC, 2020), 3D graphics (Rhinoceros; McNeel R. & others, 2010)), and 3D modelling (MOVE Suite, 2020).

5 ~~Ground-Based~~ Evidence: Mesoscale Observation and Measurement Points

In the study area, two main faults were mapped: the *Sassorotto* and the *Col Lungo* faults. These faults consist of different segments, that can be mapped thanks to geomorphological ~~features~~ and investigated in depth when exposed in outcrops, allowing to capture structural measuraments (Fig. 3).

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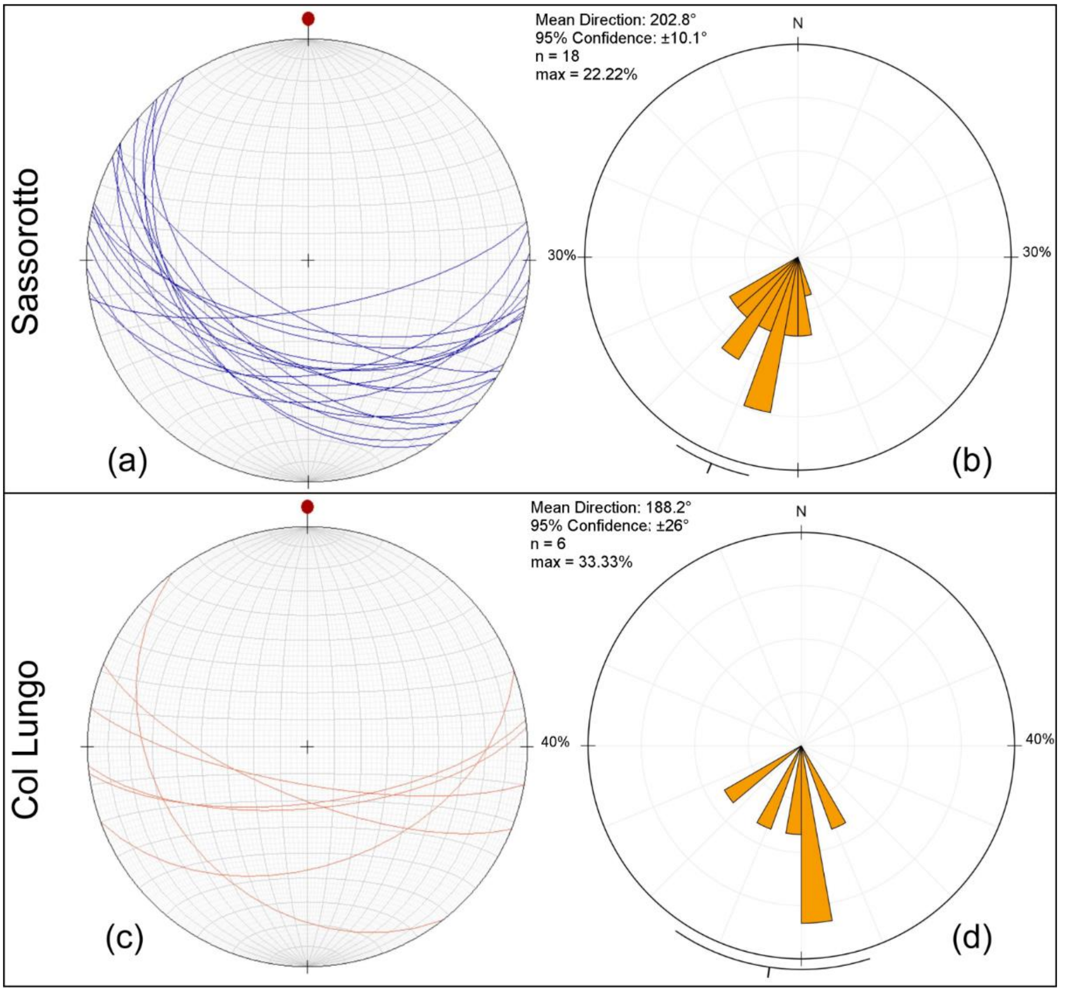

Figure 3: (a) Equal area stereonet (lower emisphere) of data from Sassorotto fault and (b) rose diagram of faults orientations; (c) equal area stereonet (lower emisphere) of data from Col Lungo fault and (b) rose diagram of faults orientations.

5.1 SR—Sassorotto Fault

This NW–SE trending fault was mapped from the Monte Forno stream to Casciaia Mochi. It affects the terrigenous turbidite sediments and the carbonatic succession almost along the anticlinal axis of the Monte Nerone. We discuss the features of 8 major outcrops along the fault trace.

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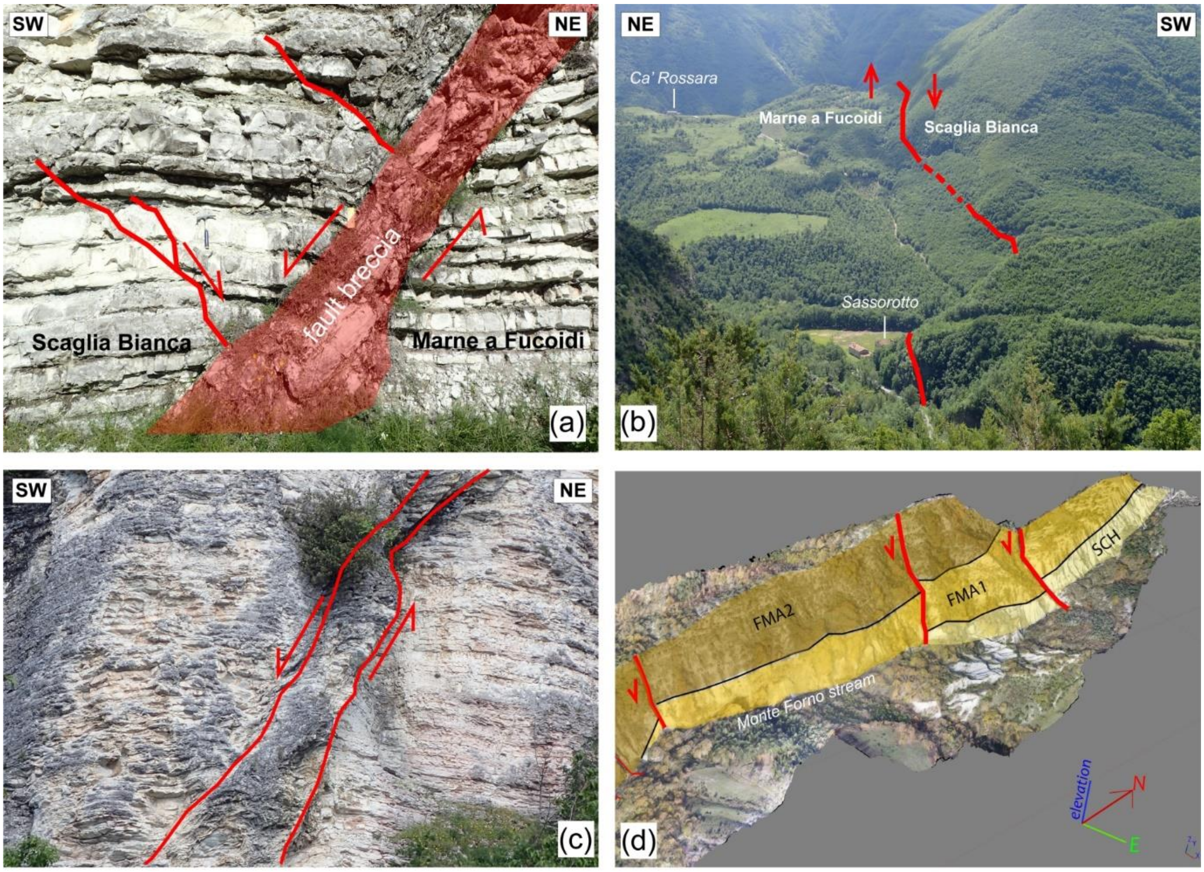

Figure 4: Sassorotto Fault (site location in Fig. 2). (a) site SR1- fault outcropping at Sassorotto locality showing a large thickness of breccia and an antithetic minor fault. (b) site SR2– the morphological scarp shows a height inversion where younger Scaglia Bianca Fm is move down to the older Marne a Fucoidi Fm (c) site SR6- fault on the outcrop at Biscubio river. (d) site SR8- the terrigenous facies of Marnoso Arenacea Fm and their relative movements respect to the interpreted faults is showed on the photo-mosaic (draped on DEM built by drone data collection).

5.1.1 SR1. Sassorotto

Along an ancient road (now a path) that starts from the Apecchiese road, near the spring of Sassorotto (which named this fault), and goes up towards the Pieve di San Cristoforo di Carda, the fault is very well exposed (Fig. 4a) and its main ~~surface~~ can be surveyed along the ridge to the other side up to the main road. Here, the main fault shows a thick breccia (30 cm) with different size blocks (millimeter to decimetric diameters) with embrication almost oriented toward the normal movement (Fig. 4a). The total displacement cannot be fully constrained in the visible outcrop but is estimated larger than 4 meters. Some minor planes with calcite striae suggest also strike slip movements, predating the more recent normal ones. In this outcrop, some synthetic faults show normal decimetric displacements. A minor antithetic fault is directly connected to the main one (see Fig. 4a)

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5.1.2 SR2. Monte Cardamagna Slope Near Ca' Rossara

To the SE of the previous point (SR1), an evident morphological change can be seen in the SW side of Ca' Rossara (Fig. 4b). While the forest does not allow direct observation of the lithological units, it is evident that in the steepest part towards the SW, the limestone layers of the Scaglia Bianca Fm ~~outcrop,~~ while in a gentler ~~incline~~ towards the NE, the Marne a Fucoidi Fm outcrops. Due to the lateral relationship between Scaglia Bianca and Marne a Fucoidi, it is possible to deduce a relative displacement, with lowering of the SW part (Scaglia Bianca) compared to that of the NE part (Marne a Fucoidi), which, despite the morphology related to the valley erosion and the different characteristics of the units, could lead one to believe the contrary (relief inversion).

Along the path that climbs from Ca' Rossara towards Monte Cardamagna, in small gullies, minor normal faults are visible and exposed. These can presumably be considered synthetic faults related to the main one.

Moving in the SE direction, towards Rio Vitoschio, the morphological evidence of the fault initially disappears (segmentation between the different sectors of the fault itself) and then reappears further to the SE.

5.1.3 SR3. At the confluence of the Pisciarello stream and Rio Vitoschio

Going up the Rio Vitoschio, on the right orographic side (5[illegible]0 m asl), the Calcari Diasprigni Fm and Maiolica Fm ~~outcrop~~ with large slopes that continue towards the mountain.

Here, the fault is not evident, but the morphological/hydrographic set-up may have promoted the erosion of the fault surface, even with landslides, as evidenced by large deposits of boulders at the slope foot.

Along the first part of the Pisciarello stream, it was possible to measure a fault plane that is antithetic to the main one.

5.1.4 SR4. Prato del Conte

SW of Prato del Conte, a right tributary of the Pisciarello stream cuts through a valley. Images collected by the drone (the descent of the valley is unsafe) show a situation very similar to that of the previous site (A3). This incision is also well recognizable from plane photos and can be interpreted as a lineation. Its extension to the SE would allow a connection with an already mapped normal fault (Regione Marche, Carta geologica regionale 1:10000, 2020).

5.1.5 SR5. Rifugio Corsini and Colonia Don Orione

Although a fault plane does not crop out, the lithostratigraphic survey for the above-mentioned geological map clearly shows a normal fault with a lowering of the SW edge. The displacement as calculated from the cartography is considerable, Calcare Massiccio Fm is in contact with Maiolica in the upper Infernaccio valley and Maiolica with Marne a Fucoidi near Colonia Don Orione.

The surveys carried out in this study confirm this tectono-stratigraphic structure. In addition, they suggest that this already mapped fault segment, even with limited displacement and map extension, is part of a more important one.

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In the SE direction, the continuation of this already mapped fault (Regione Marche, Carta geologica regionale 1:10000, 2020) can be inferred from the geomorphology up to the Pian dell'Acqua valley. In detail, along the road that leads to Pianello village, near Casciaia Mochi, an escarpment mapped as a ~~direct~~ fault is well recognizable. It lowers towards the SW ~~of~~ the Marne a Fucoidi Fm with respect to the Maiolica Fm towards the NE.

5.1.6 SR6. The Biscubio River and the "Apecchiese" Main Road at km 32

This fault plane is well recognizable (Fig. 4c), and even mapped with the drone, on the outcrops near the road and the river bed, oriented in continuity with the Sassorotto fault (site SR1) as previously described.
In addition, a step can be observed in the riverbed, which creates a hydraulic jump just upstream of the fault itself. This step creates an anomaly in the hydrographic network, as noticed in ~~Beatrice Smacchia's degree thesis (~~Smacchia, 2017~~)~~ through an analysis of the slope gradient.
The field survey highlights an anomalous accumulation of pluri-decimetric, rounded sandstone boulders as the cause of the hydraulic jump itself.

5.1.7 SR7. Villa Maria

At higher altitudes, moving in the NW direction on the ridge, only a minor fault crops out in correspondence with a Pleistocene fluvial terrace near Villa Maria. Approaching the road to the Monte Forno village~~, a dextral strike-slip fault,~~ a WSW–ENE oriented dextral strike-slip fault is evident putting in contact the most recent and terrigenous Marnoso-Arenacea Fm with the last stratigraphic terms of the carbonatic succession. This fault, displacing the thrusts, could have formed during the shortening in the tip area of the Monte Nerone anticline. The type of faulting behavior, located NW with respect to this one, is very different from those previously described, which involve the carbonatic succession.

5.1.8 SR8. Monte Forno stream

Along the ridge on the orographic right of the Monte Forno stream, terrigenous sediments of the Miocene foredeep crop out almost continuously and are mostly turbiditic and with lithological characteristics totally different from those of the carbonatic succession. This terrigenous succession consists of, at the base, a fully marly formation, the Schlier Fm, giving way, through the insertion of arenite levels, to The Marnoso-Arenacea. The latter unit is divided into two lithozones in this area: the lower consists of prevailing marls with thin beds of sandstone, while the upper one is characterized by medium and thick arenite beds (Campbell, 1967).
Along the entire extension of the outcrop, this lithostratigraphy makes it possible to recognize a set of normal faults (at least three) which lower the SE sectors. This trend was mapped in 3D thanks to drone images (Fig. 4d). Surveying the ridge, an abrupt change in lithozones is clearly visible. While it is difficult to collect fault structural data due to the marl lithology itself, the minor faults are however clearly recognizable. In some sectors of the ridge, in particular the lower one, the fragmentation of the series of arenite and marl strata is evident, with very intricate fault systems.

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Along the stream, there are numerous nick points with jumps of up to 3 meters, not related to lithology. Unfortunately, the vegetation and debris do not allow to check the fault surfaces directly. The whole stream is affected by a strong erosion with over-excavation, which is much more pronounced than the creeks in the area.
The ridge also shows an uneven, jagged morphology with abrupt non-eroded counter-slopes. These observations lead to the hypothesis that this morphology is very recent and influenced by fragile tectonics.

5.2 CL – Col Lungo Fault

This fault looks arcuated on maps. It is well exposed from La Valle Country House in the west to the top of Monte Nerone in the east. Its eastern continuation can be inferred by morphology features up to La Montagnola.

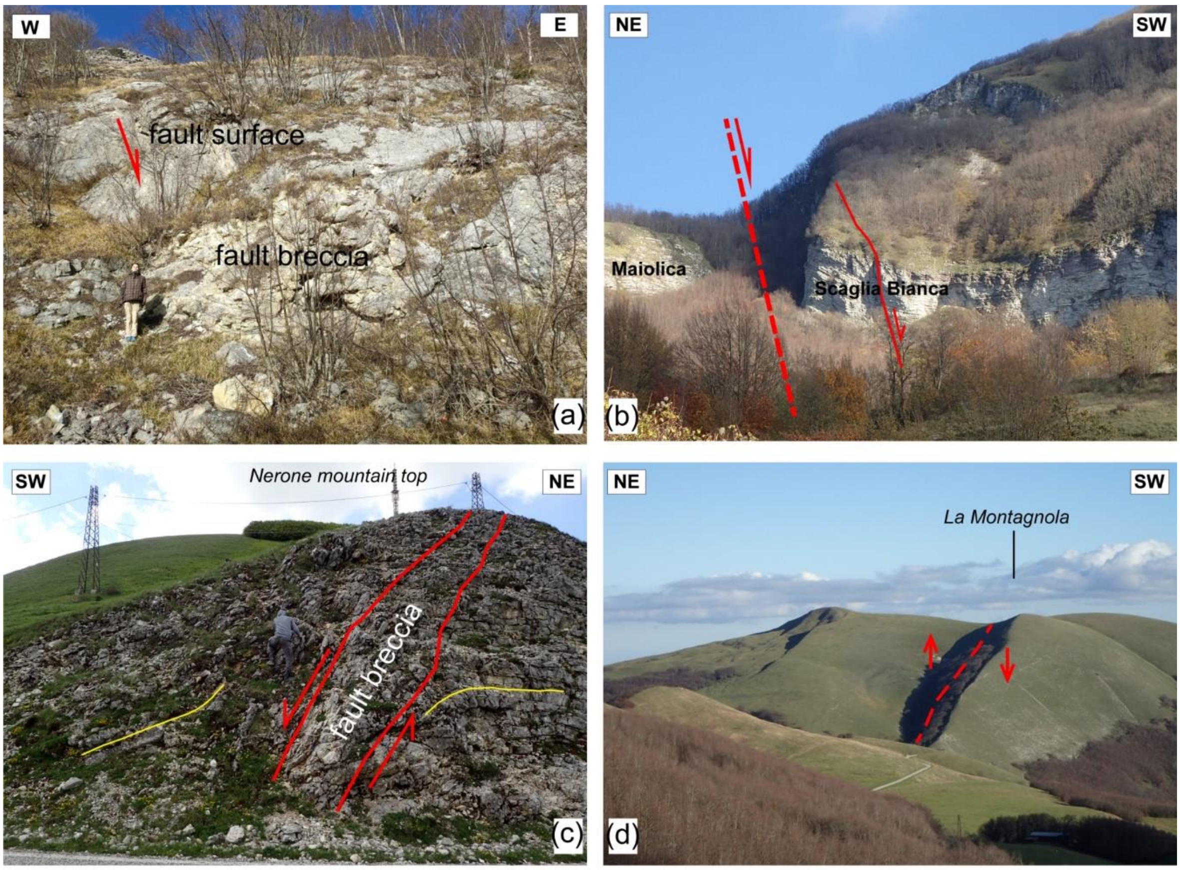

Figure 5: Col Lungo Fault (sites location in Fig. 2). (a) site CL2- large outcrop where fault surface and related breccias are well exposed. (b) site CL3- the older Maiolica Fm in the footwall is separated by a deep gorge to the Scaglia Bianca Fm in the hanging wall cut by a minor synthetic fault. (c) site CL4- normal fault in the Maiolica Fm outcrops on the road cut nearly on top of the mountain showing a fault breccia and drag folds in the footwall. (d) site CL5- interpreted prolongation of the fault along the ridge doubling on top of Montagnola Mt.

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5.2.1 CL1. La Valle Country House

Along the private road connecting the La Valle farmhouse to the provincial road to the top of Monte Nerone, layers of the Scaglia Grigia Fm and the Bisciaro Fm emerge in an almost chaotic manner. Then, in accordance with an abrupt morphological change, there is a transition to the Scaglia Rossa Fm. The fault plane is not visible there or along the path crossing the ridge. Only some minor faults are measurable on the NE flank in the Scaglia Rossa Fm, without evident correlations with the main fault.

In the Marche Region geological map (scale of 1:10,000), a normal fault that displaces a thrust in the western area is present, and in the east, it connects Maiolica with Scaglia Rossa. In addition, in this case, the cartographic extent of the fault is somewhat small (around 600 m), even with considerable displacement.

5.2.2 CL2. Col Lungo

Driving up the winding road that climbs to the top of Monte Nerone, the fault is well exposed (Fig. 5a). At the bend at 998.2 asl (Regione Marche, Carta tecnica numerica 1:10000, 2020), it is possible to see a fault plane that extends for more than 300 meters with an almost W–E direction. On the 1:10,000 scale geological map of the Marche Region, this outcrop is mapped as the Bugarone Fm, even though this formation should not be in this stratigraphic position. From a careful observation, it is evident that the is not of sedimentary origin (making the official map surveyors interpret as Bugarone outcrop) but tectonic one. This is a typical fault breccia, exposed in several outcrops along a well-developed fault plane.

5.2.3 CL3. i Ranchi

From the sharp bend of the previous site (CL2), the outcrops of Scaglia Bianca and Scaglia Rossa are clearly visible in the ~~upper wall~~ towards the east under the "i Ranchi" site (Fig. 5b). Moving in the NE direction, the outcrop ends in a narrow gorge in which a normal fault is visible (see the geological map), which lowers the Scaglia Bianca to the S compared to the Marne a Fucoidi to the N. Due to the danger of rockfall, the drone was used to map this zone.

5.2.4 CL4. Monte Nerone Road Pass

Along the road at the pass between Monte Nerone and Monte del Pantano, a normal fault clearly outcrops and displaces Majolica Fm layers (Fig. 5c). A thick fault breccia is exposed and there are some drag folds on both walls. The displacement is not evaluable.

5.2.5 CL5. La Montagnola

Beyond the sites described above, there is no clear evidence of the fault in the outcrops. Towards Montagnola, there is a clear double ridge (Fig. 5d), which is difficult to explain with the lithological characteristics since this area is made up of limestone: the Maiolica Fm.

Additionally, even on the SW flank, there are some NW–SE-oriented slopes that do not seem to represent landslide ridges. Beyond that, our understanding of the fault framework becomes quite speculative, and we did not find any clear evidence due to the lack of outcrops.

6 *GM* - Geomorphological Evidence

6.1 GM1. Monte Forno stream nick points

The creek tributary to the left of the Biscubio River, downstream of Pian di Mulino, shows a sharp incision along its entire short length from the ridge near Monte Forno until reaching the main river. The terrigenous lithologies (marls and sandstones) crop out, often showing small waterfalls related to local nick points. Field and drone surveys showed that these jumps are not strictly related to lithological differences. Indeed, they are located in the most faulted areas or where faults are inferred from the displacement of the stratigraphic lithozones, as described above.

This localized framework therefore seems to be the direct consequence of a very recent tectonics. The streams in neighboring areas do not show similar characteristics.

6.2 GM2. Biscubio river whitewater

Along the Biscubio river in the Sassorotto site, where the fault outcrops clearly point to the orographic left, a hydraulic jump is present a few meters upstream of the fault itself. Upstream, an accumulation of huge sandstone blocks transported and deposited here, coming from the Marnoso-Arenacea Fm, is evident. This crops out a few kilometers upstream. This deposit is an anomaly in the river profile (Smacchia, 2017; Piacentini et al., 2020) and is difficult to explain with the present-day conditions of the riverbed. Not being an accumulation of landslides both for the lithology and for the rounded shape of the blocks, we must assume that some sort of physical barrier blocked the transport of the sandstones boulders, a slowdown that led to a decrease in the solid flow of the river itself.

There are two hypotheses: (i) a local landslide of which there is no evidence or (ii) a fault step that created a dam. Although there is no strong evidence, both could be caused by a seismic event such as the Cagli earthquake of 1781.

In the first hypothesis of a landslide dam, it should be possible to find part of the accumulation, even among the transported sandstone blocks; however, there is no such evidence of erosion by the river, in nearby areas (towards the road).

The second hypothesis regards the fault that would have created a lowering of the hanging wall upstream with a consequent small dam basin. This is also not proven because the subsequent erosion due to the flow has dismantled this dam and part of its accumulation. The hydraulic jump, indeed, is recognizable about ten meters from the sub-outcropping fault. Figure 6 shows a possible model of the genesis and evolution of this anomalous riverbed profile.

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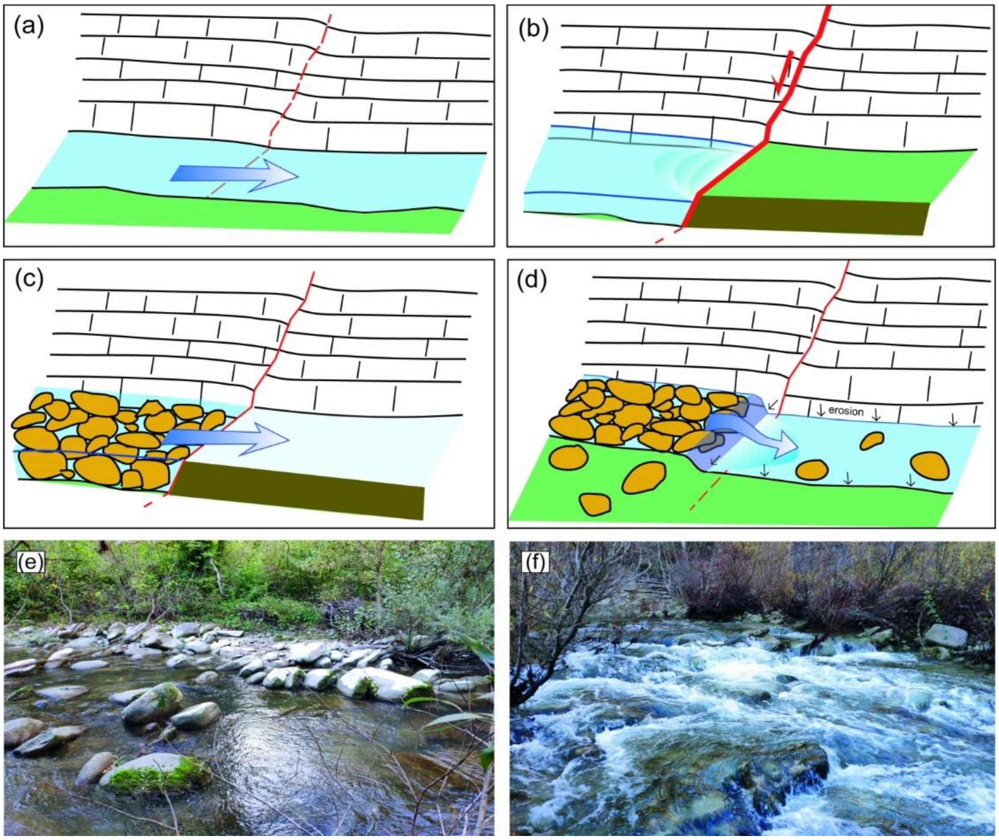

Figure 6: Whitewater evolution model by faulting, deposition and erosion. (a) pre-faulting possible situation; (b) fault movement developing a countercurrent step; (c) boulders are deposited against the fault footwall where flow energy is lower; (d) fluvial erosion eliminated the fault wall, but the boulders (even if some of them are carried downstream) became the step originating whitewater; (e) imbricated boulder deposits on the hanging wall on the Biscubio river; (f) step of boulders producing present whitewater.

6.3 GM3. Fosso del Molino

The right tributary of the Biscubio river, which flows from SSW to NNE, near Sassorotto has a large riverbed where recent alluvials together with blocks collapsed by steep slopes are gathered. The stream is now eroding these deposits, reaching the carbonatic substrate.

Right where the fault cut the riverbed, the excavation shows a transversal trend with respect to the small alluvial plain. No clear evidence of the fault has been found, but this local trend is anomalous and could be easily attributed to recent tectonic activity.

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7 Geophysical data (CROP-03 reinterpreted)

The CROP-03 seismic section at the crustal scale crosses the deeper structures a few kilometers north-westward from the study area (Fig. 1). The first geological interpretation of this seismic section was proposed by Barchi et al. (1998) in a volume collecting many contributions on the geology and geophysics of a larger area along the transect of this section.

Despite the seismic section passing a few kilometers NW of the study area, it highlights the main structure, which is the anticline relative to the Monte Nerone thrust buried under the Miocene turbidite succession.

The interpreted section shows the classical model of western extension and eastern shortening. A relevant new tectonic feature that has been proposed is the low-angle normal fault dipping to the east, now known as the Alto Tiberina Fault (ATF).

More recently, Pfiffner (2017) reinterpreted the structure of this sector of the Apennines, introducing diffuse normal faulting along the Umbria–Marche ridge.

Since the aim of this seismic line was to investigate the deep crust characteristics and geometries (CROP), its spatial resolution was not adequate to highlight the superficial structures related to recent normal faulting, whose displacement is much lower than that of the deep thrusting structures.

Some minor discontinuities could be interpreted as evidence of normal faults surveyed during fieldwork (Fig. 7).

Some of these normal faults seems to connect with the main thrust ramps; however, the displacement in the Quaternary does not overbear the Mio-Pliocene thrusting shortening and, therefore, is not so evident in this section.

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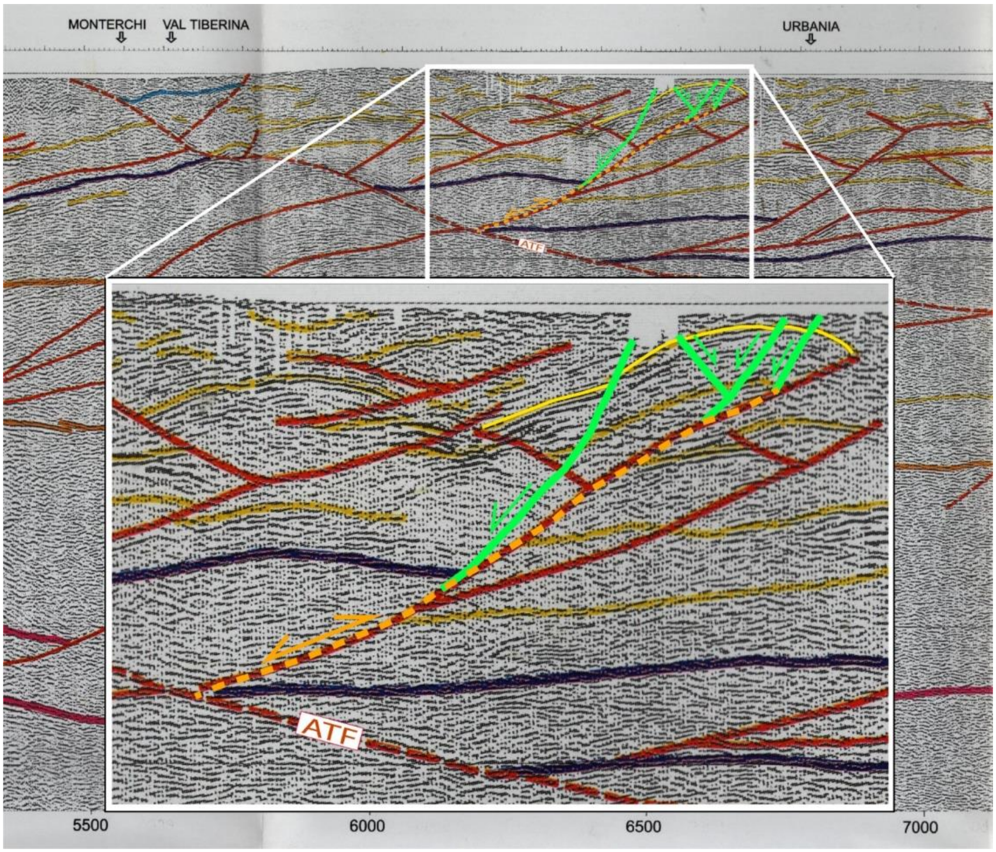

285 **Figure 7: Reinterpreted Crop-03 seismic reflection profile (Barchi et al., 1998) close to the study area. On the buried crestal sector of the Monte Nerone anticline, some extensional feature of the reflectors can be interpreted as normal faults (green) similar to the ones outcropping in the study area and their relationships with negative inversion movement (orange) on the deeper thrust ramp. ATF: Alto Tiberina Fault.**

8 Seismicity

290 To identify the historical events of Umbria, Marche, Tuscany and Romagna, data from the ~~Historical Archives Macroseismic Italian (Rovida et al., 2017~~) and parametric catalogs of Italian earthquakes (Rovida et al., 2019, 2020) were merged. These catalogs (Camassi et al., 2011) report the Cagli earthquake (Baratta, 1896; Monachesi, 1987) and other events from less reliable sources, such as that of Monte Cardamagna on April 17, 1725, which suggests important seismic activity in the study area (Fig. 8).

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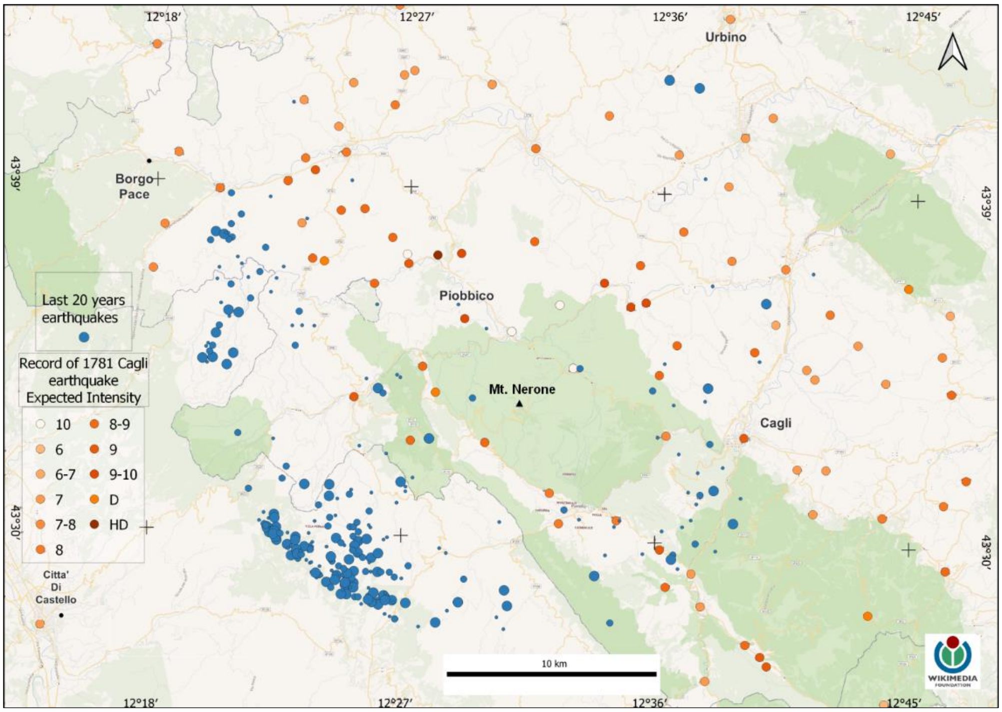

Figure 8: Map showing the locations of earthquakes around the study area over the last 20 years (data published by the Institute of Geophysics and Vulcanology - INGV web catalog), and the record of 1781 Cagli earthquake (data from the Italian Historical Macroseismic Archive - ASMI). Maps from Wikimedia (Open Data Commons Open Database License (ODbL), https://foundation.wikimedia.org/wiki/Maps_Terms_of_Use).

For the current instrumental earthquakes, we used data available on the INGV platform (ISIDe Working Group, 2007), reporting them in a three-dimensional model (Fig. 9) and reprojecting them in a geological section that shows a correspondence with the interpreted structures (De Donatis et al., 2020).

In this work we also consider the data from the TABOO network (Chiaraluce et al., 2014; Latorre et al., 2016) arranged ad hoc for monitoring the ATF and correlated structures. In particular, in this paper we consider the data used by Valoroso et al. (2017). As reported by those authors,90% of the recorded seismic events correspond to hypocenters that can be correlated to faults positioned in the ATF hanging wall.

Furthermore, some focal mechanisms are available (Chiaraluce et al., 2017; Valoroso et al., 2017) that can be clearly interpreted as normal faults.

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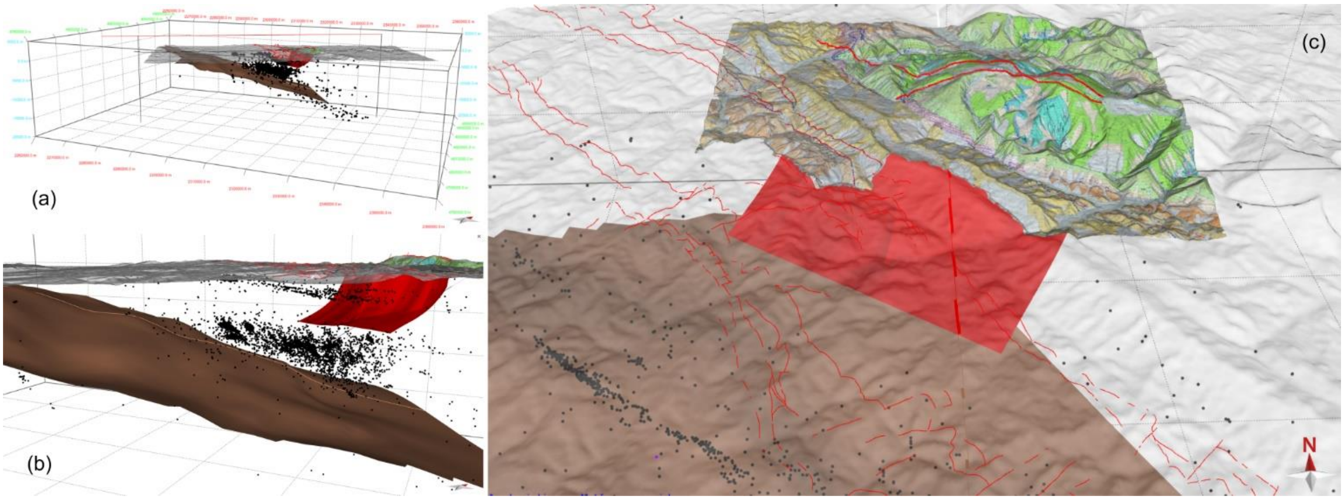

Figure 9: 3D model with DTM with wrapped geological map of the study area, showing relationships among normal fault system (red), ATF (brown) and earthquakes foci (black crosses). Detailing the model from a to c (see wind rose for orientation).

9 Comparison with Southern Sectors of the Marche–Abruzzi Apennines

The latest studies on the close sectors of the recent earthquakes (L'Aquila, 2009; central Italy, 2016), provided a huge amount of data, which allowed us to formulate new seismotectonic models in contexts very similar to this study area. Most authors agree with a extensional regime supported by seismic profiles, earthquake distribution, and focal mechanism (Chiarabba et al., 2015; Bignami et al., 2019; Iezzi et al., 2019; Improta et al., 2019; Scognamiglio et al., 2018; Boncio et al., 2010; Porreca et al., 2020; Ercoli et al., 2020; Gori et al., 2018).

In addition, the Retrace-3D project (RETRACE-3D Project, 2021) for the creation of a three-dimensional geological model highlights a congruity between earthquakes and tectonic structures. In detail, the Mio-Pliocene thrust ramps were reactivated as normal faults, with tectonic inversion (Scrocca, 2021).

As in the southern areas of the Umbrian–Marchigiano Apennines, and even in the northern areas, in comparable chain sectors, there are signs of extensional tectonics, as some authors have already evidenced (Chiaraluce et al., 2017). The structure is very similar to that of an NE-deepening LANF, with high angle-antithetic normal faults at the hanging wall, cutting or joining the Mio-Pliocene thrusts.

10 Interpretation and Discussion

From the field survey, the fault system identified in the Monte Nerone sector, which continues to the NW where foredeep turbidites ~~outcrop~~, shows clear evidence of extensional tectonics.

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The Sassorotto fault on the surface consists of a system of fractures typical of the areas where normal faults crop out (EMERGEO et al., 2016; Iezzi et al., 2019) despite being obliterated by anthropic and natural reworking ~~over the last 230 years.~~

In carbonate units, it is more evident, and it is certainly the sum of many events that allow remarkable final displacements. In the siliciclastic turbidite unit, the geometric characteristics are different, most likely related to the different rock mechanics of marls (prevalence) and sandstones. In fact, in the Monte Forno stream area, faulting is more widespread with at least three branches pointing out by stratigraphic reconstruction (Fig. 2). Here, the articulated morphology indicates that these faults were formed in very recent times. Although geomorphology studies are still in progress, the morphology of the ridge, as well as that of the impluvium, is still "fresh". This indicates that they did not undergo erosion phenomena during the most recent glacial phase, which eroded and “planed” the exposed surfaces in neighboring slope areas.

The Col Lungo fault plane also shows sharp fresh surfaces with articulated morphology that seem to suggest very recent movement.

Both in the Sassorotto and in the Col Lungo faults, kinematic indicators (Striae) can be found, which testify significant transcurrent movements (DX or SN). These movements are likely to be older; even if identifying the specific timing is not feasible, they are assumed to be related to the previous shortening phases during orogenic thrusting. In fact, these faults are oblique to thrust planes and could be seen simply as being mechanical–lateral junctions.

These discontinuities were then reactivated as normal faults in the later phases, both for their position with respect to the structures and for evidently higher brittleness.

Such superficial evidence, as previous reported, represents nothing more than the sum of several recent events. Each of them may have undergone movements of centimeters to meters, very similar to those measured in the Sibillini Mountain faults after the 2016 earthquake. From the historical and instrumental data, a real and evident similarity can therefore be inferred among the seismogenic and tectonic situation of all these districts. It is assumed that these faults can reach the region above the ATF, where earthquakes form throughout the reactivation by inversion of the thrust ramps, interpreted by previous authors with the use of commercial seismic lines (Barchi et al., 1998) and the CROP-03, which crosses this sector of the Apennines just to the NW.

In order to investigate the relationships among faults and earthquakes, we drew two schematic cross-sections from available data (Barchi et al., 1998; Mirabella et al., 2011) and this original study, on which earthquakes foci were projected (Fig. 10).

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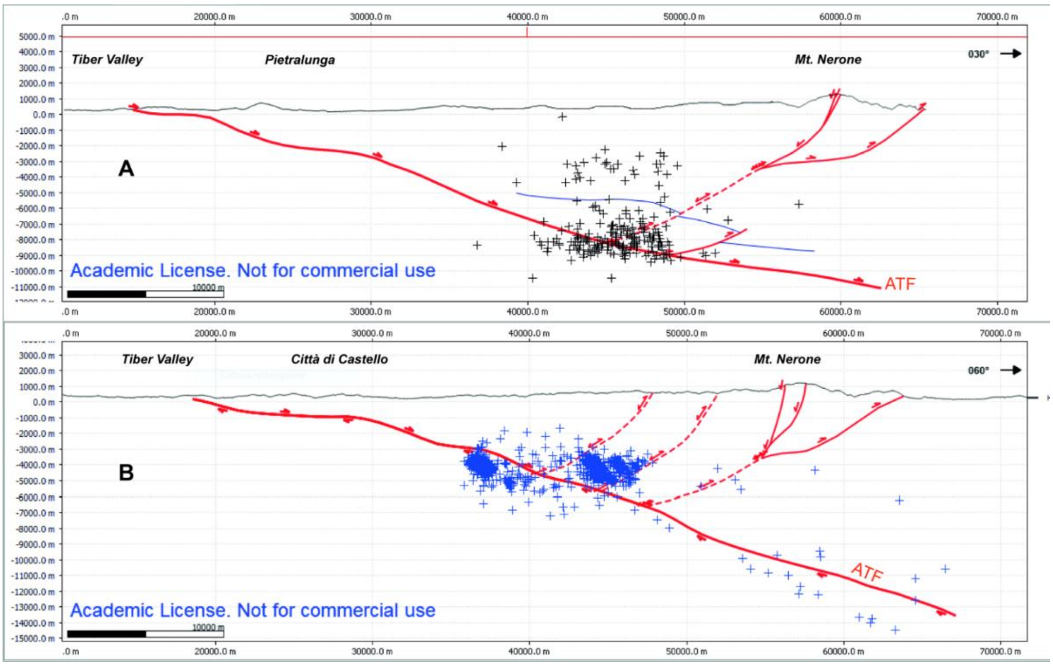

Figure 10: Schematic geological cross-sections and instrumental earthquakes foci distribution. A section SSW-NNE (redrawn from De Donatis et al., 2020) shows main faults (ATF, thrusts, studied normal faults and negatively inverted thrust ramp; instrumental projected earthquakes from ISIDe Database (ISIDe Working Group, 2007) (black crosses). B section SW-NE (Città di Castello – Monte Nerone) shows also the Marnoso-Arenacea thrusts. Earthquakes from TABOO database (from Valoroso et al., 2017) were projected on the section plane (blue crosses).

Section A was redrawn from (De Donatis et al., 2020), where data from ISIDe (ISIDe Working Group, 2007) were plotted; shows concentration of instrumental earthquakes very close to the intersection between ATF and thrust ramp inverted as normal faults. Section B was drawn following a similar section trace of (Chiaraluce et al., 2017), T1 in Figg. 2 and 3) and (Valoroso et al., 2017), 1 in Fig. 2 and 3) and re-projecting their earthquakes data from TABOO network.

As mentioned in (Chiaraluce et al., 2017), 90% of earthquake records are concentrated at the hanging wall of the low-angle ATF fault. The evident alignment of earthquakes along sections crossing the Città di Castello and Pietralunga area, beyond Monte Nerone, shows faults antithetical to the ATF, such as those under examination, although an exact correspondence has not been found.

The earthquake distribution, however, is related to the extensional tectonics of this sector. Field evidence has to be thoroughly investigated, such as the inversion of thrusts separating the tectonic units of Pietralunga and Borgo Pace of the Marnoso-Arenacea Fm. Although there are no good outcrop expositions, the anomalous stratigraphic position of some key beds at the hanging wall of these thrusts, compared to the main marker bed of the Marnoso-Arenacea Fm (Contessa key bed) at the footwall, suggests an overlap of younger and older stratigraphic units.

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Conclusions

The tectonics of this sector of the Apennines is reinterpreted in light of new field observations and deep data overviews as seismic lines and instrumental earthquakes hypocenters.

From these data, it is clear that recent tectonic activity here is extensive, as indicated recently by other authors (Chiaraluce et al., 2017; Valoroso et al., 2017) simply on the basis of focal mechanisms.

In the Marnoso-Arenacea innermost thrusts, it can be observed that these are nowadays affected by extensional movements, as evidenced in the field by the stratigraphic structure and by the distribution of the deep hypocenters.

On the surface, the faults that dissect the Monte Nerone anticlinorium proceed to the NW in the turbidite units of Marnoso-Arenacea Fm.

Although they are incontestable in some outcrops, the faults under study are not always so evident since they are recent and the last great earthquake could have activated them (historical documents dates back to 1781). Over the last two centuries, the erosion has hidden fault surfaces, if not apparently reversing the displacement (e.g., Sassorotto fault on Monte Cardamagna). Indeed, the rapid erosion of the morphologies due to faulting is also evident from the observations in the soil breaks that formed during the Castelluccio plain earthquake in 2016. Here, fault surfaces with displacements of less than 7 cm, clearly evident in the days surrounding the occurrence of the earthquake, are now erased due to soil erodibility and by agricultural activity.

The fresh and segmented morphology of the ridges and impluvium of the Marnoso-Arenacea Fm, near Monte Forno, would suggest that faults were active after the last glacial phase, which would have eroded and smoothed shapes due to fault movements. Therefore, here, the slopes and counter-slopes are clearly recognizable.

This work is just the beginning of the study of this part of the Apennines, which will have to foresee the contribution of researchers with different skills, such as quaternary geologists and geomorphologists, stratigraphers, structural geologists, and seismologists.

This contribution intends to start a debate on a seismically active sector of the Apennines, similar to that involved in the 2016 earthquake, where communities and human activities are at risk.

Author contribution.

MDD contributed to conceptualization, funding acquisition, investigation (field mapping), data curation, data analysis, supervision and validation, writing original draft preparation. GFP contributed to data curation, validation and visualization. SS contribute to investigation, data analysis and visualization. MA contribute to investigation (field mapping), data curation and data analysis. NMG contribute to data curation and validation. FO contribute to investigation (field mapping), visualization.

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Competing interests.

The authors declare that they have no conflict of interest.

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