ANNALS OF GEOPHYSICS, 69, 4, EP443, 2026; doi:10.4401/ag-9520
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# Evolution of karstic, intermontane plateaux and basins mimicking fault activity: the Rocca di Mezzo case study in the central Apennines, Italy

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Article history: received December 17, 2025; accepted March 18, 2026

## Abstract

This study investigates the Rocca di Mezzo area in the central Apennines (Italy) to evaluate the presence of a hypothesized active and capable normal fault underneath a school edifice. A multimethod approach was applied, including geologic field data, borehole data analysis, paleoseismological trenching, stratigraphic analysis. Field observations indicate the absence of structural features affecting the Meso-Cenozoic bedrock associated to extensional faulting in the sector where the supposed fault should be located. Only structural evidence of reverse faulting related to an inactive compressive tectonic phase was found. Stratigraphic data also indicate that the Meso-Cenozoic bedrock dips gradually westward, buried by Quaternary sediments in the area where the fault was hypothesized, so that the lateral contact between the bedrock and the Quaternary sediments is just related to the stratigraphic setting. Trench excavations across the southern sector of the suspected fault trace revealed lacustrine sequences, with interbedded paleosols, undisturbed by any fault planes. Radiocarbon and archaeological dating confirm the Holocene age of these lake deposits, consistent with other nearby lacustrine sequences, indicating that multiple sectors of the plateau hosted small lakes during the Holocene whose oscillations have been controlled by karstic-related processes. This oscillation has determined phases of deposition and erosion that have strongly conditioned the evolution of this part of the plateau. The present-day geomorphic characteristics of the area, including ponds and numerous dolines, suggest that karstic drainage and local erosion controlled the apparent deepening of the bedrock. The deepening is not therefore caused by the activity of the presumed fault, but it is just caused by local erosion led by karstic processes. These results demonstrate that indirect data or few hints of supposed fault activity can lead to misinterpretation of the presence of active faults. Misinterpretation can be solely ruled out by integrating multiple lines of geological evidence framed in a comprehensive neotectonic analysis, which allows resembling the whole geological evolution of an area over long time spans.

Keywords: Active and capable faulting; Quaternary geology; Karstic processes; Central Apennines; Seismic microzonation studies

## 1. Introduction

The Apennine chain represents the "backbone" of the Italian Peninsula. The reliefs of the belt are mostly composed of carbonate rocks (limestones and marls) deposited in the Meso-Cenozoic marine Tethyan environment. Since the late Cenozoic, the chain has undergone a complex tectonic evolution characterised by two main deformation phases that followed one another in close succession. The first phase was compressional and involved the stacking and imbrication of marine successions through reverse faulting and thrusting. In the central Apennines this phase lasted until the early Pliocene. Subsequently, the central Apennine chain has been affected by a tectonic phase characterised by regional uplift and extensional deformation. These tectonic processes, interacting with climatic oscillations, have played a major role in controlling the geomorphological evolution of this sector of the Italian Peninsula since the late Pliocene (D'Agostino et al., 2001; Galadini et al., 2003) and throughout the Quaternary. This tectonic evolution led to the superposition of extensional tectonic structures onto those related to the preceding compressional phase. Such a complex structural framework, coupled with the carbonate nature of the rocks forming the chain, has favoured the development of widespread karst processes throughout the belt at least since the late Early Pleistocene (Saroli et al., 2012). Studies conducted in several carbonate regions have shown that the interplay between regional uplift, base-level fluctuations and climate exerts a fundamental control on the evolution of karst systems (Audra et al., 2007; Ford and Williams, 2007; Öztürk, 2020; Filipović et al., 2025). Regional uplift promotes the subaerial exposure of carbonate reliefs and initially favours the development of surface drainage networks. With progressive base-level lowering, these networks evolve into subsurface karst drainage systems, leading to the formation of characteristic karst landforms such as sinkholes, dry valleys and flat-bottomed depressions. The geometry and efficiency of karst systems respond to both tectonic and climatic forcing. Phases of incision and erosion are commonly associated with base-level lowering, whereas base-level rise may locally cause flooding and the reactivation of pre-existing conduits, as documented in several karst regions worldwide (e.g. Audra et al., 2007; Bočić et al., 2015; Öztürk, 2020; Filipović et al., 2025 and references therein). Tectonics influences the development and evolution of karst systems in at least two main ways. First, karst landforms commonly align with structural lineaments and tectonically controlled orographic features (Bini, 2004; Rubio et al., 2007; Saroli et al., 2012, 2022; Öztürk, 2020; Čar and Šegina, 2024; Filipović et al., 2025). Second, active tectonics may significantly affect hydrogeological regimes. Strong earthquakes can induce permanent or transient changes in groundwater circulation both in the near field and at distances of several hundred kilometres from the epicentral area (e.g. Mastrorillo et al., 2019; Valigi et al., 2020; Zullo et al., 2026 and references therein). In tectonically active carbonate regions, the strong influence of karst processes on both surface and subsurface morphology significantly overlap on tectonic control and, in some cases, complicate and influence the recognition of active tectonic structures. Indeed, karst-related geomorphological evolution may locally generate morphological discontinuities and landforms that may resemble the surface expression of active normal faulting or it can influence the rise and fall of local base levels inducing phases of sedimentation or erosion that can be misinterpreted as morpho-tectonic evidence. As a consequence, the accurate analysis of karst-controlled morphogenesis represents a significant issue when investigating active and capable faults in carbonate mountain belts, where the assessment of surface faulting hazard relies on the correct identification of tectonic structures. Despite the well-recognised interaction between tectonics and karst processes in carbonate mountain belts, relatively few studies have explicitly addressed the potential for karst processes to be misinterpreted as evidence of fault activity. The case study examined in this work provides an example of the challenge that represents the identification of active and capable faults in karst-dominated carbonate terrains. The investigated area is located in the axial sector of the central Apennines, which is affected by systems of normal faults displaying geological evidence of movement during the Late Pleistocene-Holocene and therefore considered active and capable, i.e. capable of producing surface displacement (e.g. Giraudi, 1989a; Galadini and Galli, 1999, 2000; Galadini et al., 2000, 2001). The activity of these extensional tectonic structures contributed to the formation of large intermontane depressions, such as the L'Aquila, Sulmona and Fucino basins, which acted as sedimentary traps for Quaternary continental deposits. Some smaller depressions located along this sector of the chain, forming intermontane plateaux, are also bounded by active normal fault systems. Examples include the Aremogna-Cinque Miglia basin (Frezzotti and Giraudi, 1989; D'Addezio et al., 2001), the Campotosto basin (Calamita and Pizzi, 1994; Galadini et al., 2000; Galadini and Galli, 2003; Falcucci et al., 2018), the Castelluccio basin (e.g. Galadini and Galli, 2003; Di Nezza et al., 2018; Sapia et al., 2021), and the *Altopiano delle Rocche-Piano di Pezza-Campo Felice* basin system (Giraudi, 1989a; Cinti et al., 1992; Pantosti et al., 1996; Villani et al., 2024). The *Altopiano delle Rocche* plateau constitutes the focus of the present study. Many towns and villages of the central Apennines are located along or close to the surface traces of active faults. Surface faulting therefore represents one of the major geological hazards that must be carefully considered in land-use planning and management. In this context, following the 2009 L'Aquila earthquake (MW 6.2), regulations were issued to govern land use in areas affected by the surface trace of active and capable faults. These rules fall within the broader framework of the Italian Seismic Microzonation Guidelines (Gruppo di Lavoro MS, 2008; Commissione Tecnica per la Microzonazione Sismica, 2015), according to which a fault must show evidence of activity within the last 40 kyr to be classified as active and capable. In karst-dominated terrains, however, geomorphological and subsurface features related to karst evolution may locally resemble tectonic displacements, potentially leading to ambiguous interpretations during seismic microzonation studies. These guidelines represent an attempt to address the hazard associated with surface faulting by distinguishing zones across fault traces characterised by different levels of exposure to this geological hazard. A recurring difficulty arises when presumed faults are reported in the literature or hypothesised on the basis of very limited geological information. Determining whether a presumed active and capable fault actually exists often requires complex multidisciplinary investigations. These difficulties are further amplified in highly urbanised areas, where logistical constraints and limited exposure hinder direct geological observations. In recent years, an increasing number of studies have addressed the problem of active and capable faulting in the central Apennines in relation to the construction of critical infrastructures, such as schools, cultural buildings and industrial facilities (e.g. Maceroni et al., 2019, 2022; Boncio et al., 2020; Tallini et al., 2025). These studies have shown that the identification of active and capable faults requires the application of a rigorous geological approach in order to avoid premature or uncritical interpretations of fault capability based on limited and ambiguous geological evidence. Another significant example highlighting the need for a robust approach to defining active and capable faults in the central Apennines is represented by the investigations carried out in urban areas affected by the 2016-2017 seismic sequence of central Italy. These studies were conducted within the framework of an agreement between the Commissario Straordinario alla Ricostruzione and the Istituto Nazionale di Geofisica e Vulcanologia (https://sisma2016data.it/faglie-attive-e-capaci/; last accessed March 2026). This agreement represents the first Italian prototypal project led by the main national research and academic institutions addressing the issue of active and capable faulting, specifically focused on the epicentral area of the 2016-2017 seismic sequence. On these grounds, the present work addresses these methodological challenges by examining the Rocca di Mezzo area, where a previously unrecognised active and capable fault strand has been hypothesised on the basis of limited subsurface evidence. The *Altopiano delle Rocche-Piano di Pezza* plateau is located in the axial sector of the central Apennines (Fig. 1a), several tens of kilometres south-south-east of the city of L'Aquila, and hosts a number of historical villages including Rocca di Cambio, Terranera, Rocca di Mezzo, Rovere and Ovindoli, from north to south. The area has been the subject of several geological studies focused on active tectonics (Giraudi, 1989a; Cinti et al., 1992; Pantosti et al., 1996; Galadini and Galli, 2000; D'Addezio et al., 2001). These authors documented the presence of normal fault strands commonly considered active and capable. Indeed, these faults (Figs. 1b and c) are regarded as belonging to the 27-km-long Colle Cerasitto-Campo Felice-Ovindoli-Pezza active fault system (hereafter CCFOPF) (e.g. Galli et al., 2008). During preliminary investigations carried out for the Level 3 seismic microzonation study of Rocca di Mezzo (hereafter RdM), which represents the highest level of detail in the Italian seismic microzonation framework, borehole data revealed that the Meso-Cenozoic carbonate bedrock (Figs. 2a-c), upon which the village is built, locally deepens by a few metres in the western sector of RdM, specifically beneath the site of the local school building and within an area of a few tens of metres. Although the observed vertical offset is limited (a few metres), its potential tectonic origin raised significant concern because of the proximity of the village to splays of the CCFOPF (approximately 2 km in plan view; Figs. 1b and c) and the presence of a critical infrastructure.

Therefore, this bedrock deepening has been tentatively interpreted as related to vertical displacement caused by an additional, previously unidentified active normal fault splay. This hypothetical structure would strike approximately NNW-SSE and dip towards the WSW, consistent with the orientation of several segments of the CCFOPF. According to this interpretation, the activity of the presumed fault would have lowered the bedrock in the western sector of RdM. However, this supposed tectonic structure is currently undocumented in geological maps and scientific literature and was not identified even during the preliminary Level 1 seismic microzonation studies (Figs. 2a and b). This case study therefore provides an opportunity to evaluate whether such an interpretation is supported by the geological and geomorphological framework of the area, or whether alternative processes related to karst evolution may explain the observed subsurface configuration. In this work we investigate the RdM sector and its surroundings (Fig. 3) through Quaternary geological investigations framed within a neotectonic analysis (Galadini et al., 2023), based on a multi-methodological approach aimed at reconstructing

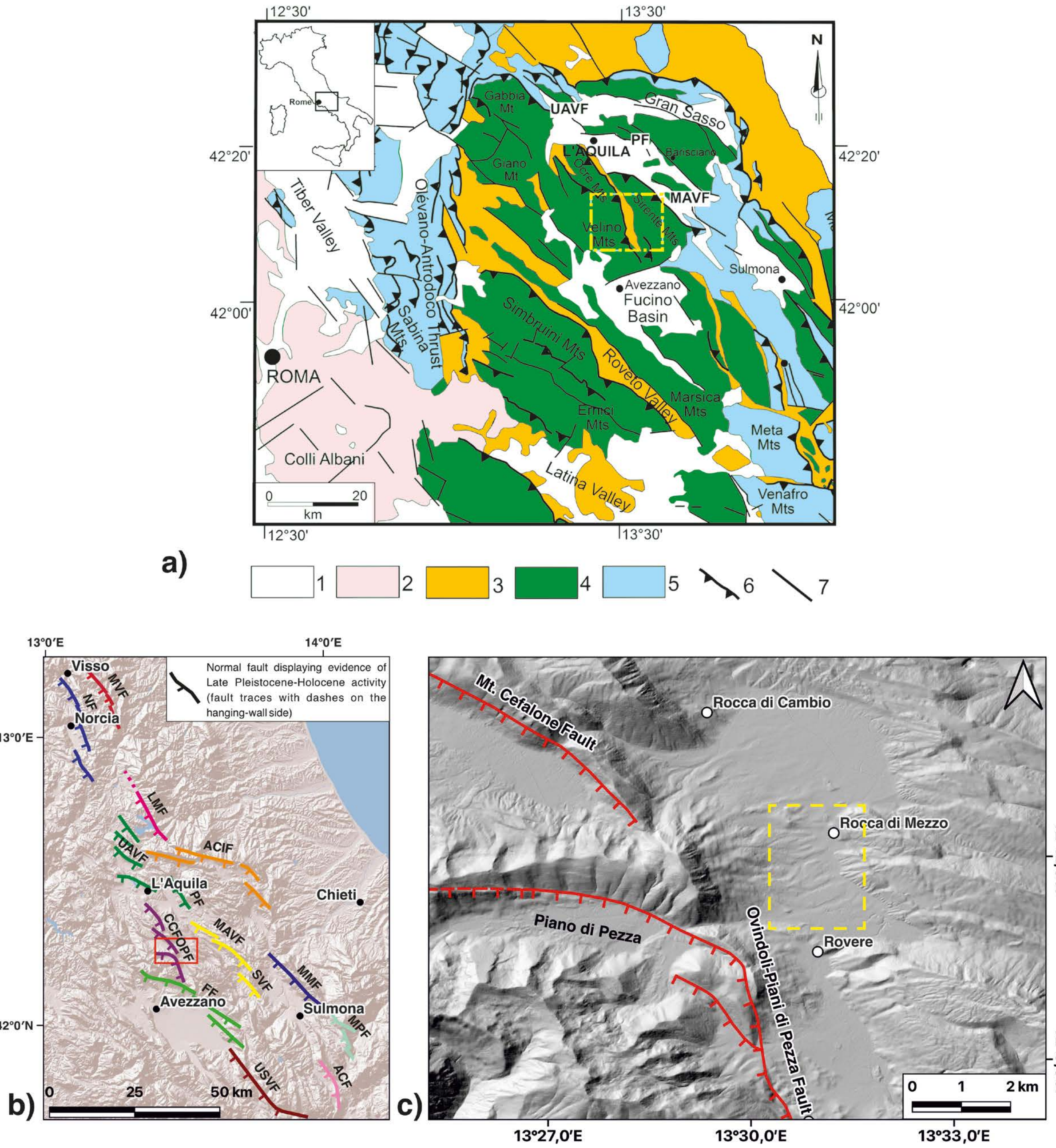

**Figure 1.** (a) Simplified geological and structural sketch map of the central Apennines: 1) Plio-Quaternary marine and continental clastic deposits; 2) Pleistocene volcanic deposits; 3) Tortonian-Pliocene synorogenic hemipelagic and turbiditic sequences; 4) Triassic-Miocene carbonate platform deposits; 5) Lias-Miocene slope and pelagic deposits; 6) Main thrust fault; 7) Main normal and/or strike-slip fault. The yellow dashed rectangle outlines the study area (modified from SGI, 1955); (b) seismotectonic framework of the central Apennines (shaded relief) showing active faults. Fault systems: MVEF, Mt. Vettore; NFS, Norcia; LMF, Laga Mts.; ACIF, Assergi-Campo Imperatore; UAVFS, upper Aterno Valley; CCFOPF, Cerasitto-Campo Felice-Ovindoli-Pezza; MAVFS, middle Aterno Valley; SVF, Subequana Valley; MMF, Mt. Morrone; FF, Fucino; MPF, Maiella-Porrara; ACF, Aremogna-Cinquemiglia; USFS, upper Sangro Valley (modified from Falcucci et al., 2011). The red rectangle shows the area detailed in panel c; (c) shaded relief of the *Altopiano delle Rocche* and *Piano di Pezza* plateaux, showing a simplified map of the Ovindoli-Piano di Pezza fault system (modified from Pantosti et al., 1996). The study area is indicated by the dashed yellow box.

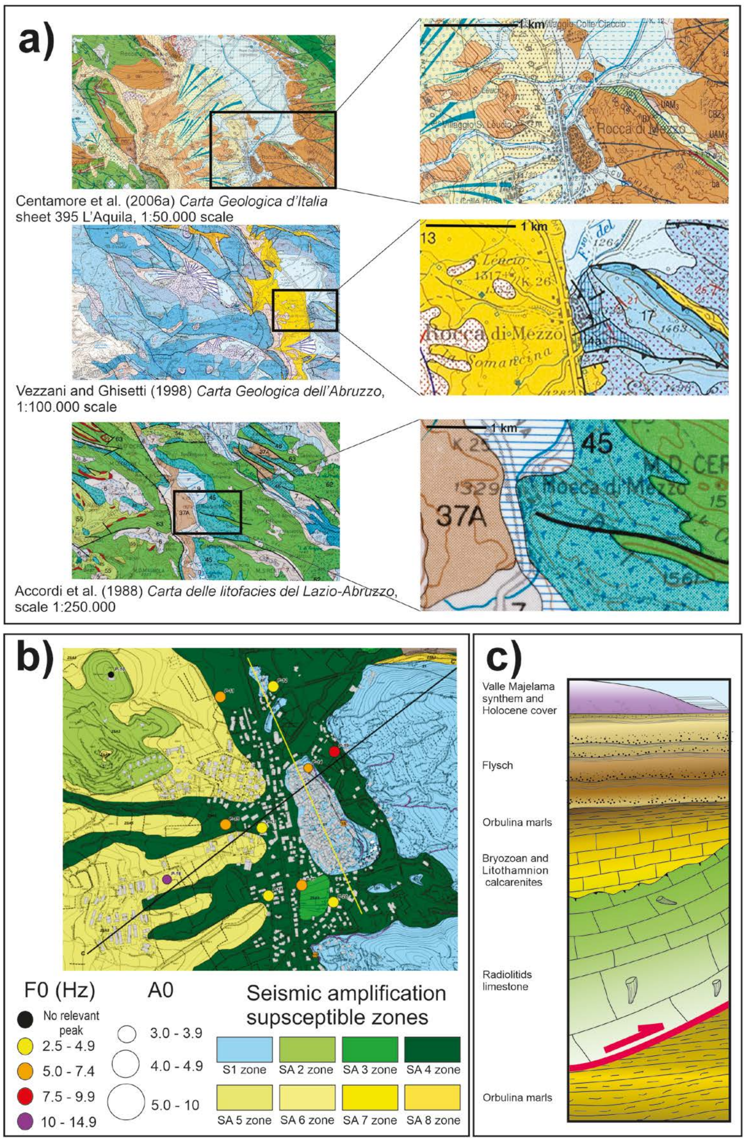


**Figure 2.** (a) Available geological cartography of the study area. On the right side, RdM area zoomed. Outcropping lithologies are described as follows by the respective authors. Centamore et al. (2005a): calcarenitic unit rich in bryozoans, bivalve fragments, lithotamnion (CBZ3, "calcareniti a Briozoi"); clayey marls and marly limestone (UAM3, "argille ad Orbulina"); micritic limestone with bioclastic horizons (IBX, "calcari intrabauxitici"); continental alluvial deposits, gravel-silty to silty-sandy (AVM, "Valle Majelama" synthem); continental alluvial and lacustrine deposits, alluvial fans and colluvium (OLO). Vezzani and Ghisetti (1998): mudstones-wackestones with bioclastic lens (17, "calcari biancastri a radiolitidi"); calcarenitic grainstones to marly calcarenites (15, "calcareniti a Briozoi e Litotamni"); Orbulina marls (14a, "marne a Orbulina"); arenaceous-pelitic turbidites (13, "flysch della Val Roveto"); lacustrine silty-sandy deposits, gravel-sandy fluvial and fluvio-glacial deposits, locally residual and terre rosse (1a), moraine deposits (1b). Accordi et al. (1988): Dogger-Lower Cretaceous peloidal mudstones, dolomitic mudstones, Orbitolina marls (63, "Marne ad Orbitolina"); packstones and grainstones with pelagic benthic fauna alternating with thick bedded skeletal grainstones (45, "Calcari a Briozoi e Litotamni"); sandy turbidites with complete Bouma sequences (37a, "Facies arenaceo-pelitica"); terraced recent alluvial deposits: sands, gravels and conglomerates, alluvial fill (9); taluses, talus fans, colluvial deposits, *terre rosse*, sinkhole floor deposits, eluvial deposits of lacustrine basins, landslides, spoils, reclamation fillings, weathering altered pyroclastic deposits (7); (b) First-level microzonation study map, showing the absence of the hypothesized fault within the village of RdM. Sampalmieri G., Gragnanini V. (October 2012) "*Microzonazione sismica Carta delle MOPS e delle frequenze fondamentali di vibrazione. Regione Abruzzo Comune di Rocca di Mezzo* (AQ)" scale 1:5000. Frequency (F0) and amplitude (A0) of the H/V peak and seismic amplification susceptibility is also shown; (c) summarised stratigraphy of the study area (not to scale). See lithostratigraphy in Section 2.2.

the Quaternary geological evolution of the area and assessing the possible effects associated with the activity of the hypothesised tectonic structure. To this end, we integrate geological-structural and geomorphological analyses with subsurface geological data, supported by the interpretation of aerial photographs and the examination of stratigraphic information derived from several boreholes drilled in different sectors of the RdM area, as well as from an excavation made for paleoseismological investigations. Through the integration of these approaches, we aim to provide a definitive assessment of the presence of the inferred fault. More broadly, this work highlights how the interpretation of potential surface faulting in carbonate environments requires in-depth geological analysis. The Rocca di Mezzo case study illustrates how karst-controlled morphogenesis may produce geological configurations that could be mistakenly interpreted as evidence of active tectonics, emphasising the importance of rigorous multidisciplinary investigations for active faulting assessment. As for the organisation of the paper, we first outline the geological framework of the region, with particular attention to the structural characteristics of the RdM area. The main body of the paper presents field data derived from geological surveys, borehole stratigraphy analysis, palaeoseismological trenching and a comprehensive geomorphological analysis of the RdM area and its surroundings. The discussion section provides an interpretation of the results obtained from these analyses. Finally, the conclusions summarise the main findings of this study and highlight broader methodological aspects concerning the identification of active and capable faults, as well as the potential risk of misinterpreting supposed tectonic features in karst-controlled environments.

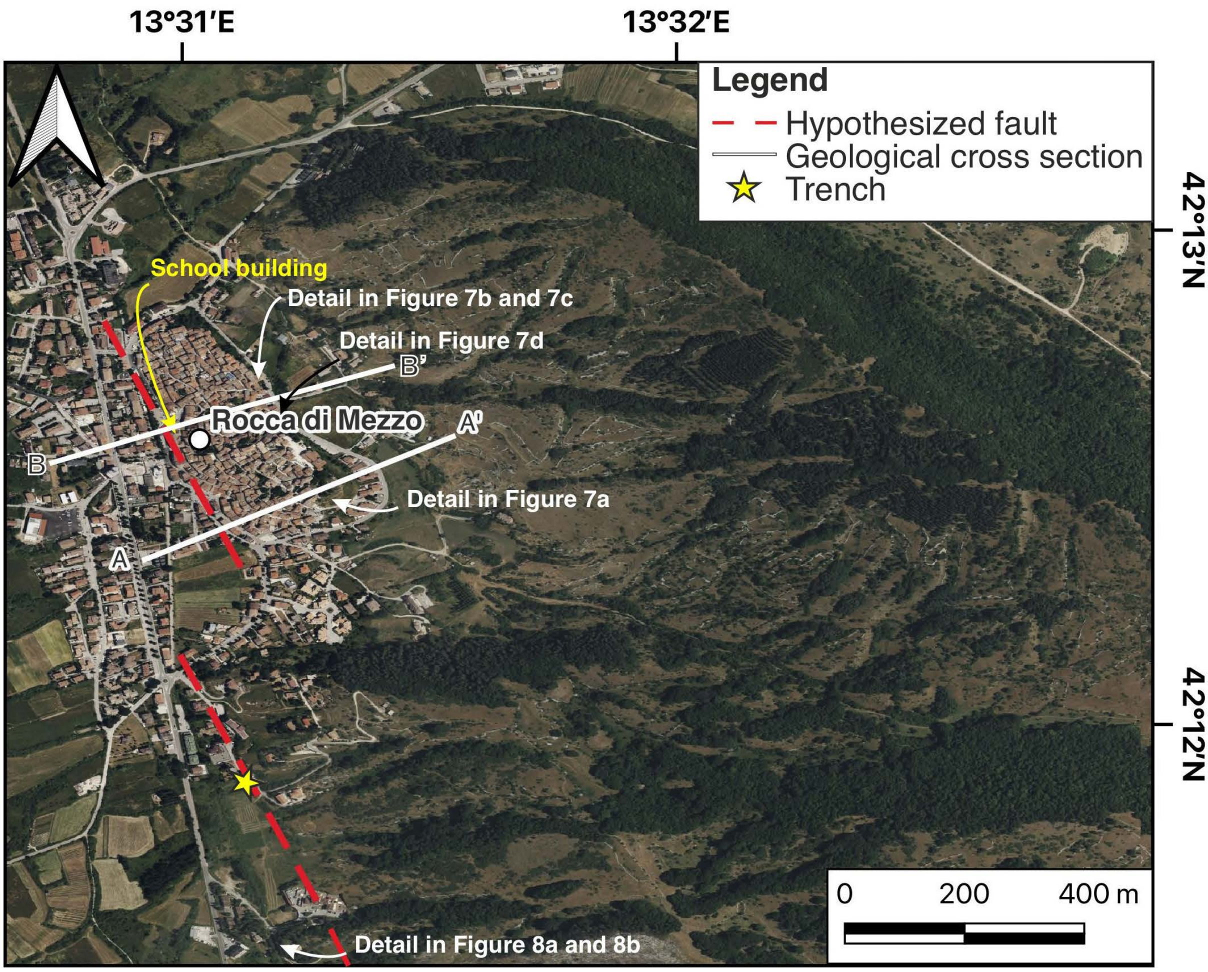


**Figure 3.** Satellite image (in plan view) of the RdM area (source: Bing Satellite, URL: https://www.bing.com/maps/?cc=it&cp=41.820455%7E12.525101&lvl=11.0; last access: May 2025. The dashed red line marks the trace of the hypothesised normal fault possibly affecting the western sector of RdM.

# 2. Geological setting

## 2.1 Tectonic framework

The Apennine chain is a post-collisional fold-and-thrust belt formed by compressional tectonic structures with a structural axis trending NW-SE. These structures developed during the Neogene period as a result of the collision and convergence between the European plate and Adria microplate. This compressive tectonic regime led to the formation of east-verging, NW-SE-trending stacked thrust units that become progressively younger towards the east (Patacca et al., 1990; Cipollari et al., 1999; Cosentino et al., 2010). This process led to development of an orogenic chain-foredeep-foreland system, in which different tectonic units have been overlapped through a piggy-back sequence (Patacca et al., 1990; Centamore et al., 2002; Cosentino et al., 2010; Carminati and Doglioni, 2012). The *Altopiano delle Rocche* plateau is surrounded by reliefs of the Sirente and Velino massifs (Fig. 1a) made of Meso-Cenozoic carbonate marine sequences and Miocene terrigenous deposits which compose five main stacked tectonic units (Centamore et al., 2005b), shown in Fig. 4. The whole area is considered part of the geological-structural framework of Mt. Giano-Marsica unit (Centamore et al., 2002; 2005b).

While the compressive tectonic deformation migrated towards the eastern and northeastern sectors, the central Apennine chain experienced uplift and contemporaneous extensional faulting along the main axis of the chain since late Pliocene (Galadini et al., 2003; Cosentino et al., 2010; D'Agostino et al., 2001; Carminati and Doglioni, 2012). This extensional regime promoted the orogenic collapse of the Apennines tectonic wedge, inherited from the preceding compressional phase, and led to the nucleation of NW-SE trending, SW dipping normal fault systems. These extensional tectonic structures led to the development of half-graben tectonic depressions, namely intermontane basins aligned following the chain trend and alternating with carbonate ridges and massifs (Ghisetti and Vezzani, 1999; D'Agostino et al., 2001; Cosentino et al., 2017). These depressions, bounded on the eastern sides by normal faults which often form tens of kilometers-long systems made of several splays, act as traps for sedimentary continental sequences (Ghisetti and Vezzani, 1999; Galadini and Galli, 2000; Galadini et al., 2000, 2003;

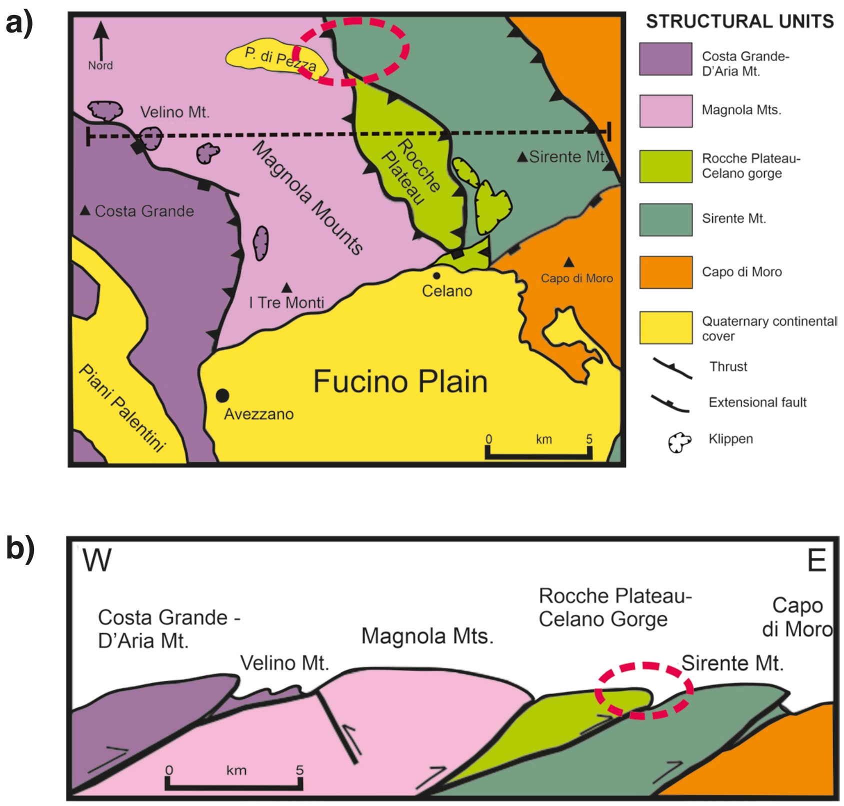


**Figure 4.** Compressive tectonic units outcropping in the study area and their structural relationship, in plan (a) and schematic section (b) view. Red dashed circle indicates the location of the study area, black dashed line indicates location of the schematic section (modified from Centamore et al., 2005b).

D'Agostino et al., 2001; Cosentino et al., 2010, 2017; Gori et al., 2017 and references therein). Geological evidence for the current activity of some of the extensional fault systems is provided by the displacement and deformation of both Late Pleistocene-Holocene continental deposits and landforms. This evidence is supported by paleoseismological investigations, which indicate that active faults within the chain are characterized by long recurrence intervals of activation, typically on the order of 1000-2000 years per fault system (Galli et al., 2008). These active faults relate to seismogenic sources that have generated earthquakes with magnitudes up to Mw 7 in the past, and which may retain the potential to produce similarly strong events in the future (Galadini and Galli, 2000; Boncio et al., 2004; Valentini et al., 2019). Notable examples include the major earthquakes that affected this sector of the central Apennines in historical times, such as the Jan. 14, 1703 Norcia (Mw 6.92), the Feb. 2 1703 L'Aquila (Mw 6.67), the 1915 Marsica (Mw 7.1) earthquake (Rovida et al., 2022) as well as the recent 2009 L'Aquila (Mw 6.29) and the 2016 central Italy (Mw 6.61) seismic sequences (Falcucci et al., 2009; Boncio et al., 2010; EMERGEO, 2010; Galli et al., 2010; Chiaraluce et al., 2011; Cinti et al., 2011; Vittori et al., 2011; Gori et al., 2012; Moro et al., 2013; Falcucci et al., 2016; Chiaraluce et al., 2017; Civico et al., 2018; Galadini et al., 2018; Gori et al., 2018; Villani et al., 2018; Cheloni et al., 2019; Cinti et al., 2019; Galli et al., 2019; Castello et al., 2022).

The *Altopiano delle Rocche-Piano di Pezza-Campo Felice* plateau (Fig. 1c), located in the central Abruzzi region at about 1300 m a.s.l., has been extensively investigated in previous studies (e.g. Bosi and Manfredini, 1967; Centamore, 2002, 2005a, 2005b; Giraudi 1989a, 1992, 1995, 1997; Villani et al., 2015; Sapia et al., 2025 and references therein). This area lies along the ~27-km-long CCFOPF, a major active normal fault system in the central Apennines (Fig. 1b), considered the surface expression of a seismogenic source potentially responsible for Mw ~6.7 earthquakes (Pantosti et al., 1996; Galli et al., 2008). Specifically, the *Piano di Pezza* sector is bounded by a WNW-ESE trending fault splay, which forms the northern margin of the intermontane basin, marked by an impressive scarp resulting from the normal fault motion (Pantosti et al., 1996). To the south, north of Ovindoli (Fig. 1c), another scarp was evident until decades ago (before the building of touristic structures), which resulted from the post Last Glacial Maximum (henceforth LGM) oblique fault motion (left-lateral component) (Giraudi, 1989a). These fault sections displaced continental deposits of Late Pleistocene-Holocene age (Giraudi, 1995; Centamore et al., 2005b; Galli et al., 2008). Paleoseismological investigations performed by Pantosti et al. (1996) permitted the authors to identify three Holocene fault activation events: the most recent events (E1) occurred between 860 and 1300 CE (1070 ± 50 yr BP and 690 ± 60 yr BP), i.e., during the Middle Ages; the intermediate event (E2) dates approximately 1900 BCE (3630 ± 70 yr BP) and the oldest event (E3) between 3300 and 5000 BCE (4540 ± 70 and 6090 ± 80 yr BP), defining a recurrence interval of fault activation of approximately 2760-3200 years.

## 2.2 Lithostratigraphy of the pre-Quaternary marine sequences

The stratigraphic sequence identified during field surveys matches with known lithostratigraphic units reported at different scales in the geological maps of Accordi et al. (1988), Vezzani and Ghisetti (1998) and Centamore et al. (2005a) (see Fig. 2a for reference).

According to available geological cartography, the Latium-Abruzzi domain experienced persistent carbonate platform sedimentation from the Pliensbachian to the Aptian-Albian, under variable environmental settings ranging from inner platform to ramp (Accordi et al., 1988). Thick mudstone sequences, interbedded with exposure-derived intraformational breccias, record restricted depositional environments, characterized by alternating cycles of subaqueous deposition and subaerial erosion.

The Eocene-Oligocene evolution of the area was characterised by a shift in basin dynamics, leading to the cessation of carbonate platform sedimentation and the development of wide transitional zones between basins and platform domains. According to Brandano (2017), from the late Paleocene to early Miocene, the Latium-Abruzzi carbonate platform was subjected to wave action, resulting in the accumulation of bioclastic sediments during transgressive and sea-level highstand phases, while during lowstand stages, eroded sediments accumulated as intercalations within basinal hemipelagites.

The transition to carbonate-ramp facies occurred during the Middle Miocene, represented by the transgression of the *Calcari a Brizoi e Litotamni* formation over the Cretaceous substrate. This environmental transition marked the onset of hemipelagic grey marls rich in planktonic foraminifera, belonging to the *Marne a Orbulina* formation. Subsequently, sandy siliciclastic turbidites were deposited in the Apennine foredeep during the Tortonian-Messinian. These deposits include complete Bouma sequences made of silty-pelitic sediments of the Flysch formation.

## 2.3 Lithostratigraphy of the Quaternary continental sequences of *Altopiano delle Rocche* and surrounding areas

In the central Apennines, including the *Altopiano delle Rocche* area, the interaction between tectonic activity and climate has resulted in a complex succession of erosional and depositional processes (Bosi et al., 2003). The late Pliocene marked the initiation of continental deposition in the central Apennines, with the formation of lacustrine and alluvial deposits (Bosi et al., 2003). The *Conglomerati di Monte Coppe* formation, which outcrops near Rovere (Centamore et al., 2005b), is an example of this oldest continental geological history. This phase of initial inland deposition was followed by progressive regional uplift that continued into the Early Pleistocene, and that incremented in rate since the Middle Pleistocene (D'Agostino et al., 2001; Cosentino et al., 2010).

Multiple glacial and interglacial cycles have profoundly shaped the landscape of the *Altopiano delle Rocche* and surroundings during the Pleistocene: evidence of moraine and outwash deposits support the importance of climatic fluctuations on sedimentation (Pantosti et al., 1996; Giraudi, 1997). The LGM itself, dated at ~26.5-15 kyr BP (e.g. Clark et al., 2009), left a clear geomorphic and stratigraphic imprint, as indicated by the studies in the geographically adjacent *Valle Majelama*, which identified extensive glacial deposits and landforms, with the maximum ice expansion occurring around 22 kyr BP (Frezzotti and Giraudi, 1992; Centamore et al., 2005a). In the subsequent Late Glacial phase, several glacial readvances occurred, which led to the formation of numerous morainic and outwash deposits, with evidence of paleosol development during warmer intervals (Centamore et al., 2005b). Accordingly, the Late Pleistocene *Valle Majelama* Synthem is characterised by several large alluvial fans, sourced from the surrounding slopes that were depleted of vegetation and soil during the cold climate of the last MIS 2 glaciation (Centamore et al., 2005a; 2005b). These alluvial fan and related plain deposits, consisting of gravel with sandy horizons or lenses, are heterotopic with coeval lacustrine sediments.

The Holocene is marked by continued deglaciation; glacial retreat led to the deposition of colluvial and detrital sediments grading laterally into lacustrine deposits (Giraudi 1997; Giraudi 1989b; Centamore et al., 2005a). Active geomorphic processes during this time included fluvial incision on older alluvial fans, as well as karst processes and ongoing slope instability (Centamore et al., 2005b).

## 2.4 Main geomorphological characteristics of the *Altopiano delle Rocche* plateau

While many of the intermontane basins in the central Apennines owe their Quaternary evolution to subsidence of the extensional faults hanging wall, other intermontane depressions and plateaux derive from the interaction of erosive processes and a specific bedrock geology (D'Agostino et al., 2001; Galadini et al., 2003; Piacentini and Miccadei, 2014). The *Altopiano delle Rocche* plateau has been defined as a suspended paleo-valley whose current form results from the combined action of tectonics and erosional processes, with karst being one of its most prominent geomorphic characteristics (Centamore et al., 2005a). As a result, the geomorphic setting is characterized by a gently sloping morphology with closed depressions, within which subsurface, endorheic drainage develops through karst processes. The plateau is developed upon a structural edifice compressive morphology consisting of stacked thrust units – composed of Cretaceous to Miocene carbonates and Tortonian sandy-siliciclastic turbidites – unconformably overlain by Quaternary slope, alluvial and lacustrine sedimentary sequences (Accordi et al., 1988; Vezzani e Ghisetti 1998; Centamore et al., 2005a). Differences in permeability between these lithologies result in differential water absorption that favours various hydrological features such as surface runoff, water stagnation or stream entrenchment (e.g. Ford and Williams, 2007). Since the late Pliocene, tectonic uplift promoted deepening of the local base level and consequent erosion; this led to a surficial drainage network – favoured according to some authors (Ford and Williams, 2007 and references therein) by the impermeable cover – which later evolved into hypogean drainage by cutting into the substrate to reach water-base level equilibrium (e.g. Audra et al., 2007; Ford and Williams, 2007; Bočić et al., 2015; Öztürk, 2020). Karst develops within this fluvial erosion-dominated environment, increasing rock permeability to the point of pervasive karst dissolution. With ongoing incision, the surficial drainage pattern becomes less efficient, and main watercourses entrench into canyons before reorganizing into subsurface settings (Audra et al., 2007; Ford and Williams, 2007; Bočić et al., 2015; Öztürk, 2020). The plateau surface displays numerous karst landforms, such as dolines, uvalas, poljes and sinkholes which formed by extensive carbonate erosion via meteoric water percolation, often eased by pre-existing fractures or substratum weaknesses (Centamore et al., 2002; 2005b). A prominent example of this activity is the Stiffe karst resurgence (located S-SE of L'Aquila), fed by a sinkhole in the northern sector of the *Altopiano delle Rocche* (Centamore et al., 2005b). Several dendritic and endorheic stream systems are distributed across the plateau, connected to many swallow holes located in different sectors (Consoli, 2004). Locally, this endorheic system controls surface water accumulation; the formation of these ephemeral (or perennial) lakes depends not only on meteoric input, but on low-discharge springs from the surrounding massifs (Giraudi, 1997; Bini, 2004; Dramis and Ollier, 2016). The stagnation prone bedrock, the structural origin, and the interior drainage system collectively identify the study area as a karst polje (Bini, 2004; Ford and Williams, 2007; Bočić et al., 2015; Öztürk, 2020). Following Čar and Šegina (2024), a polje is a large depression formed by selective karstification of tectonic structures at the groundwater level. In the study area, structural influence of the tectonic-related discontinuities clearly favoured the growth of karst features (Centamore et al., 2005a; Saroli et al., 2022). Central to polje dynamics is the inflow/outflow balance (tributaries and springs contribute to the water input, whereas the outflow is mainly attributed to swallow holes) which regulates flooding episodes in relation to the surface corrosion and water table fluctuations (Ford and Williams, 2007; Rubio et al., 2007).

# 3. Field data

The bulk of data collected through a multi-method analysis aimed at investigating the possible presence of an active fault in the RdM area is described here.

## 3.1 Geological survey

We performed a geological and structural survey in the RdM area focused to assess possible structural features associated with the suspected extensional fault strand affecting the carbonate bedrock exposed in the village. Indeed, the long-term activity of a tectonic structure is supposed to leave a "footprint" in the structural characteristics of the affected terrains. Field observations revealed that the foundation area of RdM is a carbonate relief characterized by sets of conjugate shear planes (Figs. 5 and 6). These structures were identified in several sectors and analyzed both geometrically and kinematically, in order to derive their spatial orientation and constrain their compatibility with the ongoing tectonic regime. Geometric analysis was based on measurements of strike and dip of the fault and shear planes, whereas kinematic interpretation relied on the observation of shear-sense indicators and conjugate planes. The resulting orientations and inferred sense of motion consistently indicate the presence of structural features consistent with compressional deformation, which is incompatible with the kinematics expected for a NW-SE striking active extensional fault. The structural evidence indicates that the shear planes are related to low-angle NW-SE striking reverse faults (Figs. 5a, b, 6a, b and 7) or to high-angle structures striking NE-SW (the latter being perpendicular to the trend of the supposed normal fault; Figs. 5b, c, d and 6b), adjoining to the reverse fault planes. The geometric and kinematic characteristics are thus not consistent with the presence of a NW-SE striking extensional fault; they are rather related to the compressional tectonic phase, active in this region until the Late Miocene-Early Pliocene. The high-angle NE-SW striking shear planes are likely tear faults that disrupted the NE migration of the thrust front.

Furthermore, the bedrock exhibits NW-SE to WNW-ESE-oriented layers, dipping towards the western and southwestern sectors, indicating that they are arranged as a westward-dipping monocline (Figs. 6a and 7).

The historical center of RdM is located on a carbonate cliff that geologically corresponds to a unit displaced by a NNW-SSE-oriented thrust plane identified in the eastern sector, where the *Calcari a Briozoi e Litotamni* formation overlies the *Marne a Orbulina* formation (Figs. 5a and 7).

In the western sector of the study area, the Miocene siliciclastic turbidite sequence is extensively exposed, in the hanging wall of the hypothesized normal fault. Nonetheless, the attitude of the turbidite formation is geometrically concordant with the other carbonate bedrock formation occurring in the footwall (Figs. 2a and c), suggesting geometrical and stratigraphic continuity of the pre-Quaternary marine terrains across the supposed normal fault, without any stratigraphic or geometric anomaly potentially attributable to extensional displacements.

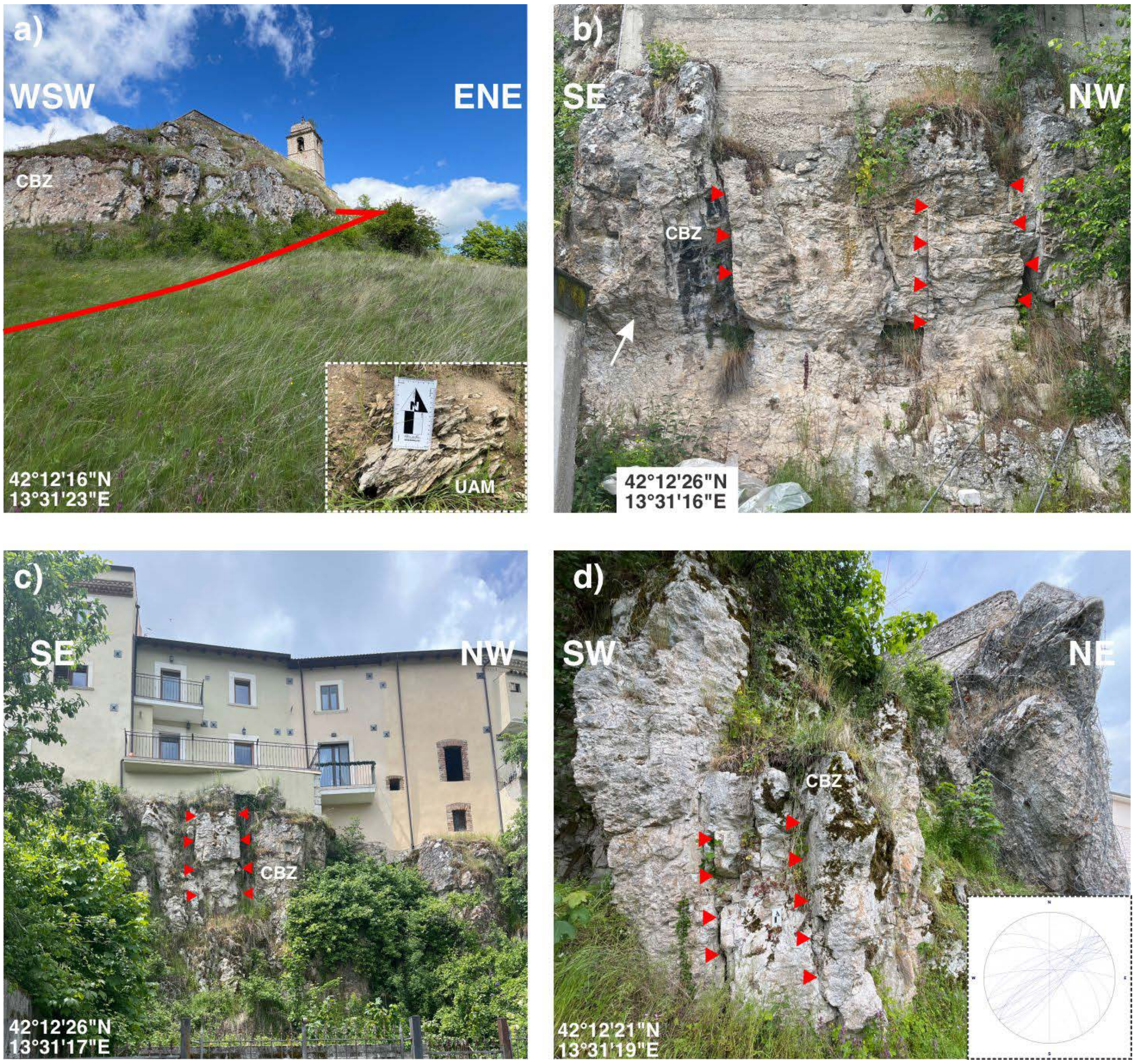


**Figure 5.** (a) Outcrop of carbonate bedrock cliff onto which the RdM village is built, showing the *Calcari a Briozoi e Litotamni* Fm. overlying the *Marne a Orbulina* Fm through a thrust (marked by the red line). A close-up view of the *Marne a Orbulina* is provided in the inset; (b), (c), and (d) high-angle shear planes (indicated by red triangles) affecting the bedrock in the RdM area, associated with compressive tectonic deformation. Stereographic projection of the shear planes shown in inset 'd'; the white arrow in 'b' indicates the thrust plane.

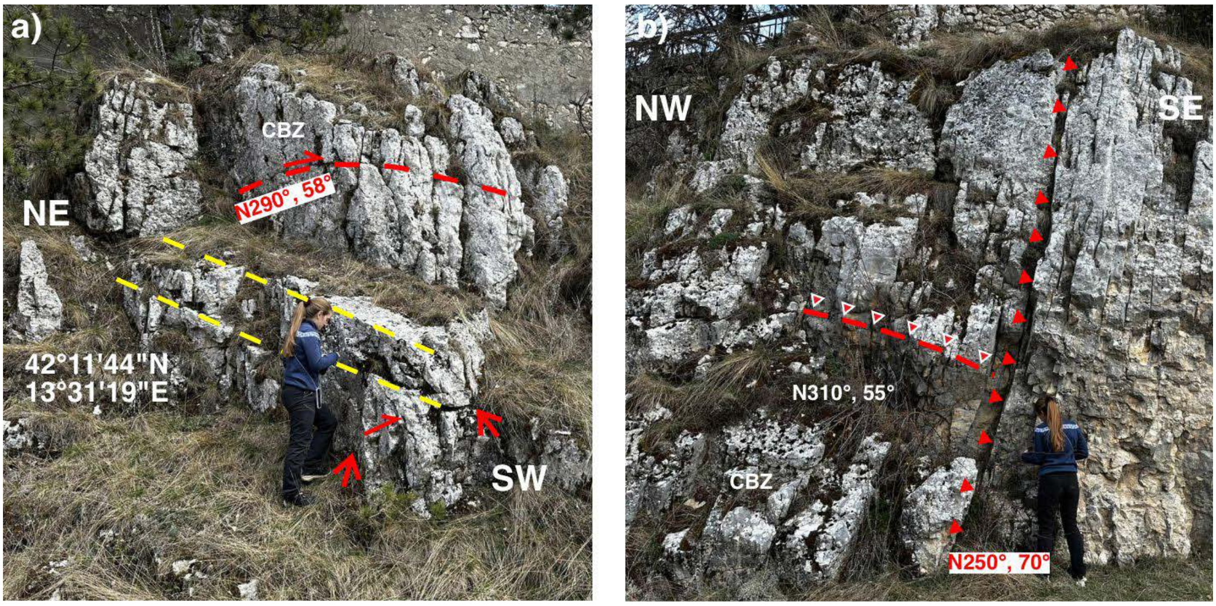


**Figure 6.** (a) Shear planes (thrusts) affecting the bedrock, highlighted by dashed red lines, associated with compressive tectonic deformation. Dashed yellow lines indicate the attitude of the bedrock; (b) high-angle shear planes affecting the bedrock (red triangles), associated with compressive tectonic deformation. Dashed red line and red-and-white triangles indicate the thrust plane.

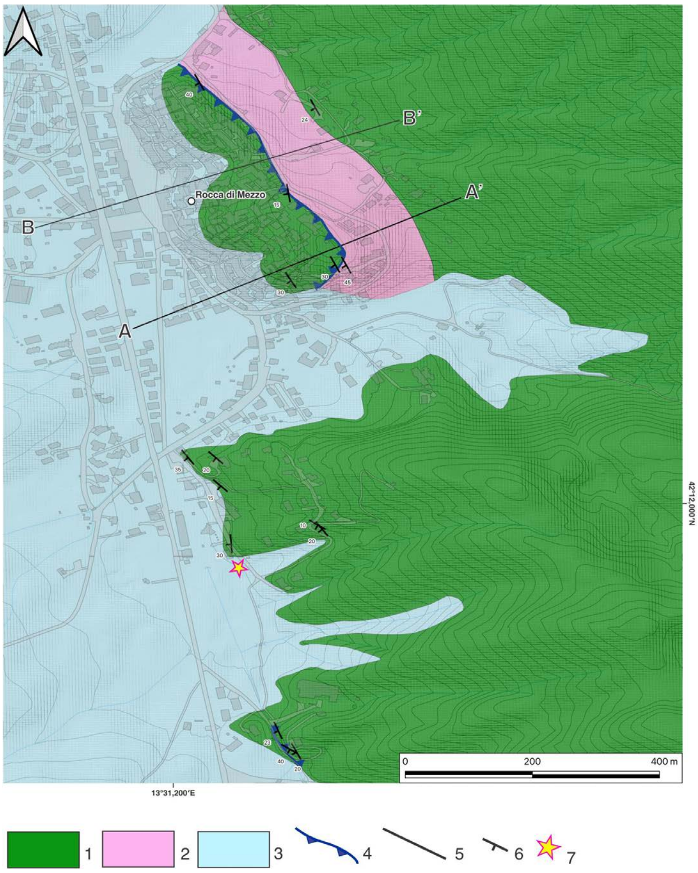


**Figure 7.** Simplified geological map of the study area derived from field and borehole data (see Fig. 8 for borehole locations and stratigraphy). Legend: 1) *Calcari a Briozoi e Litotamni* formation; 2) *Marne a Orbulina* formation; 3) Quaternary continental deposits; 4) thrust fault; 5) traces of the geological cross-sections; 6) bedding attitude; 7) location of paleoseismological trench.

## 3.2 Borehole stratigraphy analysis

To achieve a more comprehensive framework of the geological setting of the RdM area, the cores of 14 boreholes were analysed, with their locations shown in Fig. 8a and corresponding stratigraphic logs in Fig. 8b. The borehole crossed Quaternary continental deposits unconformably overlying the carbonate bedrock belonging to the *Calcari a Briozoi e Litotamni* formation.

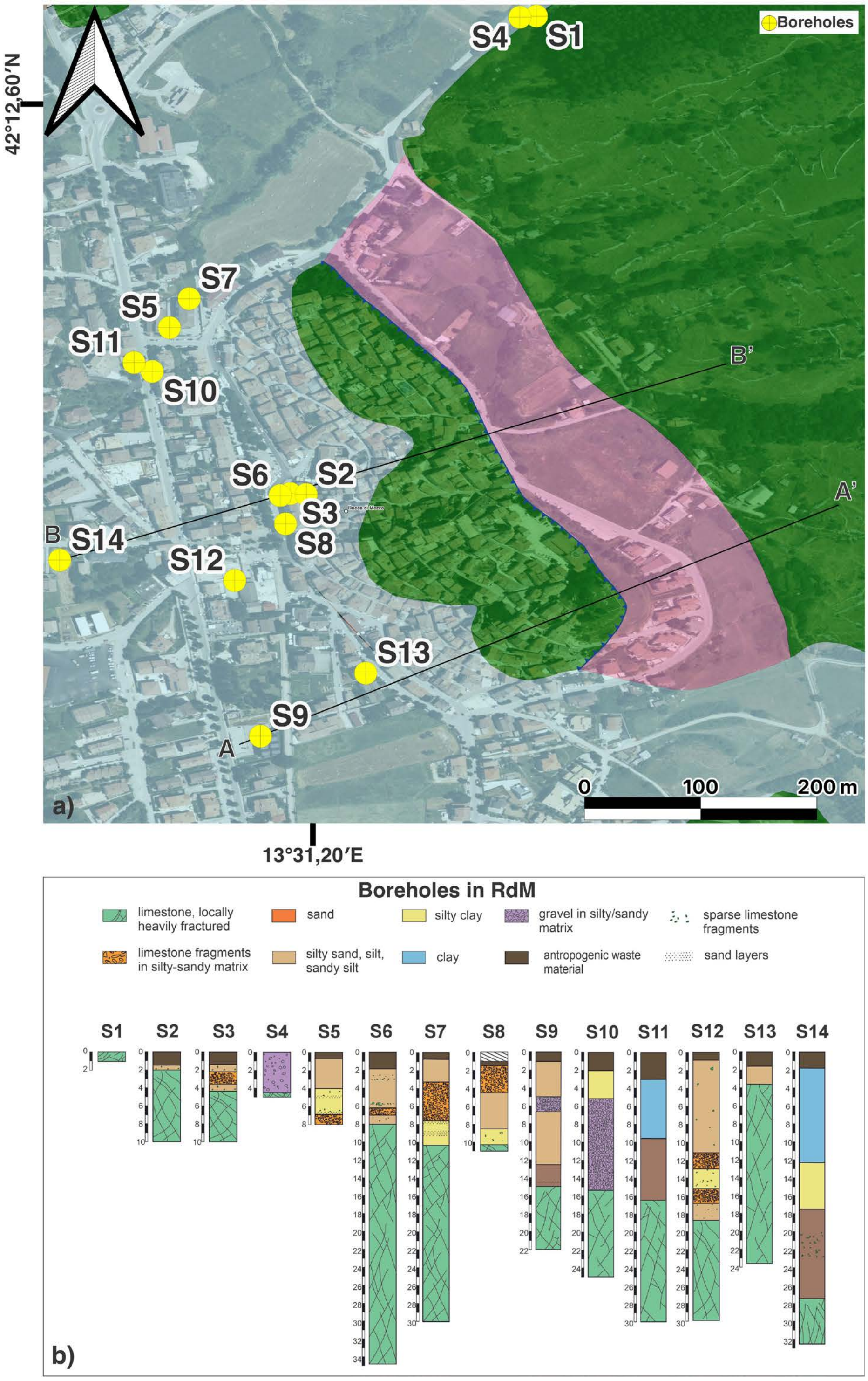


**Figure 8.** (a) Satellite image (plan view) of the RdM area showing the location of the fourteen boreholes described in the text. The geological map is superimposed with partial transparency. The thin black lines are the traces of the geological cross-sections shown in Fig. 7b. (b) Stratigraphy sequences cored by the fourteen boreholes.

The contact between the limestone and the overlying Quaternary deposits was found at different depths in the boreholes, getting progressively deeper towards the W-SW (Fig. 8). This trend mirrors and is consistent with the dip of the outcropping bedrock layers (Figs. 6a and 7) described in the preceding paragraph. The bedrock identified in cores drilled in the hanging wall of the supposed normal fault and that outcropping in the footwall belong to the same formation (Calcari a Briozoi e Litotamni fm). As for the deposits overlying the bedrock, the boreholes crossed mostly fine grain sediments (silt and clay) and very subordinately gravel. These characteristics suggest deposition mostly related to low gradient surface water flow in environment with low relief energy, consistent with the overall present-day characteristics of the *Altopiano delle Rocche* plateau, whose geomorphic setting is mostly controlled by karstic-related processes, with ephemeral stream flows and surface water stagnation. On this aspect, further observations are described in the following sections.

Borehole and field data reveal no evidence of structural features or vertical offsets at the bedrock-Quaternary interface indicative of normal faulting. If a fault were present between two boreholes, its displacement should be consistently observable along its expected trend in nearby boreholes. In this case, a hypothetical displacement between boreholes S8 and S12 should also be detectable further to the NW, in the boreholes S5, S11, and S10. However, no displacement is observed in these boreholes, which adds arguments against the presence of the extensional fault in this area. In this regard, the gradual deepening of the bedrock-Quaternary deposits interface is consistent with just the dip of the substratum layers, as the continental deposits simply covered the westward dipping bedrock layers. These findings support the geometric continuity and stratigraphic-structural relationships of the pre-Quaternary formations, without any need to invoke the presence of a dislocation related to the activity of an extensional tectonic element.

### 3.3 Trench Analysis

We dug a trench along the southern section of the suspected fault trace, in the locality *Le Caprette* situated south of the RdM village cliff, in order to achieve further information to investigate the relationship between the supposed normal fault activity and the recent continental deposition. To better locate the most suitable trenching site (yellow star in Figs. 3 and 7), the investigation was carried out near the westernmost outcropping portion of the bedrock. This location was chosen due to the impracticality of conducting the investigation in the urban area, given the presence of buildings and underground utilities. The trench was therefore excavated across the hypothesized fault trace, in an area where the bedrock disappears underneath the Quaternary deposits.

The trench orientation was approximately ENE-WSW, that is perpendicular to the presumed fault trace, with a total length of about 20 m. The trench exposed mostly fine-grain deposits that we distinguished in different stratigraphic units described below. The sedimentary sequence exposed along the trench walls has been also mapped by means of a LiDAR survey (Fig. 9). A schematic reconstruction of the stratigraphic sequence is presented in Fig. 10. In order to obtain chronological constraints for the deposition of the stratigraphic units, we collected shards of charcoals, found at different stratigraphic levels and bulks of organic sediments. Both types of material were dated by means of radiocarbon age determination using accelerator mass spectrometry (AMS) at the Beta Analytic Testing Laboratory (Table 1, see also attached supplementary material). At different stratigraphic levels, we also found shards and fragments of pottery that have been chronologically constrained by means of archaeological determinations.


**Figure 9.** Picture of the southern wall of the trench dug in the RdM southern sector. See Figs. 3 and 7 for the trench location.

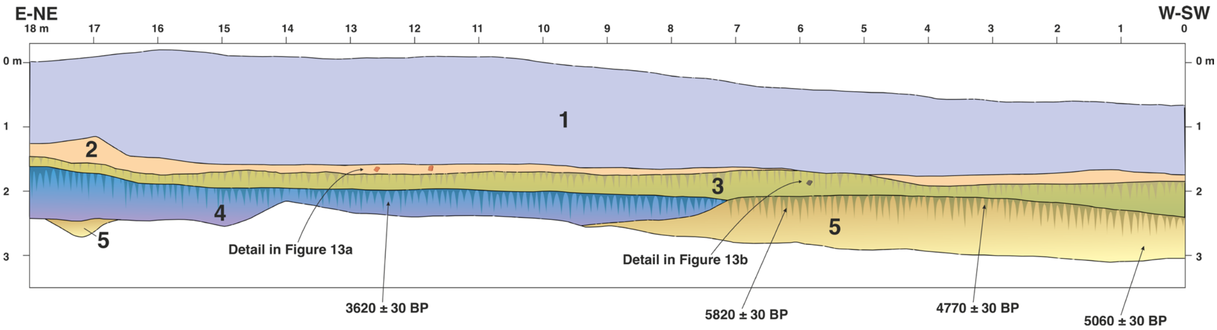


**Figure 10.** Stratigraphic scheme of trench southern wall shown in Fig. 9.

**Table 1.** Calibrated radiocarbon ages of samples from trench wall. All samples were dated using radiocarbon ($^{14}C$) analysis with an accelerator mass spectrometer (AMS) at Beta Analytic testing laboratory.

| Sample | Conventional Age (yr BP) | Calibrated ages (yr BP) | Calibrated ages (BCE) | $\delta^{13}C$ | Dated unit |
|---|---|---|---|---|---|
| RB3 | 5060 ± 30 | 5903-5731 | 3954-3782 | −25,62 | Unit 5 |
| RB8 | 4770 ± 30 | 5586-5464 | 3637-3515 | −27,09 | Unit 5 |
| RB10 | 3620 ± 30 | 3987-3839 | 2038-1890 | −22,66 | Unit 4 |
| RBBulk1 | 5820 ± 30 | 6679-6534 | 4730-4585 | −24,94 | Unit 5 |

We distinguished five sedimentary units, described as follows:

– The most recent unit 1 consists of about 1 meter-thick backfill material and reworked detrital-colluvial deposits; it represents the ploughed soil;
– unit 2 is a thin blackish colluvium with a high clay content. Sparse fragments of pottery and tiles have been found. Archaeological determination of these artifacts suggests a general attribution to the Roman period (Fig. 11a);
– unit 3 consists in a brown sandy-silty deposit (Munsell color chart of the parent material: 7.5YR 3/4), onto which incipient pedogenic processes have been observed. The unit also yielded a fragment of prehistoric pottery (Fig. 11b);
– unit 4 consists in a yellowish-grey silty-sandy deposit, lying unconformably above the lower unit. The contact between unit 4 and the underlying unit 5 represents an erosional surface, as evidenced by the geometry of the stratigraphic contact, with unit 5 thickness decreasing north-eastward and re-appearing at the trench bottom in the northernmost part of the excavation (Figs. 9 and 10). In the upper portion of this unit, traces of incipient pedogenesis are observable (Munsell color chart: 10 YR 3/4). This is shown by the brownish root-like features penetrating the deposit (Fig. 11c). Furthermore, the deposit exhibits a color gradient typical of pedogenesis, with the upper part showing a brown color associated with a clayey component, while the lower part gradually transitions to colors and grain sizes more similar to those of the parent material. Here, a charcoal fragment was found and collected for radiocarbon dating, yielding an age of 3620 ± 30 yr BP (conventional age);
– unit 5 consists in a yellowish-grey silty-sandy deposit, with incipient pedogenesis (Fig. 11c) in its upper portion (Munsell color chart 10 YR 4/4); the unit is truncated by the above-described erosion surface. Charcoal fragments were collected for radiocarbon dating, yielding ages of 5060 ± 30 yr BP and 4770 ± 30 yr BP (conventional age), respectively. Additionally, a bulk sample of the organic-rich paleosol was collected and gave a radiocarbon age of 5820 ± 30 yr BP (conventional age).

As for units 3, 4 and 5, the sedimentological characteristics (fine grain, massive-to-thinly stratified deposits, without any clast or pebble derived from the erosion of the surrounding relief) and other geomorphic evidence all

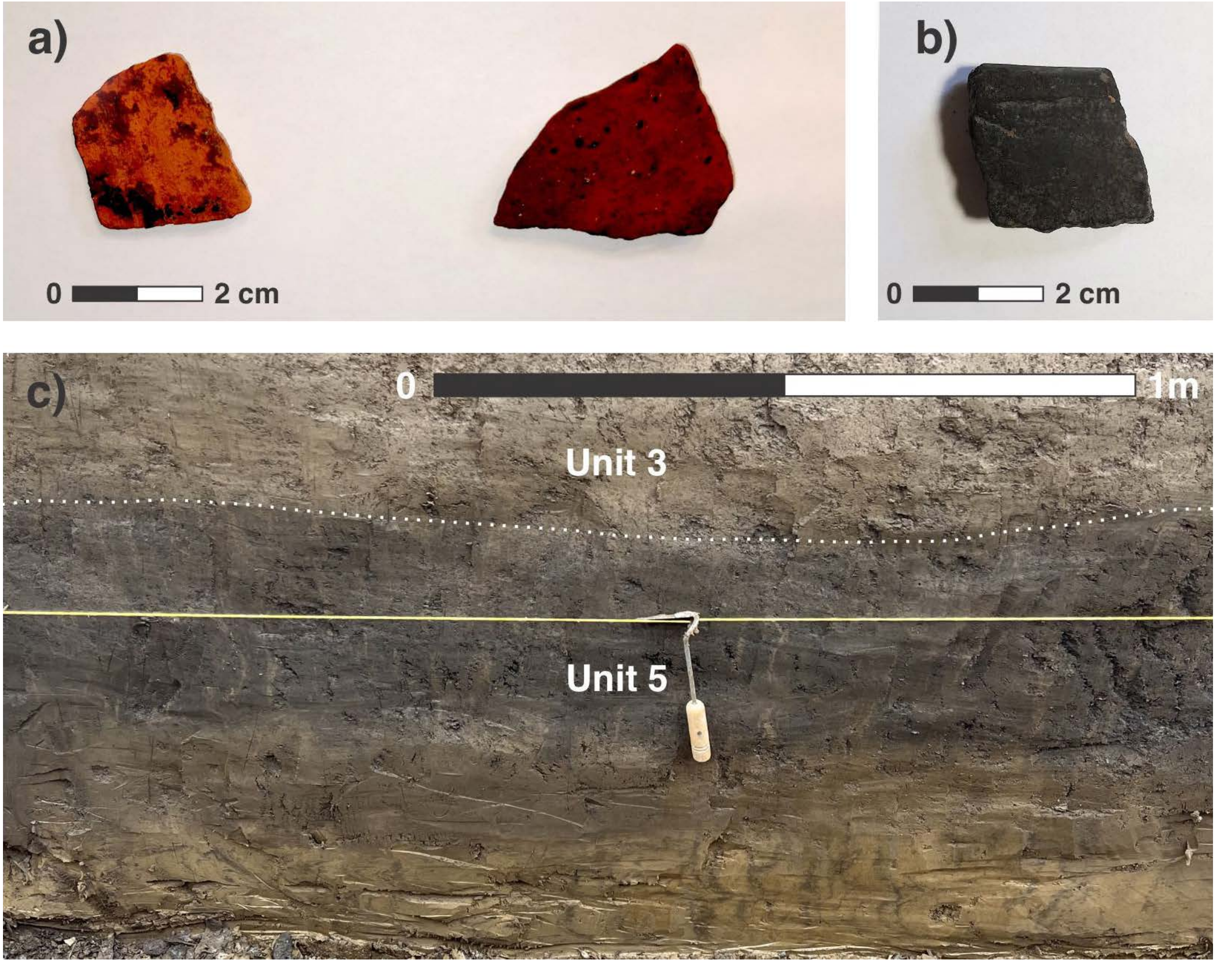


**Figure 11.** (a) Pottery fragments found within unit 2 and attributed to the Roman period; (b) a prehistoric pottery shard recovered from unit 3; (c) detail from Fig. 9 showing the portion between 3 and 4 m on the southern wall of the trench, exposing evidence of incipient pedogenesis.

along this part of the plateau, described in the following paragraph, suggest that they represent deposits related to a lacustrine-palustrine environment, which is nowadays not present in this part of the RdM. In fact, the interposed paleosols and erosional surface also indicate that this area has been occasionally occupied by a temporary lacustrine environment which underwent phases of alternating lake expansion and contraction (possibly disappearance) over the past few millennia. During the low-stand phases, lacustrine sediments were exposed, allowing for soil development. The consequent lowering of the local base level induced erosional processes.

In terms of possible dislocation related to the hypothesised fault, the trench walls showed neither evidence of faulting nor deformation (such as tilting, bending) of the whole stratigraphic sequence exposed. All the stratigraphic units displayed uninterrupted lateral continuity (except for the described local erosional surfaces) and a sub-horizontal primary attitude.

## 3.4 Geomorphological evidence of ephemeral lakes in the RdM area

The interpretation of units 3, 4 and 5 uncovered by the trench as deposits related to the presence of a lake basin in the trench area is supported by the above-described stratigraphic data obtained from the available boreholes, testifying sedimentation in a low energy hydrological environment. Moreover, geomorphological analyses in the area between RdM and Rovere, a village located some 2-3 km to the S, performed by means of field survey, aerial photographs and satellite imagery analysis, allowed the definition of the geomorphologic setting of this area. We recognised multiple flat-bottomed small depressions located at different elevations (Figs. 12a and b), suggesting

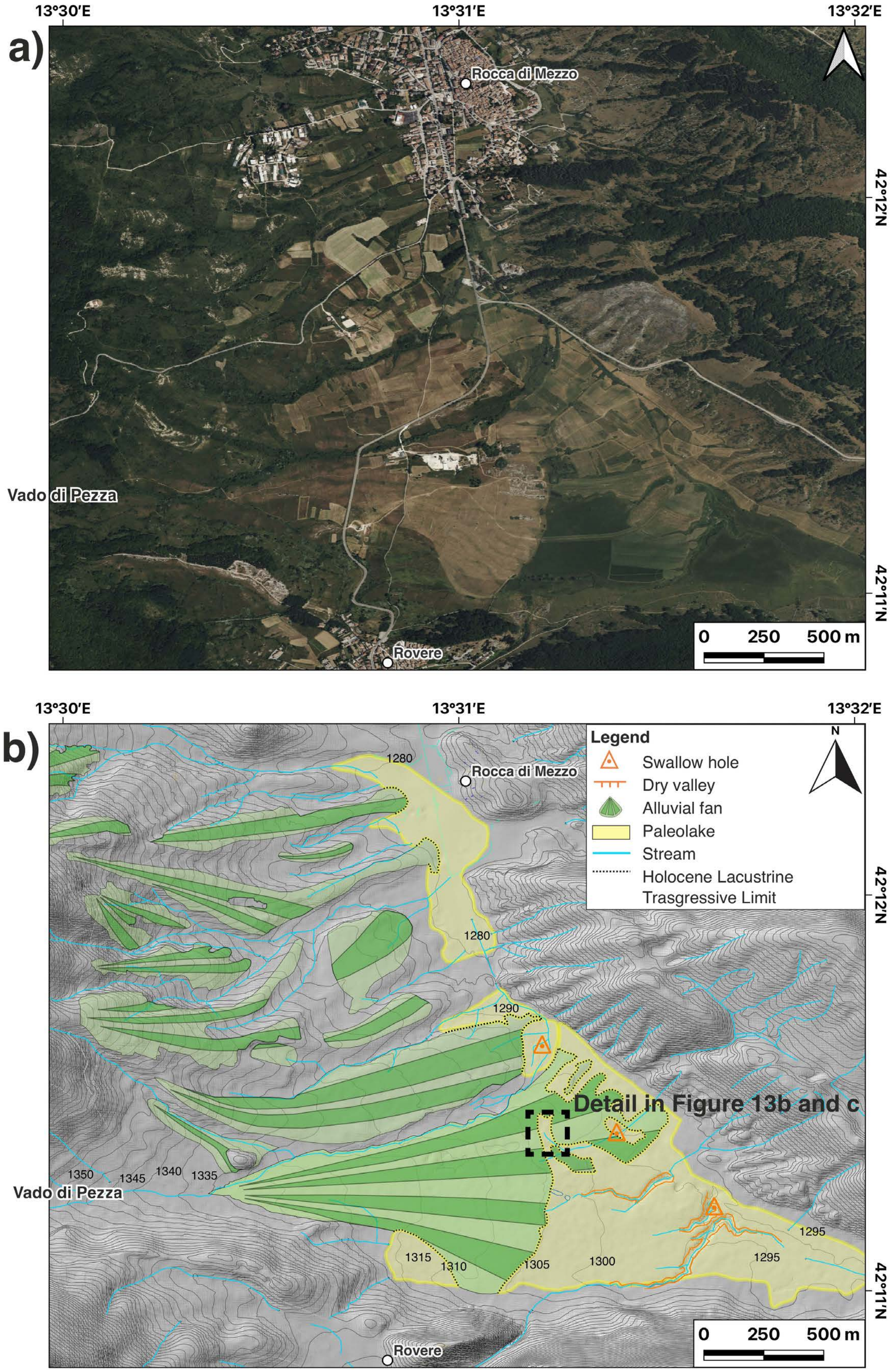


**Figure 12.** (a) Satellite image (plan view) of the area between RdM and Rovere (source: Bing Satellite, URL: https://www.bing.com/maps/?cc=it&cp=41.820455%7E12.525101&lvl=11.0; last access: July 2025); (b) Simplified geomorphological map on a shaded relief of the *Altopiano delle Rocche* (plan view). The small seasonal lake is highlighted by a black dashed rectangle.

variations in the local base level that were strongly controlled by karst processes, consistent with the widespread occurrence of karstic features throughout the plateau (as described in the paragraph 2.4). In this light, tonal variations in aerial photograph imagery, particularly the presence of darker areas within these depressions, suggest the presence of fine-grained, low-permeability sediments (e.g. organic silt and clay) deposited in zones that occasionally and repeatedly undergo waterlogging. The formation of these waterlogged areas is favoured by the persistently shallow and stable water level.

Geological survey further confirmed these geomorphic observations. Indeed, we identified traces of now-dry or seasonally active lacustrine and palustrine environments (Fig. 13).

Specifically, a small seasonal water body still persists nowadays south of RdM. This small lacustrine basin is located at the distal edges of an alluvial fan sequence fed by runoff from the western slopes of the *Altopiano delle Rocche* plateau (*Vado di Pezza*). The alluvial fan sequence relates to the *Valle Majelama* Synthem (Centamore et al., 2005a) referable to Late Pleistocene-Holocene deposits like other alluvial fan sequences observed in the Fucino Basin, *Piano di Aremogna*, *Piano di Ovindoli* and *Piano di Pezza* (Giraudi, 1989a; Frezzotti and Giraudi, 1989, 1992). The development and dynamics of the alluvial fans interplayed with karstic processes allowing the formation of small thresholds that, in turn, led to the formation of multiple lacustrine basins. Notably, the distal portion of the fans has been eroded and subsequently overlain by lacustrine deposits, an interaction still visible today owing to the presence of the small seasonal lake (Fig. 12b and Fig. 13c).

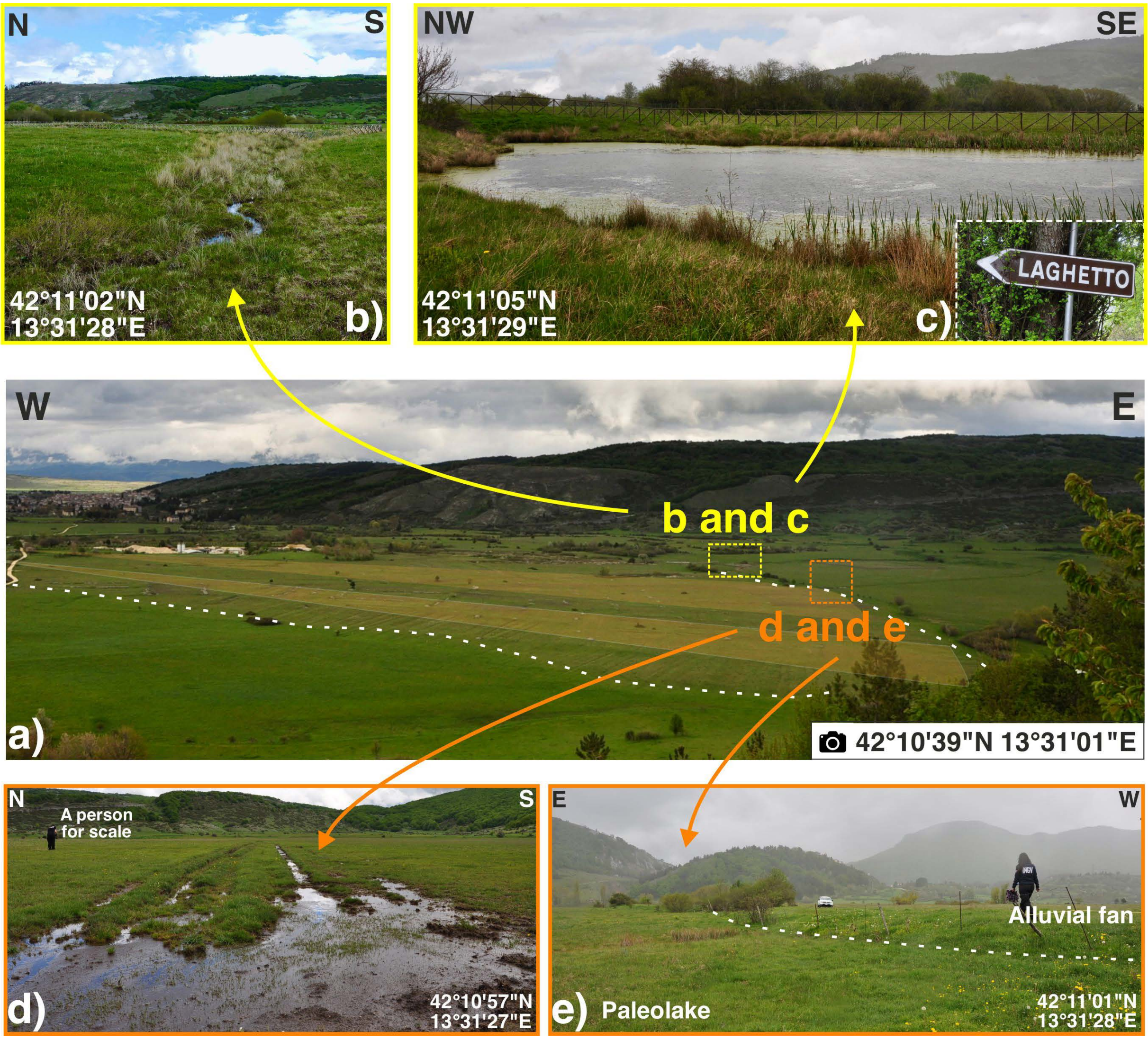


**Figure 13.** Panoramic view of the area between RdM and Rovere, where the extent of the alluvial fan is indicated by the white dotted line and details in the inset photos are highlighted with yellow and orange dashed rectangles.

Surface runoff in this sector is primarily regulated by a swallow hole located along the eastern margin of the plateau, in an area marked by widespread karst features. The alluvial fan surfaces and former lake depressions are now preserved only as relict portions. This is the result of fluvial erosion, which has incised the fan surfaces through a network of small channels, progressively enhancing surface water drainage toward the northern sector of the *Altopiano delle Rocche* (Fig. 12b). The recent activity of karst processes is driving a phase of fluvial incision and vertical deepening of the drainage network, promoting the development of a smoothly dissected and recessed landscape that reflects ongoing karst-driven morphological evolution.

Importantly, the eastern margin of the paleolake coincides with the emergence of the regular west-dipping carbonate monocline. This morpho-structural characteristic is the reason for the linear contact between the carbonate bedrock and the lacustrine deposits, visible in different sectors of the area represented in Fig. 12b. In terms of active faulting interpretation, therefore, such setting resembles that in RdM, which mimics later juxtapositions of the bedrock with sedimentary sequence supposedly due to normal faulting.

As a whole, the morpho-stratigraphic data we collected testify that the RdM area and the surrounding sectors appear to be characterised by lacustrine-palustrine ephemeral basins in relation to local alluvial systems. The evolution of these basins, characterised by aggradation and regression phases and consequent sedimentation and erosion, are strongly influenced by karstic processes.

Moreover, historical sources attest to the former presence of small lake basins in various parts of the plateau. For instance, Giandomenico Cifani in his essay *Il territorio dell'Altipiano delle Rocche* (Cifani, 1980), referring to the area near the village of Rovere, reports the following words:

*I Santi Vittore, Stefano e Giovanni, fuggendo dall'ira dei persecutori dei Crigoriani si nascondessero in antro presso il laghetto Altèo non lontano da questo Castello*.

"Saints Vittore, Stefano and Giovanni, fleeing the wrath of the persecutors of the Crigoriani, hid in a lair near Lake Altèo not far from this castle."

Cifani also refers to 19$^{th}$-century land registers that mention the existence of Lake Altèo near Rovere, as well as a small lake near Ovindoli, both of which have now almost completely disappeared. Moreover, early modern topographic maps from the 17$^{th}$ and 20$^{th}$ centuries also depict a small lake basin in the area of the *Altopiano delle Rocche*, particularly between RdM and Rocca di Cambio (Appendix A).

# 4. Discussion

The results of the geological-geomorphological analyses and geognostic investigations are here discussed.

## 4.1 Is there any deformation potentially associated with extensional faulting in RdM?

### 4.1.1 Interpreting structural data

The structural investigations performed along the bedrock cliff onto which RdM is built, as well as in the surrounding areas, presumed to coincide with the shear zone of the hypothesised active and capable extensional fault, revealed structural features (e.g. shear planes and faults; see stereonet plot in the inset of Fig. 5d) that are not consistent with the NW-SE trend and extensional kinematics expected for a normal fault in line with the trend of the extensional tectonics currently active in the central Apennines.

Geological and structural field analyses show that RdM is mostly built on a relief made of carbonate rocks pertaining to the *Briozoi e Litotamni* limestone formation of Miocene age. In agreement with Vezzani and Ghisetti (1998), we found evidence that these limestones superposed on the marls pertaining to the *Marne a Orbulina* formation through a thrust fault whose upper tip outcrops along the eastern side of the cliff (Figs. 5a and 7). As shown in Fig. 5, sets of roughly NE-SW striking high angle shear planes affect the eastern flank of the relief. The geometrical and structural relationship with the thrust fault and their attitude indicate that these high angle shear planes represent features associated to a tear fault zone, related to the thrusting, that allowed minor differential migrations towards the E-NE side of the compressive tectonic structures during the Miocene-Early Pliocene compressive tectonic phase.

Further minor shear planes have been also detected along the western flank of the RdM relief (Figs. 6 and 7). Also in this case, their orientation and kinematics are neither geometrically nor kinematically compatible with an extensional tectonic feature (that is, not consistent with a NW-SE trending normal fault related to the ongoing active stress field in the central Apennines). Instead, they appear as low-angle structural features dipping W-SW (Figs. 6 and 7) which, similarly to those observed along the eastern flank of the relief, are associated with the reverse tectonic features formed during the compressive tectonic phase.

#### 4.1.2 Surface and subsurface geological evidence

To further refine and clarify the geological framework of the RdM area, the stratigraphy of 14 boreholes was analysed (Fig. 8) and compared with field data. These stratigraphic records were used to reconstruct the subsurface geological setting and to define the interface between the carbonate bedrock and the overlying Quaternary continental deposits. Borehole data were combined with outcrop measurements. The resulting dataset was interpolated to generate a digital terrain model (DTM) of the bedrock/deposits interface (Fig. 14a).

Interpolation was carried out using QGIS software. For each borehole, the elevation of the bedrock surface was calculated by subtracting the depth at which the bedrock was intercepted from the surface elevation extracted from the regional Abruzzo DTM, which has a spatial resolution of 5 m. Where the bedrock is exposed at the surface, the elevation derived directly from the DTM was adopted. The obtained elevation values were subsequently interpolated using the Thin Plate Spline algorithm implemented in the SAGA GIS plugin, resulting in a DTM representative of the bedrock surface trend at depth. Field surveys further indicate that the carbonate bedrock forming the RdM relief exhibits a general westward dip towards the western sectors of the plateau (Fig. 14b). The reconstructed interface is shallow in the eastern sectors and progressively deepens westward. By matching the geometry of the outcropping bedrock with that intercepted with the boreholes, we demonstrate the continuity between the bedrock exposed at surface with that of the buried surface, the westward deepening of the bedrock is consistent with just the general attitude of the limestone layers, as illustrated in the cross-sections shown in Fig. 14b. Notably, local lateral juxtaposition between the lake deposits and the bedrock is not due to tectonic displacement, but reflects local erosional processes associated to local streams incisions ruled by hydrological karstic network.

#### 4.1.3 Interpreting trench data

The absence of faulting of the Holocene sedimentary sequence exposed by the trench corroborates the previous considerations. For the sake of completeness, it must be noted that paleoseismological investigation alone would have not been sufficient to exclude the presence of an active and capable fault, due to the recent age of the unfaulted deposits, which date to the Holocene. Indeed, as defined by Galadini et al. (2012), an extensional fault in the Italian Apennine geological framework has to be considered capable if it displaces deposits or landforms younger than the beginning of the Middle Pleistocene, unless it is sealed by deposits or landforms not younger than the LGM. If taken alone, the unfaulted lake sequence exposed by the trench would therefore not be old enough to consider them as sealing the fault. Nonetheless, the results of the paleoseismological investigations, combined with the previously noted absence of extensional displacement of the pre-Quaternary bedrock, corroborates the lack of any normal faulting in the area under investigation.

In this perspective, a further element that is worth noting is that if the presumed extensional fault existed, it should be part of the CCFOP active fault system, considering the proximity of RdM to the known surface traces of the active faults belonging to this tectonic structure, being just 2 km apart. The analysis of fault scarps in the Ovindoli-Piano di Pezza area shows the displacement of post-glacial and Holocene deposits (Giraudi, 1989a), as also confirmed by paleoseismological analyses conducted at *Piano di Pezza* and Ovindoli by Pantosti et al. (1996). The latter authors identified three activation events of the fault system, with consequent metre-scale surface faulting, that occurred during the Holocene, dated between 3300 and 5000 BCE (4540 ± 70 and 6090 ± 80 yr BP), around 1900 BCE (3630 ± 70 yr BP) and between 860 and 1300 CE (1070 ± 50 yr BP and 690 ± 60 yr BP).

Accordingly, assuming the hypothesis of the existence of an active and capable fault associated with the CCFOP fault system within the RdM area, evidence of this recent activity ought to be observable considering the repeated fault activation events. In contrast, the trench excavated along the hypothesised extensional tectonic structure in RdM showed no evidence of any fault planes affecting the lacustrine sequence uncovered

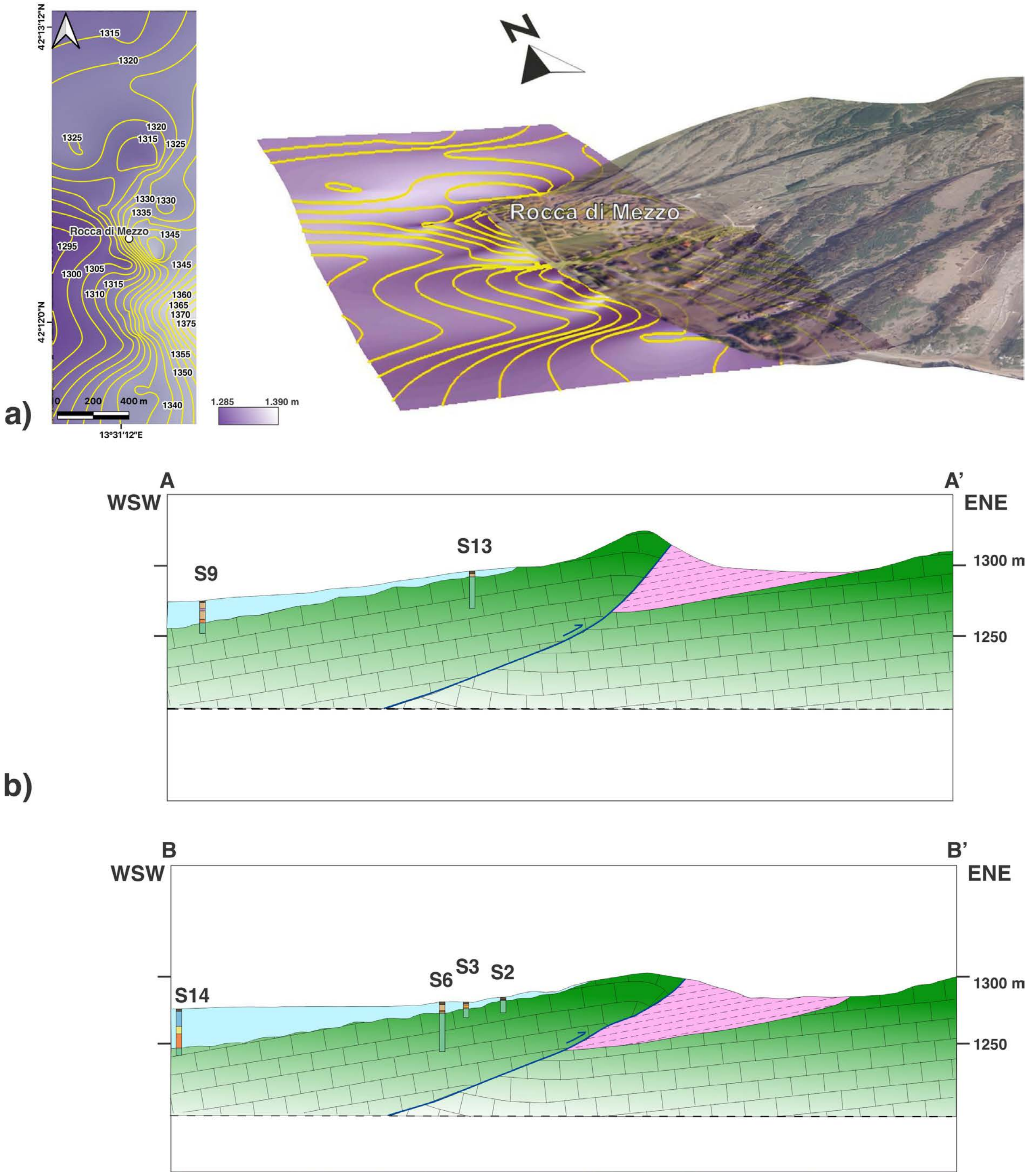


**Figure 14.** (a) Digital Terrain Model (DTM) derived from borehole data and bedrock outcrops, illustrating the reconstructed interface surface between the carbonate bedrock and Quaternary deposits. Shown both in plan view (left panel) and overlaid on a 3D Google Earth model (right). Yellow lines indicate interface bedrock (deposits elevation contours derived from surface and subsurface data. Contour interval: 5 m; (b) Geological cross-sections along the profiles A-A′ and B-B′, derived from borehole and field data, showing the south-westward dip of the carbonate bedrock (see Figs. 3 and 7 for location). The images highlight the regular deepening of the bedrock (as a monocline) toward the southwestern sectors.

by the excavation, which has an age that encompasses the three episodes of activation of the CCFOP fault system recognised by Pantosti et al. (1996). Moreover, owing to long-lasting activity of the whole fault system, a fault strand associated to this should have been responsible for a large displacement of the bedrock that has not been instead observed.

## 4.2 Geomorphic evolution of the RdM area and surrounding sectors

As exposed above stratigraphic data obtained from trenching, compared with those from existing boreholes in the RdM, suggest the presence of ephemeral, now-absent lacustrine basin located in the southern sector of the village. The stratigraphy indicates that this lake experienced phases of expansion and retreat during the late Holocene, as evidenced by the occurrence of paleosols, interposed at different stratigraphic levels to lake sediments, dated between 5820 ± 30 yr BP and 4770 ± 30 yr BP, and 3620 ± 30 yr BP, respectively.

Besides our interpretations, further evidence supports the existence of small lacustrine basins in the *Altopiano delle Rocche* plateau, described in paragraph 3.4, as well as in the nearby *Piano di Pezza* plateau, located approximately 2-3 km west of the RdM area, which undergone oscillations testified by the stratigraphic records.

In particular, in the *Piano di Pezza* plateau, Giraudi (1997) analysed a sedimentary sequence displaying sedimentological and stratigraphic features closely resembling those observed in the trench examined in the present study (Fig. 15). More specifically, the author identified five distinct lake formations in this area, spanning from Late Pleistocene to Holocene, attesting to the existence of a lake basin during specific periods and presently absent.

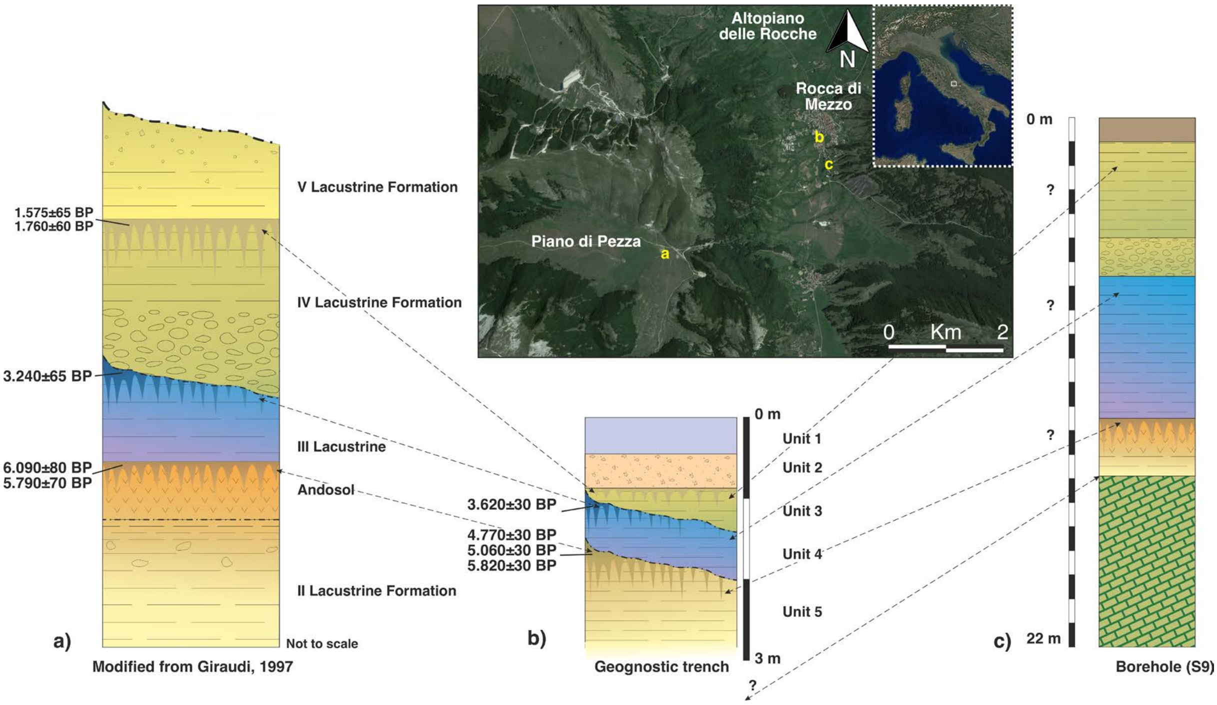


**Figure 15.** Stratigraphic correlation between the lacustrine sequence described by Giraudi, 1997 (column a), the sequence exposed in our trench (column b) and borehole S9 stratigraphy (column c). The satellite image shows the locations of the three stratigraphic records.

The first lake formation dates back to a period preceding the LGM but lacks sufficient elements for precise dating. The second formation, coeval with the LGM, represents the maximum lake level. Following this phase, a surface outflow developed, draining towards the *Altopiano delle Rocche* (Giraudi, 1989a). Overlying this formation, an andosol has developed. According to Frezzotti and Narcisi (1996, and references therein), this paleosol crops out in different sectors of the central Apennine chain at elevations ranging from approximately 900 to 1700 m and formed under humid montane climatic conditions. The andosol derives from the paedogenic alteration of the *Tufo Giallo Napoletano* tephra (Frezzotti and Narcisi, 1996), dated at 12300 ± 300 yr BP (Alessio et al., 1973). Radiocarbon ages obtained from the andosol range between 6090 ± 80 yr BP (Cinti et al., 1992) and 5790 ± 70 yr BP (Giraudi, 1997). This paleosol represents an important chronostratigraphic marker for Late Pleistocene-Holocene sequences in the central Apennines (Frezzotti and Narcisi, 1996), and its presence provides a chronological constraint on the underlying second lake formation (Giraudi, 1997), which is characterized by a pronounced erosional surface.

The overlying formations have been dated as follows: the third unit between 5790 ± 70 and 3240 ± 65 yr BP, the fourth unit between 3175 ± 65 and 1575 ± 65 yr BP and the fifth unit between 1575 ± 65 and 926 ± 40 yr BP (Giraudi, 1997).

The lacustrine sequence analysed in the present study, based on both trench and borehole data, can therefore be correlated with that described by Giraudi (1997), as they exhibit the same depositional, erosional and paedogenetic phases at least for the late Holocene (Fig. 15). This correlation aligns with Giraudi's interpretation that such phases were driven by climatic fluctuations that have affected at least the central Apennines over the past millennia. These climatic variations triggered multi-centennial phases of expansion and retreat of the intermontane lake basins, reflecting long-term environmental dynamics rather than seasonal or interannual rainfall variability (Giraudi, 1997, 1989a). Importantly, the three lacustrine units daylighted by our trench and showing evidence of pedogenesis yielded radiocarbon ages ranging from 5820 ± 30 yr BP to 3620 ± 30 yr BP, thereby confirming their attribution to three of Giraudi's lacustrine formations. Unit 5 can be correlated with Giraudi's second lacustrine formation, as it is overlain by an andosol from which two bulk soil samples were dated, yielding ages of 6090 ± 80 yr BP and 5790 ± 70 yr BP. These results are chronologically comparable with the paleosol sample collected and dated from Unit 5 (5820 ± 30 yr BP). In addition, charcoal fragments recovered within this unit provided further radiocarbon ages, indicating that the paedogenetic horizon developed above Unit 5 is slightly younger. Consequently, the age of the deposit can be revised to approximately 5060 ± 30 and 4770 ± 30 yr BP. This discrepancy can be attributed to the fact that bulk soil samples incorporate heterogeneous material from the soil matrix and are therefore more susceptible to contamination.

Radiocarbon dating of the charcoal fragment collected from Unit 4 yielded an age of 3620 ± 30 yr BP, supporting its correlation with the third lacustrine formation defined by Giraudi (1997). Finally, Unit 3 can be associated with Giraudi's fourth lacustrine formation, as it yielded a fragment of prehistoric pottery, while the overlying Unit 2 contained two Roman-period shards. These findings provide a chronological constraint for Unit 3 and support its attribution to the fourth lacustrine formation.

The stratigraphic sequence cored by the borehole shows features broadly comparable to those described by Giraudi (1997) in the *Piano di Pezza* plateau (Fig. 15). Notably, in borehole S9, a paleosol developed on a fluvial-lacustrine deposit containing volcanic material, where pedogenesis led to the formation of an andosol. The andosol may be correlated with the paleosol formed from the alteration of the *Tufo Giallo Napoletano*, although the available data do not allow this hypothesis to be unambiguously confirmed. Moreover, considering its depth, a possible association with an older volcanic deposit cannot be excluded.

In the upper part of the borehole, between approximately 1 and 7 meters, a sedimentary unit was identified that, based on its stratigraphic and sedimentological characteristics, can be attributed to Giraudi's fourth lacustrine formation. This unit consists of gravel grading upward into stratified silts, closely matching the stratigraphy described by Giraudi (1997) (Fig. 15).

Thus, the trench excavated for the present study provides clear evidence of the presence of small lacustrine basins in the area south of RdM, as well as throughout the *Altopiano delle Rocche* and the *Piano di Pezza* (as described by Giraudi, 1997). These basins were commonly separated by minor morphological thresholds, and their Holocene evolution, both past and ongoing, has been strongly influenced by climate-driven karst processes in connection characterising the last millennia.

## 4.3 Comparing the evolution of the karstic landscape of RdM area with others similar environmentsation

The dynamics of this karst system can be better understood through a comparison with analogous environments. In particular, the seasonal lake evolution in the study area appears to share similarities with the "turloughs" of the Irish karst landscape, as described by Naughton et al. (2012), where karst processes play a key role in the hydrological balance of ephemeral lakes. In the area we investigate, a large portion of the catchment areas consist of limestone formations marked by numerous karst landforms. This setting allows a significant part of precipitation to infiltrate through underground karst drainage systems (Giraudi, 1989a). Since the efficiency of these systems has varied over time, they likely influenced the lake hydrodynamics and can reasonably be linked to climatic fluctuations. Periods of swallow hole obstruction likely contributed to lake formation, while their re-opening would have promoted drainage, the eventual disappearance of the lakes (Giraudi, 1989a) and incision by local streams of the lake sedimentary sequence owing to the abrupt lowering of the local hydrological base level.

In this context, two hydrogeological models have been proposed in literature to explain the role of karst networks in the hydrodynamics of ephemeral lakes: the flow-through model and the surcharged tank model. Naughton et al. (2012) summarize these models as follows: in the flow-through model (Fig. 16a), inflow and outflow occur simultaneously and relatively independently, resulting in continuous groundwater flow through the basin and relatively short residence times. In contrast, the surcharged tank model (Fig. 16b), conceptualizes the basin as a temporary reservoir that accumulates excess groundwater without any outflow during the initial filling phase; discharge begins only once the water level has dropped sufficiently, allowing the gradual release of the stored volume. In karst environments, these two mechanisms may coexist, giving rise to a complex and temporally variable hydrological system.

The evolution of such a system in our study area likely led to the formation of a basin that was subsequently partially infilled, due to the closure of hydrological thresholds, possibly caused by the obstruction of entrances to the karst network, or of the outflow pathway, or both. Here we propose an evolutionary model connected to variable efficiency of the karstic system to drain the surficial and underground water. In the first stage (Fig. 16c), the lake basin, previously formed when the karstic system was obstructed, would begin to be filled by sediments. Just few local swamp-prone areas would remain, hosting fine-grained size sediments, such as those areas we observed between RdM and Rovere, at the outward margin of the alluvial fan. Subsequently, the establishment of a drainage network

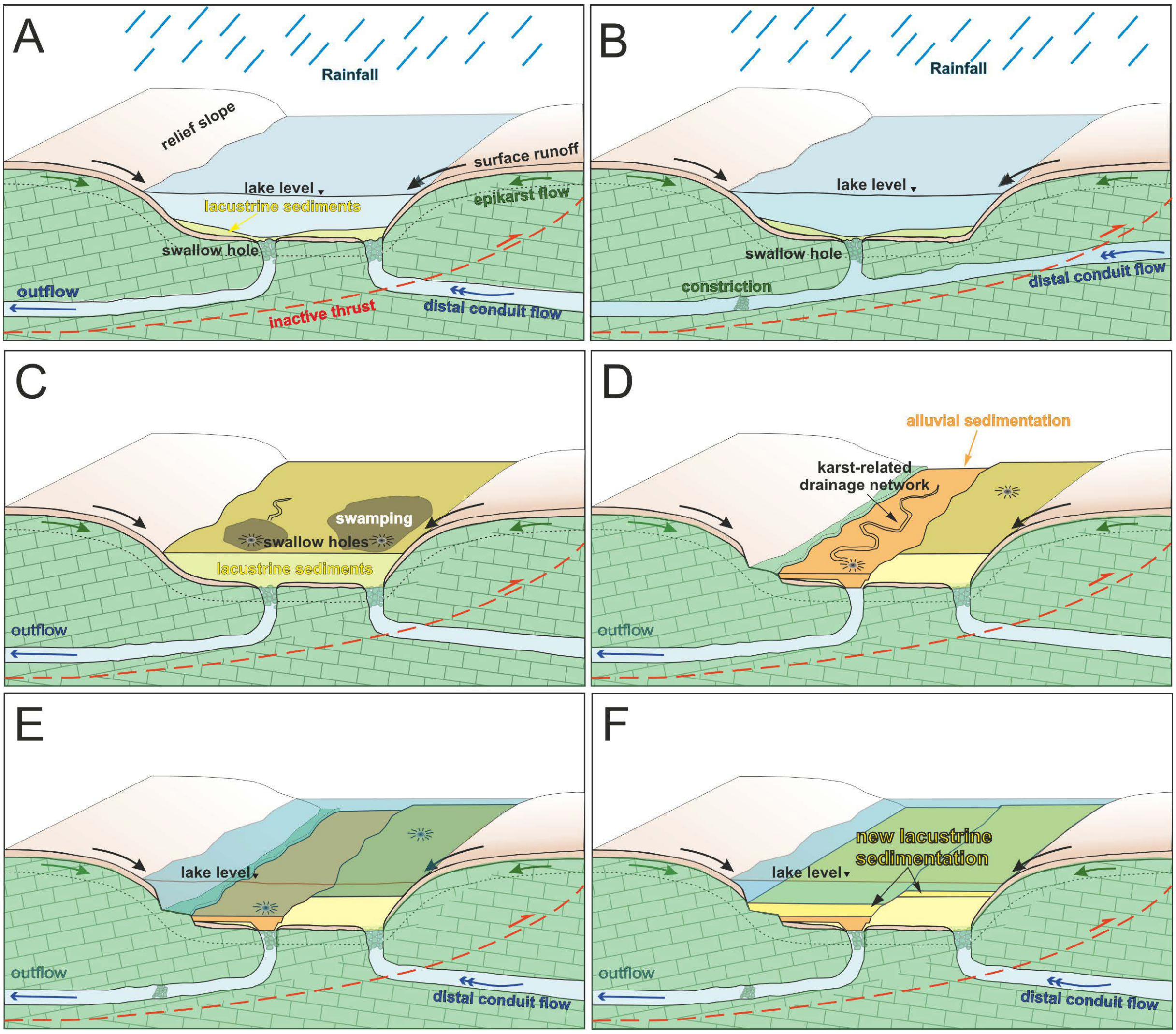


**Figure 16.** Schematic representation of an ephemeral lake operating as a flow-through system (A) and as a surcharged tank (B) (modified from Naughton et al., 2012). (C-F) Progression of the proposed evolutionary model, illustrating swamp development, karst drainage incision, subsequent lake-level rise and the deposition of new lacustrine sediments.

would fill all of the swamp-prone areas and alluvial sediments are deposited. Then, the opening of the karst-related conduits would lower the local base levels. Consequently, drainage would progressively cut into the basin fill, locally carving into both the sedimentary sequences and the underlying carbonate bedrock. Part of the eroded sediments would then be removed from the basin, likely drained through the swallow hole (Fig. 17d). In a subsequent phase, the swallow holes would become obstructed again, allowing a younger lake basin to rise again (Fig. 16e) and leading to the deposition of new lacustrine sediments (Fig. 16f). This would determine a lateral juxtaposition of newly deposited sediments with the older ones and with the carbonate bedrock. As shown in the whole Fig. 16, such configurations result from non-tectonic processes, but just from the typical dynamics of a karstic environment. In such environments, therefore, it must be underlined that the later contact of terrains (both sediments and bedrock), especially when just observed by means of indirect observation, such as geophysical investigations (i.e., lateral contact of bodies with different electric or acoustic impedance), or sparse boreholes cannot be univocally attributed to the activity of tectonic structures. Further and more robust data are needed before claiming these later contacts as the result of fault displacements.

## 5. Conclusions

Preliminary geological investigations in RdM aimed at seismic microzonation studies, based on a few borehole data, led to the hypothesis of the presence of an active and capable normal fault in the western sector of the village. This hypothesis arose from the detection of the deepening of a few meters in the pre-Quaternary carbonate bedrock in that area. Given the proximity to known splays of the active and seismogenic CCFOP fault system, this supposed stratigraphic anomaly has been hypothesised as the possible effect of an additional, previously unrecognized splay of the active tectonic structure. The supposed location of the fault affects a sector of RdM where a school building is located.

The multi-methodological analyses we conducted allowed the acquisition of a bulk of geological evidence, enabling a thorough characterization of the Holocene evolution of the area.

Overall, the results pointed to the absence of an active and capable fault in the western sector of the RdM village, as demonstrated by three main pieces of evidence:

1) No structural features related to extensional deformation affecting the bedrock were observed. Instead, the limestone bedrock, exposed in the supposed normal fault zone, displays only elements associated with the previous compressional tectonic phase, which is no longer active in this part of the Apennine chain since the late Miocene.
2) The morpho-stratigraphic configuration of the pre-Quaternary bedrock, as defined by field observations and borehole data analysis, revealed a regular westward dipping of the limestone layer and of the interface bedrock-Quaternary deposits, with no evidence of normal fault-related displacement. Moreover, out analysis reveals no stratigraphic anomalies in the bedrock across the supposed extensional fault trace, as both the outcropping and the buried substratum pertains to the Miocene *Calcari a Briozoi e Litotamni* formation. Minor local depth variations of the top of the bedrock are likely attributable to small erosional processes associated with a local watercourse ruled by karstic processes, profoundly shaping the landscape of the plateau.
3) Paleoseismological trenching we performed in the southern sector of RdM indicated the absence of any tectonic dislocations ascribable to a normal fault during the late Holocene. Although the age of the trenched deposits spans only the last few millennia, evidence of fault displacement of the sedimentary sequence should be rather expected given that the CCFOP fault system, to which the hypothesised fault strand should be associated, activated three times over the past about 6-7 kyr which is the age encompassed by the unfaulted deposits we trenched.

Overall, our investigations in the RdM sector of the *Altopiano delle Rocche* defined that the recent evolution of the whole plateau is strongly conditioned by karstic dynamic, which conditioned and still condition the geomorphologic evolution of the area, leading erosional and depositional processes. Karstic evolution of the plateau explains the preliminary incorrect interpretation of the presence of an active fault strand in the RdM area.

Within this light, in a broader perspective, the results of our study contribute to a better understanding of the evolution of several sectors of the Apennine chain or of other comparable geological settings, where karst processes are widespread. Given the ubiquitous climatic conditions of the Apennine region, ephemeral lake level fluctuations appear to have been driven by climatic variations (Giraudi, 1997, 1989a; Naughton et al., 2012) Our findings emphasize that the geomorphological evolution of intermontane plateaux is strongly governed by climate-driven karst processes.

These processes can generate morpho-stratigraphic settings that, if not well framed in a wider geological evolutionary view, may closely mimic geological features typically attributed to active faulting. Consequently, the morphogenetic evolution of karst-dominated environments should not be automatically or exclusively ascribed to active faulting. This is particularly relevant when active fault strands are proposed only based on indirect or sparse subsurface data, such as geophysical evidence (i.e. lateral acoustic or electric resistivity contrasts) or just borehole information, which may instead reflect non-tectonic processes, such as erosional/sedimentation dynamics related to karst-governed processes, or even evolution of karst-related landforms, such as, buried dolines, swallow-holes or sinkholes.

From a methodological perspective, this study highlights once again the need of acquiring a robust set of geological field evidence, framed within the wider regional geological spatio-temporal evolution perspective, to avoid overinterpretation and the erroneous identification of active and capable faults, especially when potentially affecting an urbanized area.

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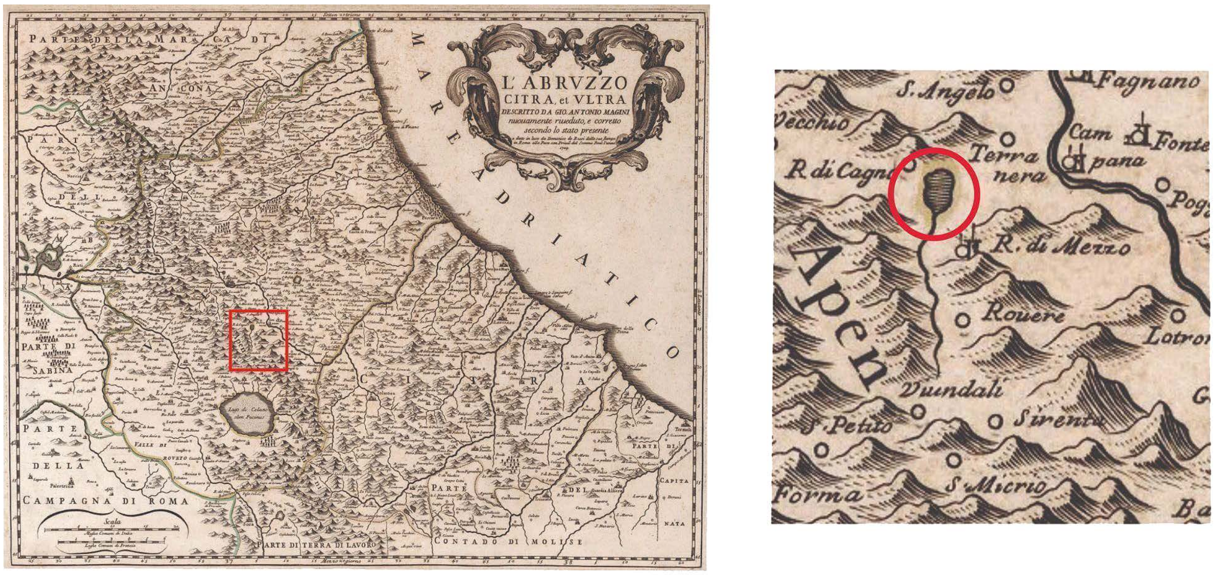
## Appendix A.

a)




b)

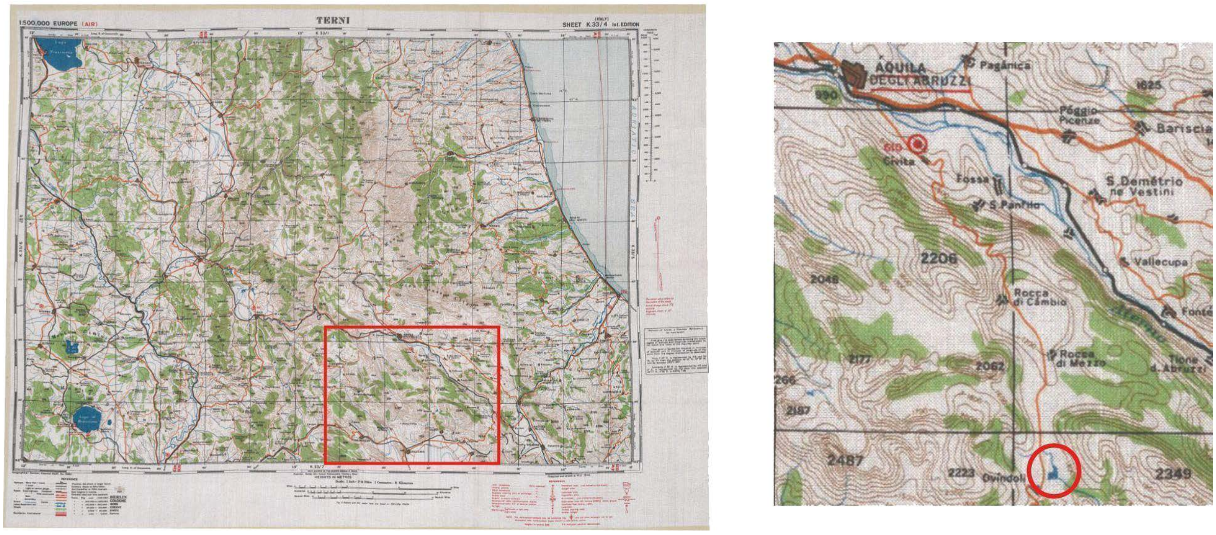



**Figure A-1.** Historic cartography from XVII and XX centuries showing the Abruzzi region and zoomed sections of the studied area (red squares), in which ancient lakes are mapped (red circles); (a) image from 1709 updated “Abruzzo citra et ultra”, based on the 1602 Giovanni Antonio Magini work, scale 1:320.000. A rather extended lake is reported between Rocca di Cambio and RdM villages; (b) 1:500.000 Terni topographic map, part of a series produced by the Geographical Section of the General Staff of the Great Britain War Office in 1944 (Terni (Italy). Sheet K. 333/4 1st. Edition. 1:500,000 Europe (Air). Geographical Section, General Staff No. 3982. Compiled and drawn at W.O.). A lake is represented east of Ovindoli. These images are part of the David Rumsey Map Collection (https://www.davidrumsey.com; last availability check July 2025).

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