



Active tectonics and paleoseismicity of a transverse lineament in the Fabriano valley, Umbria-Marche Apennine (central Italy)

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Abstract

Structural elements, transversal to the Apennine chain, display various problematic aspects connected, above all, with their origin tectonogenetic role. From a seismic point of view, they may act as a structural barrier to the propagation of the Apennine normal faults or behave as transfer zones, thus activating neighboring segments belonging to the same fault system; the largest ones can also host significant earthquakes with the hypocenters located in the basement, below the Apennine thrust belt. This paper describes a case of recurrent surface faulting that reactivates a sector of a relevant transverse feature, the "FV-VE), near the city of Fabriano (Marche, Italy). Detailed geomorphological observations connect it with past earthquakes, including the disastrous event (I0=IX MCS, about 6.2 Mw) of 24 April 1741 that struck the area with a wide distribution of damages extending along the Esino River Valley to the Adriatic coast over a distance of more than 50 km. Furthermore, paleoseismological analysis and radiocarbon datings of faulted river terraces and slope deposits, ranging in age from the end of the Middle Pleistocene to the recent Holocene, allowed us to define the evolutionary steps of the fault and estimate a slip rate of about 0.3 mm/year.

Keywords Active tectonics · Transverse lineaments · Fabriano 1741 earthquake · Umbria-Marche Apennine · Italy

Introduction

Structural elements, transversal to the Apennine chain, have been described by various authors even though they still display various problematic aspects connected, above all, with their origin, tectonogenetic role, and seismic significance (Selli 1954; Centamore et al. 1978b; Nesci et al. 1978; Calamita et al. 1979; Castellarin et al. 1982; Boccaletti et al. 1983; Dramis et al. 1991; Coltorti et al. 1996; Sorgi et al. 1998; Di Bucci et al. 2002; Della Seta et al. 2008; Centamore et al. 2009; Pizzi and Galadini 2009; Pierantoni et al. 2013; Peacock et al. 2017; Turco et al. 2021). They consist of lineaments, or more often sheaths of lineaments, up to more than a hundred kilometers long and easily recognizable on aerial photographs or satellite images because of geomorphic indicators such as straight watercourses or aligned saddles, ridges, scarps, etc.

These features show evidence of polyphasic activity, consisting of successions of horizontal, compressional, or extensional regimes, but are commonly characterized by small displacements, definitely subordinate to those of the extensional faults parallel to the Apennine ridges (Coltorti et al. 1996). Some of the transverse ("anti-Apennine") structures

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have conditioned the marine sedimentation during the main compressive phase of the Apennine (Calamita et al. 1991a, b), from the Messinian to the Early Pleistocene (Centamore et al. 1978a; Calamita et al. 1979; Boccaletti et al. 1986; Bigi et al. 1997), and then, after the emersion and the westward extension of the Apennine chain, the morphological evolution of the main river valleys (Girotti 1968; Dramis et al. 1991; Dramis 1992; Coltorti et al. 1996).

Such long-lasting and recurrent activity in various tectonic regimes suggests that these structures may reach considerable crustal depths, making them comparable with the “regmatic geofractures” described by Caire (1975) or with the trans-Himalayan faults (Dasgupta et al. 1978), capable of reappearing at the surface even after compressive phenomena had shortened the sedimentary cover. Several authors have adopted this interpretation of the transverse structures (e.g., Tavarnelli 1996; Tavarnelli et al. 1998, 2001, 2004; Butler et al. 2006; Centamore et al. 2009; Pizzi and Galadini 2009; Gori et al. 2014; Vannoli et al. 2015) who consider them “pre-existing” to the compressive phase responsible for the formation of the Apennine chain.

From a seismic point of view, they may act as “long term” structural barriers (Wheeler 1989) to the propagation of Quaternary fault systems or be reactivated as transfer zones, thus activating neighboring segments belonging to the same fault system (Pace et al. 2002; Pizzi and Galadini 2009; Vannoli et al. 2015; Gori et al. 2017). The largest ones can also host significant deep earthquakes with the hypocenters located in the basement (Valensise and Pantosti 2001; Vannoli et al. 2015) below the Apennine thrust belt, whose maximum thickness in the area is ca. 9 km (Barchi et al. 2012). Active tectonic behavior associated with deep structures is also recognized in the Marche region; it appears to be controlled by deep-seated, probably inherited, and long-lived, steep faults showing dominant strike-slip kinematics (Mazzoli et al. 2015).

This paper presents a case of recurrent surface faulting that reactivates a sector of the the “*Fossato di Vico-Valle dell’Esino line*” (FV-VE), a major transverse lineament, in the outskirts of Fabriano and puts it in relationship with the earthquakes that have hit the area several times in the past, including the disastrous event (I0 = IX MCS, ~6.2 Mw) of 24 April 1741.

Geological and geomorphological setting of the study area

The Fabriano town arises on an alluvial terrace of the Giano River (a tributary of the Esino River). Northeast of Fabriano, the alluvial plain widens out considerably inside a tectonic depression bounded to the north-east by normal faults lowering the western flank of the “Marchean Ridge” and to the

south-east by “anti-Apennine” faults following the FE-VE line (Calamita et al. 1979; Centamore et al. 1979; Servizio Geologico d’Italia 1979; Ambrosetti et al. 1981; Boccaletti et al. 1983) (Fig. 1).

As for most of the Marche hydrographic systems, the Giano River is bordered by alluvial terraces, which owe their origin to the alternation of depositional and erosive processes linked to late Quaternary climate changes, in the context of a regional uplift (Ciccacci et al. 1985; Coltorti et al. 1991; Dramis 1992).

Detailed geomorphological surveys carried out in the area allowed us to recognize three main orders of alluvial terraces: the highest order (first-order terrace) lies at about 100 m above the river bed, those of the second-order at about 50 m, and those of the third-order at about 25 m (Fig. 2a and b). The related alluvial deposits have been referred to the Middle Pleistocene, the end of the Middle Pleistocene “Riss” Glaciation), and the Late Pleistocene (Würm Pleniglacial), respectively (Alessio et al. 1979; Coltorti et al. 1991).

An even lower alluvial terrace, a few meters above the riverbed, has been related to human-induced riverbed aggradation during historical times and subsequent fluvial erosion (Biondi and Coltorti 1983).

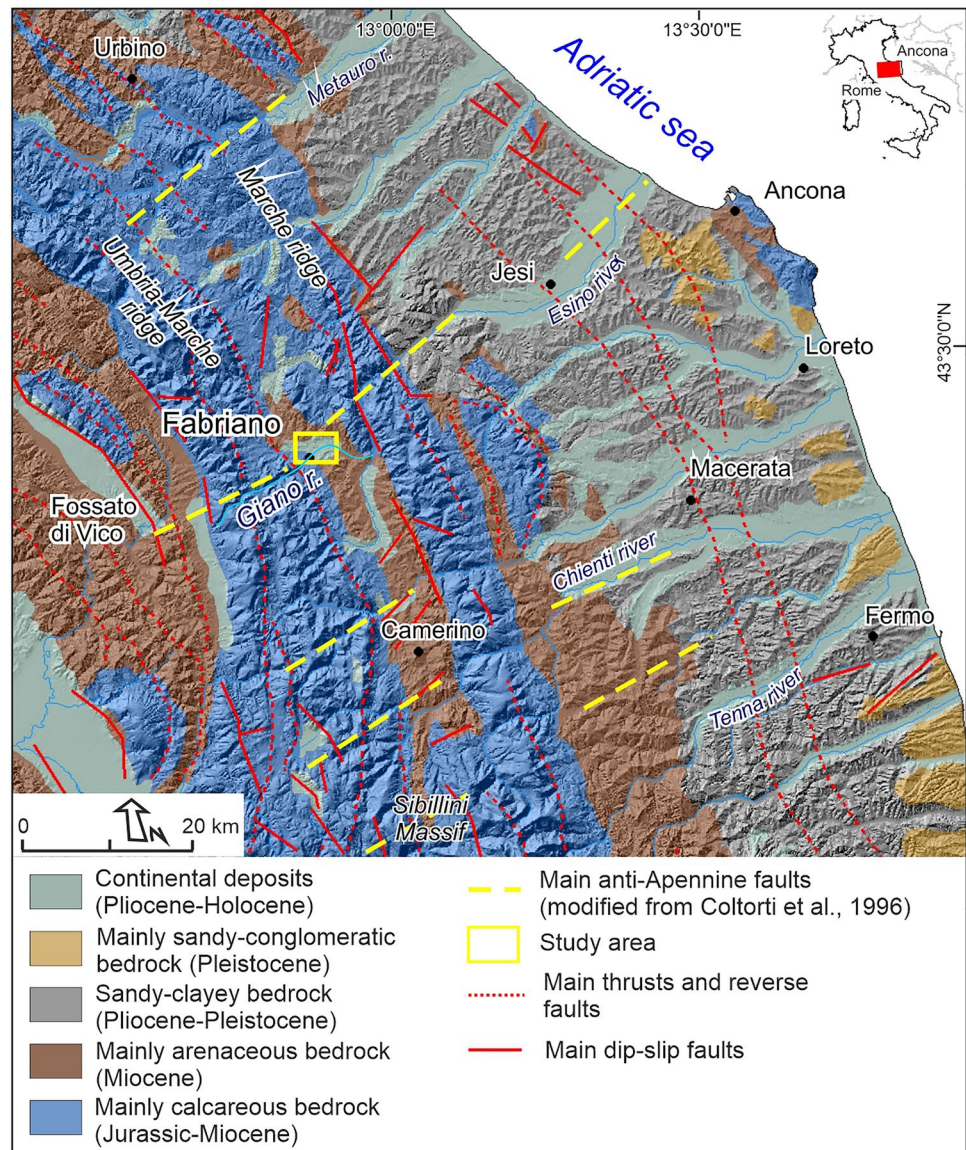
The second and third-order alluvial terraces, in particular, are notably extensive due to the Fabriano basin’s tectonic subsidence, which favored fluvial deposition and, locally, the temporary formation of lacustrine episodes (Alessio et al. 1979; Centamore et al. 1979).

Investigation methods

In carrying out the research, we essentially applied the traditional methodologies of detailed geological and geomorphological surveying to deepen the knowledge already acquired on the area (Centamore et al. 1979; Servizio Geologico d’Italia 1979). For further information, we used the borehole data obtained in the context of water research for the Municipality of Fabriano (Petrogeo-Comune di Fabriano 1976) and some original exploratory excavations.

We have also dated by ^{14}C method two significant samples (samples Rome 364 and Rome 365, “La Sapienza” University ^{14}C Lab) extracted from the borehole cores and one (sample Beta 170891, Beta Analytic Limited, London) collected during the field survey. Finally, we examined all the relevant available information regarding the earthquakes that have affected the area in the past (Postpischl 1985; Boschi et al. 1995, 1997; Rovida et al. 2011, 2020; Guidoboni et al. 2018), including the distribution of damages to the town of Fabriano caused by the strong earthquake (I0 = IX MCS, Mw ~6.2) that struck Fabriano on April 24, 1741 (Marcellini and Tiberi 2000; Castelli and Monachesi 2001).

Fig. 1 Geological sketch of the Umbria-Marche Apennine northern sector



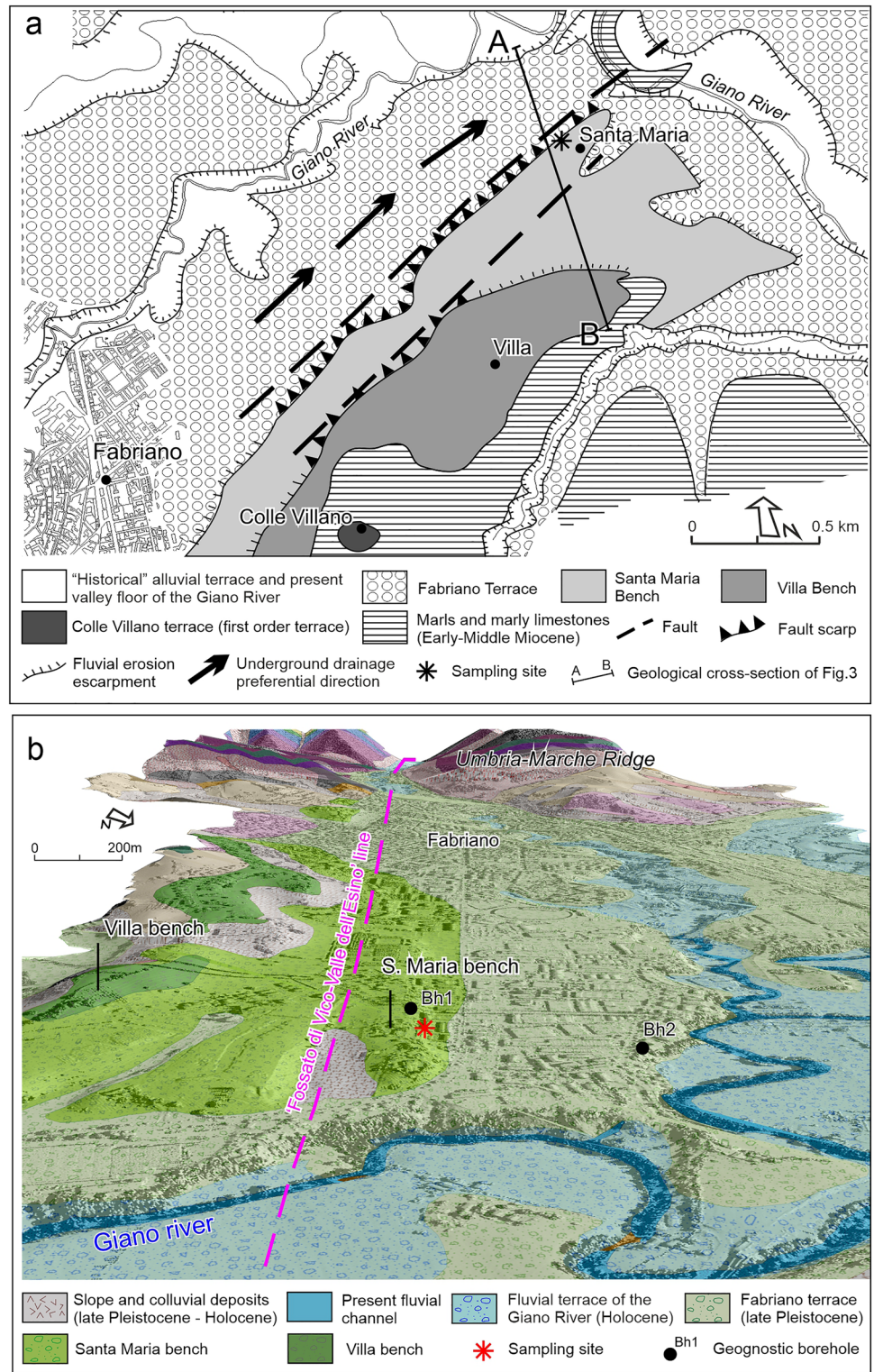
Geological and geomorphological features of the Santa Maria—Villa northern slope

Immediately north-east of Fabriano (Fig. 2a), the second-order terrace splits into two benches (the Villa Bench above and the Santa Maria Bench below), separated by a 1 km long, NE-SW running scarp. A second scarp, parallel to the first, about 15 m high and 2 km long, connects the Santa Maria Bench with the third-order plain (Fabriano Terrace). Slope processes have affected both scarps causing the emplacement of thick colluvial deposits.

The rectilinear trend of the Santa Maria Scarp, parallel to a several km long fault, mapped on the “Fabriano” 1:50,000 geological sheet (Servizio Geologico d’Italia 1979), suggests considering it as produced by a fault. The following elements confirm this interpretation.

- We observed transpressive fault planes (pitch about 20° – 25°), perfectly aligned with the Santa Maria Scarp on the right bank of the Giano River channel, in the marly-calcareous bedrock (Bisciario Formation, Early Miocene) (Fig. 3a and b). Unfortunately, due to construction works, we could not verify the prosecution of the fault into the overlying alluvial deposits.
- A section excavated at the base of the Santa Maria Scarp allowed us to observe the contact between the Santa Maria Bench alluvial deposits and a ca 4 m thick sequence of stratified debris layers, whose hook-shaped features and the vertical orientation of pebbles along the contact surface cannot be referable to erosion-sedimentation processes but to the drag effect of a fault (Fig. 4). The debris layers are deformed by undulations, anomalous thickening/thinning, and a series of modest

Fig. 2 a Geomorphological scheme of the investigated area. **b** 3D image based on a LIDAR digital terrain model



throws that are progressively more developed in the lower part of the section, indicating a growth fault's step-like movement. About 1 m of downslope inclined gravels, corresponding to the basal level of the stratified debris sequence, are present over the alluvial deposit,

on top of the footwall scarp. Similar evidence was visible in a 4 m deep and 6 m long exploratory trench, today closed., some hundred meters northwards.

(c) Higher up, an erosion surface, slightly steeper than the debris layers, cuts the slope. It is overlain by colluvial

Fig. 3 **a** Aerial photo (taken by drone) showing the alluvial plain of the Giano river and the fault alignment described in the text: in the background the town of Fabriano. **b** and **c** detail of a fault plane affecting the marly-calcareous bedrock (Schlier formation)



deposits, mainly made of gravels with a small percentage of brown soil debris. These materials terminate laterally against the fault with a thickness of ca. 50 cm and are absent in the footwall being erased by erosion (Fig. 4). We could reasonably relate their emplacement to the phase of gradual climate drying that has occurred since 3500 year BP in the Mediterranean area (Magri 1997, 1999; Ricci Lucchi et al. 2000; Dramis et al. 2014).

- (d) Near the ground, a further erosion surface follows, covered with a few decimetres thick colluvial layer,

made of gravels immersed in abundant debris brownish soil and reasonably attributable to the impact of human activities (such as deforestation and agriculture). Radiocarbon dating of organic matter taken from a debris pocket close to the erosion surface gave an age of 1480 ± 60 year ^{14}C BP/Cal 1520 to 1280 BP (sample Beta 170891) (Figs. 4 and 5). The bedding is more or less regular and conformable with the slope, apart from the portion close to the tectonic contact, where a gravity wedge of vertically arranged gravels bounded downslope by a minor “antithetic” rupture,

Fig. 4 Stratigraphical scheme of the Santa Maria section. Upper left: top of the Santa Maria scarp. Within the black and the red boxes, details of the geomorphological features observed

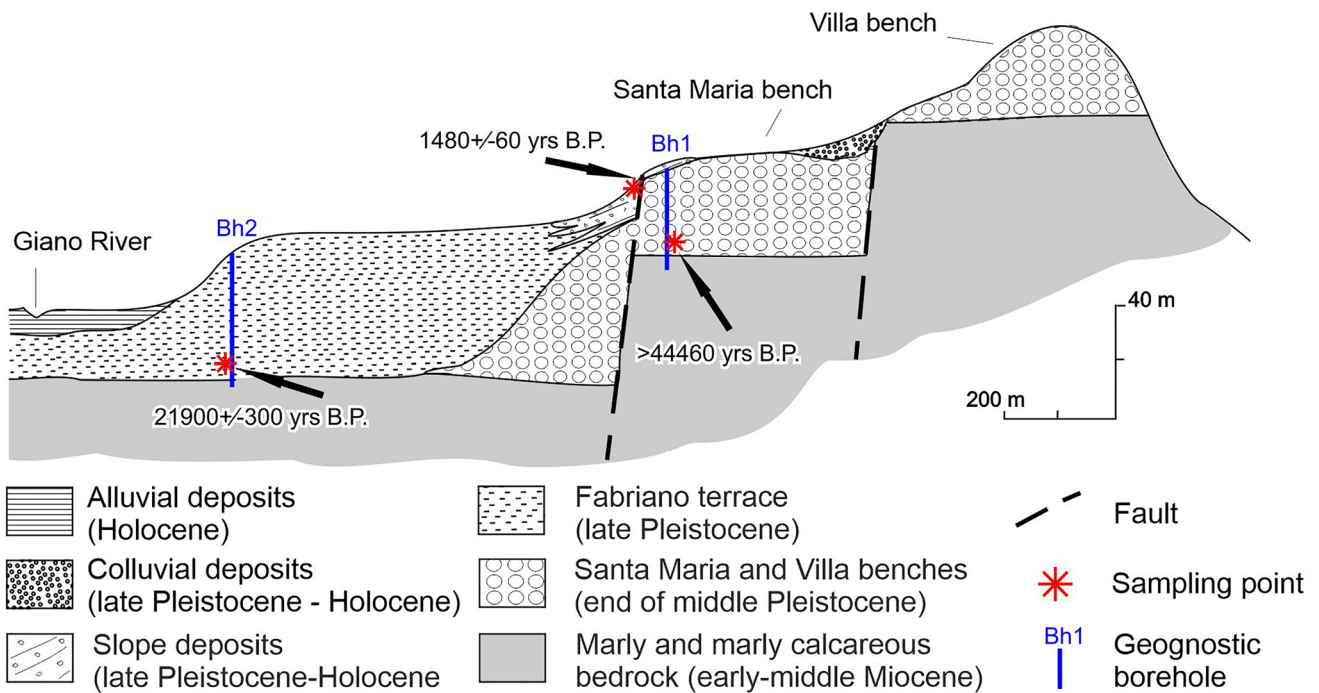
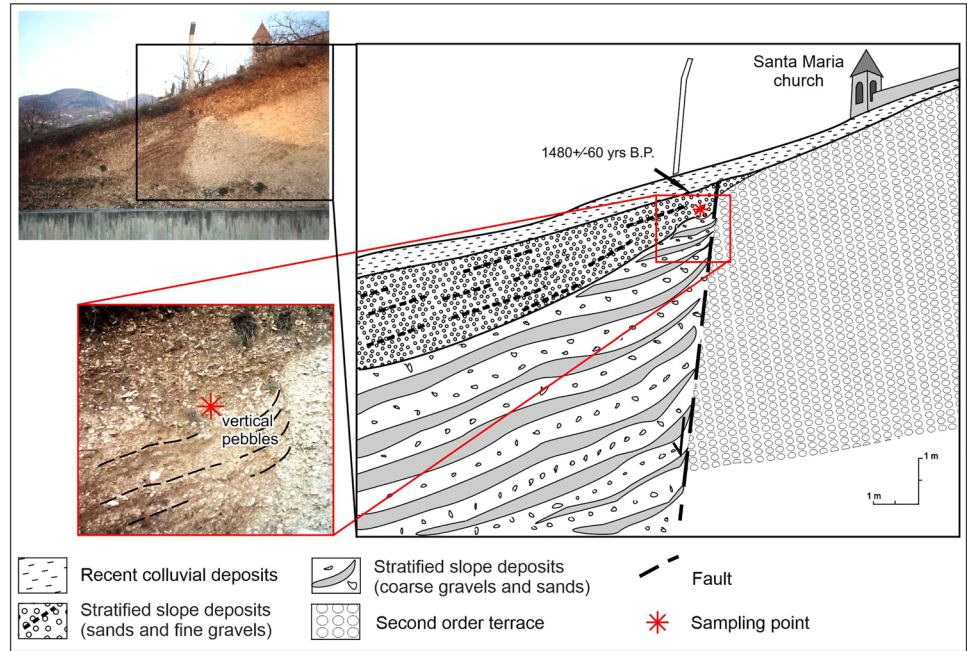


Fig. 5 Geological section across the Santa Maria and Villa scarps reconstructed based on field, observations and geognostic data (see Fig. 2a for the cross section trace)

and debris pockets, among which the dated one, testify for the ongoing displacement of the fault. Based on the above features, we could estimate a vertical offset of ca. 6 cm for the last fault step.

(e) Geognostic boreholes, drilled on top of the Santa Maria Bench close to the Villa Scarp (Figs. 2b and 5),

revealed a 10 m deep, elongate narrow depression parallel to the Santa Maria Scarp and filled with debris and soil sediments. The emergence of springs at the base of the scarp locates the marly bedrock (Schlier Formation, Middle Miocene) at shallow depth, thus supporting the Villa Scarp’s interpretation as produced by a fault.

- (f) Radiocarbon dating of borehole samples of peaty materials, found within the second-order alluvial deposits and from a shallow swampy-lacustrine level at the base of the Fabriano Terrace (third-order alluvial deposits), gave ages of 44,460 ¹⁴C year BP (sample Rome 364) and 21,900 ± 300 ¹⁴C year BP (sample Rome 365), respectively (Fig. 4 and 5).
- (g) The town of Fabriano has suffered the effects of several earthquakes since 1000 AD, six of which are characterized by an estimated magnitude ($M_w > 6$) capable of generating significant surface effects (Postpischl 0.1985; Castelli and Monachesi 2001) (Fig. 6). Among these, only the April 24, 1741 earthquake was located close to Fabriano; a minor event ($I_{max} MCS = 7, M_w = 5.1$) occurred in the surroundings of Fossato di Vico on October 14, 1612 (Monachesi 1987; Rovida et al. 2011). Differently from most Umbrian-Marchean earthquakes related to normal faults parallel to the Apennine, the isoseismal lines of the April 24,

1741 earthquake show a NE–SW trend (Pergalani et al. 1986; Monachesi 1987), parallel to the FV–VE line. Moreover, when considering the damage caused to the buildings of Fabriano, it can be observed that the most significant occurred along a line following the Santa Maria Scarp (Marcellini and Tiberi 2000).

Discussion

Geomorphological evolution of the Santa Maria and Villa fault scarps

During the first stages of fluvial aggradation, which probably initiated with the climate cooling occurred around 185 ky BP (Berger 1978; Margari et al. 2014), it is conceivable that both faults were unable to create a scarp: the aggrading

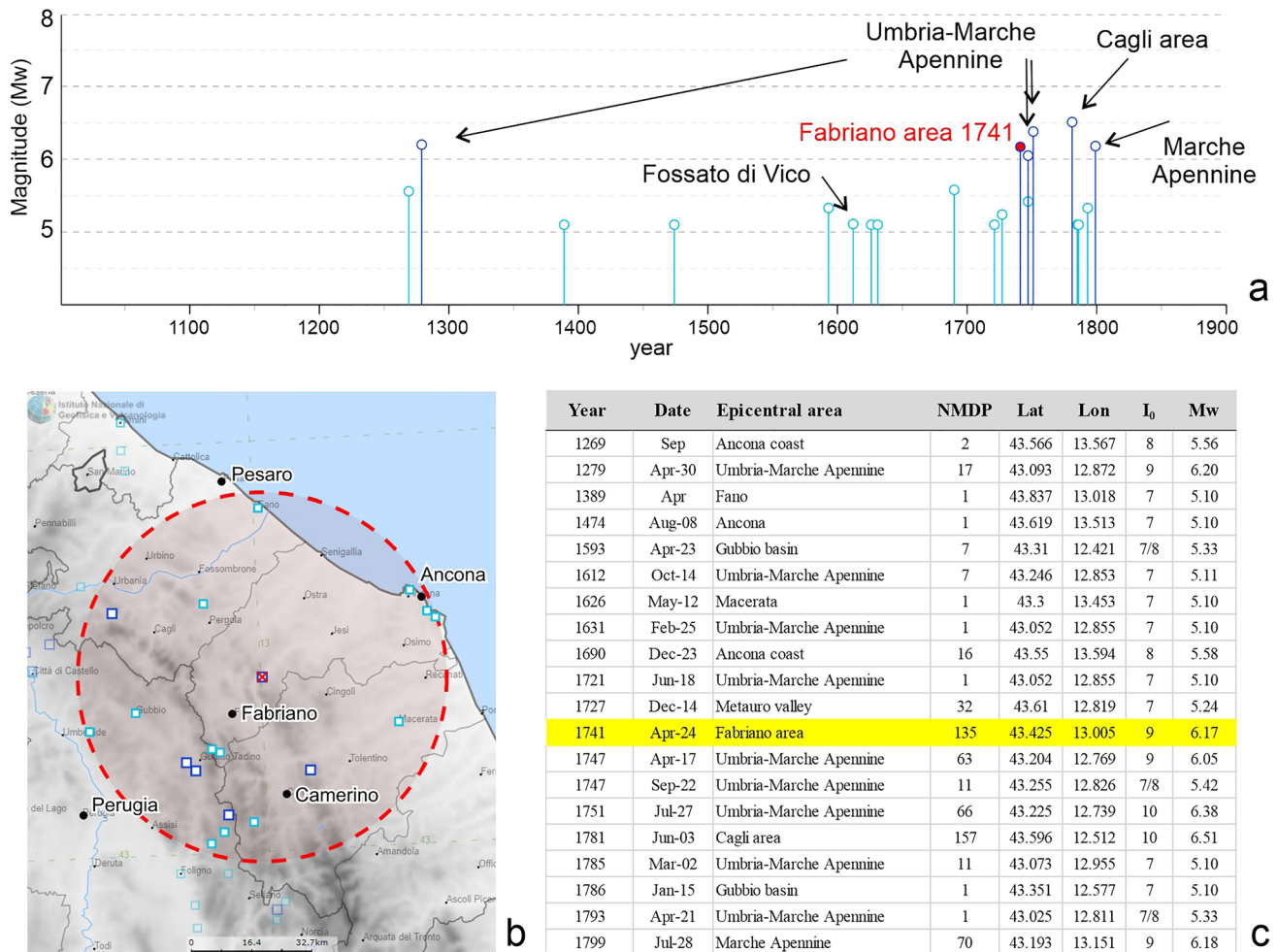


Fig. 6 Sequence (a), location (b) and list (c) of the main earthquakes that occurred in the study sector since 1000 AD (modified from Rovida et al., 2020)

alluvial sediments quickly covered the earthquake-induced surface steps, recurrently formed in the alluvial plain. Subsequently, a phase of slower deposition rate, possibly induced by a warmer interval between ca. 170 and 160 ky BP (Berger 1978; Margari et al. 2014; Rousseau et al. 2020) allowed the Villa fault scarp's initial growth. This latter separated the no longer active sector of the plain (Villa Bench) from the lower one (Santa Maria Bench), where alluvial aggradation has continued till the 127 ky BP Eemian Interglacial thermal rise (Margari et al. 2014). Subsequently, the step-like fault evolution controlled the formation of the scarp with abundant slope debris production. Erosion processes induced by the difference in elevation caused the formation of escarpments and gentler slopes that border the higher shelf on the other sides.

Unlike what happened for the Villa Scarp, the alluvial plain aggradation, more active for the lower position, prevented the Santa Maria fault from forming a scarp until the Interglacial, when the alluvial plain aggradation ceased, and the Giano River incision started. During the Last Glacial, the Fabriano Terrace's gravels accumulated against the already present scarp, which was widely affected by slope erosion and debris deposition.

Stratigraphic features and chronology of the faulted deposits

A detailed analysis of the section at the base of the Santa Maria Scarp (Fig. 5) allowed us to relate the fault evolution with the slope's geomorphological-stratigraphic features.

The basal level of the Santa Maria Bench alluvial deposits may be dated 185 ky BP if referred to the first stages of the late Middle Pleistocene Glaciation (according to Margari

et al. 2014) in agreement with the Rome 364 sample ^{14}C dating (> 44,460 ^{14}C year BP). It has been displaced by ca. 35 m, as shown by borehole exploration through the Santa Maria Bench.

We may attribute the alternating layers of gravels and reddish soil sediments that make up the lower part of the section to the Last Glacial coldest interval (22–18 ky BP according to Eyles and McCabe 1989).

Then, cold-dry climate conditions induced a drastic reduction of the vegetation cover, thus enhancing slope-wash and solifluction, and the deposition of stratified debris interfingering with the valley-floor alluvial sediments (Dramis 1983; Coltorti and Dramis 1988, 1995).

The above observations confirm that recurrent strong earthquakes induced by the long-lasting activity of this sector of the FV-VE line are responsible for the investigated stratigraphic features.

Paleoseismological aspects

The trend of the April 24, 1741 earthquake isoseismal lines, and the vast damaged area, from the Umbria region to the Adriatic coast (Pergalani et al. 1986; Stucchi et al. 1991; Boschi et al. 1995, 1997) place with good reliability the hypocentre along with the FV-VE transverse structure, below the Apennine thrust belt, as also supposed by Castelli and Monachesi (2001) from the absence of significant aftershocks (Fig. 7). In analogy to recent seismic events associated with transverse structures in the Marche area (Mazzoli et al. 2015), we could locate the hypocentre at a depth not exceeding 12 km.

Considering that the base of the Santa Maria Bench alluvial deposits (185 ky BP, if referred to the early stages

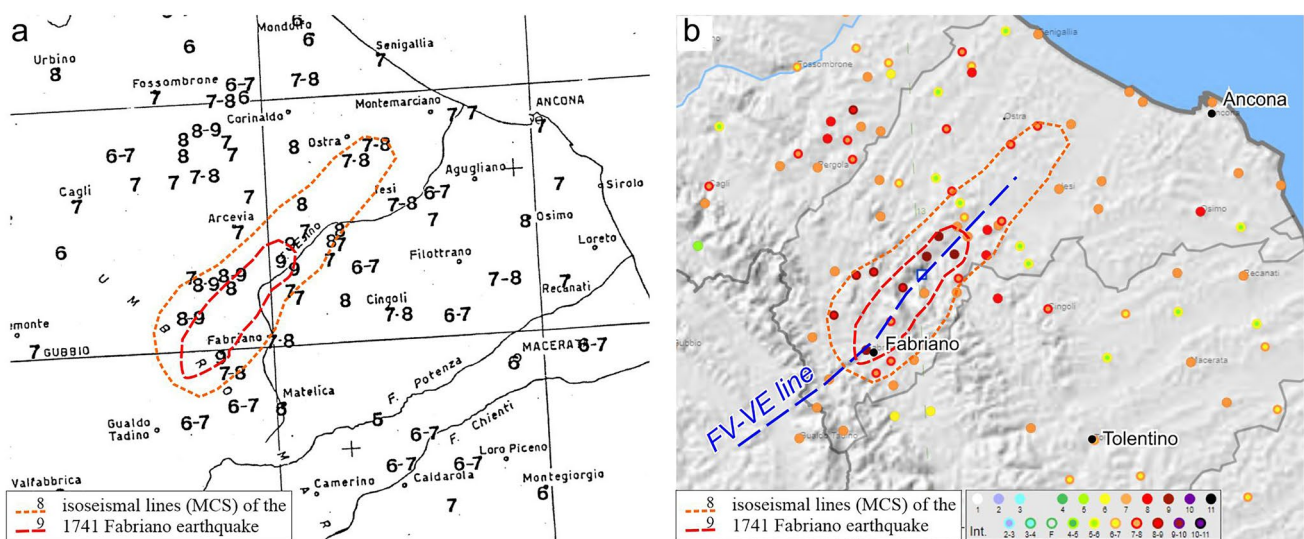


Fig. 7 Isoseismal maps of the April 24th, 1741, Fabriano earthquake, modified from Monachesi (1987) (a) and Rovida et al. (2020) b

of the late Middle Pleistocene Glaciation) has been displaced by ca. 35 m (Fig. 5), we may tentatively assess a dip-slip rate of 0.19 mm/year for the Santa Maria fault. Comparable values result from the displacement of the base of Late Pleistocene stratified slope deposits (0.18–0.22 mm/year-ca. 4 m over 22–18 ky).

From the Santa Maria fault total vertical displacement of 35 m over 185 ky, we can calculate a slip rate of ca. 0.2 mm/year to which, considering the 60 mm offset estimated for the last faulting episode, a return interval of ca. 580 year would correspond. However, no events compared with the April 24, 1741 earthquake appear in the historical record of Fabriano (Castelli and Monachesi, 2001; Guidoboni et al. 2018) unless moving to the FE-VE the strong April 30, 1279 earthquake ($I_0 = 9$ — $M_w = 6.2$; Rovida et al. 2020) so far located (albeit with some uncertainty) a few tens of kilometers southwards. The above considerations would involve a more than one thousand years return interval and the possible occurrence of even stronger events.

Conclusion

The data so far presented show the Quaternary evolution of the Fabriano area is strictly conditioned by tectonic movements along “anti-Apennine” faults, connected with the Fossato di Vico-Valle dell’ Esino line, a major transverse lineament active since the Messinian.

The recent activity of the Santa Maria fault has produced visible morphological and stratigraphic effects, which are consistent with the seismic pattern of the area. In particular, the stratigraphic analysis of a section excavated in alluvial-slope deposits indicates the recurrence in the area of strong, deep-rooted earthquakes with a total coseismic, vertical fault throw of 35 m since the late Middle Pleistocene and a slip rate ranging around 0.2 mm/year.

From the above, it is clear how detailed geological-geomorphological mapping and seismic characterization of the transverse tectonic lineaments would be crucial for a complete and exhaustive assessment of the earthquake hazard in the Apennine belt.

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Availability of data and material The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Code availability Not applicable.

Declarations

Conflicts of interest No potential conflict of interest was reported by the authors).

References

- Alessio M, Allegri L, Coltorti M, Cortesi C, Deiana G, Dramis F, Improta S, Petrone V (1979) Depositi tardowürmiani nell’alto bacino dell’Esino (Appennino marchigiano)—Datazione con ^{14}C . *Geogr Fis Din Quat* 2:203–205
- Ambrosetti P, Centamore E, Deiana G, Dramis F, Pieruccini U (1981) Schema dell’evoluzione neotettonica dell’area umbro-marchigiana tra il Tronto ed il Metauro. *Rend Della Soc Geol Ital* 4:471–475
- Barchi M, Alvarez W, Shimabukuro DH (2012) The Umbria-Marche Apennines as a double orogen: observations and hypotheses. *Ital J Geosci* 131(2):258–271
- Berger A (1978) Long-term variations of caloric insolation resulting from the earth’s orbital elements. *Quatern Res* 9:139–167
- Bigi S, Cantalamessa G, Centamore E, Didaskalou P, Micarelli A, Nisio S, Pennesi T, Potetti M (1997) The Periadriatic basin Marche-Abruzzi sector, Central Italy during the Plio-Pleistocene. *Giornale Di Geol Ser III* 59(1–2):245–259
- Biondi E, Coltorti M (1983) The Esino flood-plain during the Holocene. *Proc XI INQUA Congress Moscow* 3:45
- Boccaletti M, Calamita F, Centamore E, Deiana G, Dramis F (1983) The Umbria-Marche Apennine: an example of thrust and wrenching tectonics in a model of ensialic Neogenic-Quaternary deformation. *Boll Della Soc Geol Ital* 102:591–592
- Boccaletti M, Calamita F, Centamore E, Chiochini U, Deiana G, Micarelli A, Moratti G, Potetti M (1986) Evoluzione dell’Appennino tosco-umbro-marchigiano durante il Neogene. *Giornale Di Geol Ser III* 48(1–2):227–233
- Boschi E, Ferrari G, Gasperini P, Guidoboni E, Smeriglio G, Valensise G (eds) (1995) *Catalogo dei forti terremoti in Italia dal 461 a.C. al 1980*. ING-SGA, Bologna, pp 970
- Boschi E, Guidoboni E, Ferrari G, Valensise G, Gasperini P (Eds.) (1997) *Catalogo dei forti terremoti in Italia dal 461 a.C. al 1990*, vol 2. ING-SGA, Bologna, pp 644
- Butler R, Tavarnelli E, Grasso M (2006) Tectonic inversion and structural inheritance in mountain belts. *J Struct Geol* 28:1893–1908
- Caire A (1975) Les règles de la fracturation continentale et le rôle des géofractures dans l’évolution de l’écorce terrestre. *Rev Géogr Phys Géol Dyn* 17:319–354
- Calamita F, Centamore E, Chiochini U, Deiana G, Micarelli A, Potetti M, Romano A (1979) Analisi dell’evoluzione tettonico-sedimentaria dei “bacini minori” del Miocene medio—superiore nell’Appennino umbro-marchigiano e laziale- abruzzese: 7) il bacino di Camerino. *Stud Geol Camerti* 5:67–81
- Calamita F, Cello G, Centamore E, Deiana G, Micarelli A, Paltrinieri W, Ridolfi M (1991a) Stile deformativo e cronologia della deformazione lungo tre sezioni bilanciate dall’Appennino umbro-marchigiano alla costa adriatica. *Stud Geol Camerti* 1991:295–314
- Calamita F, Cello G, Centamore E, Deiana G, Micarelli A, Paltrinieri W, Ridolfi M (1991b) Stile deformativo e cronologia della deformazione lungo tre sezioni bilanciate dall’Appennino umbro-marchigiano alla costa adriatica. *Stud Geol Camerti* 1991:295–314
- Castellarin A, Colacicchi R, Praturlon A, Cantelli C (1982) The Jurassic-lower pliocene history of the Ancona-Anzio line (Central Italy). *Mem Della Soc Geol Ital* 24:325–336

- Castelli V, Monachesi G (2001) Seismic history and historical earthquake scenario for the town of Fabriano (Central Italy). *Riv Ital Geotecn* 2:36–46
- Centamore E, Chiocchini U, Cipriani N, Deiana G, Micarelli A (1978a) Analisi dell'evoluzione tettonico-sedimentaria dei "bacini minori" torbiditici del Miocene medio-superiore nell'appennino umbro-marchigiano e laziale-abruzzese: 5) Risultati degli studi in corso. *Mem Della Soc Geol Ital* 18:135–170
- Centamore E, Deiana G, Dramis F, Micarelli A, Carloni GC, Francavilla F, Nesci O, Moretti E (1978b) Dati preliminari sulla neotettonica dei fogli 116 (Gubbio), 123 (Assisi), 117 (Jesi) e 109 (Pesaro). Contributi preliminari alla realizzazione della Carta Neotettonica d'Italia, vol. 1, CNR, P.F. Geodinamica Pubbl 155:113–148
- Centamore E, Chiocchini M, Chiocchini U, Dramis F, Jacobacci A, Martelli G, Micarelli A, Potetti M (1979) Note Illustrative della Carta Geologica d'Italia alla scala 1:50.000—Foglio 301 Fabriano. In: Servizio Geologica d'Italia, Stab. G.E.C. s.p.a., Roma
- Centamore E, Rossi D, Tavarnelli E (2009) Geometry and kinematics of Triassic-to-Recent structures in the Northern-Central Apennines: a review and an original working hypothesis. *Ital J Geosci* 128(2):419–432
- Ciccacci S, D'Alessandro L, Dramis F, Fredi P, Pambianchi G (1985) Geomorphological and neotectonic evolution of the Umbria-Marche Ridge, northern sector. *Stud Geol Camerti* 10:7–15
- Coltorti M, Dramis F (1988) The significance of stratified slope waste deposits in the Quaternary of Umbria-Marche Apennines (Central Italy). *Zeitschr Für Geomorphol N.f Suppl Bd* 71:59–70
- Coltorti M, Dramis F (1995) The chronology of Upper Pleistocene stratified slope-waste deposits in Central Italy. *Permafrost Periglac Process* 6:235–242
- Coltorti M, Consoli M, Dramis F, Gentili B, Pambianchi G (1991) Evoluzione geomorfologica delle piane alluvionali delle Marche centro-meridionali. *Geogr Fis Din Quat* 14(1):87–100
- Coltorti M, Farabollini P, Gentili B, Pambianchi G (1996) Geomorphological evidences for anti-Apenninic faults in the Umbro-Marchean Apennines and in the peri-Adriatic basin, Italy. *Geomorphology* 15:33–45
- Dasgupta S, Mukhopadhyay M, Nandy DR (1978) Active transverse features in the central portion of the Himalaya. *Tectonophysics* 136:255–264
- Della Seta M, Del Monte M, Fredi P, Miccadei E, Nesci O, Pambianchi G, Piacentini T, Troiani F (2008) Morphotectonic evolution of the Adriatic piedmont of the Apennines: an advancement in the knowledge of the Marche-Abruzzo border area. *Geomorphology* 102:119–129
- Di Bucci D, Corrado S, Naso G (2002) Active faults at the boundary between Central and Southern Apennines (Isernia, Italy). *Tectonophysics* 359:47–63
- Dramis F (1983) Morfogenesi di versante nel Pleistocene superiore in Italia: i depositi detritici stratificati Convegno AIQUA, Como 1982. *Geogr Fis Dinamica Quatern* 6(2):180–182
- Dramis F (1992) Il ruolo dei sollevamenti tettonici a largo raggio nella genesi del rilievo appenninico. *Stud Geol Camerti* 1992/1:9–15
- Dramis F, Pambianchi G, Nesci O, Consoli M (1991) Il ruolo di elementi strutturali trasversali nell'evoluzione tettonico-sedimentaria e geomorfologica della regione marchigiana. *Stud Geol Camerti* 1991/2:287–293
- Dramis F, Fubelli G, Calderoni G, Esu D (2014) Holocene aggradation/degradation phases of tufa dams in northern Ethiopia and central Italy: a palaeoclimatic comparison between East Africa and Mediterranean Europe. *Z Geomorphol* 58(4):419–434
- Eyles N, McCabe AM (1989) The Late Devensian (<22,000 BP) Irish Sea Basin: the sedimentary record of a collapsed ice sheet margin. *Quatern Sci Rev* 8:307–351
- Girotti P (1968) Note sulla tettonica delle formazioni mioceniche dell'Ascolano. *Atti dell'accademia Nazionale Dei Lincei. Rend Della Classe Sci Fis Naturali Ser* 8(44):827–837
- Gori S, Falcucci E, Dramis F, Galadini F, Galli P, Giaccio B, Messina P (2014) Deep-seated gravitational slope deformation, large-scale rock failure, and active normal faulting along Mt. Morrone (Sulmona basin, Central Italy). *Geomorphology* 208:88–101
- Gori S, Falcucci E, Ladina C, Marzorati S, Galadini F (2017) Active faulting, 3-D geological architecture and Plio-Quaternary structural evolution of extensional basins in the central Apennine chain. *Solid Earth* 8:319–337
- Guidoboni E, Ferrari G, Mariotti D, Comastri A, Tarabusi G, Sgattoni G, Valensise G (2018) CFTI5Med, Catalogo dei forti terremoti in Italia (461 a.C.-1997) e nell'area mediterranea (760 a.C-1500). In: Istituto Nazionale di Geofisica e Vulcanologia (INGV)
- Magri D (1997) Middle and Late Holocene vegetation and climate changes in peninsular Italy. In: Dalfes HN, Kukla G, Weiss H (eds) Third millennium B.P. climate change and Old World collapse, NATO ASI Series, I, vol 49, pp 517–530
- Magri D (1999) Late Quaternary vegetation history at Lagaccione near Lago di Bolsena (central Italy). *Rev Paleobotany Palynol* 106:171–208
- Marcellini A, Tiberi P (eds) (2000) La microzonazione sismica di Fabriano. C.N.R., G.N.D.T., Regione Marche., Biemmegraf s.r.l., Macerata, pp 291
- Margari V, Skinner LC, Hodell DA, Martrat B, Toucanne S, Grimalt JO, Gibbard PL, Lunkka JP, Tzedakis PC (2014) Land-ocean changes on orbital and millennial time scales and the penultimate glaciation. *Geology* 42(3):183–186. <https://doi.org/10.1130/G35070.1>
- Mazzoli S, Santini S, Macchiavelli C, Ascione A (2015) Active tectonics of the outer northern Apennines: Adriatic vs. Po Plain seismicity and stress fields. *J Geodyn* 84:62–76
- Monachesi G (ed) (1987) Revisione della sismicità di riferimento per i comuni di Cerreto d'Esi (AN), Esanatoglia (MC), Serra San Quirico (AN). In: Osservatorio Geofisico Sperimentale, Macerata, Internal Report, pp 240
- Nesci O, Moretti E, Sacchi G (1978) Studio neotettonico della zona compresa tra i fiumi Foglia e Metauro (Marche settentrionali). *Mem Della Soc Geol Ital* 19:635–640
- Pace B, Boncio P, Lavecchia G (2002) The 1984 Abruzzo earthquake (Italy): an example of seismogenic process controlled by interaction between differently oriented synkinematic faults. *Tectonophysics* 350:237–254
- Peacock DCP, Tavarnelli E, Anderson MW (2017) Interplay between stress permutations and overpressure to cause strike-slip faulting during tectonic inversion. *Terra Nova* 29:61–70
- Pergalani F, Stucchi M, Polonara L (1986) Attività nel settore della difesa dai terremoti. In: Consiglio Nazionale delle Ricerche, Gruppo Nazionale per la Difesa dai Terremoti, Regione Marche, pp 36
- Petrogeo-Comune di Fabriano (1976) Studio idrogeologico per l'approvvigionamento idrico del capoluogo. Petrogeo, Pisa, pp 43
- Pierantoni PP, Deiana G, Galdenzi S (2013) Stratigraphic and structural features of the Sibillini Mountains (Umbria-Marche Apennines, Italy). *Ital J Geosci* 132(3):497–520
- Pizzi A, Galadini F (2009) Pre-existing cross-structures and active fault segmentation in the northern-central Apennines (Italy). *Tectonophysics* 476:304–319
- Postpischl D (ed) (1985) Catalogo dei terremoti italiani dall'anno 1000 al 1980. *Quad della Ricerca Sci* 114(2B):239
- Ricci Lucchi M, Calderoni G, Carrara C, Cipriani N, Esu D, Ferrelli L, Girotti O, Gliozzi M, Lombardo M, Longinelli A, Magri D, Nebbiai M, Ricci Lucchi F, Vigliotti L (2000) Late Quaternary record of the Rieti basin, central Italy: paleoenvironmental and paleoclimatic evolution. *Giorn Geol* 62:105–136

- Rousseau DD, Antoine P, Boers N, Lagroix F, Ghil M, Lomax J, Fuch M, Debret M, Hatté C, Moine O, Gauthier C, Jordanova D, Jordanova N (2020) Dansgaard–Oeschger-like events of the penultimate climate cycle: the loess point of view. *Clim past* 16:713–727. <https://doi.org/10.5194/cp-16-713-2020>
- Rovida A, Locati M, Camassi R, Lolli B, Gasperini P (2020) The Italian earthquake catalogue CPTI15. *Bull Earthq Eng* 18:2953–3298. <https://doi.org/10.1007/s10518-020-00818-y>
- Rovida A, Camassi R, Gasperini P, Stucchi EM (2011) CPTI11, la versione 2011 del Catalogo Parametrico dei Terremoti Italiani. Milano, Bologna
- Selli R (1954) Il bacino del Metauro. *Giorn Geol* 24:1–268
- Servizio Geologico d'Italia (1979) Foglio 301 “Fabriano” in scala 1:50.000. Grafica Editoriale Cartografica, Roma
- Sorgi C, Deffontaines B, Hyppolite JC, Cadet JP (1998) An integrated analysis of transverse structures in the northern Apennines, Italy. *Geomorphology* 25(3–4):193–206
- Stucchi M, Monachesi G, Mandrelli FM (1991) Investigation of the 18th-century seismicity in Central Italy in the light of the 1741 Fabriano earthquake. *Tectonophysics* 193:65–82
- Tavarnelli E (1996) La struttura di M. Coscerno-Rivodutri (Appennino umbro-marchigiano): unsovrascorrimento riutilizzato come faglia diretta? *Stud Geol Camerti* 1996:611–615
- Tavarnelli E, Decandia FA, Alberti M (1998) The transition from extension to compression in the Messinian Laga Basin and its significance in the evolution of the Apennine belt-foredeep-foreland system. *Ann Tecton* 12:133–144
- Tavarnelli E, Decandia FA, Renda P, Tramutoli M, Gueguen E, Alberti M (2001) Repeated reactivation in the Apennine-Maghrebide system, Italy: a possible example of fault-zone weakening? In: Holdsworth RE, Strachan RA, Magloughlin JF, Knipe RJ (eds) *The nature and tectonic significance of fault zone weakening*, Geological Society of London Special Publication, vol 186, pp 273–286
- Tavarnelli E, Butler RWH, Decandia FA, Calamita F, Grasso M, Alvarez W, Renda P (2004) Implications of fault reactivation and structural inheritance in the Cenozoic tectonic evolution of Italy. In: Crescenti U, D’Offizi S, Merlini S, Sacchi R (eds) *The Geology of Italy*, Società Geologica Italiana, pp 201–214
- Turco E, Macchiavelli C, Penza G, Schettino A, Pierantoni PP (2021) Kinematics of deformable blocks: application to the opening of the Tyrrhenian basin and the formation of the Apennine chain. *Geosciences* 11:177. <https://doi.org/10.3390/geosciences11040177>
- Valensise G, Pantosti D (2001) The investigation of potential earthquake sources in peninsular Italy: a review. *J Seismol* 5:287–306
- Vannoli P, Burrato B, Valensise G (2015) The seismotectonics of the Po Plain (northern Italy): tectonic diversity in a blind faulting domain. *Pure Appl Geophys* 172(5):1105–1142
- Wheeler RL (1989) Persistent segment boundaries on Basin and Range normal faults. *US Geol Surv Open-File Rep* 89–315:432–444