Paleoseismological surveys for the identification of capable faults in urban areas: the case of the Mt. Marine Fault (Central Apennines, Italy).

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***Abstract:** In order to constrain the Fault Displacement Hazard (FDH) of the town of Pizzoli, located 10 km NW of L'Aquila (Central Apennines, Italy), we performed two paleoseismological trenches across multiple fault splays within the hanging wall of the main Mt. Marine active normal fault. Our trenches highlighted the presence of five faults arranged both synthetic and antithetic to the main fault. The fault splays are distributed within an across-strike distance of about 500 m. Each fault segment shows evidence of repeated surface-rupturing earthquakes occurring throughout the Late Pleistocene-Holocene, proving their capability of rupturing the surface during recent earthquakes. Our study shows that multiple parallel fault splays belonging to a principal segmented fault are active during the same time interval, although the slip rates of single faults may be different through time. Our work reiterates the importance of performing paleoseismological investigation for assessing FDH in urban areas.*

***Key words**: Earthquake geology, paleoseismology, fault displacement hazard.*

INTRODUCTION

The Fault Displacement Hazard (FDH) is a localised seismic hazard due to the occurrence of coseismic surface ruptures during earthquakes. The FDH is strictly connected to the so-called capable faults, defined as faults able to release surface ruptures during earthquakes. The assessment of the FDH is very significant when capable faults are located within urban areas, with houses and facilities being exposed to permanent deformation due to the rupturing of the ground surface underneath. Hence, in order to mitigate the potential effects of the surface ruptures it is critical to identify the geometry and slip rates of such capable faults. However, the identification of capable faults in urban areas is not straightforward, because the anthropic activity often elides the geomorphological evidence of past earthquakes (e.g. fault scarps). The assessment of FDH becomes even more complex when capable faults are highly segmented, with multiple fault splays arranged both along- and across-strike. In such geological contexts, paleoseismological investigations become key for constraining both the geometry and the activity rates of the multiple fault splays.

We focus on the Mt. Marine fault (Central Apennines, Italy), an active normal fault that has already released surface-rupturing earthquakes in the past, with the most recent event occurred in 1703 AD (Blumetti, 1995; Moro et al., 2002; 2016; Galli et al., 2011; Figure 1). Paleoseismological investigations across some of the fault splays within the hanging wall of the main Mt. Marine fault identified multiple Late Quaternary surface-rupturing earthquakes. However, these studies have explored only some of the faults belonging to a more complex fault system (Figure 1b). In order to have an actual assessment of the FDH, it is important to observe whether all the fault splays are capable of producing surface ruptures and are active during the Late Quaternary with the same rates, or instead fault activity localises on some specific fault splays through time. To answer to this question, we have performed two paleoseismological surveys aimed at intercepting most of the fault splays belonging to the Mt. Marine fault. We show that there are at least five principal faults with evidence of repeated Holocene surface-rupturing earthquakes and different slip rates. We discuss the role of the identification and characterization of multiple capable faults in urban areas in taking action to mitigate the risk associated to the FDH.

METHODS

The paleoseismological trenches have been planned in order to explore (i) potential fault scarps modified by anthropogenic activity, identified through fieldwork, LiDAR and aerial photographs analysis, and (ii) discontinuities in the stratigraphic record highlighted by geophysical investigations (Electrical Resistivity Tomography (ERT), Ground Penetrating Radar (GPR)).

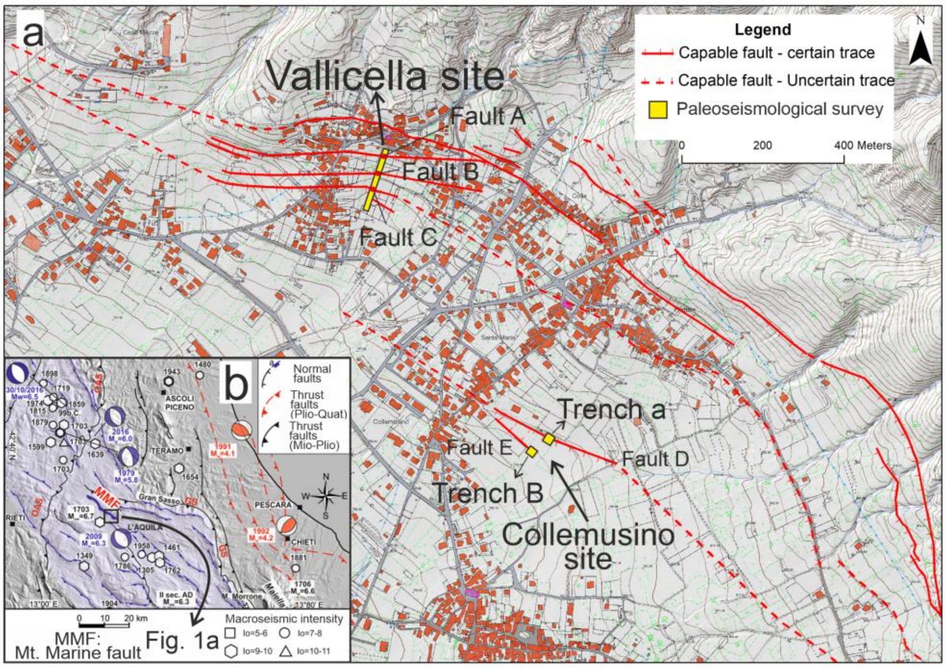

Figure 1. Location map of the study area. a) Location of the paleoseismological surveys across the multiple splays of the Mt. Marine fault. b) Location of the Mt. Marine fault within the Central Apennines Fault System. Historical earthquakes are from CPTI15 (Rovida et al., 2020).

The first paleoseismological survey (Vallicella site) is characterised by a continuous trench about 156 m long and 2.5 m deep. This trench aimed at verifying the nature of multiple topographic scarps and discontinuities in the stratigraphic record highlighted by the geophysical investigations. The second paleoseismological survey (Collemusino site) is composed by two adjacent smaller trenches of length about 20 m (Trench A) and 13 m (Trench B). These trenches aimed at exploring the nature of discontinuities in the stratigraphic record highlighted by the geophysical investigations.

The ages of the stratigraphic units were constrained by radiocarbon dating, performed at the Beta Analyitic Laboratory (Miami, FL, USA).

RESULTS AND DISCUSSION

The Vallicella site

The paleoseismological survey exposed three main faults, arranged both synthetic (Fault A and C, Figure 2a, 2b and 2d), and antithetic (Fault B, Figure 2c) to the principal Mt. Marine fault. The stratigraphic setting of the three faults is characterised by Upper Pleistocene alluvial fan deposits in the footwall of the faults, and Holocene colluvial deposits in their hanging wall. Stratigraphic units have been numbered as a whole for the entire trench, according to their combined stratigraphic position.

Fault A is characterised by a main SW-dipping fault plane (F1, Figure 2a,b), and minor faults located within its footwall (F2 – F3, Figure 2a,b). The stratigraphic record of the fault provides evidence of five surface-rupturing earthquakes. The Most-Recent Event (E1A-MRE) is suggested by the offset of the base of Unit 1 along the faults F2 and F3 (Figure 2a,b). The minimum measured offset is 12 cm, although Unit 1 has been severely reworked by anthropic activity through time. The age of the basal part of Unit 1 has been constrained in multiple localities along the trench wall, with ages being 321 BC-202 BC (sample Fb3c, Figure 2c) and 116 AD-239 AD (sample Fc6c, Figure 2d). This suggests that E1A-MRE could be representative of the 1703 AD earthquake, given that there are no other known earthquakes associated with the Mt. Marine fault in historical catalogues (Rovida et al., 2020). The penultimate event (E2-A) is shown along F1, and it is constrained by the faulting of the colluvial wedge CW1 (Figure 2a,b). No data are available to measure the coseismic offset of E2A. The *post-quem* term of the earthquake is provided by sample Fa10c (1888 BC-1792 BC) collected in Unit 3 (Figure 2b). F1 seems to be sealed by the base of Unit 1, suggesting that the earthquake occurred before its deposition. The previous event (E3A) caused the formation of CW1. The time range of occurrence of E3A is constrained by samples Fa6c (3769-3642 BC) and Fa10c (1888-1792 BC) (Figure 2b). The maximum vertical thickness of CW1 is about 60 cm. This therefore represent a minimum coseismic throw, with a maximum coseismic throw that could be as high as ~1.2 m, assuming that the coseismic offset is double the thickness of the colluvial wedge (e.g. McCalpin, 2009). Event E4A caused the faulting of CW2 (Figure 2a), with a vertical offset of about 70 cm. Event E5A caused the deposition of CW2 (Figure 2a,b). The thickness of CW2 is ~30 cm, therefore the coseismic throw could be up to ~60 cm, assuming again that the offset to be double the thickness of the colluvial wedge. Time constraints for E4A and E5A are provided by samples Fa8 (6076-5990 BC) and Fa6 (3769-3642 BC). Both E4A and E5A should have occurred within this time range.

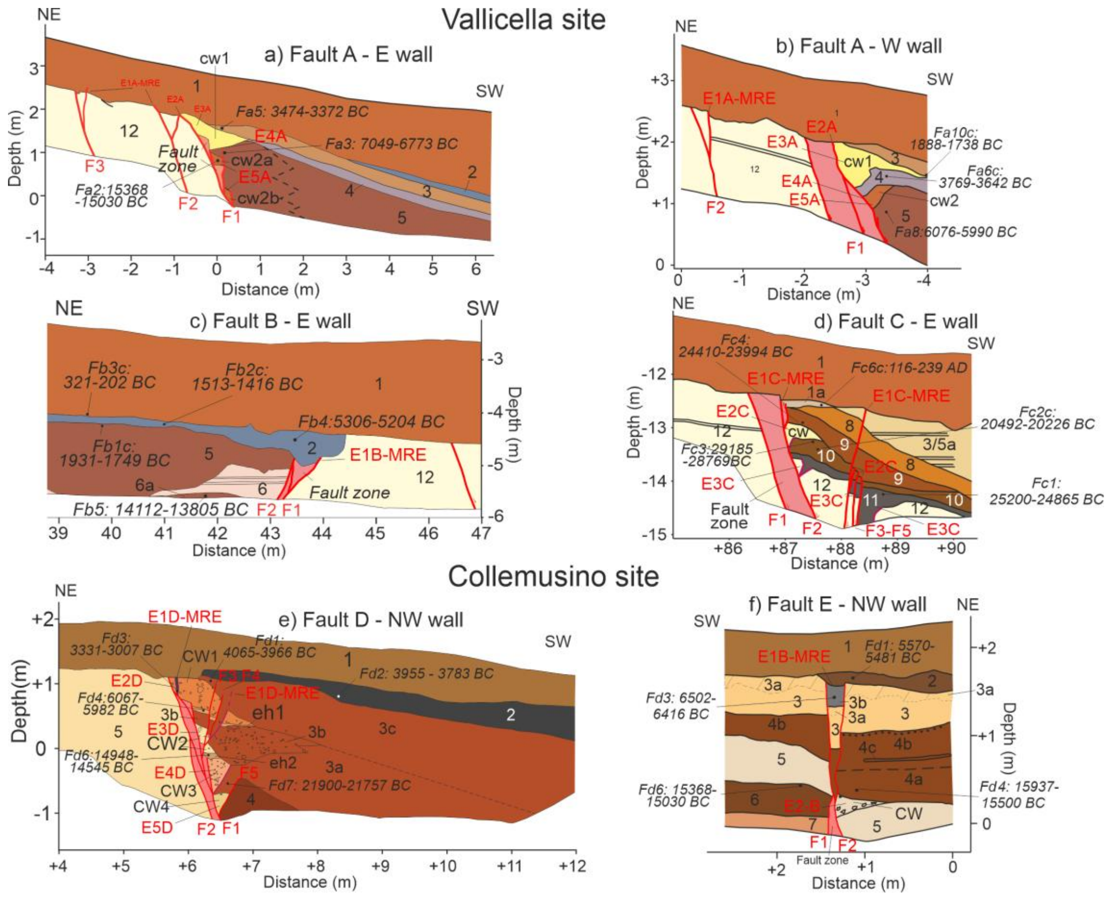

Figure 2. Stratigraphic logs of the faults shown by the paleoseismological trenches (location of the trenches in Fig.1).

Fault B is located 44 m SW of Fault A (Figure 1a). It is characterised by two NE-dipping fault planes showing evidence of one surface-rupturing earthquake (E1B-MRE; Figure 2c). The minimum measured vertical displacement is 12 cm, measured as the offset of the base of Unit 2 along F1. The time constraints for this earthquake are provided by samples Fb1c (1931-1749 BC) and Fb3c (321-202 BC).

Fault C is located 43 m SW of Fault B (Figure 1a). It is composed by a main SW-dipping fault splay (F1-F2 in Figure 2d) and a set of about vertical, slightly NE-dipping pseudo-reverse fault planes cutting across the colluvial deposits in the hanging wall of F2 (F3-F4-F5, Figure 2d). The stratigraphy shows evidence of three past earthquakes. The most recent one (E1C-MRE) cuts across the entire stratigraphy along both the main fault and the main hanging wall splay (F2 and F3, Figure 2d). The minimum cumulative offset is 24 cm. The offset of Unit 1a, dated 116-239 AD, allows us to suggest that E1C-MRE is representative of the 1703 AD earthquake. The penultimate event (E2C) caused the formation of the colluvial wedge CW and ruptured along most of the hanging wall fault splays (Figure 2d). The estimated cumulative minimum throw is 80 cm. E2C occurred prior to the deposition of Unit 9, dated 24410-23994 BC (sample Fc4). The oldest event (E3C) caused slip and opening of extensional fissures along both the main fault and the hanging wall splays (Figure 2d). The cumulative minimum throw, measured along the minor hanging wall splays, is 40 cm. The fissures are filled up by Unit 11, a colluvial unit that should have been deposited after the fractures have formed. Therefore, the age of Unit 11 (25200 - 24865 BC, sample Fc1) postdates E3C.

The Collemusino site

The two paleoseismological trenches of the Collemusino site highlighted the presence of a main SW-dipping fault (FD) in Trench A, synthetic to the principal Mt. Marine fault, and a NE-dipping secondary fault (FE) in Trench B, antithetic to the principal Mt. Marine fault (Figure 1b).

FD is characterised by a principal SW-dipping fault plane and a set of minor faults and open fissures in its hanging wall (Figure 2e), imposed in a stratigraphy of Upper Pleistocene alluvial fan deposits and Upper Pleistocene-Holocene colluvial deposits. FD recorded evidence of five past earthquakes. The most recent one (E1D-MRE) cut the entire stratigraphy along F1, being apparently sealed by Unit 1, and ruptured also along F3-F4 up to at least Unit 3c. The offset associated with the minor faults is about 10 cm, it is not possible to estimate the coseismic offset along the main fault. The infilling of a fissure within CW1 (sample Fd3, 3331-3007 BC) is interpreted to be the soil at the time of the E1D-MRE, therefore its age should predate the event. The penultimate event (E2D) caused the formation of the colluvial wedge CW1. The vertical offset estimated by the doubling the thickness of the wedge is ~90 cm. The time interval within which the earthquake occurred is 6067-5982 BC (Sample Fd4) and

4065-3966 BC (Sample Fd1). The event E3D is constrained by the formation of the colluvial wedge CW2. The vertical thickness of CW2 is 27 cm, therefore the coseismic throw could be as high as ~54 cm. The time interval within which the earthquake occurred is 14948-14545 BC (Sample Fd6) and 6067-5982 BC (Sample Fd4). The event E4D is constrained by an open fissure along the main fault splay infilled with material that recalls a colluvial wedge, for lithology and texture (Figure 2e). It is not possible to estimate the offset of the earthquake. The time interval within which the earthquake occurred is 21900-21757 BC (Sample Fd7) and 14948-14545 BC (Sample Fd6). The oldest event, E5D, is constrained by CW4, a unit localised in the hanging wall of both the main fault splay F2 and a secondary antithetic splay, F5 (Figure 2e). It is not possible to estimate the offset of the earthquake. This earthquake occurred prior to the deposition of Unit 3a, dated 21900-21757 BC (Sample Fd7).

FE is characterised by two sub-vertical NE-dipping faults. The stratigraphic setting is characterised by Upper Pleistocene alluvial fans and paleosols, and Holocene alluvial and colluvial deposits. FE shows evidence of two earthquakes. The most recent one (E1F-MRE) cuts the entire stratigraphy and it is sealed by Unit 2. The earthquake caused the collapse of the stratigraphy within F1 and F2, which has then been infilled by the paleosol of Unit 3a (marked as Unit 3b within the fissure, Figure 2f). The dating of Unit 3b (sample Fd3, 6502-6416 BC) therefore should predate E1F-MRE. The older earthquake, E2F, is constrained by the colluvial wedge CW, lying over the top of Unit 5 (Figure 2f). Moreover, the top of Unit 5 in the footwall seems to have retreated from its original position in proximity of the fault plane. The same nature of the sedimentary material forming both Unit 5 and CW suggests that the latter is made of the eroded material of Unit 5. The offset associated with E2F is 55 cm, calculated as the offset of the top of Unit 5 minus the offset associated with E1F-MRE. The age of Unit 6 immediately underneath Unit 5 dates the age of E2F to be post 15368-15030 BC (sample Fd6).

Overall, our study provides evidence of the occurrence of several surface-rupturing earthquakes on multiple fault splays arranged parallel to the strike of the main Mt. Marine fault. We show that multiple synthetic and antithetic fault splays have been active during the Late Pleistocene-Holocene, with most of the activity being localised on the synthetic faults. The studied faults seem to have different slip rates: FA experienced 5 earthquakes during the last 8 ka, FC shows evidence of two older earthquakes (>24 ka) and of a very recent one (1703 AD), FD experienced 5 earthquakes in the last 22 ka. Although the stratigraphic record of FC might be influenced by erosional processes that have possibly elided evidence of paleoearthquakes, our results suggest that most of the recent activity has been localised on FA. More work is needed to confirm this by comparing our results with existing paleoseismological studies on the Mt. Marine fault (e.g. Moro et al., 2002; 2016; Galli et al., 2011).

Moreover, our findings provide multiple insights on different aspects of seismic hazard. Firstly, we reiterate the crucial role that paleoseismological studies have in assessing the FDH in urban areas. That is because they have the ability to unveil active faults also where the anthropic activity may have elided their surficial evidence. Secondly, our study shows that multiple fault splays belonging to a principal fault are active during the Late Pleistocene-Holocene, suggesting that their simultaneous rupture during large earthquakes is a recurrent feature through time. Thirdly, the different slip rates we observe between the studied faults suggest that the earthquake activity may be localised on specific faults through time. This provides important insights also on probabilistic approaches for the FDH, because knowing where most of the activity is localised in recent time could help in weighing the probability of occurrence of fault displacement in future earthquakes, even if the studied faults appear to belong to the same fault ranking (e.g. Baize et al., 2019).

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