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Geomorphic signatures of recent normal fault activity *versus* geological evidence of inactivity: Case studies from the central Apennines (Italy)

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A B S T R A C T

We have here analysed two normal faults of the central Apennines, one that affects the south-western slopes of the Montagna dei Fiori–Montagna di Campli relief, and the other that is located along the south-western border of the Leonessa intermontane depression. Through this analysis, we aim to better understand the reliability of geomorphic features, such as the fresh exposure of fault planes along bedrock scarps as certain evidence of active faulting in the Apennines, and to define the Quaternary kinematic history of these tectonic structures. The experience gathered from these two case studies suggests that the so-called 'geomorphic signature' of recent fault activity must be supported by wider geomorphologic and geologic investigations, such as the identification of displaced deposits and landforms not older than the Late Pleistocene, and/or an accurate definition of the slope instabilities. Our observations indicate that the fault planes studied are exposed exclusively because of the occurrence of non-tectonic processes, i.e. differential erosion and gravitational phenomena that have affected the portions of the slopes that are located in the hanging wall sectors. The geological evidence we have collected indicates that the Montagna dei Fiori–Montagna di Campli fault was probably not active during the whole of the Quaternary, while the tectonic activity of the Leonessa fault ceased (or strongly reduced) at least during the Late Pleistocene, and probably since the Middle Pleistocene. The present lack of activity of these tectonic structures suggests that the fault activation for high magnitude earthquakes that produce surface faulting is improbable (i.e. $M>5.5$–6.0, with reference to the Apennines, according to Michetti et al. [Michetti, A.M., Brunamonte, F., Serva, L., Vittori, E. (1996), Trench investigations of the 1915 Fucino earthquake fault scarps (Abruzzo, Central Italy): geological evidence of large historical events, J. Geoph. Res., 101, 5921–5936; Michetti, A.M., Ferreli, L., Esposito, E., Porfido, S., Blumetti, A.M., Vittori, E., Serva, L., Roberts, G.P. (2000)]). If, according to the current view, the shifting of the intra-Apennine extension towards the Adriatic sectors is still active, the Montagna dei Fiori–Montagna di Campli fault might be involved in active extensional deformation in the future.

1. Introduction

The urge to identify active faults in the Italian territory has led to the massive use of geomorphological analyses since the 1970s (e.g. Bosi, 1975), when "probable active faults" were detected along several mountain slopes of the central Apennines. After the 'pioneering' study of Bosi (1975), there were many studies on active tectonics (e.g. Barchi et al., 2000; Galadini and Galli, 2000; and references therein). In some cases, however, the geomorphologic investigations consisted of the recognition of a single indication of recent fault activity along an entire fault. In some cases, the lack of a complete picture of the late Quaternary fault history implies that the attribution of recent activity (and the consequent existence of strong paleo-earthquakes) cannot be considered as conclusive. In the central Apennines, the use of bedrock fault scarps as a certain indication of tectonic activity during the Late Pleistocene–Holocene is an example of such a non-exhaustive methodological approach (e.g. Bosi et al., 1993; Bartolini, 2004).

In the present study, we present our results from geomorphological field surveys that were carried out along the normal faults that affect the south-west slopes of the Montagna dei Fiori–Montagna di Campli relief (the Montagna dei Fiori–Montagna di Campli fault; MFCF) and the south-west flanks of the Leonessa basin (the Leonessa fault; LF) of the central Apennines, Italy. The surficial expressions of these two faults indeed resemble those typical of certain active normal faults, as they are associated with the formation of valleys or basins, which are characterised by bedrock fault scarps along the adjacent mountain slopes.

Our analyses were designed to cast light on the late Quaternary activity of these faults. Within this perspective, it is worth noting that the MFCF was considered as having been active during the Pleistocene by Ghisetti and Vezzani (2000), while the recent activity of the LF is

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currently under debate (e.g. Barchi et al., 2000). Moreover, we also provide evidence that in some cases the use of only the so-called "geomorphological signature" for the definition of recent fault activity can be misleading.

After short sections dedicated to the geological and seismotectonic framework of the central Apennines, we introduce and discuss the collected data. In our concluding remarks, we will analyse the implications that our results have in terms of: 1) the improvements to our knowledge of the seismotectonic characteristics of the central Apennines; 2) the structural evolution of this part of the Apennine chain; and 3) the methodological approaches for active faulting studies.

2. The geological setting of the central Apennines

The Apennines consist of a fold and thrust chain that developed after the Oligo-Miocene as the result of the westward subduction of the Adriatic lithosphere and its progressive eastward flexural retreat, within the framework of the Africa–Europe convergence (Malinverno and Ryan, 1986; Royden et al., 1987; Patacca et al., 1990, 2008). The central sector of the Apennines has been affected by extensional tectonics since the Pliocene, contemporaneous to significant uplift (by more than 1000 m) of the chain (Parotto and Praturlon, 1975; CNR-PFG, 1987; Doglioni, 1995; D'Agostino et al., 2001; Galadini et al., 2003~~a,b~~) and to the back-arc

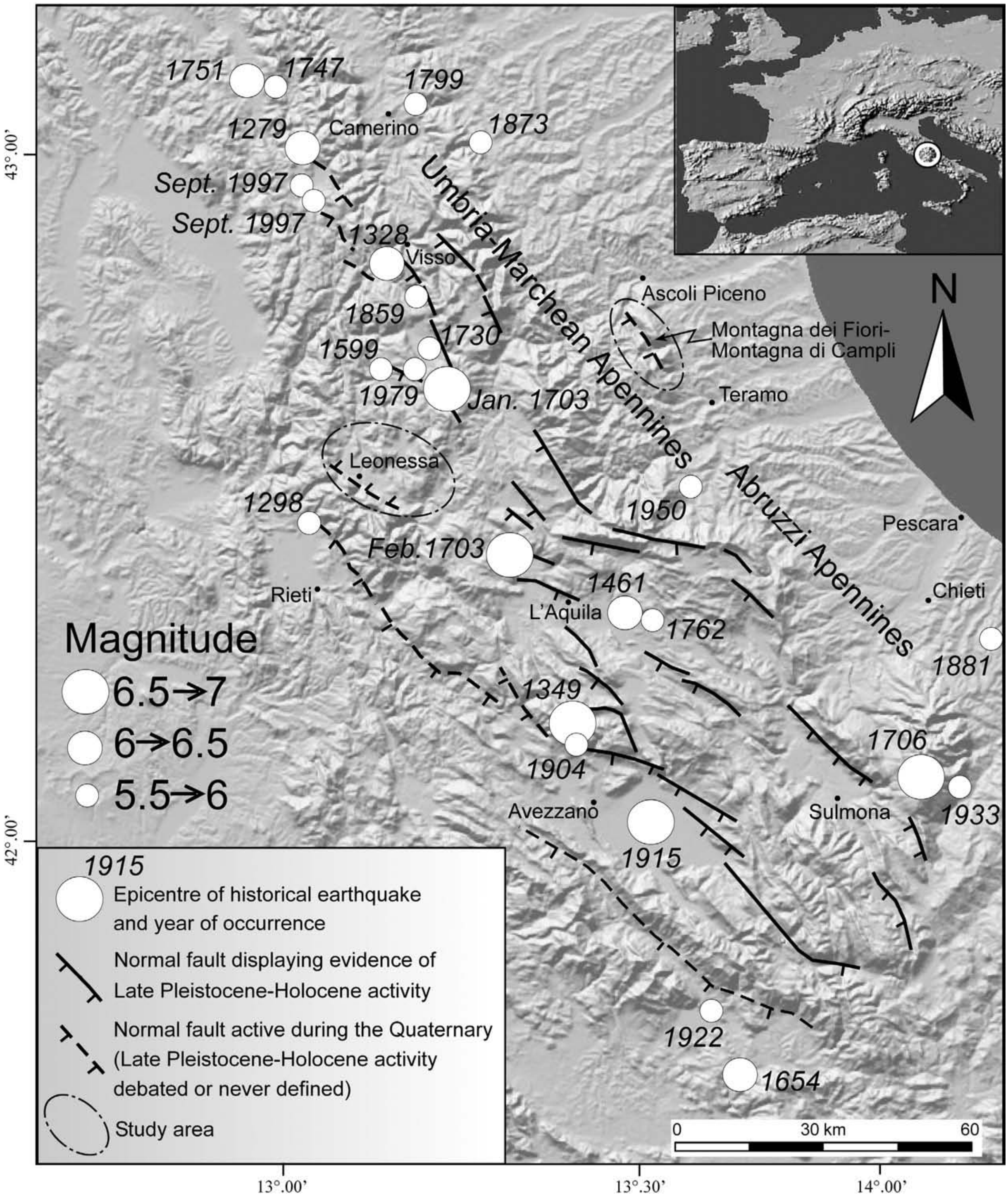

Fig. 1. Seismotectonic framework of the central Apennines (modified from Galadini and Galli, 2000).

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opening of the Tyrrhenian basin (Faccenna et al., 1996; Cavinato and De Celles, 1999; Meletti et al., 2000; Patacca and Scandone, 2001). The extensional deformation, which was superimposed over the compressive one, occurred on sets of newly formed, NW–SE trending normal faults and on extensional structures that resulted from the re-use of inactive, high-angle, reverse fault planes that were inherited from the compressive phase (Cavinato et al., 1994). These extensional tectonic structures were responsible for the formation of the main intermontane basins in the central Apennines (e.g. the Rieti, Norcia, Cascia, Leonessa, Colfiorito, Fucino, Sulmona and L'Aquila basins) and for minor depressions that are located in the mountainous areas (e.g. the Campo Imperatore, Campo Felice and Castelluccio plains, and the Salto and

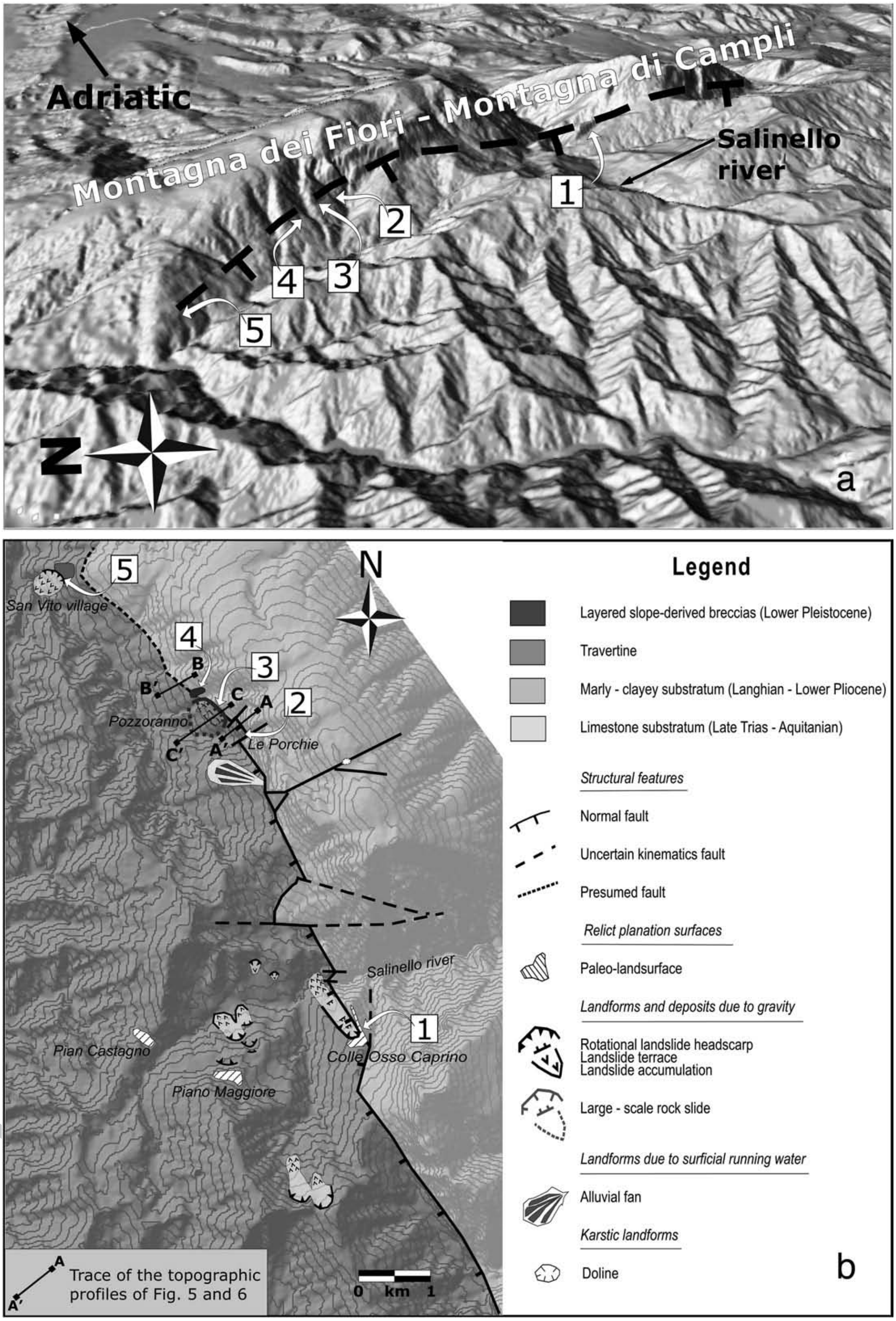

Fig. 2. (a) Reference map of the area under study. The black dashed line marks the MFCF trace and the sites cited in the text are indicated by numbers; (b) Synthetic geomorphological map of the SW slope of the Montagna dei Fiori–Montagna di Campli relief. The numbers refer to the sites described in the text.

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Turano valleys). Continental deposits of Plio-Quaternary age were deposited within these depressions (Cosentino and Parotto, 1986; Bosi and Bertini; 1970; Giraudi, 1988; Bosi and Messina, 1992; Miccadei et al., 1997; Bosi et al., 2003). The persistence of normal faulting in the central Apennines through the Quaternary resulted in the displacement of the continental successions and of the associated erosional/depositional landforms (CNR-PFG, 1987).

According to the available literature, as with the front of the compressive deformation, the intra-Apennine extension has also been characterised by a progressive north-eastward migration (Lavecchia et al., 1994; Martini and Sagri, 1994; Bartole, 1995; Calamita et al., 1999; Galadini and Messina, 2004), which was due to the Adria lithosphere flexural retreat (Patacca et al., 1990; Ghisetti and Vezzani, 1999; Cavinato and De Celles, 1999). This determined the formation of extensional tectonic structures that are progressively younger heading eastwards.

3. The seismotectonic framework of the central Apennines

The Late Pleistocene–Holocene activities of some of the extensional faults have been demonstrated by numerous studies that have dealt with active tectonics (Barchi et al., 2000; Galadini and Galli, 2000; Valensise and Pantosti, 2001) and paleoseismology (Galli et al., 2008, and references therein), and by matching these with the historical seismicity, i.e. with earthquakes that were characterised by magnitudes of up to 7.0 (Working Group CPTI, 2004) (Fig. 1). In particular, a comparison between ~~an~~ active fault array and the damage distribution of the strong historical earthquakes (Working Group CPTI, 2004), integrated with paleoseismologically inferred data, has allowed the attribution of the 1703 (January 14) (Maw = 6.81), 1703 (February 2) (Maw = 6.65) and 1915 (January 13) (Maw = 6.99) earthquakes to ruptures of the Norcia, Upper Aterno and Fucino fault systems, respectively (Galadini and Galli, 1999; Moro et al., 2002; Galli et al., 2005).

Although the seismotectonic characteristics of the central Apennines are probably the best known in Italy (e.g. Galadini and Galli, 2000), some problems however still remain to be solved. Apart from the existence of moderate-to-high-magnitude seismic events ~~that has~~ never been attributed to the activation of known tectonic structures, such as the 1706 and 1933 earthquakes (Maw = 6.6 and 5.7, respectively; Working Group CPTI, 2004), the main issue concerns the presence of normal faults for which the Late Pleistocene–Holocene activity

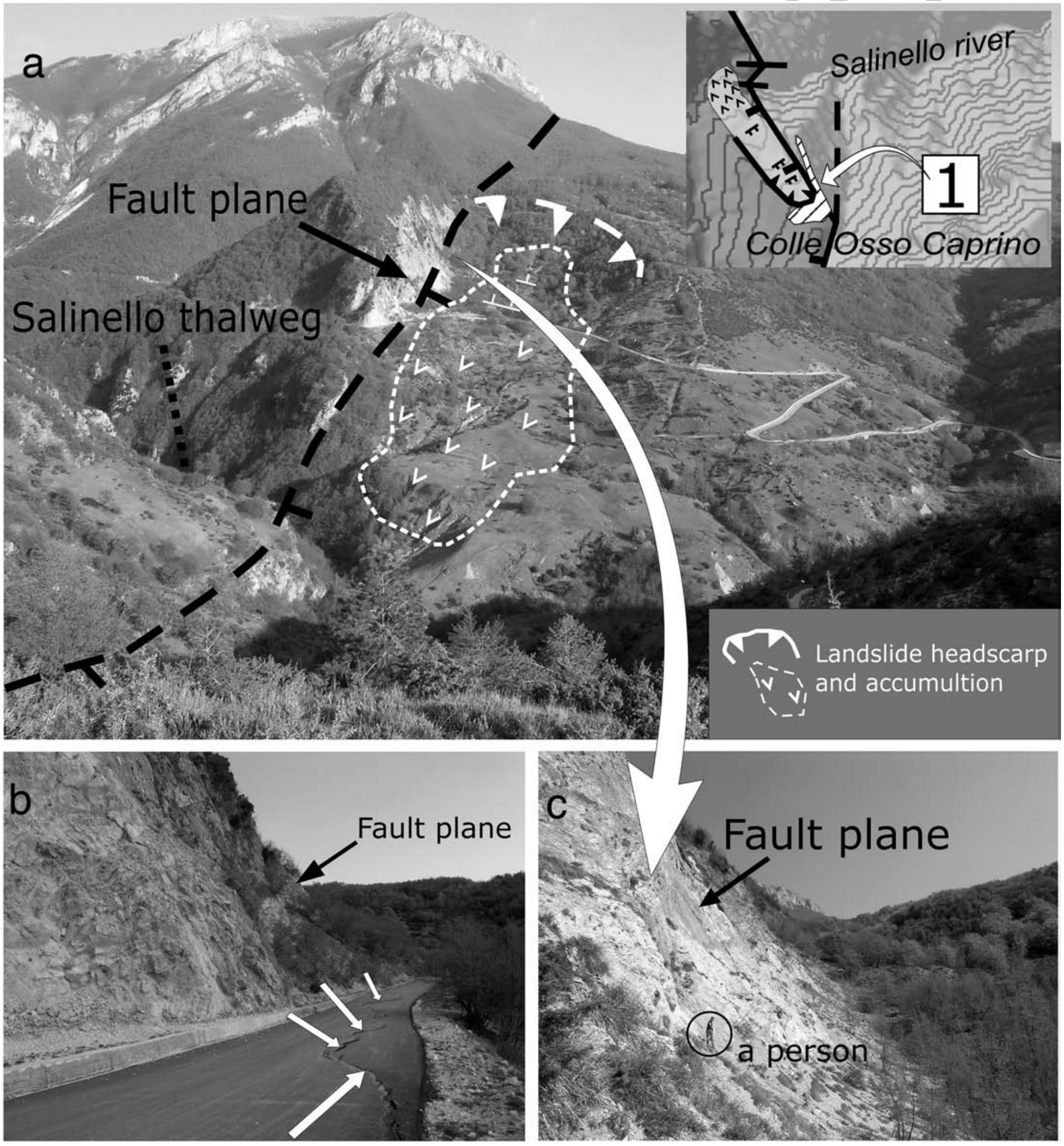

Fig. 3. (a) Panoramic view of the large-scale rotational landslide affecting the clayey–marly substratum outcropping in the MFCF (black dashed line) hanging wall at the Colle Osso Caprino locality. Inset: detail of the geomorphological setting of this site; (b) Tension cracks (indicated by the white arrows) affecting the road and indicating the present activity of the landslide; (c) Right flank of the rotational slide coinciding at the surface with the MFCF plane.

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is currently under debate, such as the Caramanico (Scisciani et al., 2000; Ghisetti and Vezzani, 2002), Leonessa (Barchi et al., 2000) and Montagna dei Fiori–Montagna di Campli normal faults.

4. Case studies

4.1. The Montagna dei Fiori–Montagna di Campli normal fault

Montagna dei Fiori–Montagna di Campli is one of the easternmost reliefs of the central Apennines (Fig. 1), and it is located across the administrative boundary between the Abruzzi and the Marche regions. It consists of a NW–SE trending anticline that is related to a thrust fault that was formed during a time span between the Late Messinian and the Lower Pliocene. It was probably re-activated subsequently (as an ‘out of sequence’ development), during a period that was not more recent than the Upper Pliocene (Mattei, 1987; Calamita et al., 1998; Scisciani et al., 2002). The thrust displaced the Meso-Cenozoic pre-orogenic carbonate sequences of the Umbria–Marche sequence, which is overlain by Miocene syn-orogenic deposits (Mattei, 1987).

The south-western slopes of this relief are affected by a NW–SE trending, 15-km-long, normal fault (the MFCF) (Fig. 2a) that has been described in previous studies (i.e. Mattei, 1987; Ghisetti and Vezzani, 2000). According to Scisciani et al. (2002), the activity of this tectonic structure probably began during the Miocene, when the Montagna dei Fiori–Montagna di Campli sector represented a foredeep domain, during the pre-thrusting phase. This normal fault displaced the carbonate substratum by several hundred metres (the vertical offset across the fault is about 1000 m; Calamita et al., 1998; Ghisetti and Vezzani, 2000; Scisciani et al., 2002), and placed the limestone of the Castel Manfrino Formation (Crescenti et al., 1969), the Calcare Massiccio and Corniola Formations, which are outcropping in the footwall, in contact with the marly and marly–clayey substrata of the Scaglia Cinerea, Marne con Cerrogna and Bisciaro Formations (Mattei, 1987), which are outcropping in the hanging wall.

The morphological evidence of normal faulting along these slopes consists in a fault scarp (up to 50 m high) that is carved into the carbonate bedrock, with the fault plane showing a high degree of karstic weathering and running-water erosion. Nevertheless, this fault plane outcrops very discontinuously along the bedrock scarp that is located at the base of the slopes and it can be exclusively detected at three sites (Fig. 2b, sites 1, 2 and 3): the Colle Osso Caprino, Le Porche and Pozzoranno localities.

At the Colle Osso Caprino site (Fig 2b, site 1), the fault separates the limestone rocks of the Corniola Formation (which is outcropping in the footwall block) from the clayey–marly rocks of the Bisciaro Formation (which is outcropping in the hanging wall block) (Figs. 2b, 3a, inset). Close to the fault zone, the rocks of the Bisciaro Formation are affected by a presently active, large-scale rotational slide, the sliding surface of which is more than 50 m deep (Fig. 3a, b). The occurrence of this landslide is due to the progressive deepening of the Salinello river thalweg that is progressively undermining the slope and increasing the local relief. The

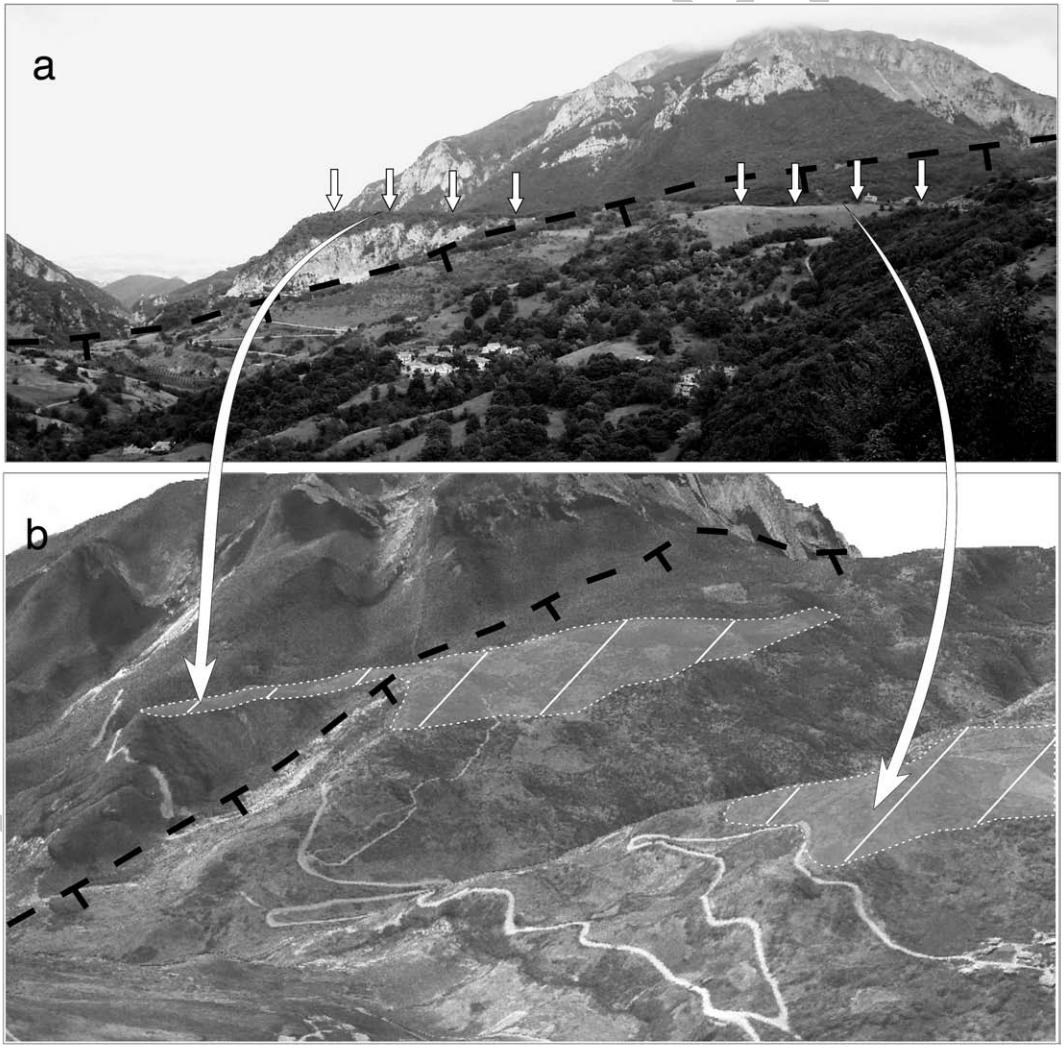

Fig. 4. (a) Paleo-landsurface (marked by the white arrows) of erosional origin sealing the MFCF (black dashed line); (b) Digital Elevation Model of the Colle Osso Caprino site. The wide erosional paleo-surface crosscutting the fault is indicated by the grey-shaded areas.

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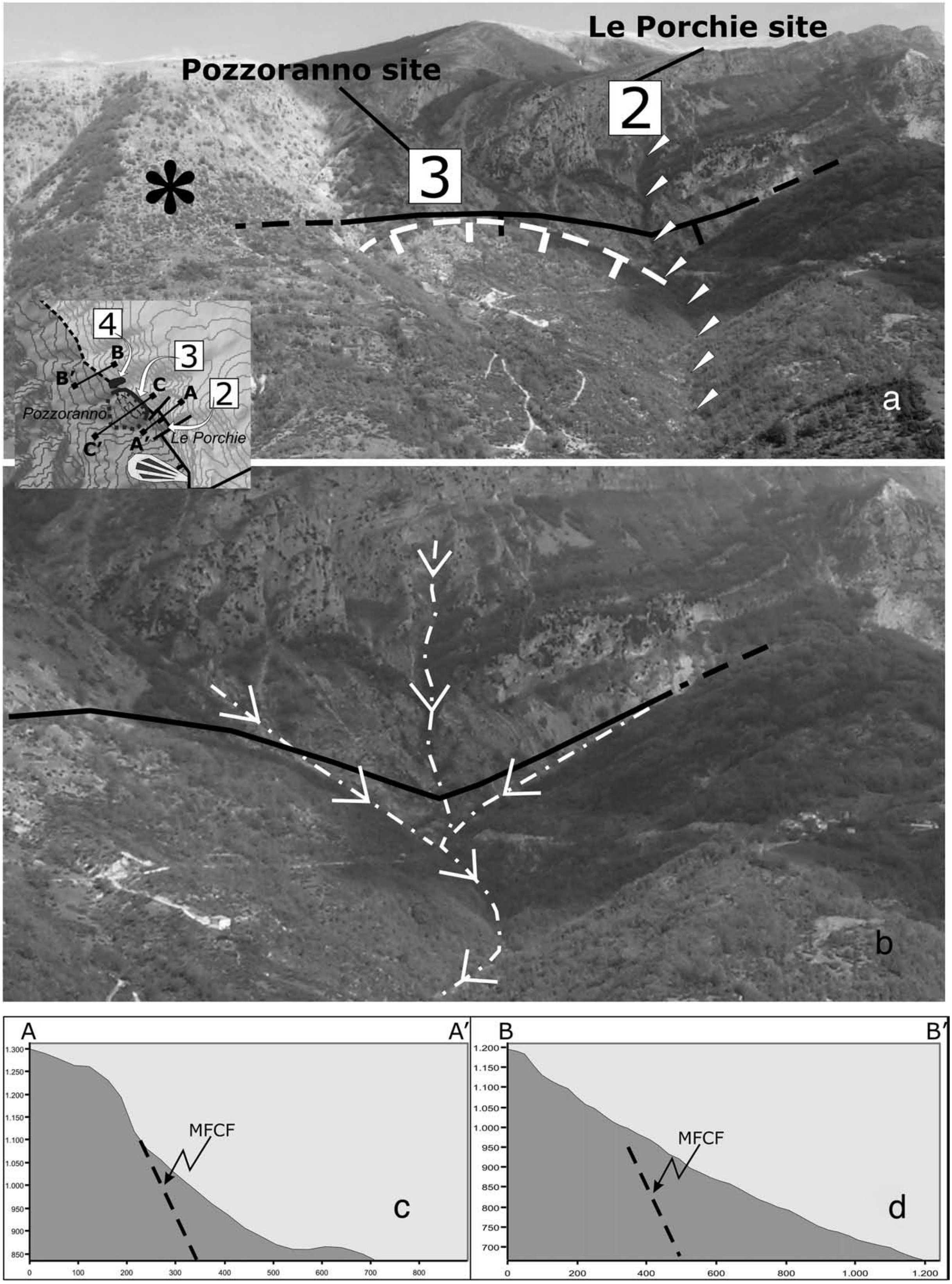

Fig. 5. (a) Panoramic view of the Le Porchie and Pozzoranno sites (sites 2 and 3, respectively). The white triangles indicate the stream incision perpendicular to the slopes and exhuming the MFCF plane (black line) at the Le Porchie site. The white dashed line marks the headscarp of the large-scale rock slide detected at the Pozzoranno site. Inset: an expanded view of the geomorphological map (Fig. 2b) of this area; (b) Close-up photographs of the Le Porchie site showing the stream incisions exhuming the MFCF plane; (c) Topographic profile of the slope at the Le Porchie site (the trace is reported in Fig. 2b), showing a step as the profile crosses the exhumed MFCF plane. (d) Topographic profile of the slope (the trace is reported in Fig. 2b). No step or anomaly of the profile occurs across the fault away from the stream incision seen at the Le Porchie site.

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presence of tension cracks along the right flank of the landslide accumulation and of compressive deformation along the left flank suggests that the geometry of the sliding surface is strongly conditioned by subsurficial geometrical features (i.e. the strike and dip) of the fault plane that bounds the sliding mass to the right side (Fig. 3c). This morphological setting indicates that the outcrop of the fault plane is due to continuous landsliding. Moreover, this fault is sealed by a sub-horizontal paleo-landsurface of erosional origin that is carved into the substratum rocks and suspended about 400 m over the present Salinello thalweg (Fig. 4a, b).

This type of landform is widespread in the Colle Osso Caprino locality and the surrounding areas (i.e. the Piano Maggiore and Pian Castagno sectors), and from an elevation between 1085 and 1110 m a.s.l., it dips gently towards the bottom of the Salinello Valley (Figs. 2b and 4b). This probably represents the remains of an ancient surface that was formed at an elevation close to the level of the local paleo-base. The absence of chronologically constrained deposits associated with the landsurface has prevented the possibility of defining the period of its formation. However, this landform is suspended several hundred metres over the present Salinello thalweg, and it represents the oldest continental landform that was formed after the compressive tectonic phase (since it is completely carved into the compressively deformed carbonate substratum), which in this area probably lasted until the Upper Pliocene. These data, together with a review of the available literature, suggest that this morphological feature was probably formed between the Upper Pliocene and the Early Quaternary. This chronological attribution is supported by several studies that have commonly referred such relict landsurfaces to the Upper Pliocene–Early Pleistocene (e.g. Dramis, 1992; Bosi et al., 1996; Centamore et al., 2003; Galadini et al., 2003~~a,b~~). The basis for this lies in

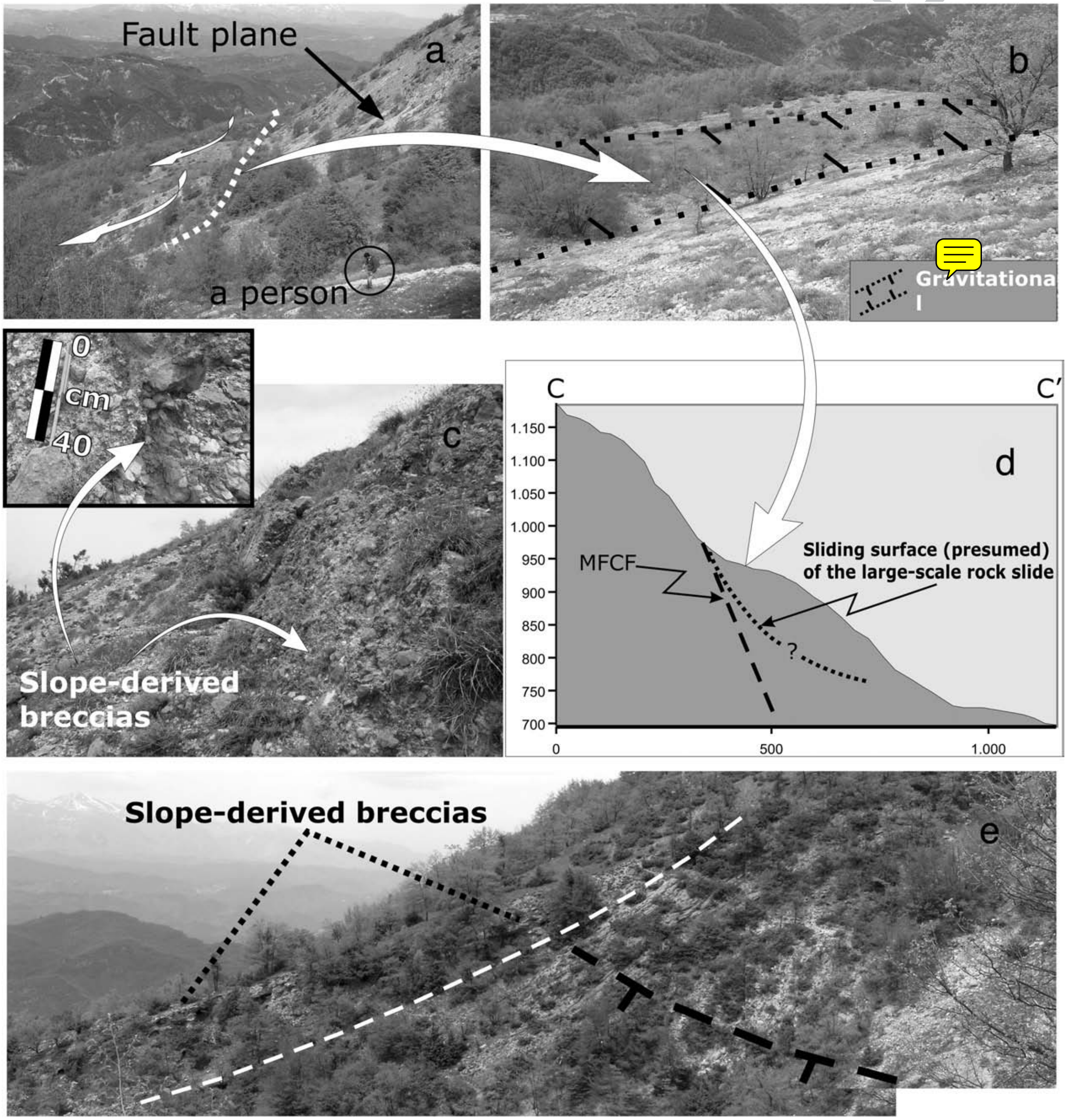

Fig. 6. (a) Large-scale rock slide detected at the Pozzoranno site. The white dotted line marks the trench located at the top of the sliding rock mass. The white arrows indicate the direction of sliding; (b) Close-up image of the gravitational trench located at the top of the large-scale mass movement; (c) Slope-derived breccias dragged along the headscarp of the rock slide (detail in inset), coinciding at the surface with the MFCF plane; (d) Topographic profile of the slope at the Pozzoranno site (the trace is reported in Fig. 2b) showing that the MFCF plane and the headscarp of the rock slide coincide at the surface; (e) Slope-derived breccias sealing the fault a few tens of metres north of the rock slide headscarp. The white dashed line marks the sedimentary, 'unfaulted' attitude of the breccias.

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their common characteristics of: *i*) being widespread throughout the central Apennines; *ii*) being carved on the compressively deformed substratum; *iii*) occurring in the uppermost part of the reliefs; and *iv*) displaying geomorphic features (such as their elevation a.s.l.) that are comparable to the landsurface detected at the Colle Osso Caprino site.

Along the central-northern sector of the slopes, exposed fault planes and related bedrock fault scarps can be detected at the Le Porchie and Pozzoranno localities (Figs. 2b and 5a, sites 2 and 3, respectively; Fig. 5a, inset). At the Le Porchie site, the fault plane is exposed (Figs. 2b and 5a, site 2; Fig. 5b), where a stream incision, which runs perpendicular to the

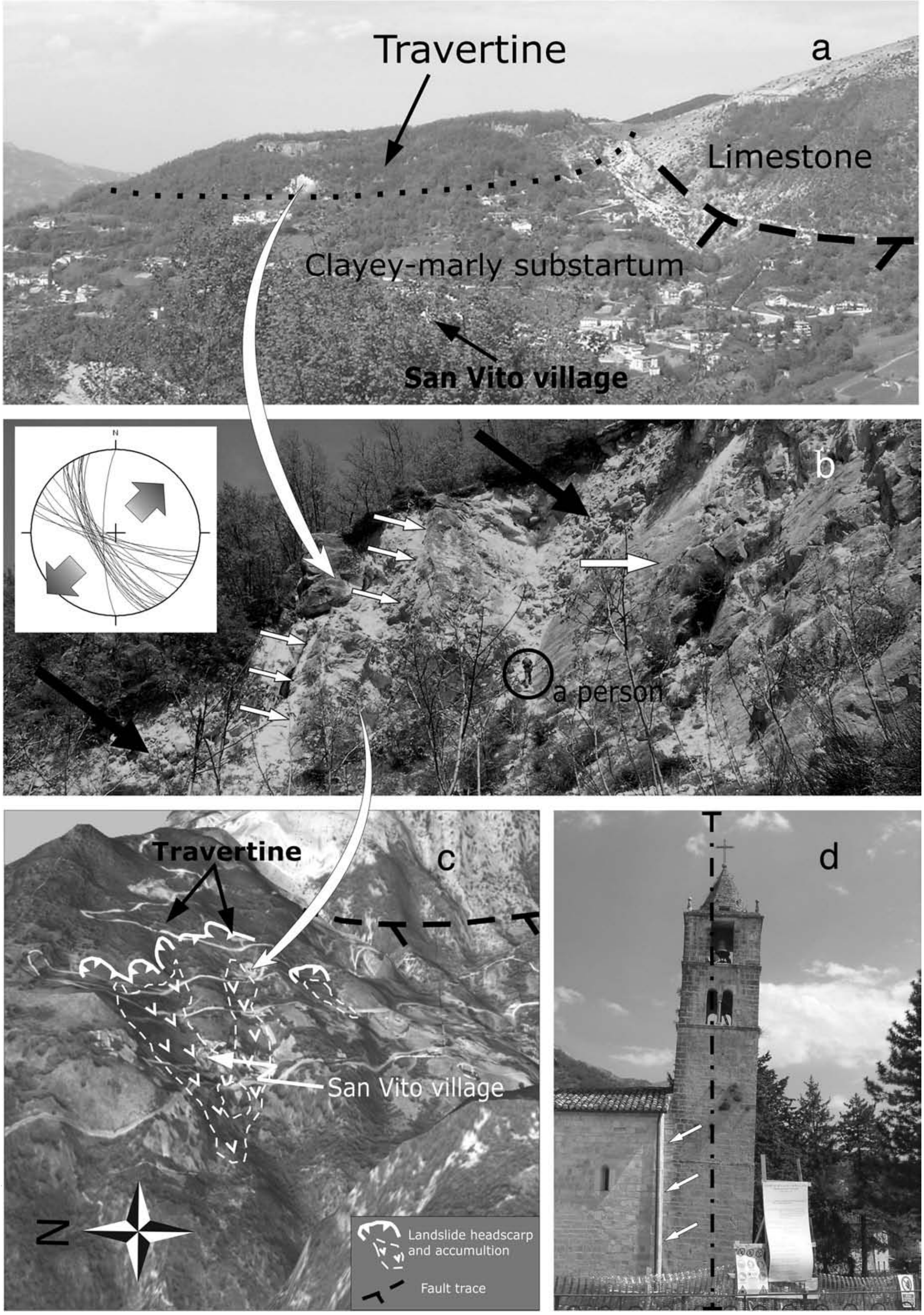

Fig. 7. (a) Travertine deposits detected in the area of the village of San Vito, close to the northern tip of the MFCF (black dashed line). The black dots mark the contact between the travertine and the marly–clayey substratum rocks; (b) Travertine deposits, exposed by a quarry, affected by open fractures (marked by the white arrows). The black arrows indicate the debris formed at the expense of the travertine itself and filling the fractures. Inset: stereonet that shows the azimuth of the shear planes and fractures that affect the travertine. The grey arrows indicate the axis of maximum extension, consistent with the gravitational kinematics; (c) Gravitational movements that affect the substratum rocks and the travertine; (d) A bell tower in the village of San Vito that is clearly tilted because of the gravitational instability affecting the clayey–marly substratum rocks on which San Vito is built. The white arrows indicate a part of the bell tower that was damaged (and restored) because of the tilting.

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slopes, and small tributaries, which parallel the fault scarp, are located (Fig. 5b). The different susceptibilities to erosion of the Scaglia Bianca Formation limestone, which is outcropping in the footwall, and the Scaglia Variegata Formation marly rocks, which are outcropping in the hanging wall, have resulted in the uncovering of the fault plane (Fig. 5c). Away from the stream incision, the fault plane is no longer exposed and the slopes show a linear topographic profile (Fig. 5a, asterisk; Fig. 5d).

At the Pozzoranno site (Figs. 2b and 5a, site 3), the fault plane can be detected along the main scarp of a large-scale gravitational deformation (i.e. a large-scale rock slide) that affects the marly-clayey rocks of the Scaglia Cinerea and Scaglia Variegata Formations that are outcropping in the hanging wall. The headscarp of the rock slide has a semi-circular shape that is in plan view and it coincides at the surface with the fault plane (Fig. 6a, c). This sliding mass has an outward bulging profile, and it is bordered towards the NW and SE by stream incisions that have curvilinear patterns. Moreover, a trench is easily detectable at the top of the gravitationally unstable rock mass (Fig. 6a, b).

Slope-derived breccias that are at present suspended about 300 m over the valley bottom have been detected in this sector (Fig. 2b). In their distal portion, these deposits are laid almost sub-horizontally on the carbonate bedrock, which suggests that they were deposited on a paleolandscape that was close to the local base level. Taken together with the lithological characteristics of the breccias, which are made of angular-to-sub-angular pebbles in a sandy brown-reddish matrix, this geomorphological framework has allowed them to be attributed to the "second sedimentary unit" of the continental stratigraphic succession that was proposed by Bosi et al. (2003), which is not younger than the lower Middle Pleistocene.

Along the main scarp of the above-mentioned large-scale gravitational deformation, these deposits have clearly been dragged along the fault plane (Fig. 6c). In contrast, slightly to the north and just a few hundred metres far from the main scarp of the rock slide, the breccias seal the tectonic structure (Fig. 2b, site 4; Fig. 6e), and the slope has clearly been smoothed by exogenous processes.

On the basis of these characteristics, we can conclude that the formation of the fault scarp and the exposure of the fault plane are only due to deep-seated movements of the rock mass.

Close to the village of San Vito, which lies along to the northern tip of the MFCF (Fig. 2a, b, site 5), there are travertine deposits that were attributed to the Early Pleistocene by Mattei (1987) and can be detected in the fault hanging wall at an elevation of about 900 m a.s.l. (Fig. 7a). These deposits have been affected by extensional shear planes, which are parallel to the fault, and by tension fractures that have been filled with debris that was fed by the travertine itself (Fig. 7b). These structural features that indicate its extension perpendicular to the slope (Fig. 7b, inset) are consistent with the gravitational kinematics. In particular, the displacement is attributable to the superposition of the massive and hard travertine, which displays a brittle behaviour, over the ductile and easily erodible clayey-marly rocks of the Marne con Cerrogna and Bisciaro Formations. This

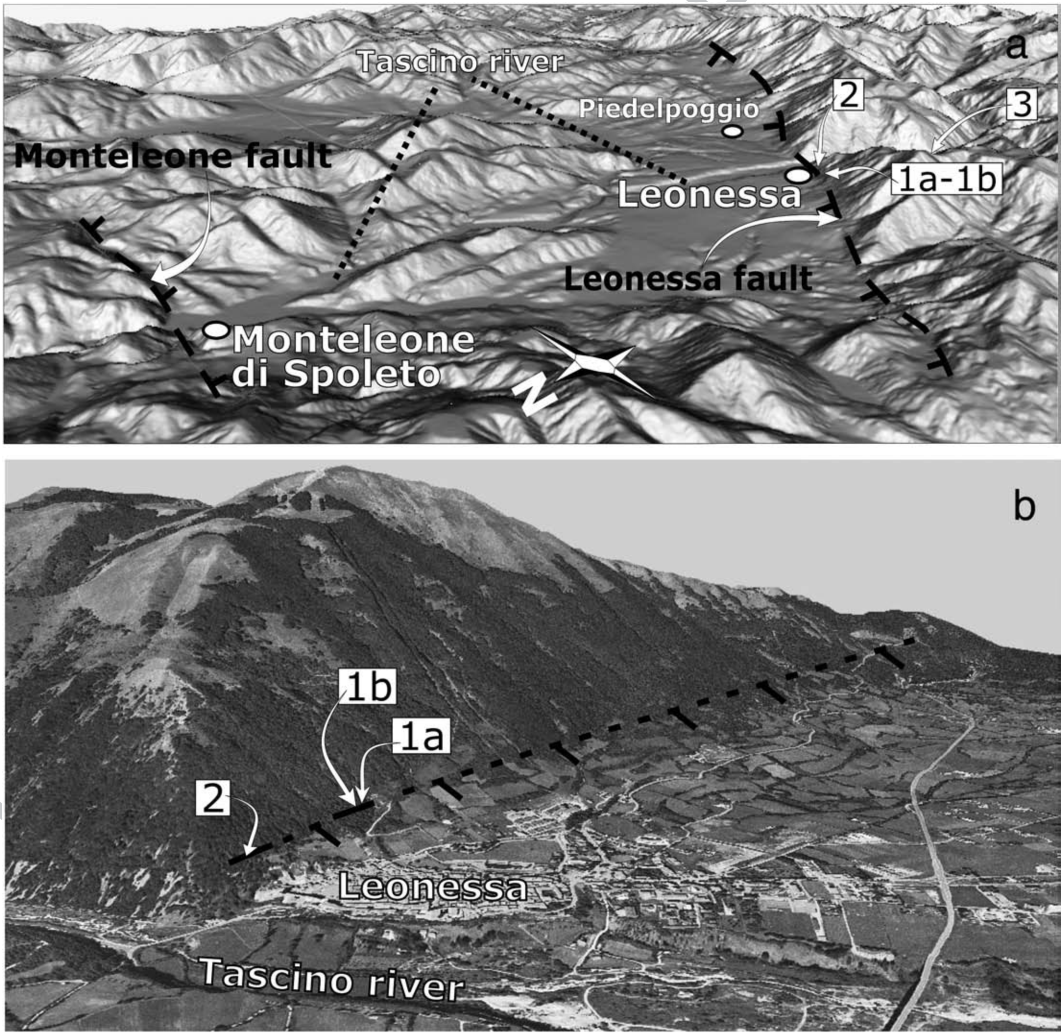

Fig. 8. (a) Reference map (Digital Elevation Model) of the area under study, with the location of the LF (black dashed line). The numbers indicate the sites described in the text; (b) Panoramic view of the slope bounding the Leonessa basin to the southwest, with the locations of the sites (numbers) cited in the text.

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stratigraphic setting is basically responsible for the lateral spreading phenomena and rotational slides that have affected the rocks of the Marne con Cerrogna and Bisciaro Formations, which have been seen in the outcrop area of the travertine (Fig. 7c, d).

4.2. The Leonessa basin

The Leonessa basin is an intermontane depression that is located about 20 km NNE of the town of Rieti, in the northern Latium sector of the

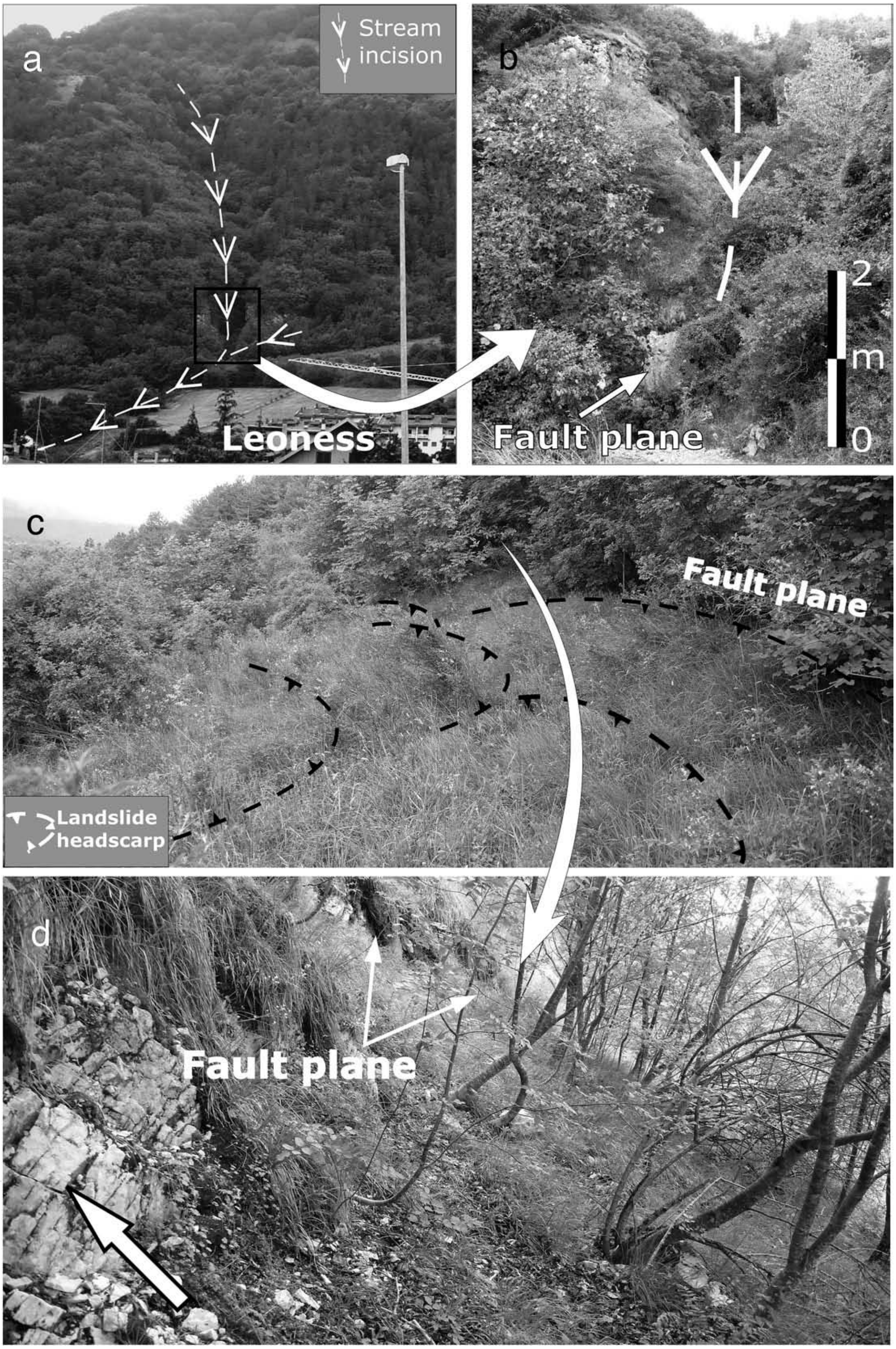

Fig. 9. (a) Panoramic view of site 1. The white dashed line marks the stream incision crosscutting the slope and exhuming the LF plane; (b) Detail of the base of the stream incision and of the exhumed fault plane; (c) Rotational landslides affecting the scree deposited at the base of the fault scarp that permitted the exhumation of the fault plane (site 1b, as described in the text); (d) Translational slides that affect the debris outcropping in the fault hanging wall, determining the exposure of the fault plane. The white arrow indicates the substratum rocks outcropping in the footwall of the fault.

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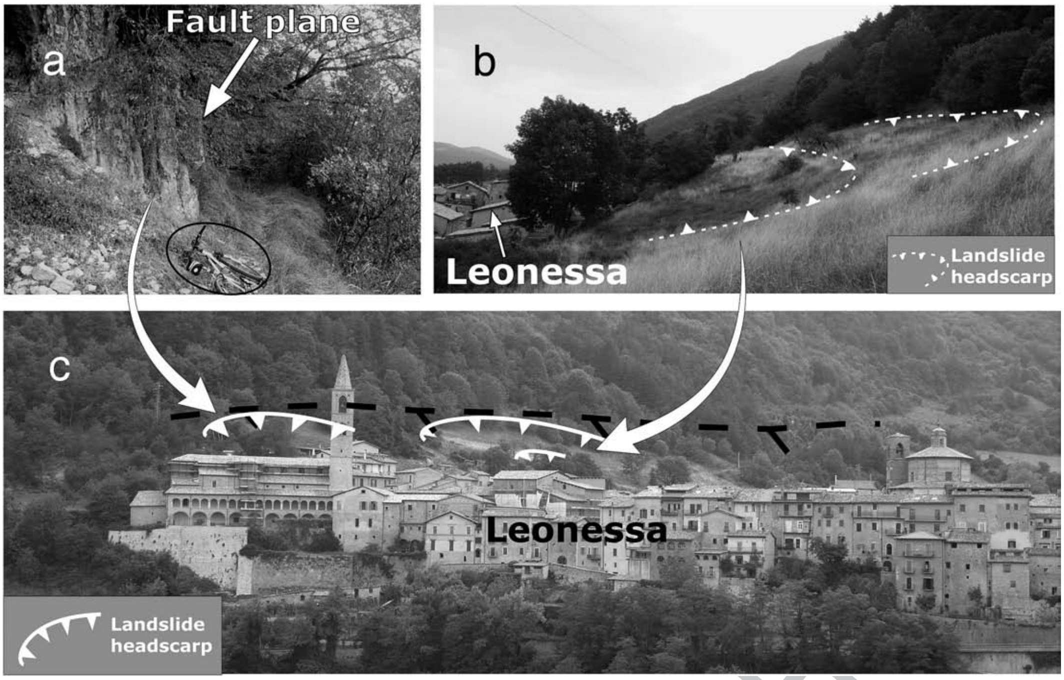

Fig. 10. (a) LF plane exposed close to the village of Leonessa (site 2 in the text); (b) Rotational landslides affecting the scree deposited at the base of the fault scarp; (c) Panoramic view of site 2 with the location of the headscarps of the rotational landslides coinciding at the surface with the fault plane (black dashed line). The gravitational movements have allowed the exhumation of the fault plane.

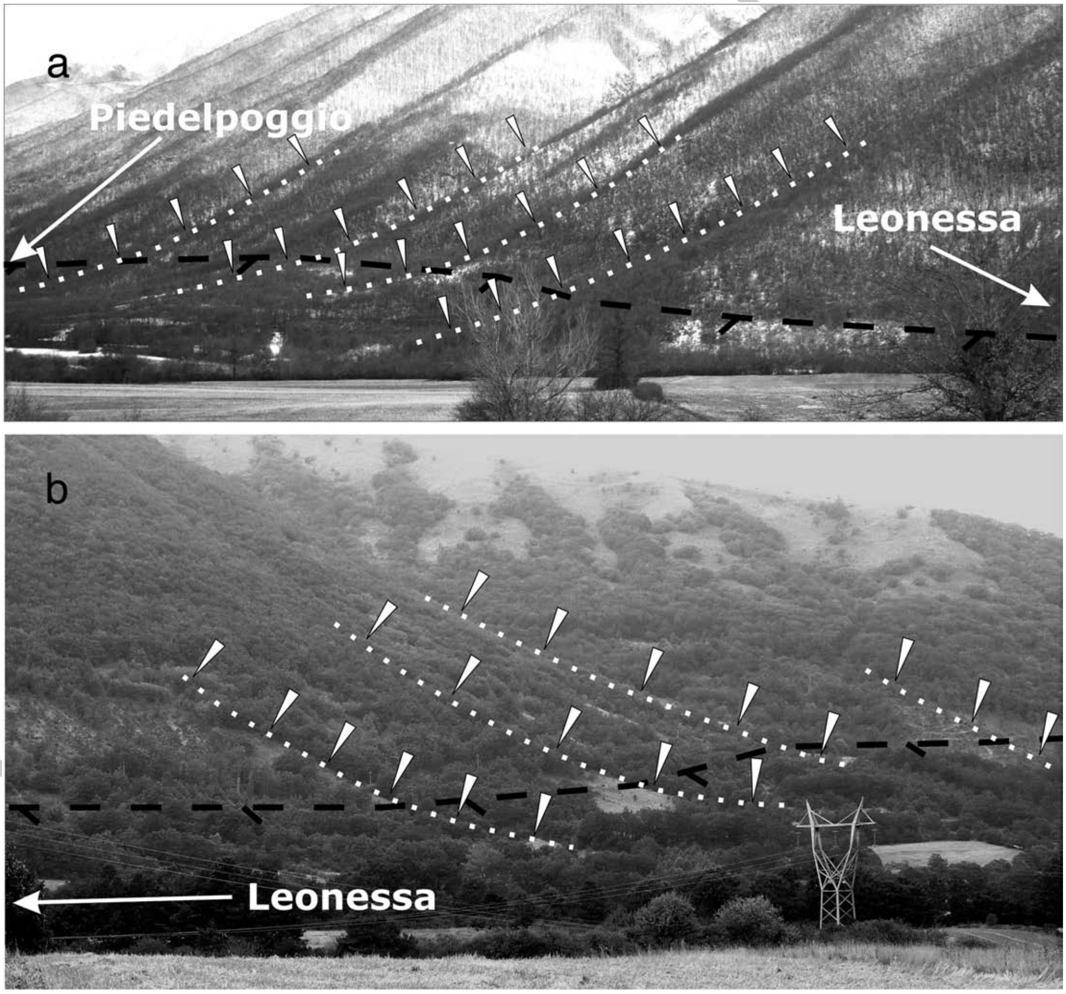

Fig. 11. Sectors of the slope that have been supposed to be affected by the LF and clearly smoothed by the exogenous processes, and that display linear topographic profiles (marked by the white dotted lines and by the white triangles). Along these sectors the LF plane is not outcropping.

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central Apennines (Fig. 1). In this area, there is outcropping of the Meso-Cenozoic carbonate sequences of the Umbria–Marche succession (Lotti and Crema, 1927). The depression is bounded by the Terminillo Massif to the south, by Mt. Tolentino to the north, and by Mt. Boragine to the east.

According to Michetti and Serva (1990) and Fubelli (2004), formation of the basin was due to the activity of a WNW–ESE trending normal fault, i.e. the LF, which had already been detected by Scarsella (1951), GE.MI.NA. (1963) and Bosi (1989). The LF affects the base of the slope bounding the depression to the SW and it dips towards the NE. Our observations have indicated that the length of the LF is roughly 15 km, although Cello et al. (1997) have reported a length of about 20 km. An antithetic, secondary, SW dipping normal fault has been detected along the northern border of the basin (i.e. the Monteleone fault; Fubelli, 2004) (Fig. 8a).

The morphological expression of the LF is seen as a very discontinuous fault scarp, at the base of which the fault plane is exposed in only a few places along the whole tectonic structure (sites 1a, 1b and 2 in Fig. 8a and b), which often shows a high degree of karstic weathering and running-water erosion. A few hundred metres NW of the village of Leonessa, the

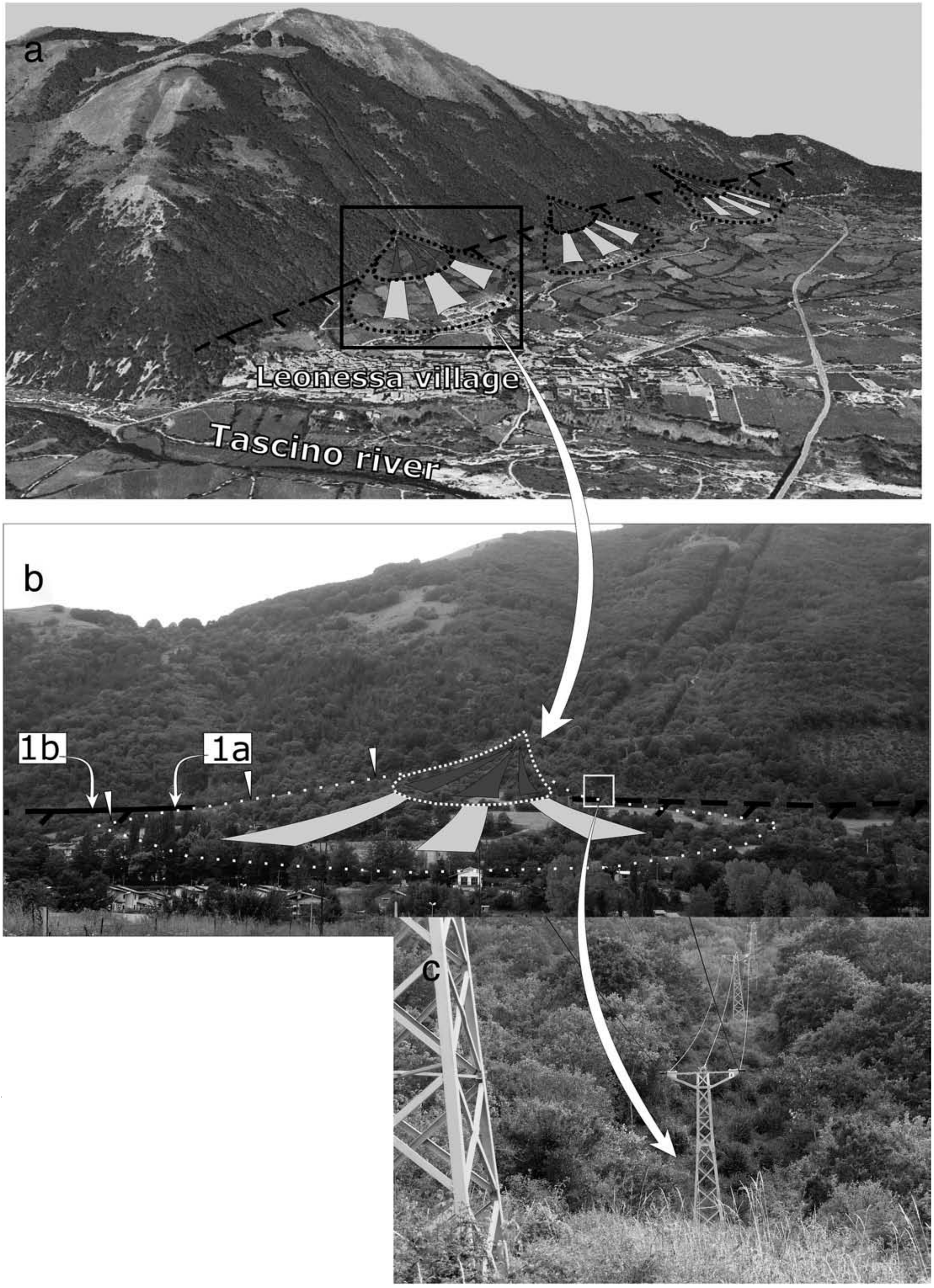

Fig. 12. (a) Panoramic view of the slope bounding the Leonessa depression to the southwest. The black dotted lines mark the two orders of the alluvial fans sealing the LF; (b) Close-up image of the alluvial fans sealing the LF (their bounds are marked by the white dotted lines). The white triangles indicate the "unfaulted" top depositional surface of the alluvial fan of the first order; (c) Where non-tectonic processes do not occur, which permit the outcropping of the fault, the fault plane is not exposed along the slope.

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fault plane is exposed for about 100 m (Fig. 8a, b, sites 1a, b). At site 1a (Fig. 8a, b), the fault plane crops out because of erosion of the unconsolidated scree at the base of the scarp. This was caused by the small streams that run perpendicular to the slope, and by tributaries that run parallel to the fault scarp (Fig. 9a, b). For site 1b (Fig. 8a, b), instead, the exposure of the fault plane is due to the following: *i*) the occurrence of active landslides that have affected the scree deposited at the base of the fault scarp, and the sliding planes that coincide at the~~ir~~ surface with the fault (Fig. 9c, d); and *ii*) the different degrees of erodibility of the rocks that are outcropping in the footwall (i.e. limestone) and in the hanging wall (i.e. slope-derived debris).

The fault plane also outcrops in Leonessa (Fig. 8a, b, site 2; Fig. 10a). In this sector, the scree has been displaced by coalescent rotational landslides (Fig. 10b), which were also reported in the “Piano stralcio di bacino per l'~~as~~setto idrogeologico-P.A.I.” performed by the Autorità di Bacino del Fiume Tevere, Rome, The major sliding surfaces ~~are~~ 3 m in depth at least, and the fault plane coincides ~~with~~ the surface (Fig. 10c). This suggests that the exposure of the fault plane can be attributed to landsliding. Where no erosional and/or gravitational processes have occurred, the fault plane is not exposed and the hillside has been smoothed by the exogenous slope processes (Figs. 11a, b, and 12c). Moreover, the fault is sealed by two orders of alluvial fans, which have already been detected by Rasse (1995), and which are fed by streams that run perpendicular to the slopes and have small drainage basins (Fig. 12a, b). According to Rasse (1995), Fubelli (2004) and Fubelli et al. (~~in press~~), these fans can probably be attributed to the Late Pleistocene, as they overlie deposits that were related to the Middle Pleistocene by Fubelli (2004), Fubelli et al. (~~in press~~), through paleontological findings

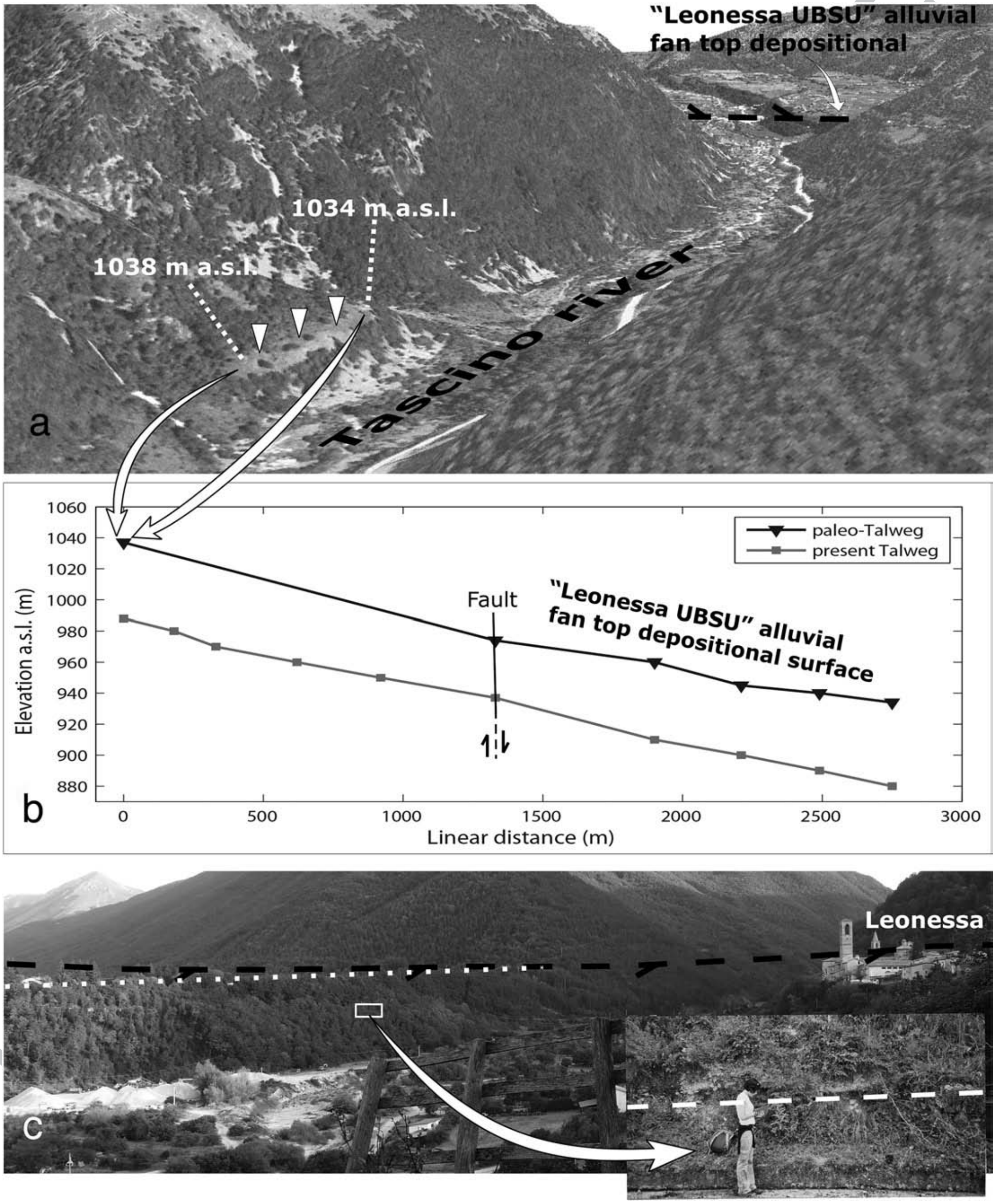

Fig. 13. (a) Panoramic view of the erosional terrace (marked by the white triangles) suspended over the present Tascino thalweg; (b) Topographic profiles (not to scale) of the present Tascino thalweg and of the paleo-Tascino thalweg, the latter being defined through the correlation between the erosional terrace and the top depositional surface of the “Leonessa UBSU” alluvial fan. The two profiles show a comparable gradient, supporting the topographic correlation between the landforms described; (c) Panoramic view of the proximal sector of the “Leonessa UBSU” alluvial fan, the top depositional surface (marked by the white dotted line) and layers (marked by the white dashed line in inset) of which dip almost horizontally towards the basin, and show no tilting against the LF due to the movement of this tectonic structure.

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(i.e. a tusk and a tooth of *Mammuthus* (mammuthus) cfr.M. (M.) *trogontherii* (Pohlig)) and paleomagnetic analyses, which were supported by geomorphological observations.

The wide alluvial fan that fills the Leonessa basin (i.e. the "Leonessa UBSU" alluvial fan in Fubelli et al., ~~in press~~) is part of the Middle Pleistocene succession. It characterises the local landscape with a barely northward inclined top depositional surface that hangs some tens of metres over the present bottom of the Tascino Valley (i.e. roughly 40–50 m). This paleo-landsurface probably correlates to a degradational fluvial terrace that is the only terrace that has been detected in the fault footwall close to the basin area. This terrace is carved into the carbonate substratum and suspended about 40 m above the present valley bottom (Fig. 8a, site 3; Fig. 13a). This 140 m-long landform lies between 1038 m and 1034 m a.s.l. Similar relationships between erosional and depositional landforms across mountain slopes where rivers run in deep incisions and abruptly open onto alluvial plains are usual and diffuse throughout the central Apennines (e.g. Galadini and Messina, 1993; Chiarini et al., 1997). In this case, the geomorphic correlation between these landsurfaces is supported by the following: *i*) they are located at comparable heights above the present thalweg; *ii*) the extension of the degradation terrace suggests that it formed during the most important climate/geomorphic phase that is detectable in the basin, which is consistent with that responsible for the deposition of the "Leonessa UBSU" alluvial fan; and *iii*) the present Tascino river is eroding the carbonate substratum in the fault footwall, while in the basin area it has a braided plain regime, i.e. a geomorphic framework that is comparable to that which existed when the correlated landsurfaces formed.

Hence, all the above suggest that these terraces represent a Middle Pleistocene Tascino thalweg that was located about 40 m higher than at present. As shown in Fig 13b, this was characterised by a topographic profile and a gradient that was comparable to that of the present bottom of the Tascino Valley. This, and the lack of any step or anomaly along the profile of the paleo-thalweg across the fault zone (Fig. 13c), suggest that the activity of the LF ceased or has been strongly reduced at least from the Middle Pleistocene. This conclusion is supported by the evidence that the layers of the "Leonessa UBSU" alluvial fan and its top depositional surface show no evidence of faulting and are not tilted against the fault (Fig. 13c, inset).

5. Discussion

The collected data indicate that the surficial evidence of the faults investigated and of their related bedrock scarps can be exclusively ascribed to: 1) the differential erosion of the rocks outcropping in the hanging wall and footwall of the faults; 2) the occurrence of gravitational movements that have affected the rocks (or the deposits) outcropping in the hanging wall block. In the latter case, the fault planes had an exclusively passive role in leading the evolution of the mass movements.

In the other areas, where the geomorphic processes described here did not occur, the slopes have linear profiles that have resulted from the areal erosional/depositional processes, events that have generally been attributed to the post-Last Glacial Maximum geomorphic processes (e.g. Dramis, 1983). Moreover, in these cases, the fault planes are not exposed. When this is taken together with the high degree of karstic weathering that has affected the exposed planes (i.e. indicating the lack of fault rejuvenation), and the scattered outcrops of the fault planes and scarps along the slopes, these all suggest a non-tectonic cause for the exposure of both the Montagna dei Fiori–Montagna di Campli and Leonessa normal fault planes. Moreover, the geological and geomorphological surveys have collected data that have been useful for the definition of the Quaternary kinematic history of the tectonic structures analysed.

In particular, the MFCF is sealed by an erosional paleo-landsurface that can be attributed to the Upper Pliocene–Early Quaternary, and by slope-derived breccias of an Early Pleistocene age. Furthermore, the shear planes and the open fractures that have affected the Early Pleistocene travertine that has been observed close to the village of San Vito (which might be misleadingly interpreted as tectonic displacement) are gravity-related structures that are due to the general slope instability. These data have allowed us to hypothesise that the MFCF has not been active since the Early Pleistocene, and therefore, it has not been active during the whole, or most, of the Quaternary. However, as mentioned above, our results differ from those obtained by Ghisetti and Vezzani (2000), who have proposed that the MFCF has indeed been active during the Pleistocene, on the basis of morphotectonic and structural analyses.

In the case of the LF, the data that are available can be summarised as follows: 1) the tectonic structure has been sealed by two orders of alluvial fans, which are probably related to the Late Pleistocene; 2) the contemporaneous degradation terrace that is located in the footwall block, and the top depositional surface of the Middle Pleistocene "Leonessa UBSU" alluvial fan, have not been displaced by the fault activity; 3) the deposits and the top depositional surface of the "Leonessa UBSU" alluvial fan do not show evidence of displacement due to fault movement. These data suggest that the LF was active until the Early Pleistocene, with it being responsible for the formation of the depression where the deposition of the "Leonessa UBSU" alluvial fan has occurred. Since the Middle Pleistocene, the activity of the tectonic structure has probably ceased (or been strongly reduced). This evidence yields a kinematic history of the LF that is different from that which has been proposed by Michetti and Serva (1990) and Cello et al. (1997), who considered the LF as presently active on the basis of morphotectonic analyses. In more detail, the study of Michetti and Serva (1990) proposed a slip rate for the LF of between 0.1 mm/year and 0.4 mm/year, which was obtained by correlating the "Leonessa Surface" (i.e. the top depositional surface of the "Leonessa UBSU" alluvial fan, as described in the present study), which they considered as an erosional surface, with landsurfaces located in the footwall and which they interpreted as degradation terraces. However, these supposed erosional sub-horizontal terraces that have been detected in the footwall block exclusively consist of the exposure of the sub-horizontal layers of the substratum rocks (the Marne a Fucoidi Formation). This is the case for the surface described in this study at the Prima Forca locality. In contrast, the geomorphic setting discussed in the present study indicates that the landforms that can be correlated across the faults have not been displaced.

Moreover, both Michetti and Serva (1990) and Cello et al. (1997) state that the outcrop of the fault plane, which has been exposed for a few metres at only two sites along the entire 20-km-long fault (the same sites analysed in the present study), testifies to a recent faulting. As demonstrated by our observations, however, other non-tectonic geomorphic factors have been responsible for the exposure of the fault.

In more recent studies, the activity of the LF has been discussed further. Roberts and Michetti (2004) consider the LF as being active, exclusively on the basis of the evidence of activity described by Michetti and Serva (1990) (discussed in the previous paragraph), without providing any new data that support this activity of the LF. Roberts et al. (2004) have attributed a throw rate to the LF by solely adopting the slip rate defined in the previously mentioned study of Roberts and Michetti (2004). Papanikolaou et al. (2005) have re-used the outcrops described by Michetti and Serva (1990), and have provided an updated slip rate estimate for the LF through a consideration of the height of the exposed fault plane that they interpreted as the result of post-Last Glacial Maximum co-seismic fault activation. Thus Papanikolaou et al. (2005), who provide the geographic coordinates of the outcrops analysed, state that to accurately define the slip rate, they have only considered the exposure of the fault planes where clear tectonic evidence is available. Nevertheless, they have provided no geological evidence to support

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this "clear tectonic evidence". Moreover, the fault exposure that they have described coincides with site 1b described in the present study (see Section 4.2), where our observations have indicated that the exposure of the fault plane was due to non-tectonic processes (i.e. landsliding and differential erosion). This makes unreliable the evidence of the LF activity provided by Papanikolaou et al. (2005), along with their tectonic slip rate estimate.

Whittaker et al. (2007) performed a detailed investigation of the Fosso Tascino (i.e. the Tascino River incision mentioned in the previous section), to determine how the LF activity has influenced the geomorphic characteristics of the river incision. They considered the LF as active just based on the study of Roberts and Michetti (2004) discussed above, and they have used the throw rate estimate defined by this study. The results presented in this study of Whittaker et al. (2007) are based on: 1) an age of 0.75 Ma of the "Leonessa Surface" (although no information supporting this chronological attribution is given); and 2) a thickness of the continental deposits in the Leonessa basin of 380 m. However, for point 1 here, the so-called Leonessa Surface has a more recent age, as already indicated by Michetti and Serva (1990), and later demonstrated by Fubelli (2004) and Fubelli et al. (~~in press~~). And for point 2 here, the boreholes performed by GE.MI. NA. (1963), which are the deepest boreholes that are available for this area, did not reach the base of the whole Quaternary continental succession at 380 m. Thus, the thickness mentioned for the continental sediments must be considered to be a minimum value. Hence, these observations indicate that the results of Whittaker et al. (2007) are at least problematic. Moreover, the same results that they obtained could have been arrived at by exclusively considering a constant uplift of the area, without implicating LF activity at all.

From a regional point of view, the present inactivity of both the MFCF and the LF has implications in terms of the Quaternary structural evolution of the central Apennines. Indeed, our results fit the model proposed by Galadini and Messina (2004), who stated that the NE migration of the extensional domain in the central Apennines is revealed by the inactivity of the westernmost normal fault systems of the central Apennines, which were activate during the Pliocene, since the Early Pleistocene (e.g. the Turano Valley fault) or since the beginning of the Middle Pleistocene (e.g. the Salto and Liri Valley faults). On the other hand, the easternmost fault systems (e.g. the Campo Imperatore and Mt. Morrone fault systems), which were activate during the Early Pleistocene, can be considered to be active at present.

Hence, with this in mind, assuming a still active NE migration of the intra-Apennine extensional domain towards the Adriatic sectors, the inactivity (or at least the strong reduction in activity) of the LF since the Middle Pleistocene probably indicates that this tectonic structure is no longer under a great amount of extensional deformation, i.e. that the faults that are under extension in this region are located east of the Leonessa basin. In contrast, the inactivity of the MFCF through the Quaternary suggests that the active intra-Apennine extension has not yet reached this easternmost sector of the chain.

A different Plio-Quaternary structural evolution of the central Apennines was proposed by Roberts et al. (2002). They considered that the MFCF and the LF are active, and stated that the present pattern and slip rates of the central Apennine active normal faults have been determined by a process of interaction and linkage of some of the central Apennines normal faults, which occurred during the Early Pleistocene. This process would have resulted in a disappearance of a number of normal faults, according to the fault growth models proposed by Cowie and Roberts (2001), and an increase in the slip rates of the remaining active faults, and in particular of those located in the centre of the fault array.

This model, however, was based on a set of central Apennine active normal faults and their related slip rates that were a lot different from those defined by Barchi et al. (2000), Galadini and Galli (2000) and Galadini et al. (2002). These studies summarised the available knowledge of active faults in Italy, referring to a number of studies that had demonstrated the inactivity of some of the central Apennine faults that were considered as active by Roberts et al. (2002). This is the case for the Valle del Salto fault (Chiarini et al., 1997; Galadini and Messina, 2001), the Vallelonga fault (Galadini and Messina, 2001) and the Liri Valley fault (Galadini, 1999). For these reasons, we believe that the model proposed by Roberts et al. (2002) cannot be considered as being completely reliable.

6. Conclusions

Geological and geomorphological investigations that have been performed along the south-western slopes of the Montagna dei Fiori–Montagna di Campli relief and along the reliefs bordering the Leonessa basin to the south-east (the central Apennines), have provided a definition of the kinematic history through the Quaternary of the normal faults in these sectors, and have allowed us to draw some conclusions about their recent activity. In both cases, our analyses have indicated that the fault planes are exposed because of non-tectonic geomorphic processes, i.e. through differential erosion and gravitational displacement. The former is due to the different erosional susceptibilities of the rocks and/or the deposits that are outcropping in the footwall and hanging wall of the fault. These processes are due to the erosive action of streams (i.e. mainly gullies) that are perpendicular to the slopes. For the gravitational displacement, landslides (rock slides and rotational landslides) have affected the rocks that are outcropping in the hanging wall sectors. The movements of the landslides have resulted in the continuous and progressive exposure of the fault planes.

On the whole, we can conclude that the fault exposures in the cases investigated are exclusively due to exhumation, and more generally, that the related tectonic structures can be considered as being inactive at present.

For the MFCF, as this fault has been sealed by an erosional paleosurface that is of probable Upper Pliocene–Early Quaternary age, and by Lower Pleistocene breccias, this indicates that the tectonic structure was not active during the Quaternary.

For the Leonessa basin, the LF is sealed by two orders of alluvial fans that have been attributed to the Late Pleistocene. Moreover, the Middle Pleistocene landsurfaces are continuous across the LF, and therefore they have not been displaced by fault movements. These observations suggest that the LF has not been active since at least the Late Pleistocene, or probably since the Middle Pleistocene.

These results have implications in terms of: 1) methodological approaches for active faulting studies; and 2) improvements to our knowledge of the seismotectonic characteristics of the central Apennines. For point 1 here, we want to stress that rapid detection of geomorphological features (e.g. fresh exposures of fault planes, and step-type fault scarps) can often be misleading in the definition of fault activity. And for point 2 here, the inactivity of these faults makes it unlikely that there ~~was~~ the occurrence of earthquakes of such high a magnitude as to have produced co-seismic surface faulting (i.e. with $M > 5.5–6.0$ in the Apennines, according to Michetti et al., 1996, 2000) along these tectonic structures.

Lastly, our results suggest that the LF is probably no longer under a great amount of extension (since the Middle Pleistocene), while the MFCF, which is characterised by a geometry that is consistent with that of the active intermontane normal faults, might be involved in active extensional deformation in the future if the migration of the intra-Apennine extensional domain towards the north-east is still active.

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