3. Camerino (MC) - Colfiorito (PG). 1997 Central Italy Earthquake: tectonic ground rupture along the Costa Fault (Colfiorito) and large scale gravitational phenomena near Sellano (PG)

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Introduction

The Colfiorito basin has been the epicentral area of a major seismic sequence in 1997. During the visit in the Colfiorito area we will have the opportunity to observe two sites where coseismic ground displacement has been documented, the Costa fault and the Sellano sites. The interpretation of the tectonic vs. gravitational nature of this ground displacement has generated quite a long debate. We will present the data, and the interpretation that is in our opinion better supported by the data. This presentation will be mostly based on the paper by Vittori et al. (2000). During the field trip we will stop at the Costa fault site and at the Sellano gravity fracture site only; the section including the relative descriptions are marked by an underlined title. However, this guidebook also illustrates several other sites in the Colfiorito area, which we will not have the opportunity to check in the field, but are relevant for understanding the issues discussed below.

Most relevant issues

Since September 1997, the Umbria - Marche region in Central Italy has been affected for several months by a seismic sequence, which has caused the loss of 12 lives and severe damage to ca. 300 localities, including many old historical towns, as Assisi, Camerino and Foligno (Fig. 1). A first shock on September 3 (at 22:07 GMT, Ml 4.5) was followed, on September 26, by two moderate earthquakes (Fig. 2A) with epicenter in the Colfiorito area (Mw = 5.7 at 00:33 GMT and Mw = 6.0 at 09:40 GMT), which produced the highest damage (Intensity IX-X MCS, Camassi et al., 1997), and by two other main shocks on October 3 (Mw = 5.4) and 14 (Mw = 5.7), the last one with epicenter more to the south, near Sellano (Fig. 1). Due to the vicinity of the main shocks, the macroseismic intensity rating, based on the MCS scale, depicts the cumulative effect of several events (Camassi *et al.*, 1997). All these events were characterized by shallow focus (4 to 9 km of depth) and nucleated along northwest-southeast-striking and southwest-dipping faults with dominant normal dip slip components, as indicated by a) the tectonic structure (e.g. profile in Fig. 1) and the geological evidence discussed in this paper, b) the focal mechanism solutions and the distribution of aftershocks (Boschi and Cocco, 1997; Morelli *et al.*, 1998; Cattaneo *et al.*, 2000) and c) the geodetic measurements, in particular GPS data and SAR interferometry (Fig. 2C; Salvi *et al.*, 2000).
Since the very morning of Sept. 26 a field survey was conducted in the epicentral area, aimed at describing the earthquake environmental effects (Figs. 2 and 3). Among these effects, which included typical features such as ground fractures, slides, hydrogeological anomalies, we observed, along the west-verging northwest-southeast-trending normal faults bordering the

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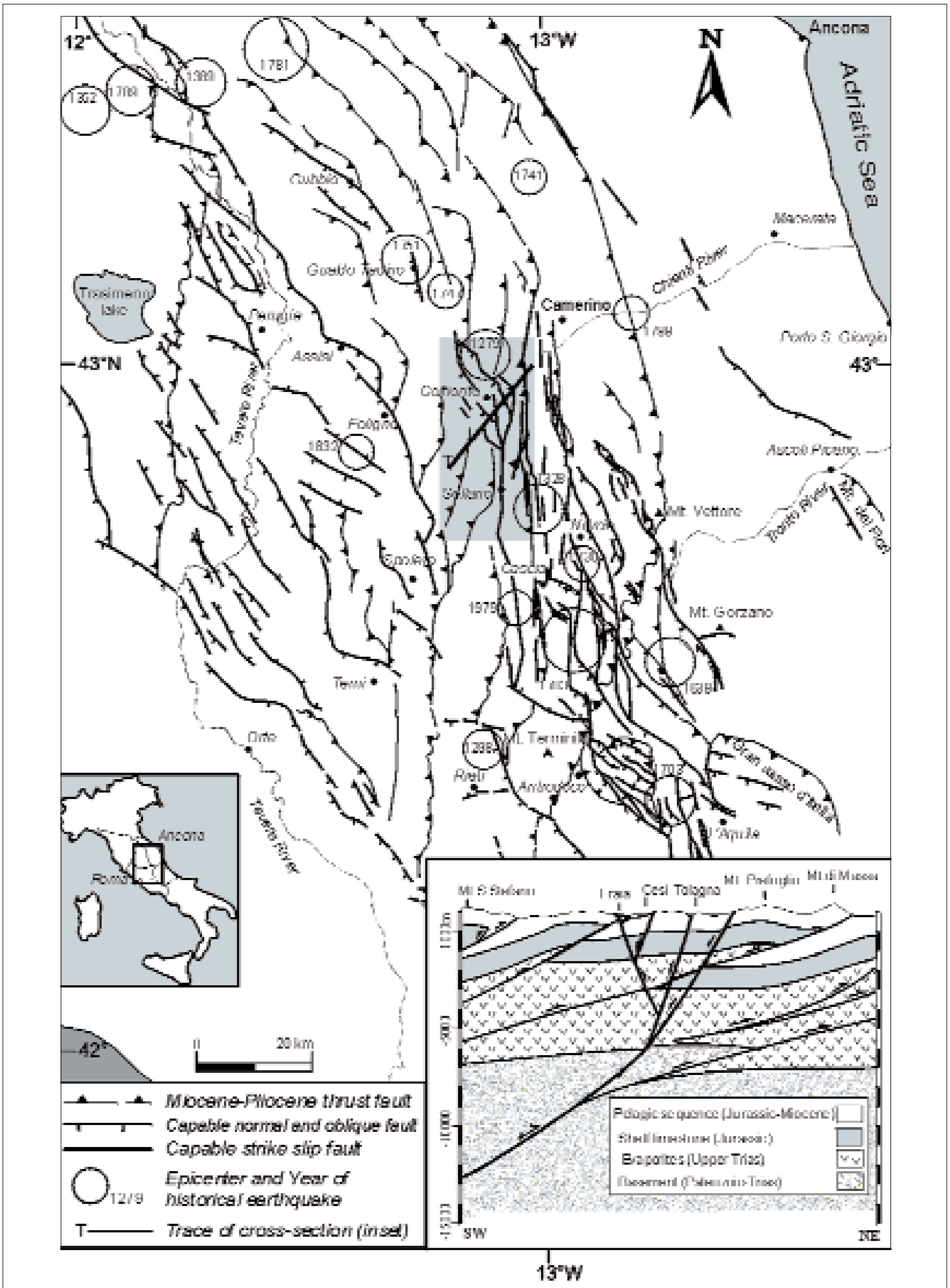


Fig. 1. Structural sketch of Central Italy (from Calamita and Pizzi, 1993; Vittori et al., 1995; Cello et al., 1997); circles mark epicenters of I ≥ IX MCS earthquakes (from Boschi et al., 1995; 1997; Camassi and Stucchi, 1998), shaded area shows location of figure 2. Inset is an interpretative cross-section of the Colfiorito area, based on surface geology and seismic reflection lines. (From Cello et al., 1998a, modified).

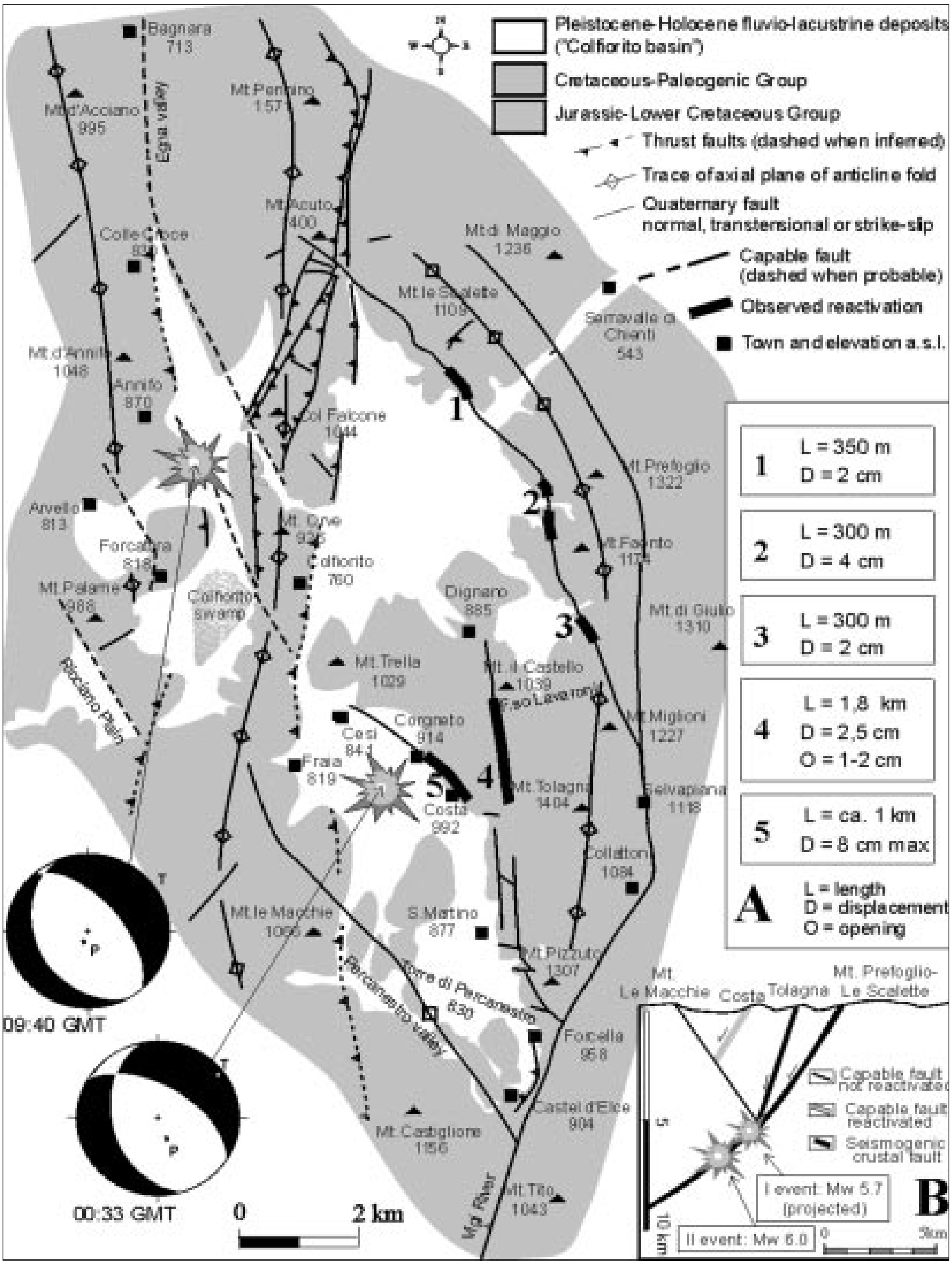


Fig. 2 Surface faulting during the September 26, 1987, earthquakes drawn over the map of capable faults of the Colfiorito basin (from Cello et al., 1998a, modified); A) observed vertical displacement, length, and opening of surface ruptures at sites 1 to 5 described in text. Epicenter locations are inferred from preliminary instrumental data and ground effects distribution (see Fig. 4); focal mechanisms are after Harvard CMT catalogue; B) Interpretative section showing the inferred prosecution at depth of the main capable and reactivated faults and the hypocenters of the 26 September 1997 earthquakes.

intermontane Colfiorito tectonic basin and its southern prolongation, systematic normal slips in the range of 2 to 8 centimeters inside discontinuous rupture zones with an overall length of ca. 12 kilometers.

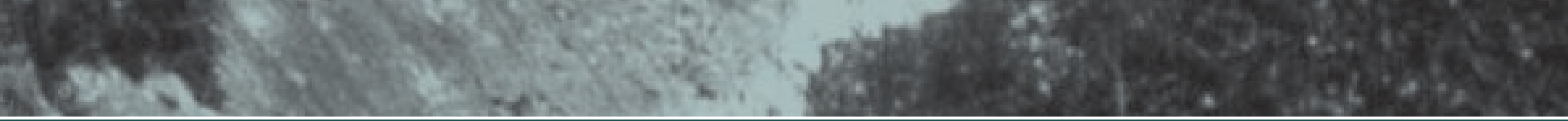
One delicate question, which has arisen among Italian geologists and geophysicists (Boschi and Cocco, 1997; Basili *et al.*, 1998; Cello *et al.*, 1998a), is the interpretation of the displacement observed along sections of these fault scarps (slickensides) as true coseismic faulting or as shaking effects, without a direct link to the seismogenic slip. As a matter of fact, the level of magnitude of the main events, between 5.5 and 6.0 (Mw), is in the lower boundary of observed cases of surface faulting during recent crustal earthquakes worldwide (Wells and Coppersmith, 1994). However, subdued surface faulting for such moderate earthquakes might be more common than expected, being easily missed or misintepreted. Deciding if the ground effects were due to surface faulting or to simple shaking is not a trivial matter, since it has enormous impact, for example, on how to scale the coseismic offset seen in paleoseismic trenches or along the slickensides, in order to assess the magnitude of the causative event.

In fact, the essential questions for seismic hazard assessment (SHA) (e.g., dePolo and Slemmons, 1990) where geological studies (*paleoseismology*, e.g., Vittori *et al.*, 1991) prove fundamental are: 1) is the last event typical (*characteristic*) for the area? 2) if a larger event is foreseeable, how big it will be? 3) what are reliable slip-rate and recurrence interval for the damaging events? We therefore briefly analyze the distribution and characteristics of the environmental effects related to the main shocks of the sequence, as observed in the field (see Cello *et al.*, 1998a; and Esposito *et al.*, 1998, for their detailed description), illustrating their relevance for SHA. Subsequently, we will focus on the coseismic surface displacement occurred between Renaro and Mevale, near Sellano, a feature, that in our opinion can be interpreted as the reactivation of a large-scale gravitational movement. The comparison among the tectonic rupture at Costa and the gravitational rupture near Sellano will allow us to discuss in the field the relative morphogenic role, the relations, and the criteria for discriminating, between tectonic-earthquake and gravity-driven deformation features in the active crustal extension setting of the Apennines.

Geological and seismological framework

The Umbria-Marche region is part of the east-verging Neogene thrust and fold belt of Central Italy (Bally *et al.*, 1988; Patacca *et al.*, 1992; Calamita *et al.*, 1994). Middle-late Quaternary normal faults and related intermontane tectonic depressions, overprinted onto the thrust structure, are the preferential *loci* of strong to moderate earthquakes, as shown by historical and instrumental data (Fig. 1) and geological evidence (e.g. Cello *et al.*, 1997; Vittori *et al.*, 1997). In particular, this system of capable normal faults is
represented in the epicentral area of the 1997 earthquake sequence by 3 main normal fault segments: the central Colfiorito segment, the Norcia segment to the SE, and the Gubbio segment to the NW.

The Colfiorito basin (Fig. 2A), elongated in a NNW-SSE direction, is a typical actively expanding, fault-bounded, depression inside the Apennines; its flat valley floor is slightly above 800 m a.s.l. and is now artificially drained toward NE in the Chienti river valley, being the natural drainage hindered by the recent activity of the Colfiorito border fault. The surrounding mountains reach maximum elevations of ca. 1570 m a.s.l. (Mt. Pennino) and are mostly made of mesozoic limestones and marls. The valley fill, not exceeding 120 m, is made of alluvial and lacustrine sediments, whose deposition started about 1 million years ago, slightly before the Jaramillo palaeomagnetic event (Coltorti *et al.*, 1998). Several authors had already evidenced Late-Pleistocene to Holocene dip-to-oblique slip offsets along the main faults bordering the epicentral area, with maximum cumulative Quaternary



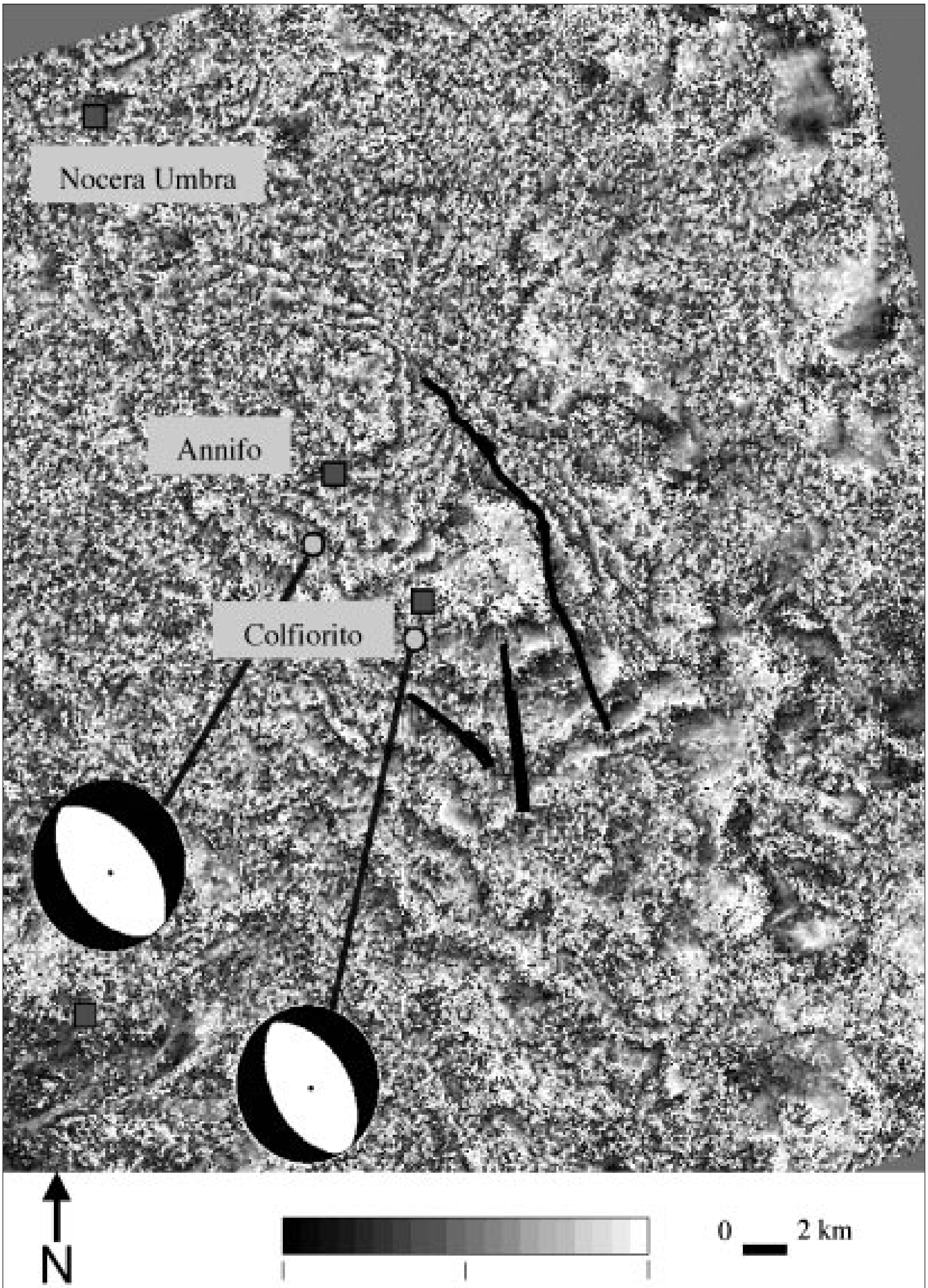


Fig. 2C. September 26, 1987, Colfiorito earthquakes Mw = 5.7 – 6.0: focal mechanisms, displacement field from radar interferometry (1 fringe = 28 mm; Salvi et al., 2000) and surface faulting (Cello *et al.*, 1998).

stratigraphic offsets in the order of 150 to 200 m (e.g., Centamore *et al.*, 1978; Calamita and Pizzi, 1993). In particular, Cello *et al.* (1997) and Tondi *et al.* (1997) had mapped in detail capable (*sensu* IAEA, 1991; i.e., the subset of active faults with the potential for surface rupture, commonly associated to moderate to strong crustal earthquakes) normal faults in the region including the Colfiorito basin, also emphasizing their potential for coseismic ground displacement. Furthermore, historical catalogues show that events of similar and even larger size repeatedly affected the Umbria-Marche region over the last millennium (Boschi *et al.*, 1995; 1997; Monachesi and Stucchi, 1997; Camassi and Stucchi, 1998).

The available instrumental data for recent moderate events in the Umbria Marche region show that typical hypocentral depths are in the order of 6 to 15 km (Haessler *et al.*, 1988; Deschamps *et al.*, 1992), and that the prevailing focal mechanism solutions suggest mostly normal faulting along roughly NW-SE-trending structures (Anderson and Jackson, 1987; Scarpa, 1992; Montone et al., 1997).

To allow a comparison of the ground effects of the 1997 sequence with historical documentation, we provide a short summary of the preceding events and their known effects on the environment. Table 1 and Fig. 1 show a selection of the most relevant seismic events included in the presently available historical catalogues and syntheses (Postpischl, 1985; Boschi *et al.*, 1995; Boschi *et al.*, 1997; Castelli, 1997; Camassi and Stucchi; 1998). These earthquakes were generally felt in a wide area of Central Italy including Rome, and occurred in long seismic crises sometimes preceded by foreshocks. The magnitudes given here for pre-instrumental events are those listed in the catalogues, based on correlation estimates between intensity and magnitude for instrumental data. Intensities are given in the MCS (Mercalli-Cancani-Sieberg) scale, particularly suitable for masonry constructions; see for example Reiter (1990) for a comparison with MM and MSK scales. A generalized map of the earthquake ground effects reported in the region for historical and modern events is presented in Fig. 3. A more detailed discussion of this topic can be found in Esposito *et al.* (2000).

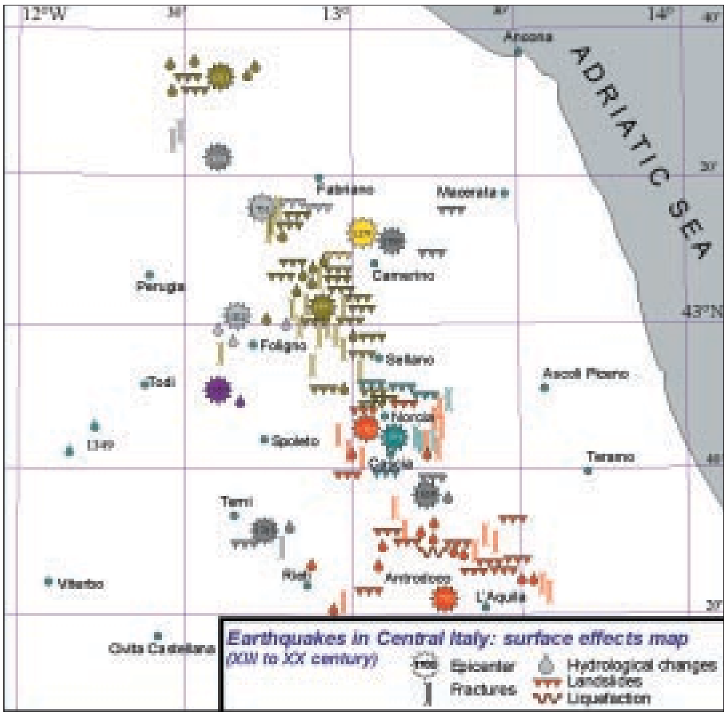


Fig. 3. Distribution of ground effects induced by historical earthquakes since XIII century.

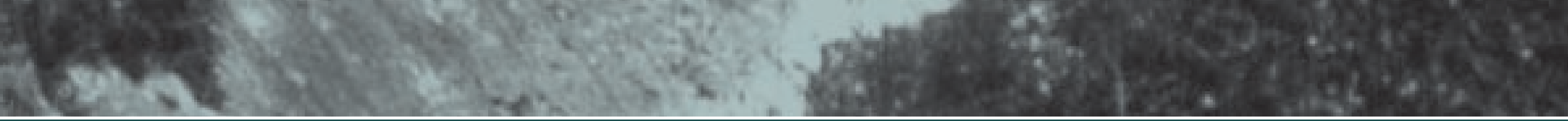


Table 1. Major historical and recent earthquakes in Umbria-Marche and surrounding region (I max ≥VII MCS) and inferred magnitudes as listed in NT4.1 (Camassi and Stucchi, 1998) and CFTI (Boschi *et al.*, 1995; Boschi *et al.*, 1997) catalogues.

Date	Epicenter	I max NT4.1	magnitude NT4.1	magnitude CFTI
268 b.C.	Picenum	-	-	-
100 b.C.	Picenum	8,5	-	5,8
99 b.C.	Norcia	9	-	5,6
1279 04 30	Camerino	10	6,7	6,6
1298 12 01	Reatino	10	6,4	6,3
1328 12 01	Norcia	10	6,7	6,2
1349 09	Valle del Salto	9.5	6,4	6,7
1352 12 25	Monterchi	9	6,2	5,7
1389 10 18	Bocca Serriola	9	6,2	6,0
1458 04 26	Città di Castello	9	6,2	5,4
1599 11 05	Cascia	8,5	5,9	-
1639 10 07	Amatrice	10	6,7	5,4
1703 01 14	Norcia	10	6,7	6,5
1703 02 02	L'Aquila	9	6,2	-
1719 06 27	Valnerina	7,5	5,2	-
1730 05 12	Norcia	9	5,9	6,4
1741 04 24	Fabrianese	9	6,2	6,4
1747 04 17	Fiuminata	9	6,2	5,7
1751 07 27	Gualdo Tadino	10	6,7	6,0
1781 06 03	Cagliese	10	6,4	6,0
1785 10 09	Piediluco	8	5,5	5,6
1789 09 30	Val Tiberina	9	5,9	5,4
1791 10 11	Scopoli	7,5	5,2	-
1799 07 28	Camerino	9,5	6,2	5,6
1832 01 13	Foligno	8,5	5,9	5,7
1838 02 14	Valnerina	8	5,5	-
1859 08 22	Norcia	8,5	5,9	-
1917 04 26	Monterchi	9,5	5,6	5,7
1930 10 30	Senigallia	8,5	6,0	5,9
1972 02 04	Ancona	8	4,5	5,6
1972 06 14	Medio Adriatico	8	4,3	5,4
1974 12 02	Monte Fema	7	4,7	-
1979 09 19	Norcia	8,5	5,9	5,8
1984 04 29	Gubbio	7	-	5,6
1987 07 03	Porto S.Giorgio	7	4,9	-
1997 05 12	Massa Martana	7	4,5	-
1997 09 26	Colfiorito	9,5	6,0	-

Ground effects of the 1997 umbria-marche earthquakes

Based on field investigation, we recognized ground effects in a ca. 700 Km^2 wide roughly elliptical area around the Colfiorito epicentral zone (Fig. 4) (Cello *et al.*, 1998a; Esposito *et al.*, 1998; Esposito *et al.*, 2000). The observed phenomena were classified as *primary effects* (surface faulting) and *secondary effects* (ground fractures, landslides, local ground settlements and hydrological changes). The former results from the propagation up to the

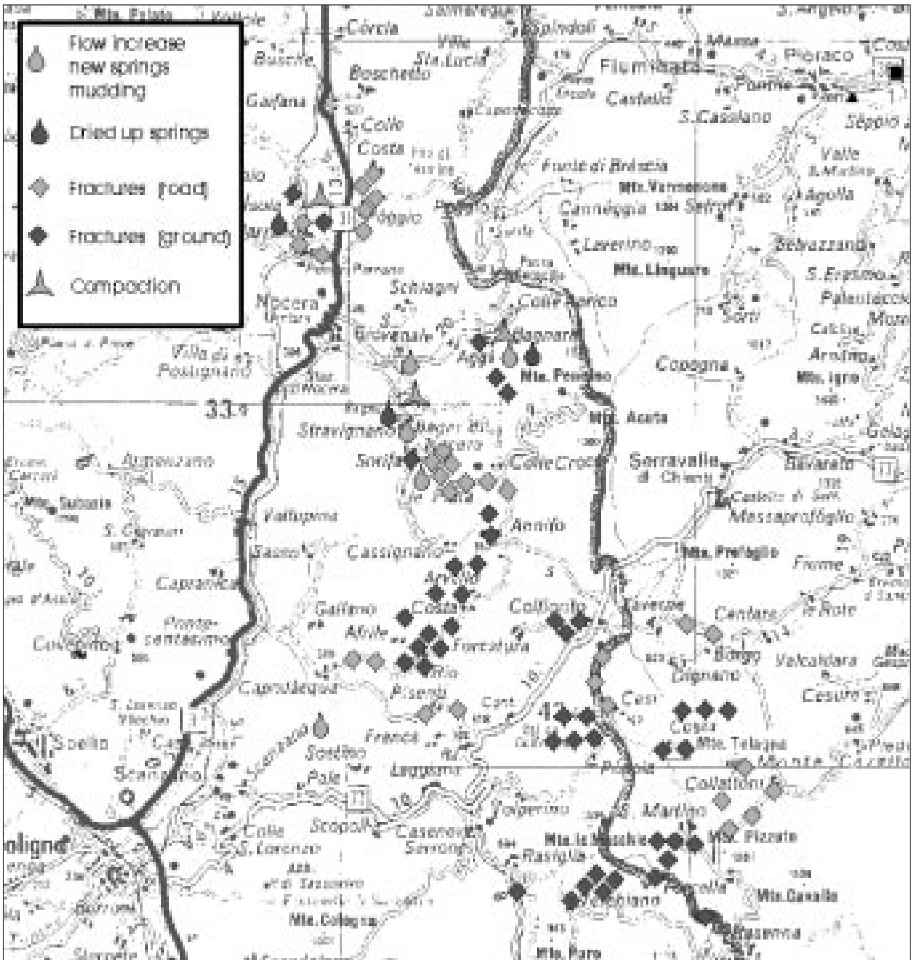


Fig. 4. Distribution of ground effects of the 1997 Umbria-Marche sequence (after Esposito *et al.*, 2000)

surface of the seismogenic slip at depth, giving direct evidence of the size and kinematics of the earthquake. Instead, the presence, activation threshold, spatial distribution, number and size of secondary effects depend on frequency content and duration of seismic shaking, which is a function of the local geology (stratigraphy, water saturation, morphology) and of the travel path of seismic waves, as well as of the source parameters.
In the following sections we describe the secondary effects first, because they have also served as indicators of the most likely location of primary faulting. However, the gravitational feature at Sellano is illustrated after the primary effects, to allow better comparison between surface faulting features and non-tectonic earthquake ruptures.

Secondary effects

Ground fractures, either in Quaternary colluvial, and fluvio-lacustrine deposits and in rock formations, were concentrated in a NNW-SSE elliptical area (Fig. 4) and mainly struck conformably with the reactivated faults (inset in Fig. 5A). Their highest concentration and dimensions well fit the macroseismic and instrumental epicentral area. About the typology of the phenomena (examples in Fig. 5A), the open fractures (tension cracks) were prevalent, from a few meters up to hundreds of meters long, generally from some millimeters to a few centimeters wide and with relative vertical displacements ranging from a few millimeters to 5 centimeters.

The most common landslides were represented by rock falls (ca. 60%), probably due to the relatively high vulnerability of the outcropping formations in the epicentral area, mostly consisting of densely fractured limestone and marly limestone, sometimes interbedded with clay and sandstones; rotational and translational slides also occurred (ca. 35%), with only a few cases of earth flows.

Most of the rock falls, consisting of some cubic meters of stones, occurred along the artificial scarps (road cuts) which border the main and secondary roads. Sliding slopes involving considerably larger volumes of material occurred at Sorifa (thousands of cubic meters), at Stravignano Bagni (hundreds of cubic meters), and in Val Nerina (blocks larger than 10 cubic meters).

Rotational sliding phenomena mainly occurred in debris deposits. Three interesting cases were observed respectively at Afrile, at middle slope of the valley right above the Acciano soil dam and on the down-slope side of the road Bagnara-Colle Croce. For these landslides were observed: arcuate crowns some hundreds of meters long, open fractures developed along the main scarps, about tens of centimeters wide and with vertical displacements varying from units to tens of centimeters (Fig. 5B). At Monte d'Annifo an already existing rotational slide was re-triggered, with a main scarp about 200 m long, and a total vertical displacement of about 40 cm. It must be noted that some of these slides continued their motion for days after the Sept. 26 quake, for example the Acciano slide.

The landslide distribution indicates that the area of maximum density is consistent with the VIII-IX MCS damage level. Most of the landslides occurred within a distance of 10 km (ca. 60 % of the total), their number decreases progressively within a distance of 20-25 Km (Esposito *et al.*, 1998). It should be noted that, fortunately, the very dry conditions of the late summer season prevented the occurrence of many rotational slides, being most of the area very prone to this phenomenon in wet conditions (Guzzetti and Cardinali, 1989).

For the same reason, no liquefaction was observed, but only localized ground compaction and artificial fill settlements, mainly concentrated near Nocera Umbra. At Le Molina (Nocera Umbra), a road entering the town suffered noticeable settlements (some centimeters). This phenomenon was enhanced by the contact between the road and a little bridge, whose rigid structure (made of reinforced concrete) laid on a large wall of gravel caissons stiffer than the road subsoil.

A complex phenomenon was observed in an earth dam near Acciano, where significant settlements deformed the top rim of the dam. Some small deformations observed along one of the two slopes of the dam suggest that both compaction and localized slides probably occurred.

A major surface effect occurred on the hill of the Holy Monastery in Assisi. A wide area of the *Piazza Inferiore* (lower square) in front of the church suffered noticeable vertical displacements; this area, delimited by an arch-shaped fracture and by the border of the square towards the hill, appears as the main scarp of a landslide body. Nevertheless, no clear evidence of a sliding phenomenon was observed along the slope of the hill, which is partially retained by an ancient and huge masonry wall. Hence, once again, the interpretation of the phenomenon is rather difficult, being probably caused by the combination of different earthquake-induced mechanisms; in any case the settlement of the subsoil materials appears to play a significant role.

Several hydrological effects were mainly concentrated in the area around Nocera Umbra. They include flow increase, turbid water and drying up of existing springs, and even creation of new springs. On September 26, after the first event (00:33 GMT), water mudding affected the Topino River springs near Bagnara for several hours; after the second event (09:40 GMT)

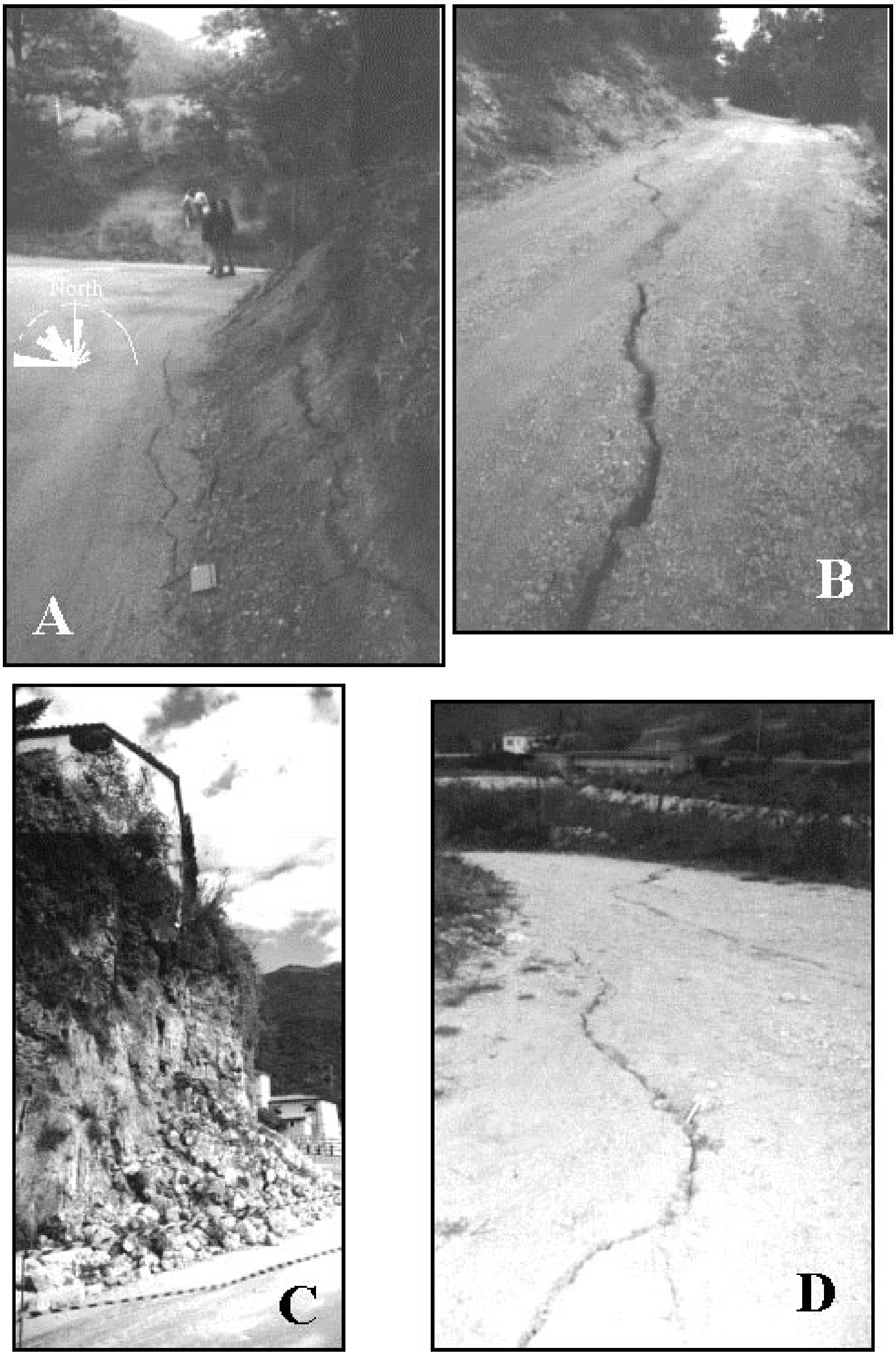


Fig. 5. Examples of ground effects of the Sept. 26, 1997, events (location in Fig. 4). A) ground crack that developed for several hundred meters near Col Pasquale; here local inhabitants noted a violent gas emission (in inset: windrose diagram of fracture orientations within the earthquakes area); B) Typical landslide crown at Afrile; C) rock fall near Stravignano; D) ground settlement in the Topino river bed near Bagni di Nocera.

Fig. 6. View of the Costa-Corgneto range front taken from SW; arrow marks the site of reactivated slickensides shown in Fig. 7 (site 5 in Fig. 2A).

the flow was interrupted for about two hours and then started again with mud water at an intensity lower than the regime flow (100 l/s). Analogous phenomena occurred at S. Giovenale water wells. Other significant hydrological effects were observed after the 9:40 event: new springs were active for a few hours in the area of Le Prata village; some springs temporarily dried up, e.g. the Angelica spring near Bagni, and a small spring that fed a fountain in the center of Isola; water mudding affected for several hours the Roveggiano stream at Capodacqua and the Montenero spring at Campodonico.
Finally, gas emissions and some variations in chemical parameters of spring waters were observed at different locations (Calcara *et al.*, 1997), also outside the epicentral area (e.g., Umbertide town, Martinelli and Albarello, 1997).
In general, it was noted a level of secondary effects in good accordance (Esposito *et al.*, submitted) with what expected for the corresponding levels of intensity based on the historical database (Serva, 1994).

Primary effects

Based on the preliminary appraisal of the distribution of damage and environmental effects, we checked all the already known capable faults located within the epicentral area (Colfiorito basin, Fig. 2A) in the hours and days following the main shocks, observing a subtle but systematic slip on some of them (see Cello *et al.*, 1998a, for a more detailed description). These faults, which border the range fronts, generally mark the interface between the Meso-Cenozoic calcareous or marly bedrock and the late Quaternary slope deposits, typically related to the latest Glacial age (20 to 15 ka B.P.) (Coltorti and Dramis, 1987). In general, the scarps carved in calcareous rock are well exposed and often display up to 2-3 meters high well preserved slickensides.
We mapped surface ruptures along several segments of the main faults (Fig. 2): a) Costa-Corgneto segment of the Cesi-Costa fault; b) Tolagna segment of the Dignano-Forcella fault; c) Mt. Le Scalette, Mt. Faento and La Pintura segments of the Colfiorito border fault. The Costa rupture occurred during the 00:33 shock, because the road cracks associated to it were observed before the second 09:40 event; for the other cited ruptures we cannot discriminate which was the causative event between the two. The coseismic motion was generally normal dip-slip, with only a minor left-lateral component near the Costa village. These faults have been re-surveyed several times during a period of more than one year to document possible additional slips, which have not occurred, and the morphological evolution of the free-faces.

Costa-Corgneto segment This fault segment (Fig. 2A, site 5) trends ca. N130 and shows a fresh-looking slickenside for most of its length, generally marking the contact of Mesozoic limestone with stabilized and cohesive slope scree, which hosts a dense wood (Fig. 6). Behind Costa, a coseismic slip affected the slickenside determining a continuous 7-8 cm high free-face over a length of 80 m, marked by a brown strip due to a veneer of soil coating the base of the fault plane (Fig. 7A-

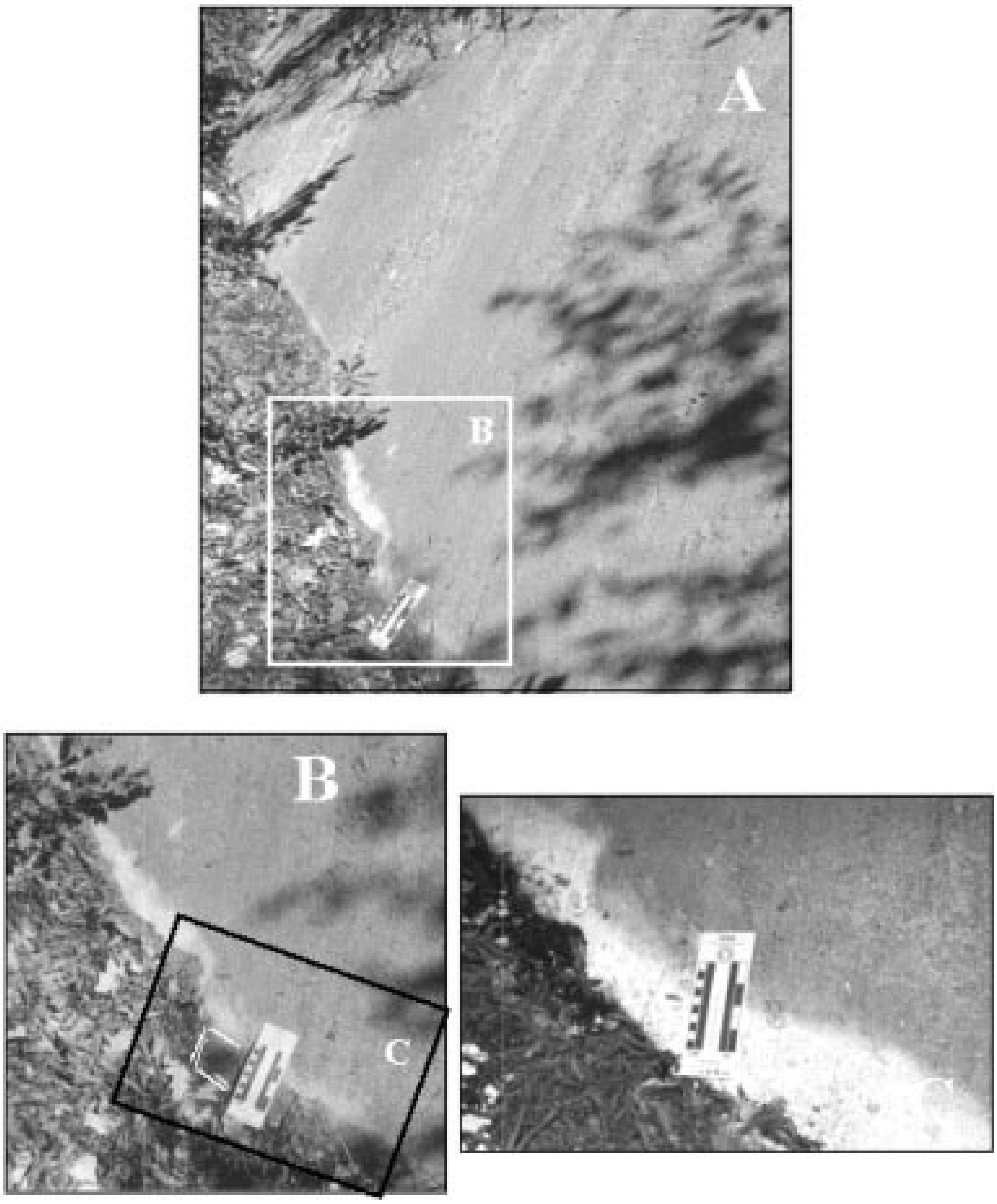


Fig. 7. A) Slickenside with basal 7-8 cm high free-face along the Costa bedrock fault scarp; B) Detail of the free-face, marked by a brown soil-coated strip. Photographs taken on September 27, 1997; C) Detail of the free face taken about one year later, on October 1998.

7B). One year later a pale strip had remained (Fig. 7C), while the soil had been washed out. A similar reactivation was observed on a 40 m long segment of the limestone scarp near Corgneto, where the brown strip marking the free-face was 4 cm high. Between Corgneto and Costa, and SE of Costa, the bedrock fault scarp showed only local evidence of tension gashes in the soil. In the SE termination of the Costa scarp free-face, where the bedrock is present in both sides of the slickenside, we observed small faults and fractures in the slope immediately below the fault scarp and along the dirt road connecting Costa to the Mt. Tolagna area. Very likely, the few centimeters of measured coseismic fault slip were, here and between Costa and Corgneto, spread over a network of minor hanging-wall fractures. Hence, we have concluded that the end-to-end rupture length along this segment is about 1 km.

Other relevant sites

Tolagna segment - At Fosso Lavaroni (Fig. 2A, site 4; Fig. 8) the bedrock scarp, N160 trending and SW dipping, 1 to 1.5 m high, juxtaposes slope deposits against Mesozoic limestone. Over a length of ca. 200 m the coseismic motion produced a continuous, 2.5 cm high free-face. At the SE termination of the scarp, it displaced of the same amount a dirt road. Here the fault plane is exposed in the road cut and the observed thickness of slope deposits is minimal. Moving south after the road, the bedrock fault scarp maintains the same height, but, being completely mantled by soil, it shows only diffuse ground cracks at its base over a distance of 1.6 km along the slope of Mt. Tolagna; hence, the cumulative end-to-end length of the ruptures associated with this fault segment is ca. 1.8 km.

Mt. Le Scalette, Mt. Faento and La Pintura segments - At Mt. Le Scalette (Fig. 2A, site 1) N130 to 150 trending, SW dipping, fresh slickensides outcrop along a 2 to 4 m high bedrock fault scarp. This segment records the maximum stratigraphic offset of the whole Colfiorito border fault, that is 150 to 200 m. At its SE termination, the fault displaces middle Pleistocene and recent lake sediments, damming the NE-ward drainage of the Colfiorito basin into the Chienti River valley (Centamore *et al.*, 1978). The coseismic offset in this area produced free-faces 2 to 4 cm high over a discontinuous length of ca. 350 m (Figs. 9 and 10). As well, along the slope of Mt. Faento (Fig. 2, site 2) we observed a 4 cm high basal free-face along a ca. 300 m long section of the slickenside in the Maiolica Fm. in contact with slope deposits.

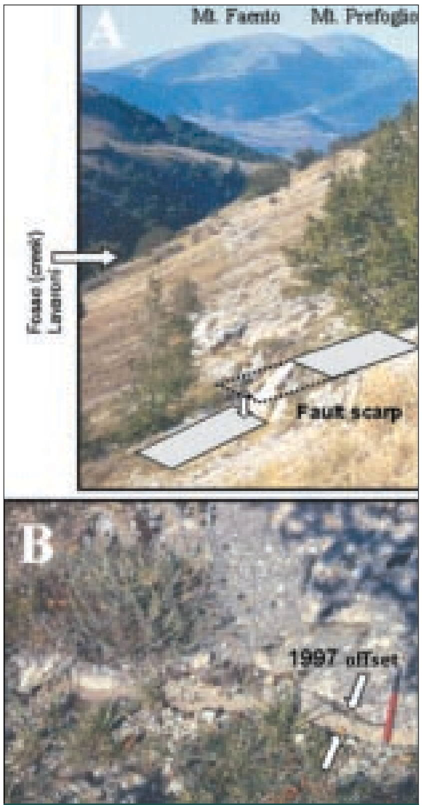


Fig. 8. A) View of the Tolagna bedrock fault scarp near Fosso Lavaroni (site 4 in Fig. 2A). The free-face height is remarkably uniform (2.5 cm) while slope deposits thicken from SE (right side of this image) to NW; B) detail of the free face, partially coated with soil. Photographs taken on September 27.

At La Pintura (Fig. 2, site 3) the coseismic rupture cut obliquely across the slope intersecting a winding dirt road at two sites. Along this segment the observed rupture length was ca. 300 m with a maximum displacement of 2 cm.

The mapped surface breaks provide a minimum value for rupture length assessment

Fig. 9. A) View of the Mt. Le Scalette range front from SW; note the bedrock fault scarp with the reactivated slickensides; B) Detail of the free-face (4 cm high, brown soil-coated strip). Photographs taken on October 3.

along this fault. As noticed at La Pintura, the fault reactivation can be precisely mapped and the offset measured, only where reference features such as slickensides or road cuts occur along the fault trace. Likewise, ground breaks having only a few centimeters of slip are generally undetectable to map where the wood covers the fault zone. Therefore, Cello *et al.* (1998a) have estimated the minimum rupture length of the Colfiorito border fault as the end-to-end reactivation between Mt. Le Scalette and La Pintura, i.e. no less than ca. 6 km (Fig. 2).

Evidence for large-scale coseismic mass movements near Sellano

Either on September 26 and October 14 other surface ruptures occurred unrelated to known capable faults, for instance near Fraia, Sellano, Renaro, Mevale and Rasenna (Fig. 4). In particular, discontinuous superficial breaks occurred over a distance of about 1.7 km between Renaro and Mevale during the October 14 shock (Fig. 11). Near Renaro the fracture was up to 5 cm wide on October 14, and opened up to ca. 10 cm until October 29. The rupture partly run within the Scaglia Fm. parallel to bedding. Some authors (Basili *et al.*, 1998) attribute to the Renaro-Mevale ruptures a tectonic significance. Addressing the interested readers to them for details of their interpretation, we underline that the tectonic significance of these features is questionable in our judgment mainly because of a) the morphological and structural setting, for example the lack of a normal fault in the vicinity of the ruptured zone with any evident pre-existing morphological and stratigraphic offset; b) the displacement was not instantaneous, but continued for days after the quake; c) the displacement was essentially in the shape of a tension crack up to 10 cm large, without appreciable vertical or lateral components. In our opinion, this feature might be interpreted in several ways, all tectonically controlled but related to an indirect expression of the faulting at the hypocenter. Most likely, it was a gravity-related *sackung*-like phenomenon (e.g. Beck, 1968; Radbruch-Hall *et al.*, 1976), very common feature all along the Alps and the Apennines (e.g., Blumetti, 1995, and references therein). Less likely, it may also be considered a *subordinate rupture*, as defined in Clark *et al.* (1991) or a *fraglia* as defined in Serva (1995). This last term comes from *frana* (landslide) and

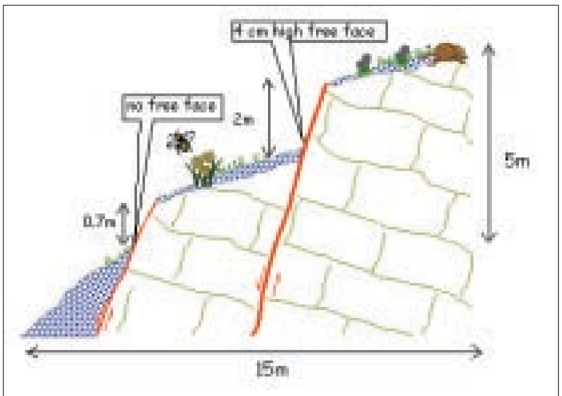


Fig. 10. Interpretative geological section across a 15 m long portion of the Mt. Le Scalette fault, where coseismic slip occurred within the limestone bedrock.

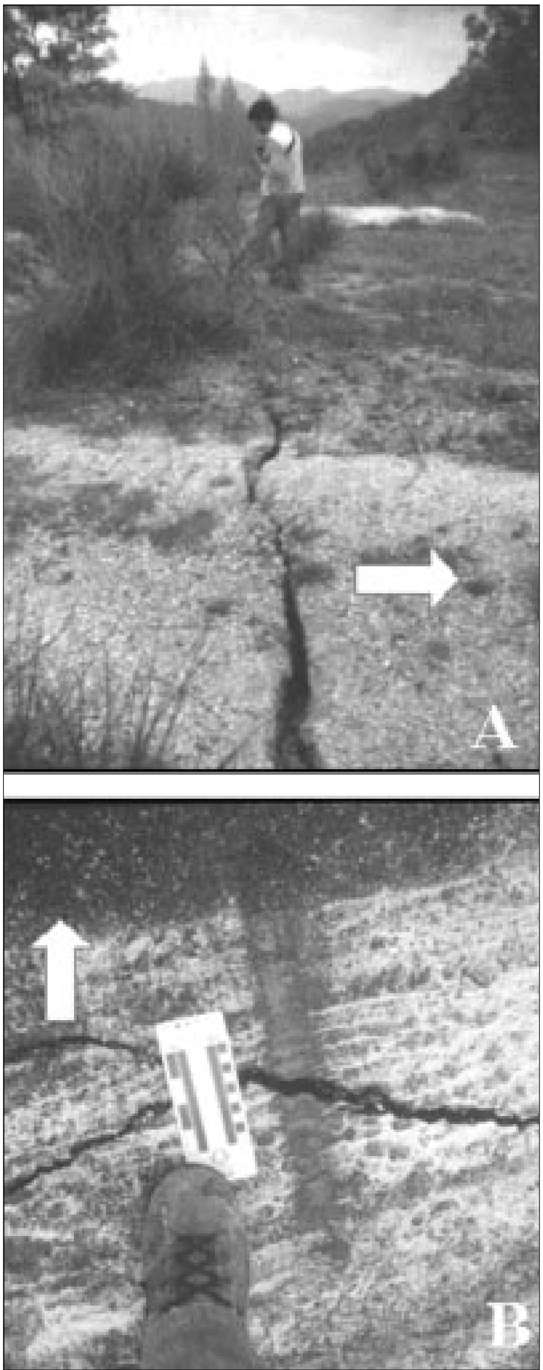


Fig. 11. A) Tension gash up to ca. 10 cm wide near Renaro (ca. 5 km south of Rasenna, Fig. 4) along a fracture zone extending NNW-SSE for ca. 1.7 km between Renaro and Mevale originated during the Oct. 14, 1997, earthquake; B) Some ten meters to the north, the same fracture crossed a paved road, which, repaired the day after the earthquake, showed that this fracture was still widening on Oct. 29, 1997.

faglia (fault) and has been proposed to describe a set of features, still poorly studied, resulting from a combination of these two phenomena, i.e., fault-controlled very deep landslides.

It is important to note that the Sellano, October 14 earthquake ruptured a fault section located at the SE termination of the Colfiorito normal fault segment. In the Apennines many remarkable, large-scale, gravity deformations occur at or near normal fault segment boundaries.

Discussion

The significance of the observed slip along faults bordering the Colfiorito basin has caused a great debate among Italian scientists, having been interpreted either as (1) the compaction of the debris deposit, (2) a gravity effect or (3) a true fault reactivation.

The reliability of hypotheses (1) and (2) can be tested based on soil mechanics principles, which allow to evaluate the behaviour of the debris deposit under the seismic excitations. As a case-study, we have analysed in some detail the fault reactivation near Costa. Here the free face was practically uniform (7 to 8 cm) along the contact between the bedrock and the recent deposits, even if the latter had thickness variable from less than one meter

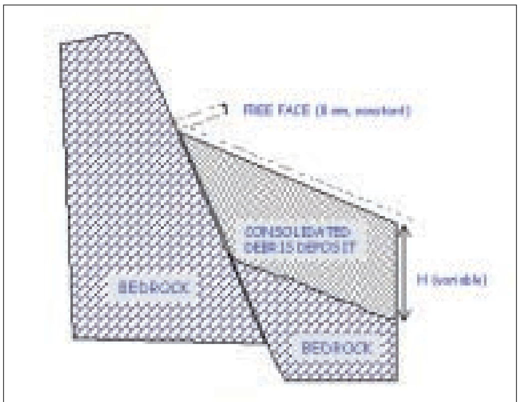


Fig. 12. Schematic section of the reactivated fault zone at Costa, used for modeling the possible causes of observed slip.

to tens of meters (Fig. 12). We have estimated the order of magnitude of the potential settlements induced by the September 26 first earthquake from the geotechnical viewpoint. First of all, it must be observed that, even if the dynamic excitation and the material stiffness are assumed constant along the fault, nevertheless the amount of settlement varies with the height of the debris deposit: in particular, on the basis of a simple model, the settlement is a quadratic function of the deposit thickness. Hence, varying the deposit height between units and tens of meters, the settlement should vary at least of two order of magnitude. A rough but effective evaluation of such settlements, adopting the most conservative values of debris stiffness (thousands of kg/cm^2) and seismic accelerations (ca. 0.5g constant in the debris deposit), gives maximum settlements of the order of a few millimeters, at least one order of magnitude lower than the measured one. In the calculation we have taken into account only the vertical component of the acceleration, being the horizontal components relatively small in the near field. In conclusion, the hypothesis (1) is not reliable.
About the hypothesis (2), it must be firstly underlined that, because of the stiffness of the debris material, the landslide mass should behave as a rigid body, without significant volumetric changes. As a consequence, noticeable variations of the shape of the deposit should be evident elsewhere (downward), consistently with the amount of measured settlements of the scarp; furthermore, a soil or debris slip would have occurred on a plane inclined less than 30°-35° (rest angle), for example along the contact with the bedrock underneath the debris deposit, thus displaying an appreciable horizontal component away from the slickenside. Instead, the relative movement occurred exactly along the contact surface between the slickenside and the debris deposit: neither tension gashes were generally observed, nor any small graben-like settlement (gravity faulting). The illustrated conclusions, based on physical considerations and on simple but effective analyses, allow to assess that the observed phenomenon is the experimental evidence of a rigid sliding movement between the fault bedrock and the debris formation, which perfectly agrees with the hypothesis (3) of the capable fault reactivation.
Taking into account the geologic and geomorphologic recent evolution of the reactivated bedrock fault scarps and the Quaternary setting of the Colfiorito basin, many other pieces of evidence sum up to indicate that the surface ruptures associated with the September 26, 1997, earthquakes in the Colfiorito basin have a tectonic significance. Coseismic surface slip occurred along pre-existing Quaternary faults responsible for the recent tectonic evolution of the area. Fresh limestone slickensides were reactivated, which are characterized by geomorphic features unequivocally related to paleoseismic surface faulting, such as a) the position within prominent bedrock fault scarps at the base of young tectonic slopes and b) the juxtaposition with thick, faulted latest Glacial to Holocene stratified slope-waste deposits. It is worth noting that such deposits must have suffered repeated seismic shakings during the Holocene (extrapolating the relatively short historical sample), which had certainly determined their settlement. The soil-coated strip observed just after the earthquake has become after about one year (during which the soil has been washed out) similar to the pale strip described for the 1915, Fucino, earthquake (Vittori *et al.*, 1991; Michetti *et al.*, 1996). The same feature has been described for recently activated limestone earthquake scarps worldwide, see for example Stewart and Hancock (1990) for the Egean region, which also discuss its genesis and evolution. Therefore, the Colfiorito surface ruptures confirm that the so-called *nastri di faglia* (Segre, 1950; Vittori *et al.*, 1991; Yeats *et al.*, 1997) are in general evidence of very recent paleoseismicity, although local erosional conditions, which a correct geomorphological analysis can easily identify, may enhance or even produce the same feature over limited (meters to tens of meters) distances.
Along the reactivated fault segments, surface offset is remarkably constant over tens to several hundreds of meters, while the thickness of slope deposits varies from a few centimeters to tens of meters. Comparable displacements have been observed at sites showing different morphological features, such as slope angle and position of the reactivated fault along the

slope. Slope deposits were in dry conditions and generally stabilized by tree root penetration. Finally, we have monitored the free faces in the following days and months without detecting any additional slip, which should have been expected in case of gravity movements, due to the numerous events of the seismic sequence (some with M > 5) and the very humid environmental conditions (rainfalls and snow) that have characterised the subsequent months. As previously described, significant creep has instead widened in the following days the tension cracks opened after the Renaro-Mevale earthquake on October 14, which we are prone to interpret as a *sackung*-like movement. As well, post-seismic movements were observed in several slides in the epicentral area, all displaying features and morphological settings sensibly different from those of the reactivated fault scarps. As a matter of fact, the different long-term morphological evolution of deep-seated fault slips and superficial, landslide or sackung-like movements make it quite easy their discrimination.

Geodetic, satellite and SAR data have recognised a permanent ground deformation in the Colfiorito area (Salvi et al., 2000), which is in good agreement with a normal slip along the NW-SE-trending and SW-dipping basin border faults. As well, the aftershocks related to the Colfiorito sequence concentrate in the hangingwall of the reactivated faults. The fault parameters and seismic moments (0.4 and 1.0 $x10^{18}$ Nm) of the two main shocks, as derived from strong-motion data are compatible with the observed surface ruptures, taking into account the shallow hypocenters: 38 and 37 cm of slip along 6 and 12 km long and 6 and 7.5 km wide faults, respectively.

It is noteworthy that the application to the Colfiorito events of the magnitude vs. rupture length and magnitude vs. displacement relationships, derived from the empirical database for earthquake faulting worldwide (Wells and Coppersmith, 1994), suggests values in good agreement with what observed (4 to 8 cm maximum over lengths of several kilometers) (Fig. 13).

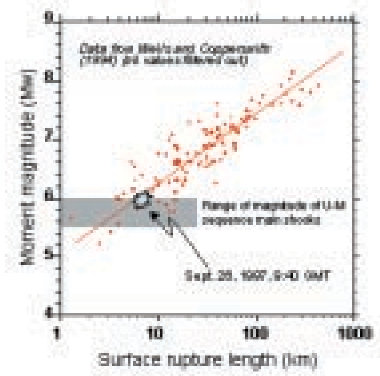


Fig. 13. Plot of Mw vs. surface rupture length from worldwide database (Wells and Coppersmith, 1994). The Colfiorito main shocks are in the lower zone of occurrence of surface faulting.

Some constraints on the seismic potential in the Colfiorito area

Following the Sept. 26 events we have observed up to 8 cm of coseismic slip. We know that at the end of the last Glacial epoch the mountain slopes were shaped as relatively regular surfaces because smoothed by a very effective climatic morphogenesis (Brancaccio *et al.*, 1979; Blumetti *et al.*; 1993; Giraudi, 1995, Giraudi and Frezzotti, 1997). Hence, we can assume the interval 18 to 14 ky (ending part of last Glacial to beginning of Holocene) as a reliable age estimate of mountain slopes in the Apennines; therefore, these slopes may be assumed as reference surfaces to measure the tectonic mobility of the capable faults of this region. The present displacement of these slopes across fault planes, estimated as 2-3 meters maximum (Cello *et al.*, 1997), is the cumulative effect of repeated coseismic slips during the Holocene. Such time span is that of major interest for SHA, although the repeat time of large earthquakes can be in the order of several thousands of years. On this basis, it is possible to estimate a Holocene slip-rate along dip of 0.1-0.2 mm/year (0.07-0.14 vertical and

horizontal components for 45° dipping fault planes), without taking into account any possible strike-slip component.
Although the time span of historical information is relatively long, only the 1279 event appears to fit the last earthquake for epicenter location, intensity and distribution of effects. On this basis, we assume the 1279 event as the preceding event in the Colfiorito area, yielding an interval time of ca. 7 centuries. This would give ca. 20-25 such events since the end of the last Glacial epoch. The repetition of 25 Colfiorito-like events would determine the observed Holocene displacement with 8-12 cm of slip per event. Actually, the maximum observed slip was 8 cm (Costa segment), while 2 to 4 cm were observed on the main fault system. It is likely that such slip represents only a portion of the actual slip, being the "missing" part distributed in a way not directly visible on the ground, because of the small offset and the "ductile" characteristics of the hangingwall deposits and soil-vegetation cover. Such hypothesis might be supported by the ca. 20 cm of vertical slip measured by the geodetic network.
If we extrapolate such slips per event and return periods to a time range of one million years, which is the inception time of the basin (see Geological Background), we obtain a rough estimate of vertical offsets of ca. 100-150 m, in agreement with the stratigraphic and morphological offsets (150-200 m, Calamita and Pizzi, 1993). Hence, reasonably we may hypothesize that, being magnitude 5.5-6 the threshold for the occurrence of surface faulting, the local morphology can derive from the cumulative effect of repeating events of such magnitude, once the climatic forcing is filtered out.
Obviously, without additional constraints, it would be arbitrary to assume the last Colfiorito event as "typical". In fact, based only on the historical record, how can we rule out the possibility of previous events larger than it, may be alternating in time, and the occurrence of clustered activity? The September 26 rupture was distributed in two sub-events; if they ruptured at the same time, the size of the earthquake would have been larger, probably affecting also the amount of offset. Can this happen in the future? What seismotectonic significance should we attribute to the local geological and geomorphological parameters? A tentative answer may be given comparing the shape of the Colfiorito basin, which is made of a nested network of small depressions with limited thickness of the valley fill and is bounded by fault segments up to 15 km long, to other intermontane basins of the Apennines where much stronger earthquakes have occurred. A typical example is the Fucino basin, located in the Abruzzo region, ca. 130 km to the southeast, which hosted the Avezzano earthquake (magnitude ca. 7) in 1915. Here the geological slip-rate since the Middle Pleistocene is at least 0.4 mm/y, high enough to drown the secondary structures within the basin, and the length and stratigraphic offsets of the master faults (Michetti *et al.*, 1996) are sensibly larger than those in the Colfiorito basin. These differences can derive from the younger inception of the Colfiorito basin and its much lower slip rate. Another interesting fact is that the hypocentral depths of the Colfiorito events appear significantly shallower than that of the major seismic events of this century in Italy. Does this necessarily imply a much lower seismic potential, as also suggested by the historical seismicity? How thick is the seismogenic layer in the area and how this affects the fault segmentation? What is the potential of nearby basins, e.g. Norcia and Gubbio, which display characteristics somehow in the middle between Colfiorito and Fucino?
To answer these main questions for SHA, we need to determine, as precisely as allowed by geological, geomorphological and geophysical methods, a number of parameters on geometry and recent history of all capable faults in the area (Cello *et al.*, 1997; Michetti *et al.*, 1997; Tondi *et al.*, 1997; Vittori *et al.*, 1997; Azzaro *et al.*, 1998). At this end, we emphasize the need for paleoseismological analyses in the area and along other tectonic structures in the Apennines, showing similar historical seismicity levels and evidence of capability.

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Colfiorito - Rieti, Valle del Salto. Holocene surface faulting along the Fiamignano Fault and associated large scale slope deformation

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After more than ten years of research conducted by the Authors and others research groups (e.g. Bertini & Bosi, 1976; Raffy, 1983; Barberi & Cavinato, 1993; Michetti *et al.*, 1995, and references here in), a significant geological database is available for the region of Central Italy centered on the Rieti basin. To understand the pattern of recent gravitational deformations and capable earthquake faulting along the Fiamignano Fault, it is very important to frame the local setting into the Quaternary evolution of the surrounding areas. Figures 1 to 4 show the example of the changes in the drainage pattern of the Rieti basin and nearby areas in Central Italy over the Quaternary. These maps are based on mostly 1:10,000 scale field survey of the Quaternary deposits, interpretation of airphoto coverages with different scales, geomorphic analyses, paleoseismic and stratigraphic trench investigations soil surveys, geophysical prospecting, radiocarbon and Ar/Ar dating, and detailed analyses of several ad hoc drilled boreholes. The most significant result from these investigations is the understanding of the relative importance of tectonic and climatic processes in controlling the landscape evolution. In tectonically active provinces like Central Italy, only once typical earthquake ground effects, style of faulting, fault rupture length, displacement per event and slip-rates have been reasonably well constrained, it is possible to reconstruct the local geomorphic evolution. The growth of the Valle del Salto, Rieti, Terni and Leonessa intermountain basins and footwall mountain ranges is here related with the activity and interaction of the dominant normal faults in the area, which strongly influenced the drainage network (e.g., Michetti *et al.*, 1995; Mazzi, 1996; Guerrieri *et al.*, submitted; Brunamonte *et al.*, in prep.).

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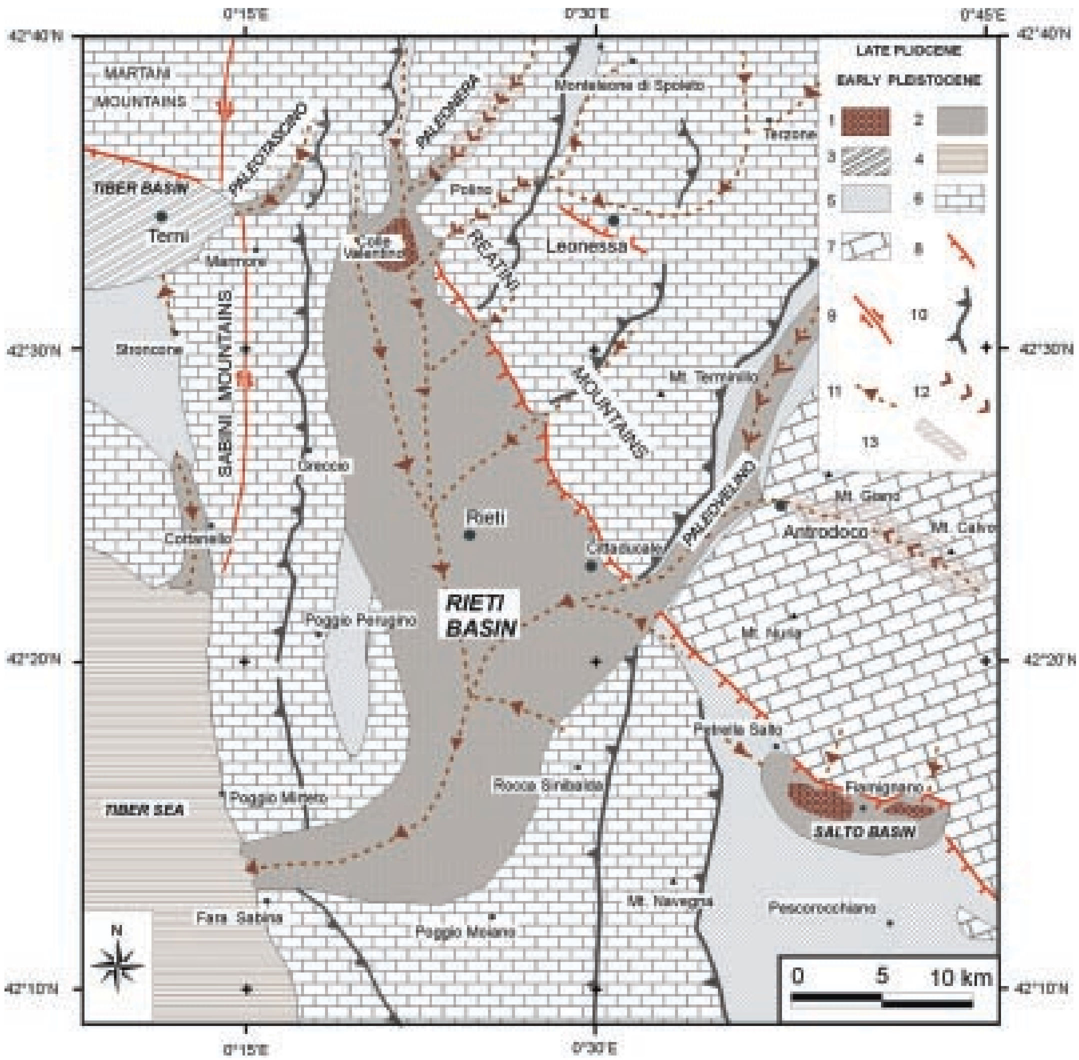


Fig. 1. Late Pliocene – Early Pleistocene: 1. Continental deposits of Rieti and Salto basins still preserved as remnants; 2. Hypotetical distribution of not preserved continental deposits; 3. Lacustrine deposits (Ponte Naja Unit, Tiberin Basin); 4. Tiber Sea sequence;
Bedrock: 5. Flysch deposits (Miocene); 6. Limestones and marls of Umbrian sequence (Jurassic-Miocene); 7. Limestones of Latium and Abruzzi sequence (Triassic-Miocene);
Structural elements: 8. Normal fault, active in Late Pliocene–Early Pleistocene time; 9. Strike-slip fault, active in Late Pliocene – Early Pleistocene; 10. Thrust;
Geomorphological features: 11. Rivers and streams: the triangle indicates the draining direction; 12. Wind-gap; 13. Erosional paleosurface.

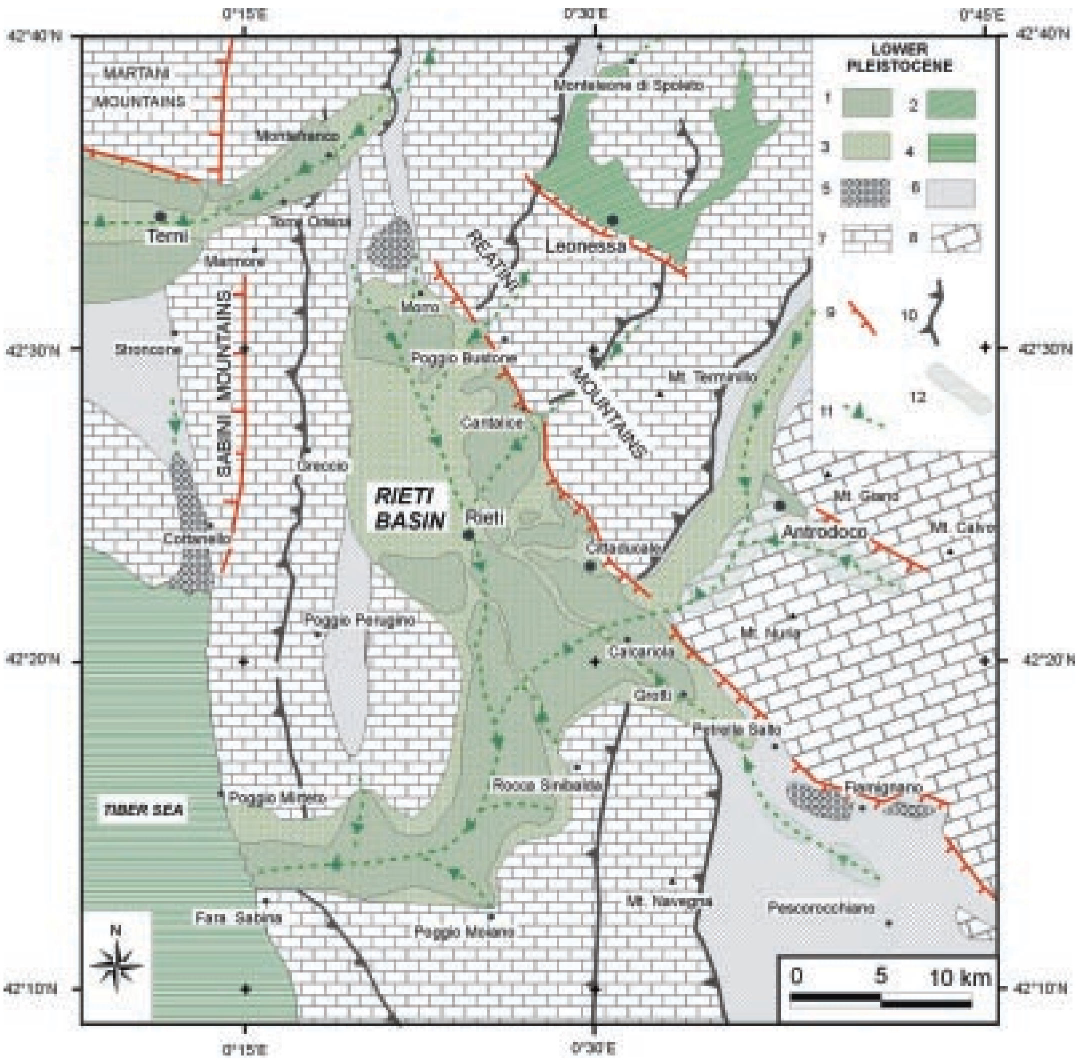


Fig. 2. Lower Pleistocene: 1. Fluvial deposits of Rieti and Terni basins still preserved as remnants; 2. Lacustrine and marsh deposits of Leonessa basin; 3. Hypotetical distribution of not preserved continental deposits; 4. Tiber Sea sequence.
Bedrock: 5. Older continental deposits (Late Pliocene – Early Pleistocene); 6. Flysch deposits (Miocene); 7. Limestones and marls of Umbrian sequence (Jurassic-Miocene); 8. Limestones of Latium and Abruzzi sequence (Triassic-Miocene).
Structural elements: 9. Normal fault, active in Lower Pleistocene time; 10. Thrust;
Geomorphological features: 11. Rivers and streams: the triangle indicates the draining direction; 12. Erosional paleosurface.

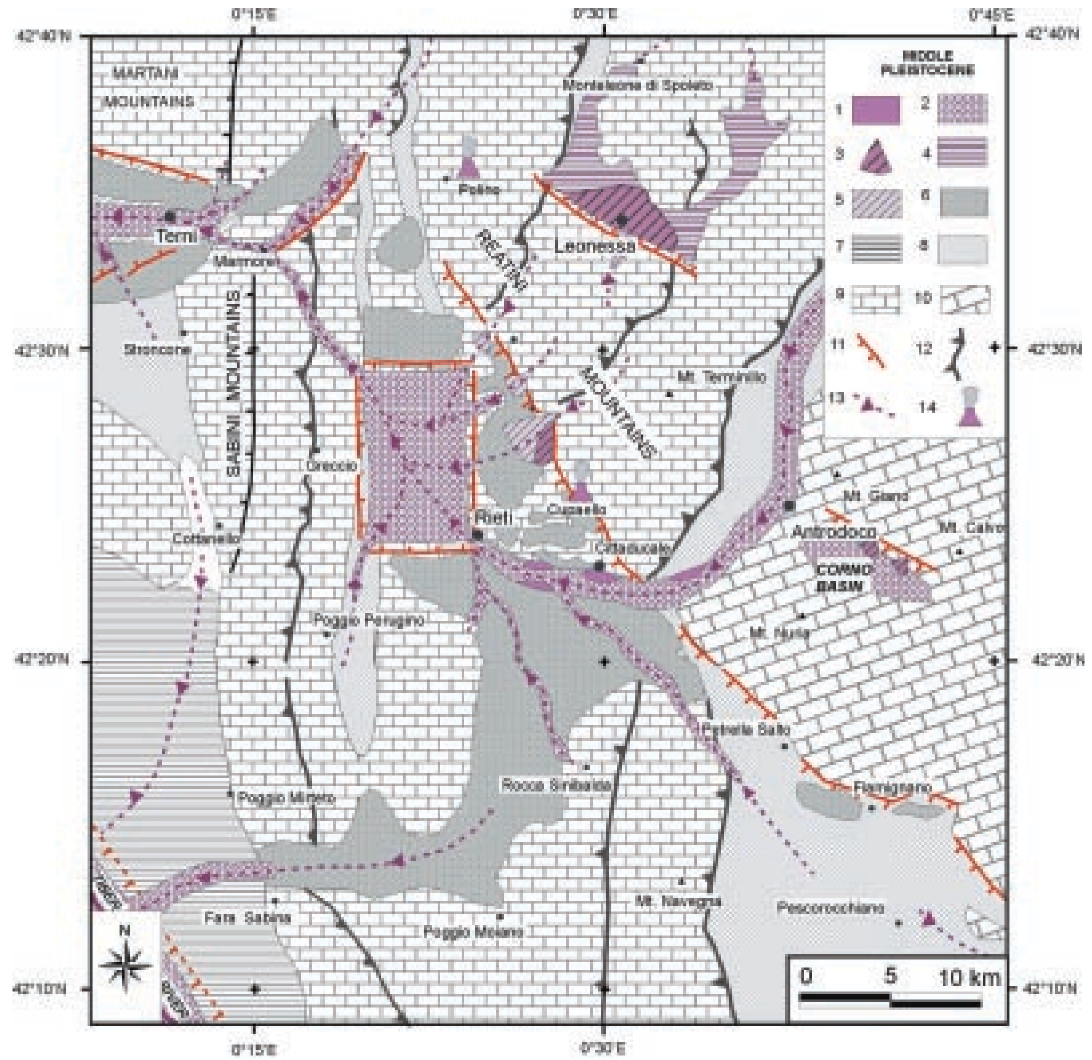


Fig. 3. Middle Pleistocene: 1.Travertines with related fluvial and lacustrine deposits; 2. Hypotetical distribution of not preserved fluvial deposits; 3. Alluvial fan deposits; 4. Lacustrine and marsh deposits of Leonessa basin; 5. Hypotetical distribution of not preserved alluvial fan deposits;
Bedrock: 6. Older continental deposits (Late Pliocene–Early Pleistocene); 7 Sands and clays (Tiberin Sea sequence, Pliocene–Early Pleistocene); 8. Flysch deposits (Miocene); 9. Limestones and marls of Umbrian sequence (Jurassic-Miocene) 10. Limestones of Latium and Abruzzi sequence (Triassic-Miocene);
Structural elements: 11. Normal fault, active in Middle Pleistocene time; 12.Thrust;
Geomorphological features: 13. Rivers and streams: the triangle indicates the draining direction; 14. Local volcanic eruption.

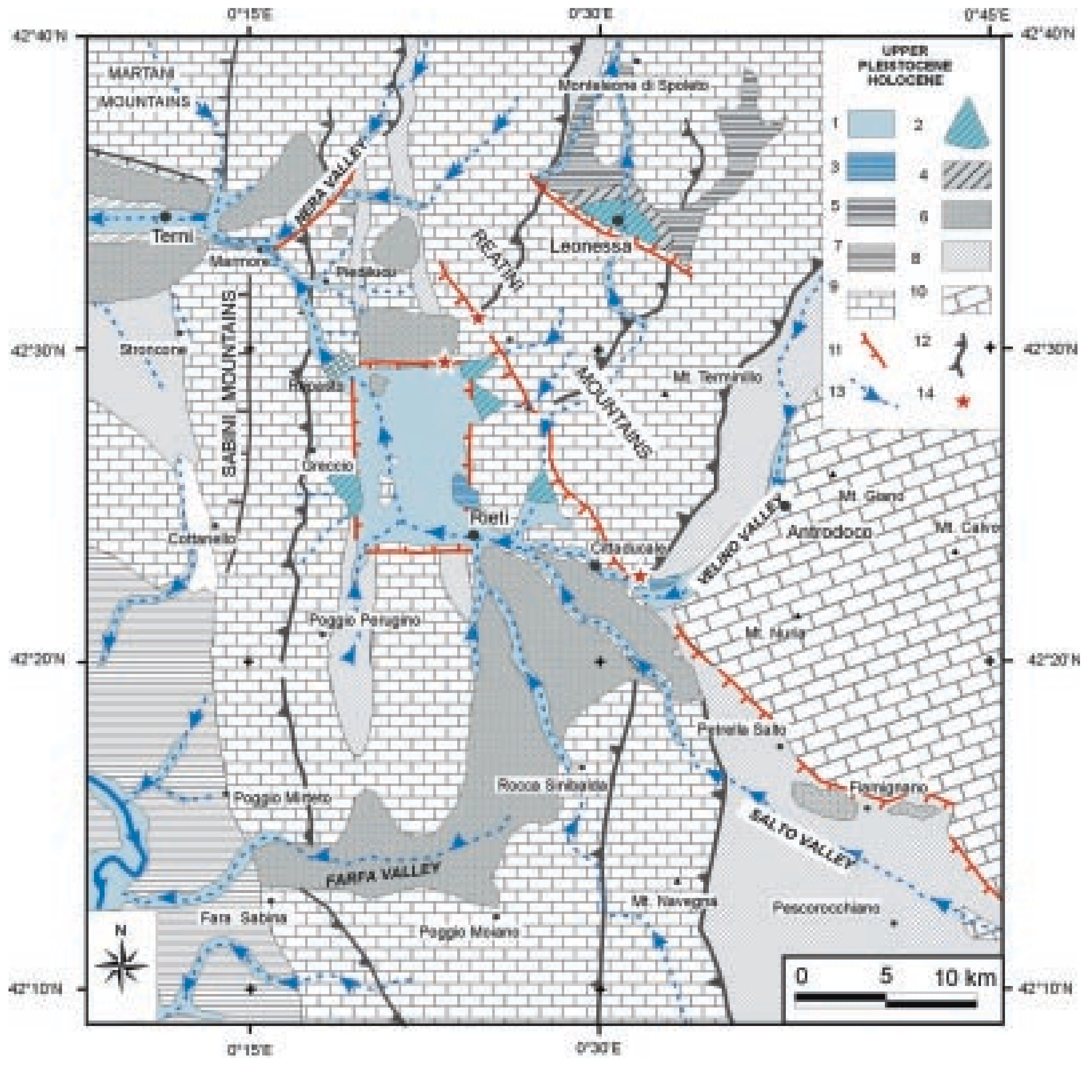


Fig. 4. Upper Pleistocene – Holocene: 1. Fluvial and lacustrine deposits; 2. Alluvial fan deposits; 3. Travertines with related fluvial and lacustrine deposits;
Bedrock: 4. Older alluvial fan deposits (Middle Pleistocene); 5. Lacustrine and marsh deposits of the Leonessa basin (Lower-Middle Pleistocene); 6. Older fluvial deposits (Late Pliocene-Lower Pleistocene); 7. Sands and clays (Tiber Sea sequence, Pliocene–Early Pleistocene); 8. Flysch deposits (Miocene); 9. Limestones and marls of Umbrian sequence (Jurassic-Miocene); 10. Limestones of Latium and Abruzzi sequence (Triassic-Miocene);
Structural elements: 11. Normal fault, active in Upper Pleistocene to Holocene time; 12. Thrust; 13. Rivers and streams: the triangle indicates the drainage direction; 14. Late Quaternary evidence of surface faulting and site of exploratory trenching for paleoseismological analyses.

However, in the long term the river drainage system have been able to overcome the tectonic control, due to average erosional and depositional rates much higher than the average slip-rates of the local normal faults. In mid-Pleistocene times, after 2 to 3 Ma since the inception of crustal extension in this sector of the Apennines, the fluvial network developed in one single, large catchment basin (the Nera River catchment basin; Fig. 2-4). Obviously, this history of the landscape depends on the peculiar features of the Central Apennines, in terms of Quaternary climatic conditions, rates of tectonic activity and paleoseismological relations. As illustrated in Figures 1 to 4, the Salto River Valley have been an independent, normal-fault controlled, sedimentary basin only in late Pliocene to early Pleistocene times. Subsequently, the drainage network evolution led to the opening of a direct connection with the Rieti basin. The geomorphic setting of the area is shown in Figure 5. The present slope height, strictly connected to the climatically controlled talweg elevation (Fig. 6; see Carrara et al., 1993; Calderoni et al., 1995; Calderini et al., 1998), promotes surficial instability mainly related to the lithological and structural features of the slopes and triggered by intense rainfall events or by earthquakes, as suggested also by historical documents.

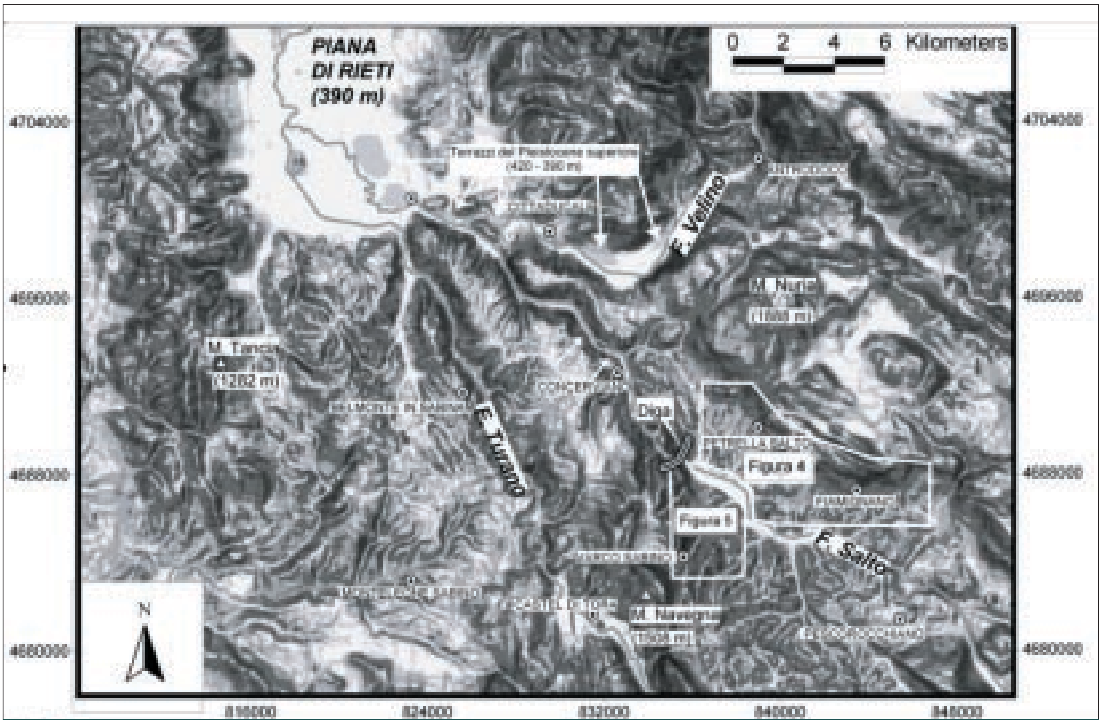


Fig. 5. Location of the studied area and relations with the Rieti area

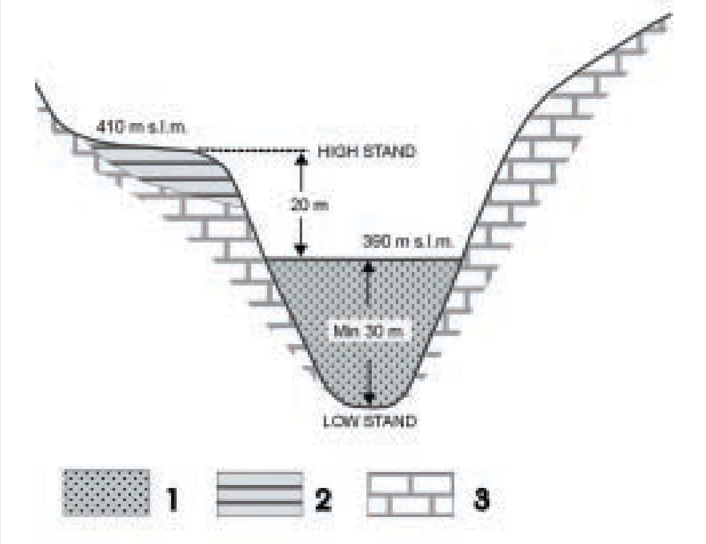


Fig. 6. Schematic section in the downstream sector of the Salto River dam showing the variation of the valley floor elevation due to recent climatic changes, including the Last Glacial Maximum Low Stand, due to erosion of the Marmore travertine threshold. Legend: 1) Recent alluvial deposits (Holocene); 2) Fluvial terrace (Upper Pleistocene); 3) Bedrock.

However in the long-term landscape evolution, a primary role was played by deep seated gravitational movements which sign the north western sector (Fiamignano and Petrella Salto) probably due to a greater slope height and also to the presence of a capable normal fault. Evidence for this will be reviewed in the field in the area between Petrella Salto and Fiamignano (Figs. 7 to 10).

Gravitational collapses, carved only in the pre-Holocene landscape (Colle della Sponga and S.Vittoria paleolandslides; Fig. 9) and not recorded in the historical data, is probably related to higher and steeper slopes during low-stand climatic conditions.

A sequence of flooding events is well known in the Rieti basin, downstream of the studied area, constrained in the Holocene stratigraphy and historical documents. These processes were probably influenced by anthropic deforestation since the Middle Age, and today are controlled by a dam.

The recent activity of the Fiamignano Fault is well documented at this site (Bosi, 1975; Mariotti and Capotorti, 1988). A ca. 8 km long, continuous, Holocene bedrock fault scarp characterizes the base of the mountain front between Petrella Salto and Brusciano (Fig. 10A). Here, a sequence of young, post-glacial small drainages carved in the bedrock are systematically offset across the fault scarp (Fig. 10B). The recent activity of this fault is also documented by the analysis of Late Glacial to Holocene slope deposits. At the Poggio Poponesco site, stratified Late Glacial debris are backtiled against the fault (Fig. 10C). Overlaying Holocene colluvial debris, including a soil horizon dated 4440 + 140 yr BP, are also offset by the fault (Fig. 10D). These observations strongly suggest that earthquake surface faulting along the Fiamignano Fault may influence the deep-seated gravity deformations of the NE slope of the Salto River Valley.

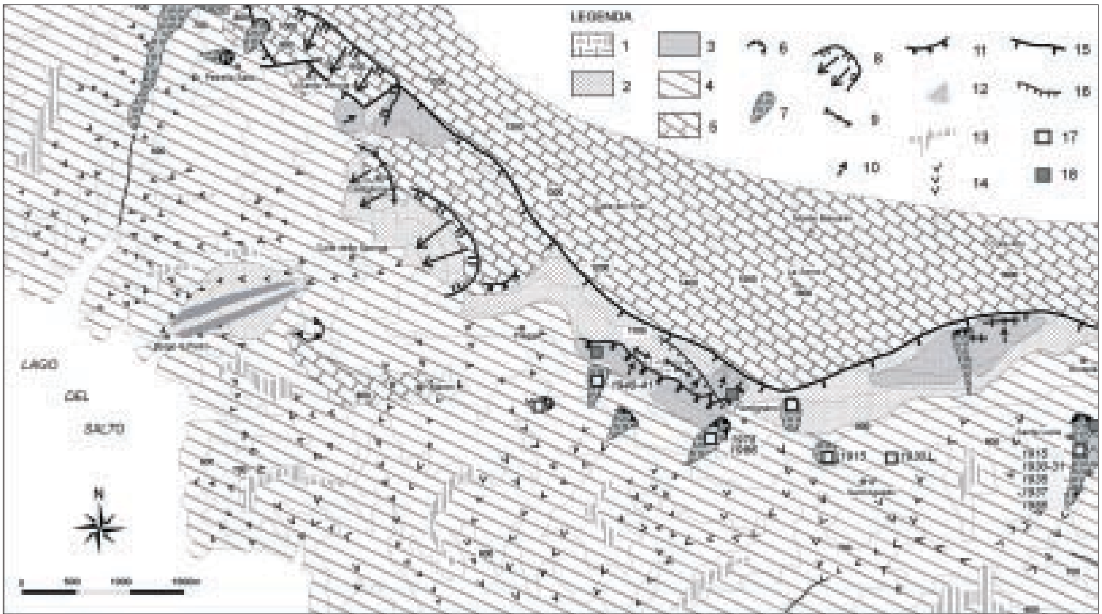


Fig. 7. Geological and geomorphological sketch in the area between the Petrella Salto and Fiamignano villages and the Salto Lake. Legend: 1) Eluvial and colluvial deposits; 2) Recent talus; 3) Old cemented breccias; 4) Clays, sands and sandstones; 5) Limestones and calcarenites; 6) Landslide main scarp; 7) Landslide body; 8) Slope affected by deep seated gravitational movements; 9) Trench; 10) Sector of a slope inclined in the opposite direction; 11) Rock fall scarp; 12) Alluvial fan; 13) Erosional surface; 14) Erosional channel; 15) Staffoli-Fiamignano fault; 16) Fault scarp; 17) Sliding historical events; 18) Rock fall historical events.

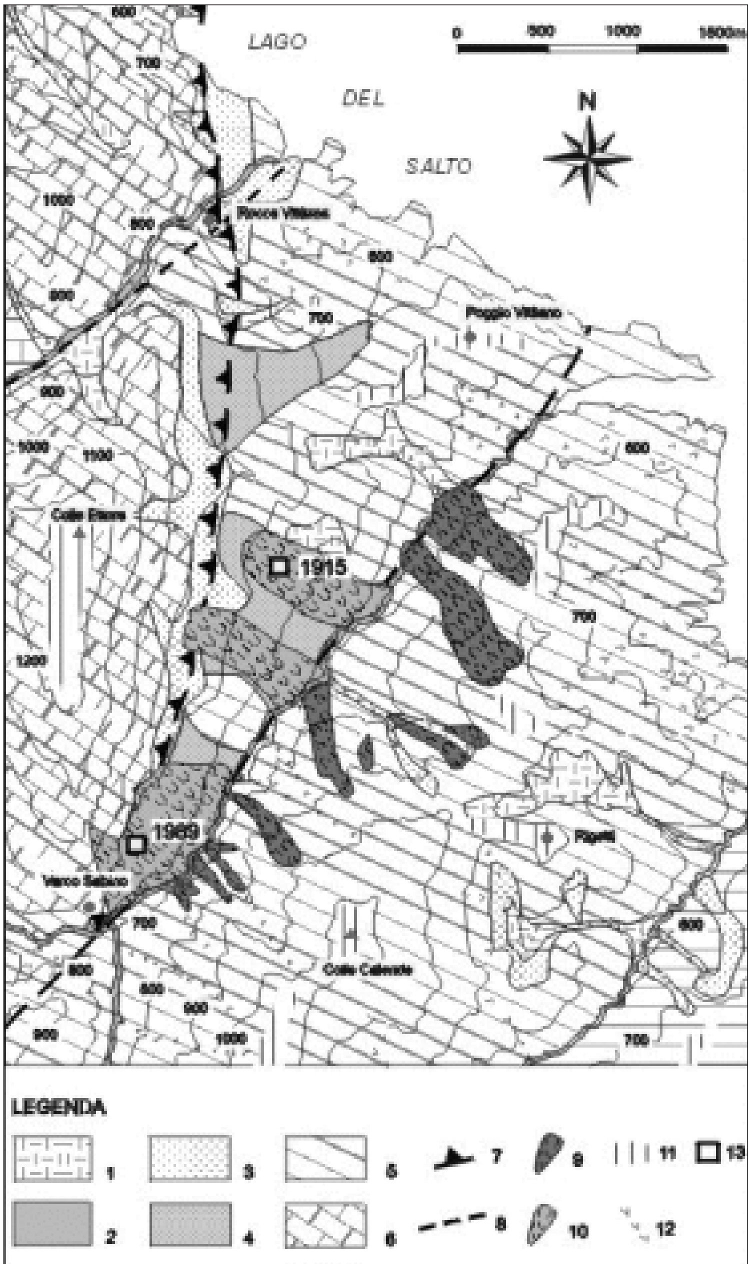


Fig. 8. Geological and geomorphological sketch in the area between the Varco Sabino village and the Salto Lake. Legend: 1) Eluvial and colluvial deposits; 2) Recent alluvial deposits; 3) Recent talus; 4) Old cemented talus; 5) Clays and sandstones; 6) Limestones and calcarenites; 7) Olevano-Antrodoco thrust line; 8) Normal fault; 9) Earth flow; 10) Complex landslide; 11) Paleosurface; 12) Erosional channel; 13) Historical landslide event.

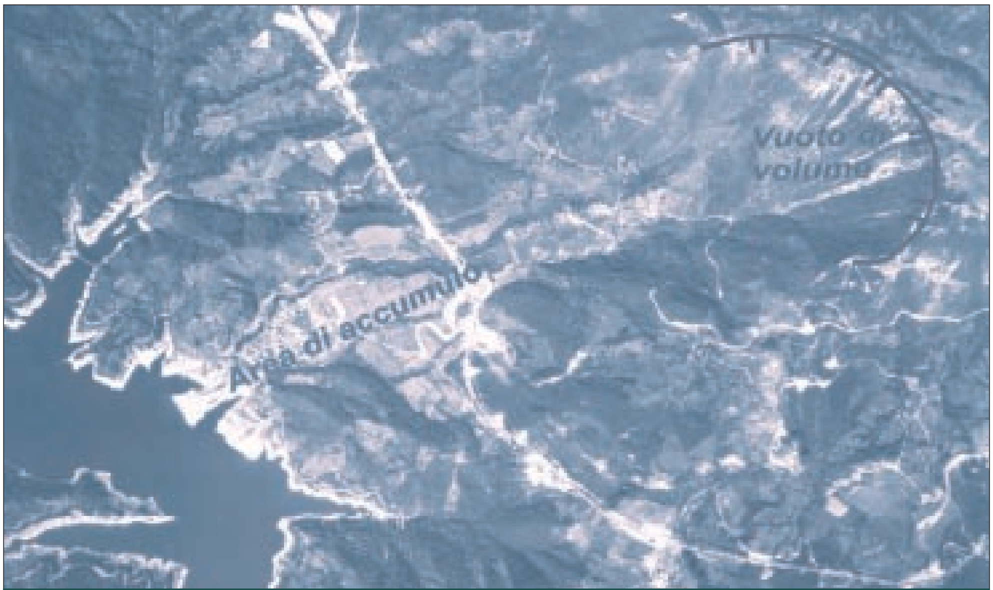


Fig. 9. Aerial photo showing the ancient landslide affecting the slope up to Colle della Sponga village. The landslide accumulation body is still preserved near Borgo San Pietro village, shaped by areal earth surface processes.

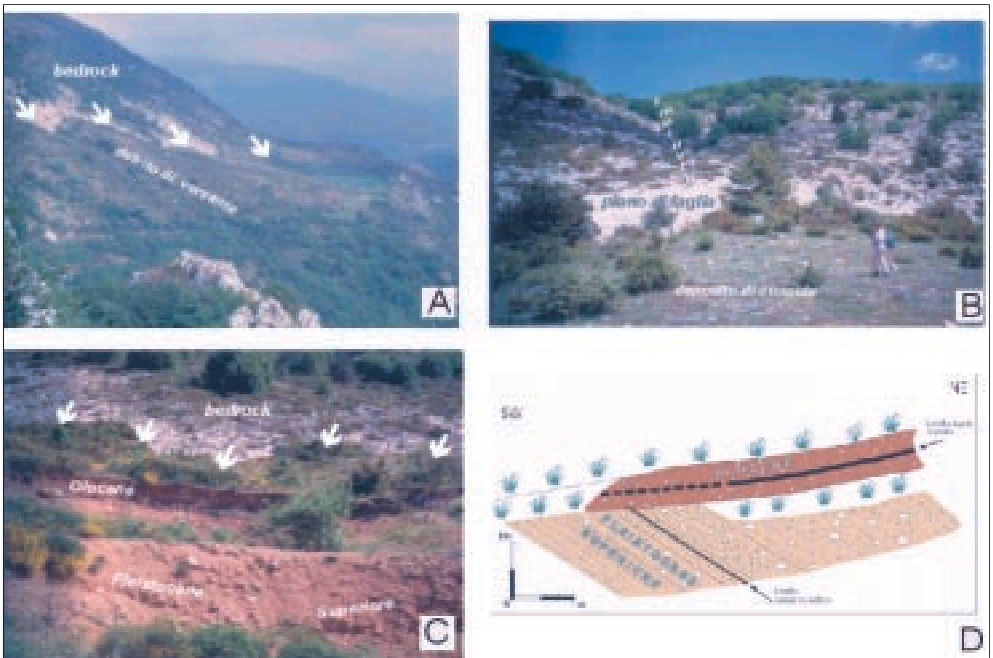
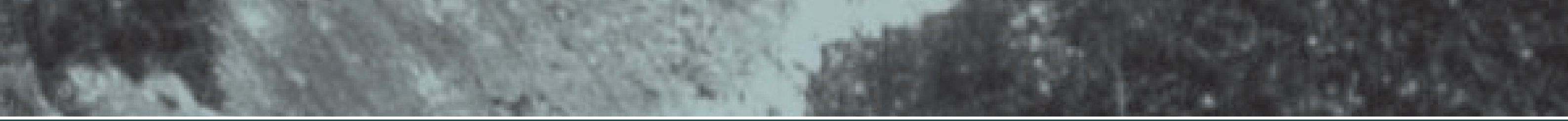


Fig. 10. Tectonic activity along the Staffoli-Fiamignano fault A) Panoramic view of Poggio Poponesco area: the outcropping rock fault scarp is evident; B) Detail of the previous picture showing the same fault displacing an Upper Pleistocene erosional channel; C) Slope deposits sequence studied in detail; D) Upper Pleistocene slope deposits are tilted and at present dip in the opposite direction. Also Holocene colluvial deposits are displaced by the Staffoli-Fiamignano fault.



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