EARTHQUAKE GROUND EFFECTS AND RECENT LANDSCAPE EVOLUTION IN THE APENNINES

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Paleoseismicity is the study of ground effects from past earthquakes as preserved in the geological and geomorphic record. Through the integration of Quaternary geology, seismology, and tectonics information, paleoseismic reserach provides data and criteria for (a) quantifying the rates of ongoing tectonic (or seismic) activity in a region and (b) understanding the influence of this activity on the local landscape (e.g. Serva *et al.*, 1997; Michetti and Hancock, 1997). For instance, in Italy the results of the recent extensive application of paleoseismological techniques for the study of Holocene earthquake surface faulting in the central and southern part of the peninsula, combined with both (1) the unique quality and quantity of historical macroseismic observations and (2) the geomorphic analysis of Quaternary faults, allow to identify and to calculate - in terms of earthquake magnitude and frequency - the seismic (or tectonic) component in the Pleistocene and Holocene geomorphic evolution of the Apennines. The Apennines (Fig. 1) are a mountain chain undergoing active crustal extension in a back-arc plate tectonic setting. Since late Miocene, following the eastward retreat of the subducting Adriatic slab, crustal extension migrated from the west (Sardinia), leading to the formation of a new oceanic basin (Tyrrhenian Sea). The tectonics of the present-day mountain belt is governed by a system of Quaternary normal faults, which is responsible for moderate to strong crustal (typical hypocentral depths of 7-15 km) earthquakes and an immature basin-and-range topography.

The logic of this research is to progressively extend back in the past the information obtained from seismological and macroseismic data. Therefore, the first crucial step is the systematic compilation and critical analysis of the geological phenomena induced by events recorded in the over 2000-years-long seismic catalogue of Italy. The most important results from our revision of these data can be summarized as follows. The threshold for surface faulting along the Apenninic segmented belt of normal faults is M5.5 to 6.0, as illustrated during the M5.7 and 6.0, 1997 Colfiorito (Cello *et al.*, 1998), and M5.6, 1998 Lauria (Michetti *et al.*, 2000a), earthquakes. The tectonic rupture of the ground surface is systematically accompanied by a set of impressive secondary effects, including reactivation of "sackungen", liquefactions and disappearance of springs. For many events, these secondary effects are especially well described in the historical reports. Primary and secondary ground effects are concentrated within intermountain tectonic basins. Furthermore, earthquake surface ruptures in the Apennines display distinctive characters associated with dip-slip faulting. Coseismic fault scarps invariably follow the trace of Quaternary normal faults showing distinct geomorphic expression. This extensional style of earthquake faulting is apparently confirmed by the dominantly normal fault focal mechanisms available for moderate to strong earthquakes in the last century.

The dimensions of coseismic ground effects, their number, and the extent of territory affected by, scales with earthquake size. The use of ground effects in the macroseismic intensity scales in Italy, for instance the MCS (Mercalli - Cancani - Sieberg) scale, makes clear this point. In particular, this is true for surface faulting effects. It is well known that the extent (in terms of rupture length and displacement) of surface faulting is related with the strength of the causative earthquake (in terms of earthquake magnitude and macroseismic intensity; e.g., Wells and Coppersmith, 1994; Esposito *et al.*, 1997). In the Apennines, studies of several surface faulting earthquakes (such as the ca. M7, 1703 Norcia and L'Aquila; ca. M7, 1805 Molise; ca. M7, 1857 Val d'Agri; M7.0, 1915 Fucino; M6.9, 1980 Irpinia; M5.7 and 6.0, 1997 Colfiorito; and M5.6, 1998 Lauria, earthquakes) and paleoearthquakes (such as for the Fucino, Colfiorito, Norcia, Rieti, L'Aquila, Irpinia, and Pollino fault segments and related sub-segments) are now available. These data show that typical normal fault displacement varies from a few centimeters for ca. M6 to about one meter for ca. M7. The associated rupture length ranges from 10 to 30 - 40 km, which are the typical proportions of Apenninic intermountain basins and fault-generated range fronts. Trench investigations show that, in the Holocene, recurrence interval of surface faulting events ranges from few hundreds to few thousands of years, and normal fault slip-rates are in the order of 0.1 to 1.0 mm/yr. Short-term, Holocene slip-rates are consistent with the long-term, Quaternary evolution of related footwall mountain fronts and hangingwall basins. Therefore, we can interpret these geomorphic features as the cumulative result of mainly coseismic effects over the lifetime of the basin itself. Following this reasoning, "Pliocene" basins in the western part of the Apennines close to the Tyrrhenian coast are

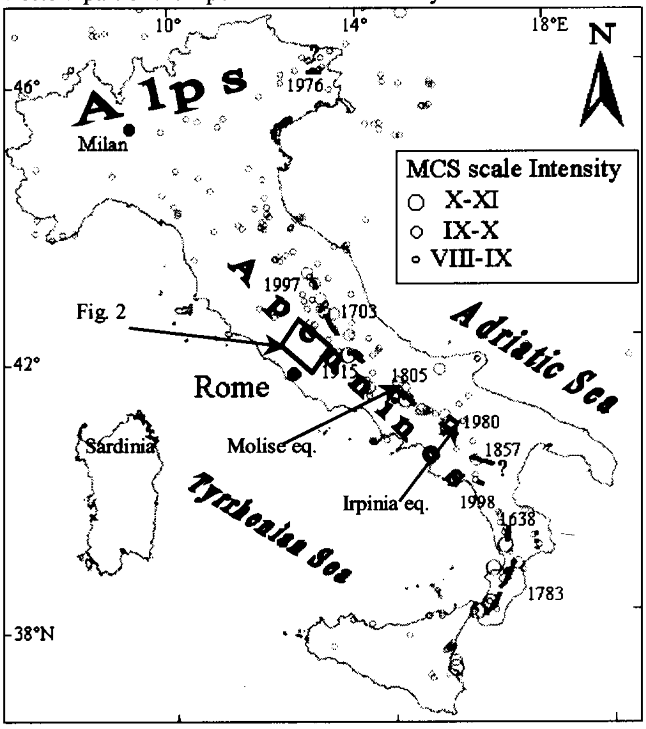


Fig. 1 – Historical seismicity in Italy (Boschi et al. 1999) and cases of historical surface faulting where detailed studies are available. In the Apennines, surface faulting always occurred along Quaternary normal faults.

now too old to produce strong earthquakes, also because of the high heat flow affecting this region. While "Quaternary" tectonic depressions within the mountain chain are presently growing through recurrent moderate-to-strong-magnitude surface faulting events. Normal fault segmentation and sub-segmentation here can be easily identified based on geomorphic and Quaternary geology features of intermountain basins. The dimensions of extensional basins and related footwall mountain fronts in the Apennines are a function of the "characteristic" earthquake that can be generated by the causative normal fault. Likewise, the evolution of mountain slopes, alluvial fans and drainage patterns results from the interaction among (1) normal fault growth, propagation, and linkage, (2) short- and long-term climatic variations during the Quaternary, and (3) local lithology and structural features.

For illustrating these points, we discuss some results from ongoing research projects in the Apennines. At first we focus on two strong earthquakes in Southern Italy, having approximately the same magnitude, the 1805, Molise (Intensity X MCS, that is about the same as X MM or MSK), and 1980, Irpinia - Lucania (Ms = 6.9) earthquakes (Fig. 1). The comparison of a historical event with a modern one shows very interesting regularities both in the occurrence of primary and secondary ground effects, and in their relations with the geomorphic and tectonic setting.

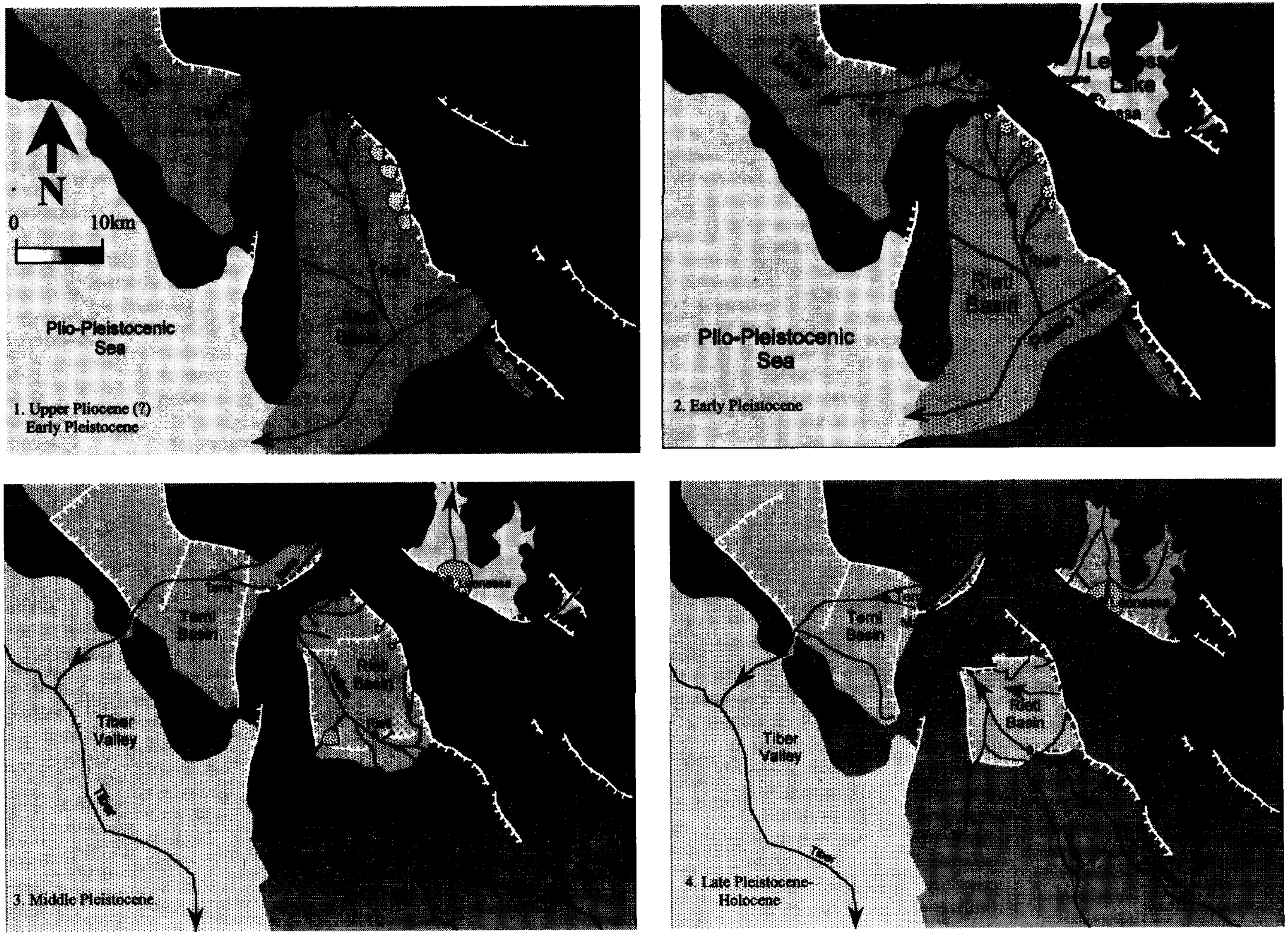
For the July 26, 1805, Molise, earthquake we recognized at least 50 cases including surface faulting and fracturing, ridgetop depressions (sackungen) reactivation, liquefactions, landslides and hydrogeological phenomena (e.g. Esposito *et al.*, 1987). These effects are distributed over the whole macroseismic field, however their occurrence is highly concentrated within the epicentral area. Several reports contemporary to the earthquake describe extensive ground ruptures with vertical displacement up to ca. 100 - 150 cm, locally associated with burned grass, fruits and limbs fall from trees, and creation of new springs with sulfurous smell (Poli, 1806; Pepe, 1806; Fortini, 1806; Capozzi, 1834). The interpretation of these data allowed identifying the likely reactivation of several Quaternary normal faults along the NE mountain front of the Matese Massif, for a total end-to-end rupture length of ca. 45 km. It is not possible to state if this rupture length is relative only to the mainshock occurred at 21.01 GMT, or to the mainshock plus the strong aftershocks that followed before midnight. The ruptured system of synthetic and antithetic normal faults controlled the recent evolution of four intermountain tectonic depressions (the Bojano basin and other smaller nearby basins (Guerrieri, 2000; Corrado *et al.*, 2000). Fresh bedrock fault scarps and offset Late Glacial to Holocene alluvial fans clearly show evidence for repeated 1805-like paleoseismic events. Progressive offset of geomorphic surfaces of increasing age shows evidence for consistent normal slip-rates over the Quaternary (Guerrieri, 2000). Fault scarps cutting active alluvial fans show vertical offset in the range of 0.8 to 1.5 m, possibly related to the 1805 earthquake plus one previous event. Late Glacial carbonate slopes are displaced 10 to 15 m in the last 10 to 20 kyr, yielding a slip-rate of 1.0 ± 0.5 mm/yr. The Late Pleistocene surface of the Campochiaro alluvial fan is displaced of 25 to 30 m in the last 25 to 50 kyr, yielding a slip-rate of 0.8 ± 0.4 mm/yr. The surface of the mid-Pleistocene San Massimo lacustrine deposits is displaced 300 to 460 m in the last 400 to 800 kyr, yielding a slip rate of 0.7 ± 0.3 mm/yr.

The comprehensive revision of the literature on the geological phenomena induced by the 23 November 1980 earthquake, integrated with airphoto interpretation, field survey and eyewitnesses interview allowed until now to map several coseismic features, including landslides, deep-seated gravity deformations, soil fracturing and tectonic surface ruptures (some of which reported for the first time in Michetti et al., 2000b). The exceptional increase in water flow from the Sanità spring at Caposele immediately after the mainshock (Cotecchia *et al.*, 1986) seems to imitate the effects described by Poli (1806) for the Bojano spring after the 1805 earthquake. Both these springs are located along coseismically reactivated normal faults. As for surface faulting effects, other than published reports (Cinque *et al.*, 1981; Bollettinari and Panizza, 1981; Carmignani *et al.*, 1981; Westaway and Jackson, 1984; Pantosti and Valensise, 1990) we reconsidered the original field maps drawn immediately after the earthquake by Carmignani *et al.* (1981). Field inspection coupled with new eyewitnesses reports, lead to substantial reinterpretation of the available information. In particular, the ground fractures mapped by Carmignani *et al.* (1981) at the Costa Pannicaro site, between Muro Lucano and Castelgrande, in fact represent evidence for surface faulting, being associated with a down-to-the-SW vertical displacement of 10 to 20 cm for a length of ca. 4 km. At the nearby Costa Monticello site, eyewitnesses described the coseismic reactivation of (a) a sackung with the formation of a trench in the limestone bedrock, ca. 200 m long and up to 2 m wide and 4 m deep, and (b) a SW-dipping limestone bedrock fault scarp, with the formation of a ca. 20 to 30 cm free-face at the base of the scarp for a length of some kilometers. Note that apparently there was no written account of the effects at the Costa Monticello site before our study. The Costa Pannicaro and Costa Monticello sites are located along the same Quaternary tectonic structure, including three main SW-dipping normal faults showing the geomorphic characters typical of capable faults (sensu Azzaro *et al.*, 1998) in the Apennines. Assuming the whole structure ruptured during the 1980 earthquake, the end-to-end rupture length would be of ca. 8 km. This surface rupture might have been associated with the sub-event occurred at 40 seconds along a SW-dipping fault (Ms = 6.2; see, for instance, Westaway and Jackson, 1987). Work is in progress to verify this hypothesis.

Like in the 1805, Molise, earthquake, the coseismic ruptures associated with the 1980 Irpinia – Lucania event follow synthetic and antithetic Quaternary normal faults responsible for the recent evolution of several intermountain tectonic depressions, such as the basins of San Gregorio Magno, Costa Pannicaro, Costa Monticello, Piano di Pecore and Piano il Parco. In particular, trench investigations at Piano di Pecore and San Gregorio Magno allowed to calculate Holocene slip-rates of ca. 0.3 mm/yr (D'Addezio *et al.*, 1991; Pantosti *et al.*, 1993). Assuming similar slip-rates over the whole Quaternary, most of the local topography can be explained as the cumulative result of recurrent 1980-like surface faulting events.

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 landscape evolution of a region. Figure 2 shows 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 growth of the Rieti, Terni and Leonessa intermountain basins and footwall mountain ranges is related with the activity and interaction of the dominant normal faults in the area, which strongly influenced the drainage network (e.g.,

Fig. 2 – Plio(?)-Quaternary evolution of drainage network, earthquake normal faulting and intermountain basins and in the Rieti area, Central Apennines.



Michetti *et al.*, 1995; Mazzi, 1996). 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. However, in the Apennines like in many other regions of the Earth, the use of paleoseismic analyses is the breakthrough that is providing new and original perspectives for modeling the recent landscape evolution.

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