Paleoseismological evidence of repeated large earthquakes along the 1980 Irpinia earthquake fault

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Abstract
The past seismic behaviour of the Irpinia earthquake fault has been investigated by trenching at two sites located on the middle and southern sections of the 1980 fault scarp. The stratigraphic sequences exposed in the trench sections are rather similar at both sites; they are composed of intercalated colluvial and lacustrine beds of Holocene age. Buried sediments are warped and faulted at the same location and with the same style of the 1980 surface deformation. The occurrence of repeated surface faulting events along this fault has been recognized on the basis of stratigraphic indicators and amount of displacement across the fault zone. The study and detailed mapping of the trench sections allowed us to recognize four surface faulting events preceding the 1980 earthquake at both sites. A graphic reconstruction was used to characterize each of these events in terms of geometry and amount of displacement. Dendrochronologically corrected C^{14} ages from organic samples collected at different levels in the stratigraphic sequences provided a chronologic framework for the age of paleoearthquakes.
The similarity of the deformations produced from the four paleoearthquakes to each other and to those observed following the 1980 earthquake, along with the consistency of the timing of the earthquake sequence recognized at the two sites, suggests that the 1980 earthquake is *characteristic* for the Irpinia earthquake fault (in the sense of Schwartz and Coppersmith). These results indicate that the Irpinia earthquake fault represents a permanent seismogenic source of southern Apennines at least during the time spanned by the sequences exposed in the trenches (about 10 000 y). Based on the displacement of the sedimentary beds and on the range of age for each of the paleoearthquakes, a slip rate of $(0.17 \div 0.40)$ mm/y and an average recurrence time of 1684-3140 y for the Irpinia earthquake fault have been estimated. These evaluations provide an unprecedented tool for understanding the present tectonic regime acting in the southern Apennines.

1. Introduction

The 23 November 1980 normal faulting earthquake has been recognized by several investigators as a complex event characterized by the occurrence of three subevents within the 40 s following the mainshock (Westaway and Jackson, 1987; Bernard and Zollo, 1989; Pantosti and Valensise, 1990). The first two subevents ruptured along a main NE-dipping normal fault while the third subevent occurred along an antithetic fault. Surface faulting occurred along a main fault plane, and is formed by three main scarp sections separated by two gaps (fig. 1). The fault scarp extends for a total length of about 40 km and shows an average strike of 314°, with northeast side down. No surface faulting was produced by the third subevent.

Since the 23 November 1980 earthquake is the first large Italian earthquake for which sizable and unequivocal surface faulting has been documented (Westaway and Jackson, 1984; Funiciello *et al.*, 1988; Pantosti and Valensise, 1990), it lents a unique opportunity to start paleoseismological investigations in Italy. To shed light on the past seismic behaviour of this fault, trenching has been performed at two trench sites: Piano di Pecore and Pantano di San Gregorio Magno. These sites are located along two distinct sections of the 1980 scarp; the middle (Marzano-Car-

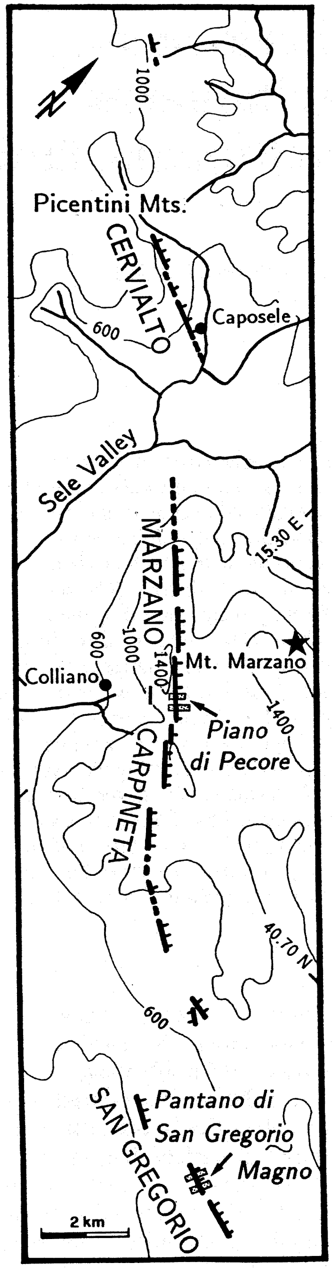

Fig. 1. Location of Piano di Pecore and Pantano di San Gregorio trench sites. The heavy line represents the trace of the 1980 fault scarp; thicks point the downthrown block. The star represents the instrumental location of the mainshock from Westaway and Jackson (1987). Arrows indicate the trench sites.

pineta) and the southern (San Gregorio) sections (fig. 1). At these locations trench investigations were possible because of the co-existency of a favorable geomorphological setting, suggesting the repeated occurrence of 1980-type surface faulting, together with the presence of unconsolidated recent sediments favoring the preservation of the records of past coseismic deformations and making the excavation possible.

2. The trenches

2.1. *Piano di Pecore site*

The first selected site is a small intermountain basin, located along the middle portion of the Marzano-Carpineta scarp section (fig. 1), that interrupts the continuity of the Mt. Marzano-Mt. Carpineta calcareous ridge. Following the 1980 earthquake the fault scarp displaced this basin of (50÷80) cm, causing the subsidence of the middle portion relative to the natural spillway toward the Sele Valley. The scarp interrupted the drainage across Piano di Pecore causing flooding and ponding of sediments on the NE side during the wet season. Trench 1 was excavated in the middle of the basin while trench 2 was located next to its western boundary, where the basin deposits abut the limestone of the Mt. Marzano ridge. The distance between the two trenches is about 80 m. The trench sections exhibited a 4 m thick sedimentary sequence of alternated lacustrine and colluvial deposits (fig. 2 and 3). Reworked volcanic materials related to the plinian eruptions of Mt. Vesuvio, about 80 km northwest, are frequently the main component of the sedimentary suite. The lacustrine deposits are particularly abundant in the subsided portion of trench 1 and they are mainly related to episodic damming-flooding-ponding cycles similar to the one started following the 1980 earthquake (for the detailed description of the sedimentary sequence see Pantosti *et al.*, 1993).

The sedimentary sequence is deformed at the same location and with the same geometry of the 1980 fault scarp in both trenches. In spite of the trenches proximity, the style of deformation is rather different (fig. 3). Ductile deformation prevails in trench 1. At this location the 1980 surface

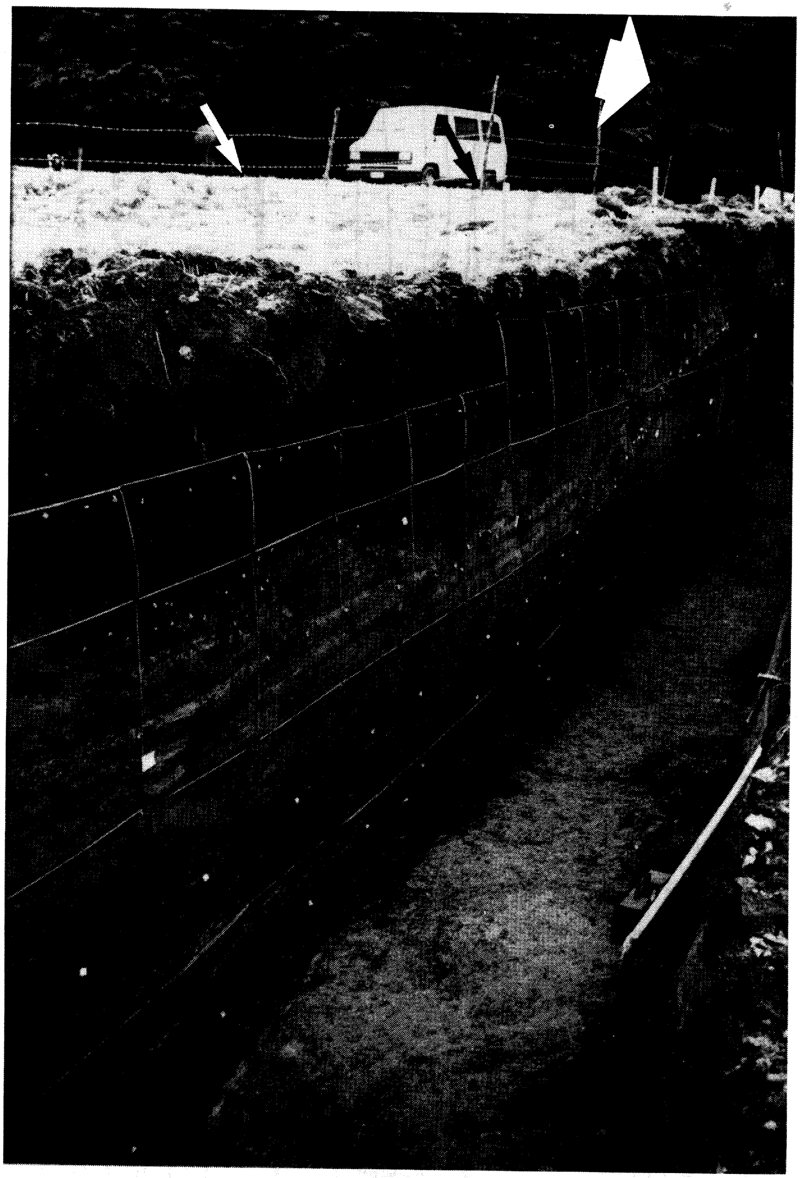

Fig. 2. View of the eastern wall of trench 1. The stratigraphic sequence exposed in the trench is warped and faulted consistently with the geometry and location of 1980 fault scarp (indicated by small arrows). The displacement recorded by the layers increases with their age as a result of the cumulative deformation related to the 1980 event and to four paleoearthquakes occurred during the last 8600 y. As it occurred following the 1980 earthquake, each paleoevent caused the subsidence of the central portion of the Piano di Pecore with respect to the natural spillway (large arrow) interrupting the drainage across the Piano and starting a new overflooding cycle that caused the ponding of sediments. Repeated sequences of ponded sediments are deposited against the buried scarp; they can be clearly recognized because of their onlap geometry on top of the previous displaced deposits. Small flags mark the faults and the boundaries between stratigraphic layers. The reference square net is 1 m wide.

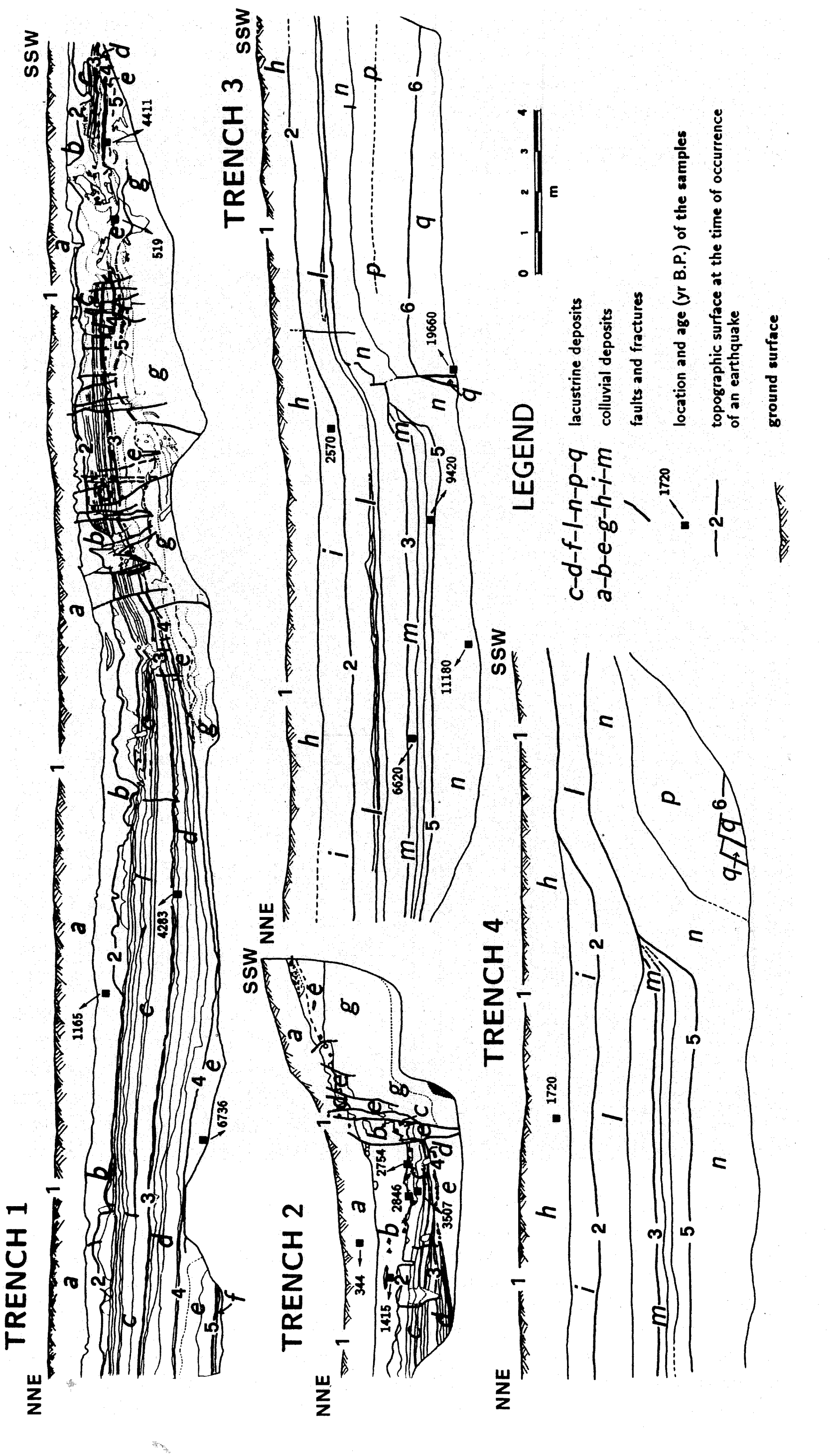

Fig. 3. Logs of the eastern walls of the trenches opened at Piano di Pecore site (1 and 2), and at Pantano di San Gregorio site (3 and 4). Bold face numbers indicate the paleoearthquakes that have been recognized in each trench. Earthquakes that have been correlated between the two sites are indicated with the same number that is also the same used in table I. The lack of event 4 in trenches 3 and 4 is discussed in the text.

deformation appears as a 50 cm high flexure of the ground surface. The fault zone at depth is expressed as a 5 m wide flexure accompanied by a secondary net of joints and faults showing only a few cm displacement. The 1980 surface deformation is a 50 cm high flexure. The lower deposits show also a secondary antithetic deformation zone in the downthrow block, causing the formation of a 12 m wide graben. No evidence for this secondary deformation was found following the 1980 earthquake. Pure brittle deformation characterizes trench 2. The fault zone is 2 m wide and is expressed by four main normal faults; the 1980 surface deformation is represented by a free-face (50÷70) cm high. The different style of deformation in the two trenches can be interpreted as the result of differences in lithology and in water content of the faulted deposits, and to the depth of the calcareous bedrock.

2.2. *Pantano di San Gregorio Magno site*

The second site selected for trenching is located in a wide alluvial depression on the southern section of the 1980 scarp, the Pantano di San Gregorio Magno (fig. 1). This area was reclaimed for agricultural use at the end of the last century. The 1980 surface faulting formed several strands in the Pantano (Pantosti and Valensise, 1990). Trenches 3 and 4 have been excavated across the strand running in the easternmost part of the Pantano at a distance of about 35 m to each other. This strand does not show any relation with the present geomorphological setting of the area. At this location the fault scarp displaced the sub-horizontal ground surface of (45÷65) cm causing the subsidence of the NE side of the basin. Immediately after the earthquake, because of the heavy rain season, the subsided area was transformed into a swamp where sediments from the surrounding slopes and from the degradation of the fault scarp started to accumulate. Unfortunately the intensive agricultural modification of the last years strongly modified the morphology of the scarp and prevented the preservation of the deposits and structures related to the 1980 earthquake.

The 5 m thick stratigraphic sequence revealed by both trenches is composed of massive alluvial deposits intercalated with lacustrine beds (fig. 3 and 4) and, similarly to the Piano di Pecore site, contains abundant reworked volcanic materials related to the Mt. Vesuvio eruptions (for the detailed description of the sedimentary sequence see D'Addezio *et al.*, 1991). In both trenches, the sediments are warped and faulted in correspondence of the 1980 scarp (fig. 3 and 4). The fault zone is characterized by two distinct deformation styles: brittle in the lower part of the sequence, where the beds are displaced along a well-defined fault plane, and mainly plastic in the upper part, where the beds describe a tight flexure (fig. 4). However in 1980 a clear free-face formed on the surface. Distinct deformation styles can be seen as the result of the different degree of deposits compactness related both to lithology and depth.

3. The seismic history

The recognition of stratigraphic indicators of the formation of fault scarps, as colluvial wedges, angular discordancies, and sediments pinching out against the fault zone, have been used to infer the occurrence of past surface faulting events and determine *event horizons*. The *event horizon* represents the topographic surface at the time of occurrence of a specific earthquake. In this study we had also the opportunity to establish event horizons using the amount of displacement recorded from the buried deposits. In fact having the possibility to correlate individual beds across the fault zone, we noticed that their displacement increases with the age. This increase occurs in discrete amounts that are comparable in size to the 1980 deformation (fig. 3) and that we interpreted as the deformation produced by repeated surface faulting events along the Irpinia earthquake fault. The sequence exposed in the trenches can be divided into sets of beds that show the same amount of displacement. The surfaces that separate these sets and across which the displacement increases abruptly are interpreted as the *event horizons*; they coincide with those established on the basis of the stratigraphic indicators (Pantosti *et al.*, 1989; D'Addezio *et al.*, 1991; Pantosti *et al.*, 1993). On this basis four events of surface faulting, occurred along the

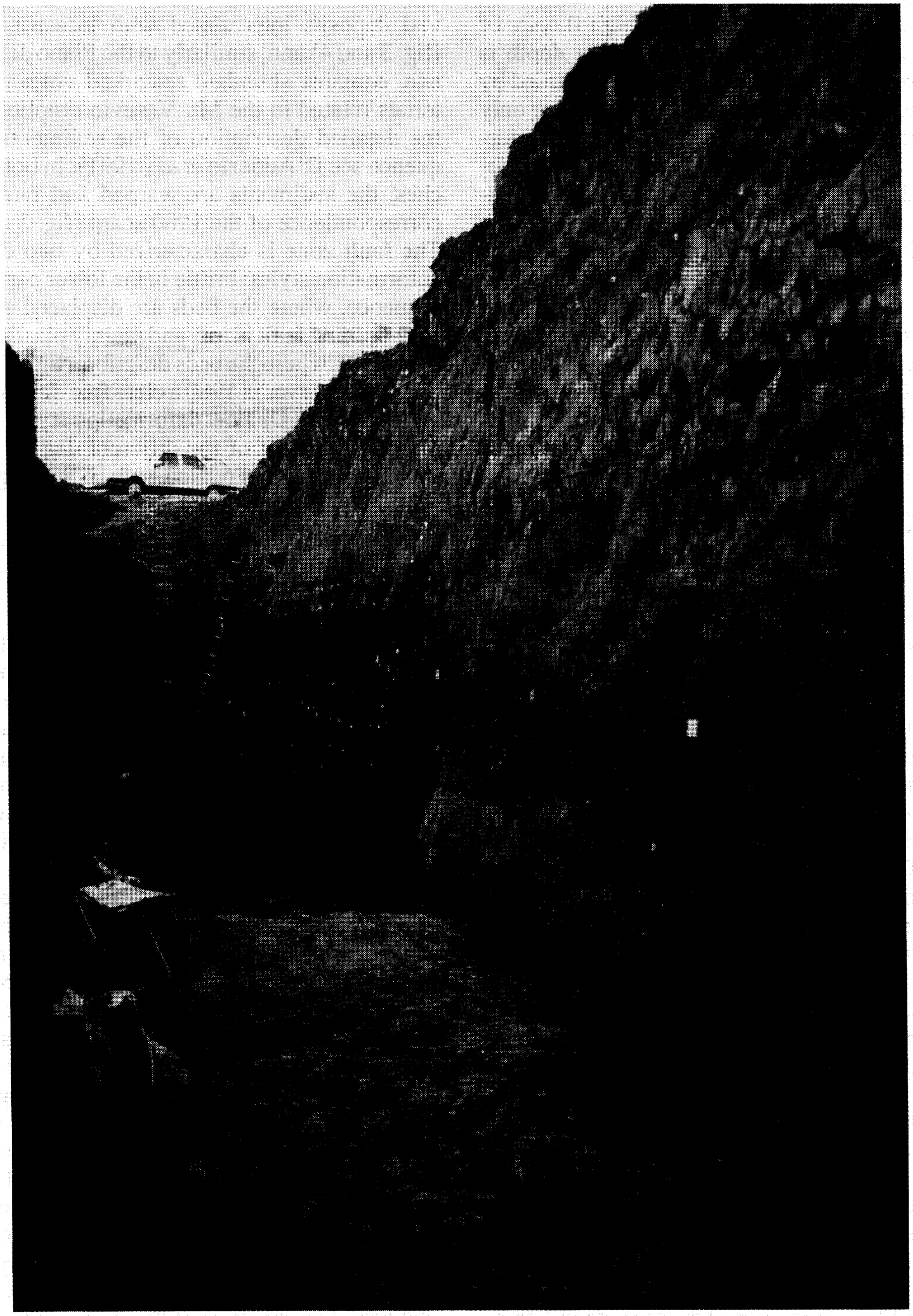

Fig. 4. View of eastern wall of trench 3. The zone of deformation is 2 m wide and coincides, on the surface, with the location of the 1980 free-face, presently modified by the intensive agricultural activity. The beds are clearly faulted at the base of the trench and tightly folded in the upper part.

Irpinia earthquake fault and preceding the 1980 earthquake, have been recognized at both sites. As the recognition of these events is based on the abrupt displacement of the ground surface and on the following particular sedimentation, we exclude that the observed deformation is attributable to creeping processes.

Based on detailed logging of the trench sections and using a graphic technique for reconstructing pre-event conditions, the seismic history of the sites has been investigated. The deformations related to each earthquake, starting from the most recent one, were subtracted from the total deformation (fig. 5). Following this technique back to the older events, the trench sections were restored to the setting after and before each earthquake. This reconstruction provided the detailed characterization of each event in terms of geometry and size of deformation.

Radiometric dating on several detrital charcoal samples, humus-enriched horizons, and in place burns, collected from different stratigraphic intervals in the trenches, provided a time frame for the seismic history. Locations and dendrochronologically corrected ages of the dated samples are shown in fig. 3. On this basis the age of occurrence of the events at each site has been constrained and correlations between the two sites made (table I). Each event is identified by a number; the events that occurred within a comparable interval of time at both sites are indicated by the same number. The 1980 earthquake is event 1. A good consistency on the ages of the earthquakes 2 and 3 and possibly of the event 5 has been found between the two sites. Evidence of event 4 has not been found at the Pantano di San Gregorio Magno site; this lack could be due to the difficulty to decipher the geological records of this event in the massive deposits of trenches 3 and 4 or to a low energy of the event that did not rupture to the surface at this site (D'Addezio *et al.*, 1991). At Piano di Pecore site the trenches were not deep enough to show the deformations possibly related to event 6.

4. Conclusions

Trenching at Piano di Pecore and Pantano di San Gregorio Magno shows evidence for repeated events of Holocene surface faulting that occurred along the Irpinia earthquake fault. Four paleoearthquakes preceding the 1980 event have been recognized. Using the age range of occurrence estimated for each event and the amount of displacement observed in the trenches (table I), we evaluated slip rates and average recurrence time for the Irpinia earthquake fault:

1) At Piano di Pecore site slip rate and average recurrence time are (0.29÷0.40) mm/y and (1684÷2150) y, respectively.

2) At Pantano di San Gregorio site slip rate and average recurrence time are (0.17÷0.40) mm/y and (2206÷3140) y, respectively.

The lower values of slip rates and longer recurrence time obtained for Pantano di San Gregorio can be mainly related to the lack of the recognition of event 4 at this site (see table I). Assuming that the average fault dip is 60°, as suggested from seismologic and geologic observations, the overall contribution of the Irpinia earthquake fault to the extension of this portion of the Southern Apennines would be close to 0.2 mm/y.

The similarity in terms of geometry and amount of deformation between the paleoearthquakes and the 1980 event suggests that the 1980 earthquake can be considered *characteristic* for the Irpinia earthquake fault in the sense formalized by Schwartz and Coppersmith (1984). This hypothesis can be more strengthened on the basis of the consistency of the timing of the earthquakes at the two sites (with exception for Event 4). The trenching results indicate that the Marzano-Carpineta and San Gregorio fault sections, that during the 1980 earthquake have been responsible for the two first subevents, were active at the same time and with the same modality also during the large Holocenic events occurred along the fault. In this light the boundaries of the Irpinia earthquake fault can be considered stable and the fault represents a permanent seismogenic structure for this stretch of the Apennines, at least at the time scale spanned by the trenches (about 10 000 y).

Assuming that the paleosismological slip rate has been constant and using simple stratigraphic observations on the Irpinia earthquake fault, it is

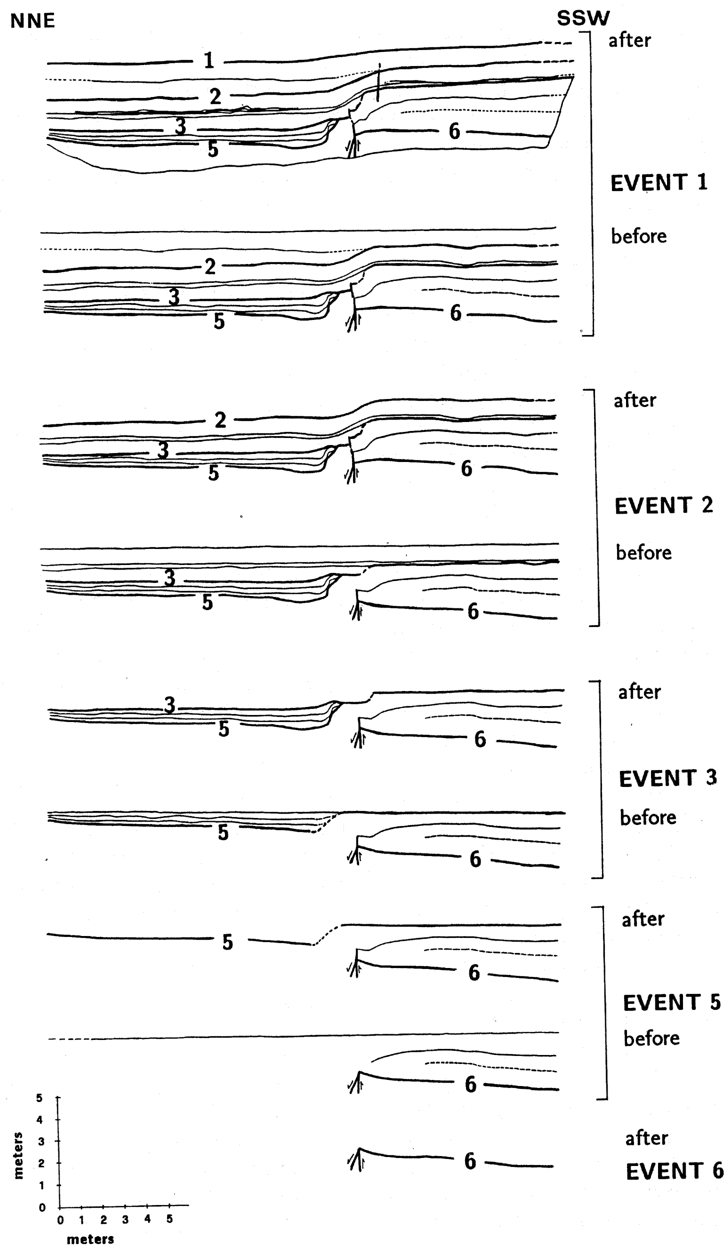

Fig. 5. Graphic reconstruction of the sequence of dislocation-sedimentation events recognized in trench 3. The structural and stratigraphic setting of the section following and preceding the occurrence of each event are re-established substracting the deformations produced by all the events that occurred prior to that one. On this basis the geometry and size of deformation produced by each event is determined. At the same time the influence of the tectonic events on the sedimentation and erosional processes of the site is shown. The trace of ground surface at the time of occurrence of each earthquake is represented by the heavy lines numbered as in the text and table I.

Event	Piano di Pecore		Pantano di San Gregorio	
	Age (y B.P.)	Vertical throw (cm)	Age (y B.P.)	Vertical throw (cm)
1	**1980 A.D.**	45-53	**1980 A.D.**	42-58
2	1415-**2754**	47-55	1720-**2570**	67-83
3	3507-**4283**	47	2570-6620	58-66
4	4411-**6736**	73-81	?	
5	>6736-8600	74-98	6620-**9420**	42-66
6	–	–	11180-19660	?

Table I. Age ranges for the occurrence of earthquakes are established on the basis of dendrochronologically corrected ages of organic samples collected in the trenches. The age in bold face is the preferred age of the event based on stratigraphic considerations. Vertical throws for the Piano di Pecore site are calculated in trench 1 because of the favorable possibility of evaluating the displacement of several layers across the fault zone. However trench 2 shows that the 1980 vertical throw was larger than in trench 1. Consequently a 40% underestimate of the rates of deformation could have been introduced. Vertical throws for the Pantano di San Gregorio site are calculated in trench 3.

possible to calculate the age of activity of this fault that results to be younger than $(0.7 \div 1.0)$ Ma (Pantosti and Valensise, 1990; Pantosti *et al.*, 1993). The young age of the present tectonic regime prevents a clear geomorphologic evidence of its activity, as instead it would be expected in a region that ranks among the most seismic in the world. The present topography still reflects the Upper Miocene-Upper Pliocene major compressional events.

Being the first results of this kind for the Apennines they provide new and valuable insights for our present knowledge of tectonism and seismicity of the area but, at the same time, they highlight large contradictions with the previous thoughts and interpretations and open new debates. The main controversies and subjects of discussion concern: 1) the lack, in the trenches, of the geological records of the 1694 earthquake that is usually considered the direct ancestor of the 1980 event (Serva, 1981); 2) the paleoseismologic average recurrence time that is 4 to 5 time longer the recurrence time based on the 2000 long Italian seismic historical record (Scarpa and Zollo, 1985; Pantosti and Valensise, 1988); 3) the paleoseismologic extension rates that are significantly slower that those estimated on the basis of instrumental data (Anderson and Jackson, 1987; Jackson and McKenzie, 1988; Westaway *et al.*, 1989); 4) the age of the present tectonic regime, of which the Irpinia earthquake fault is a direct expression that results to be younger than 1 My.

Extensive discussion on these controversies is presented by Boschi *et al.* (1990), D'Addezio *et al.* (1991) and Pantosti *et al.* (1993). This led to the conclusion that a substantial improvement of our knowledge on the active tectonic processes taking place in the southern Apennines can be provided by a careful reconsideration, in the light of the lesson learned from the 1980 earthquake, of historical seismicity data, instrumental data, geology, and geomorphology. At the same time, such a reconsideration can provide basic and valuable information for assessing seismic hazard in this region.

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