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Source geometry and long-term behavior of the 1980, Irpinia earthquake fault based on field geologic observations

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Abstract
Starting in 1986 we performed a systematic and detailed survey to investigate the location, orientation and extent of the fault scarp produced by the November 23, 1980 normal faulting earthquake ($M_S = 6.9$). The fault scarp extended for a total length of 38 km between the north-facing slope of Mt. Cervialto (near Lioni, Avellino) and the Pantano di San Gregorio Magno (Salerno). The average strike was 308°. The scarp height was 40 to 100 cm, northeast side down. Based on its orientation, net throw and setting we divided the scarp into three main sections separated by gaps.
The rupture length and continuity and the nature of the scarp's interaction with the topography clearly indicate its genetic link with the coseismic deformation at depth. While the excellent agreement between surface observations and seismological and geodetic data strengthens the link between surface and deep deformation, it also shows that field observations represent a powerful contribution for characterizing an active structure.
Based on field observations we determined important earthquake parameters such as fault strike, length, average slip, and constrained other significant source properties such as the seismic moment.
Recent paleoseismologic investigations indicated that the 1980 earthquake is *characteristic* for its causative fault. Therefore the information we obtained can be used not only to investigate the 1980 event but also to make important inferences on the long-term behavior of the adjacent seismogenic zones.

1. Introduction

The 1980 Irpinia earthquake was the first in Italian history, and among the few in the Mediterranean basin, for which sizable and coherent surface faulting was recognized. Soon after the earthquake several workers (Bollettinari and Panizza, 1981; Cantalamessa *et al.*, 1981; Carmignani *et al.*, 1981; Cinque *et al.*, 1981; Cotecchia, 1981; Ortolani, 1981; Ortolani and Torre, 1981; Bousquet *et al.*, 1983) focused on a large number of surface ruptures that it produced all over the epicentral area. However, while early interpretations from Bollettinari and Panizza (1981) and Cinque *et al.* (1981) hinted at the existence of truly tectonic coseismic faulting at the surface, it was only in 1984 that a 10 km fault scarp was positively described as such by Westaway and Jackson (1984).

Based on field work of the past four years we reconstructed a fault scarp that extends from both ends of that detected by Westaway and Jackson (1984).This scarp has been interpreted as fully representative of the seismogenic fault at depth. The field investigations have been mostly based on direct observations of the fault scarp; nevertheless, eyewitness accounts from local inhabitants were also used, especially in the most densely populated areas where the degradation of the ruptures is extremely fast.

As a whole, geologic observations of the 1980 earthquake have provided a basis for determining the fault's precise location and dip direction, and for strengthening the determination of nearly all the remaining source parameters. More importantly, they shed new light on tectonic processes taking place in the southern Apennines, providing basic guidelines for the recognition of active faults and setting new constraints on the region's rates of tectonic deformation.

2. Structural setting

The structural setting of the epicentral area clearly reflects the complex tectonic history of the Apennines, that is dominated by east and northeast thrusting of highly deformed nappes and by widespread normal faulting. The present topography of the region is strongly influenced by the juxtaposition of nappes of different lithology resulting from the compressional tectonic phases. The boundaries between units characterized by different erodability, such as those between limestones and terrigenous deposits, comprise the main geomorphological traits of the region and are subject to continuous rejuvenation by selective erosion, as for instance along the southern flank of the Ofanto Valley. According to most investigators, in this area the present extensional regime took over the previous compressional phase starting in the Middle-Upper Pliocene in conjunction with the tectonic phase that is thought to be responsible for the collapse of the Tyrrhenian margin. However, no seismicity is associated with the most obvious normal faults that bound the main structural highs and lows, such as the north-south trending Upper Sele Valley. On the contrary, very little field evidence is available for those extensional structures whose activity is indeed testified by large earthquakes. The 1980 earthquake provided clear evidence that in some cases traditional geomorphic indicators such as linear valleys, rejuvenated mountain fronts or scarps in Holocene deposits cannot and should not be used to infer the presence of active and seismogenic faults. The location of the 1980 scarp, running high on a mountain range with little relation to the present topography, suggests that this earthquake is in fact the witness of a young tectonic extensional regime, which has not yet developed mature geomorphic features that can be easily detected in the field.

3. The 1980 scarp

The 1980 scarp extends along the southwestern edge of the epicentral area between the northernmost tip of the Picentini Mts., southwest of Lioni, and the Pantano di San Gregorio Magno (fig. 1). The average strike of the scarp is 308°, consistently down to the northeast with a vertical throw in the range 40 to 100 cm (fig. 2). The scarp runs at high elevation along the Mt. Valva-Mt. Marzano-Mt. Carpineta range (fig. 1), cuts at a low-angle older westnorthwest-trending structural features (Salvi and Nardi, 1991) and exhibits little or no direct relationships with the preexisting topographic setting (Pantosti and Valensise, 1990). The absence of traditional indicators of long-term activity suggests that the inception of this fault is extremely recent. Most of the scarp cuts modern soil and slope debris that overlies the Cretaceous limestone forming the backbone of the mountain range, but polished limestone facets and the associated fault breccia appear at a limited number of sites (Pantosti and Valensise, 1990).

Based on the scarp geometry, height and nature of the interaction with the local topography, the scarp has been subdivided into three distinct sections. From the northwest to the southeast, they were named *Cervialto scarp*, *Marzano-Carpineta scarp* and *San Gregorio Magno scarp* (fig. 1). The three scarp strands are separated by two gaps in surface faulting respectively named *Sele gap* and *San Gregorio Magno gap* (Pantosti and Valensise, 1990).

The northernmost strand, the *Cervialto scarp*, is also the most poorly expressed. It runs discontinuously along the northeast-facing foothill of the Picentini Mts. for about (8÷10) km, between Mt. Caravella and the village of Caposele, at an elevation of about 800 m. The scarp strikes 305°, about 10° more westerly than the average instrumentally determined fault plane. The net scarp height, where still observable, is in the range (40÷60) cm (fig. 1 and 2). The structural arrangement of the scarp appears to be the same observed for most active normal faults worldwide, where the slippage causes subsidence of the valley relative to the mountain range and the breakage involves thick talus deposits overlying the bedrock of the hanging-wall. An important feature of this scarp is that it runs right above the Sanità Springs, located in Caposele, that give origin to the River Sele. The springs dramatically increased their characteristic discharge rate during the two months after the earthquake (Celico, 1981; Cotecchia, 1981). Based on the proximity

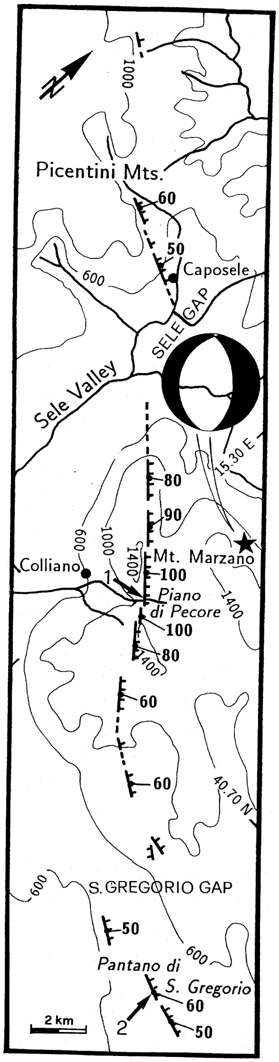

Fig. 1. Map of the 1980 fault scarp. Ticks point to the downthrown block. The scarp heights are in cm. A star indicates the location of the mainshock (from Westaway and Jackson, 1987). The focal mechanism is from Giardini *et al.* (1984). The arrows indicate the Piano di Pecore (1) and Pantano di San Gregorio Magno (2) trench sites. The scarp runs across the mountain range and exhibits little or no relation with the present topography. The continuity of the scarp is interrupted by two main gaps, the *Sele gap* and the *San Gregorio Magno gap*, where the scarp strike, height and relation to topography change abruptly (from Pantosti and Valensise, 1990).

of the active trace of the 1980 fault and on geodetic evidence Pantosti and Valensise (1990) interpreted this phenomenon as resulting from permanent tectonic lowering of the aquifer threshold. The *Cervialto scarp* dies out at the *Sele gap*, a 6 km long discontinuity in surface faulting coinciding with the crossing of the Sele Valley, where Mesozoic limestones cropping out along the main topographic highs of the region give way to terrigenous Miocene and alluvial Quaternary sediments. The middle section of the scarp is named *Marzano-Carpineta* from the name of the ridges it runs along. This scarp section trends 315°, coincident with the strike determined by the teleseismic focal mechanism for the northeast-dipping plane (Giardini, this volume). This circumstance is consistent with the fact that this scarp is the closest to the instrumental epicenter, located about 5 km to the northeast (Westaway, this volume). The *Marzano-Carpineta scarp* is generally a well-defined single scarp, largely disrespectful of the preexisting topographic features, and only occasionally it splays into two or more subdued parallel scarplets. From a morphological point of view this scarp can be divided into two main sections (fig. 1). The first, named Marzano section, is a 7 km long, remarkably clear and continuous scarp extending from the *Sele gap* to Piano di Pecore, a small circular depression located at about 1200 m of elevation and filled with lacustrine sediments and slope-wash deposits. The vertical throw is sometimes in excess of 1 m; an average value for the whole scarp is 90 cm (fig. 2). It produces subsidence of the northeastern block, consistently with the earthquake focal mechanism and with the present local topography. It displaces a 1 to 2 m thick soil and visibly involves the limestone bedrock, which frequently appears mylonitic. Small limestone facets dipping approximately 60° to the northeast and striking northwest sometimes protrude from the soil. A 2 m deep trail recently excavated across to the scarp exposed the downward continuation of the rupture in the limestone bedrock with a dip of 60°-70°. Before dying out at the foothill of Mt. Carpineta, the Marzano section intersects Piano di Pecore. This depression was formed by recurrent slip along the 1980 fault at the intersection with a deeply incised valley perpendicular to the range. The formation of the

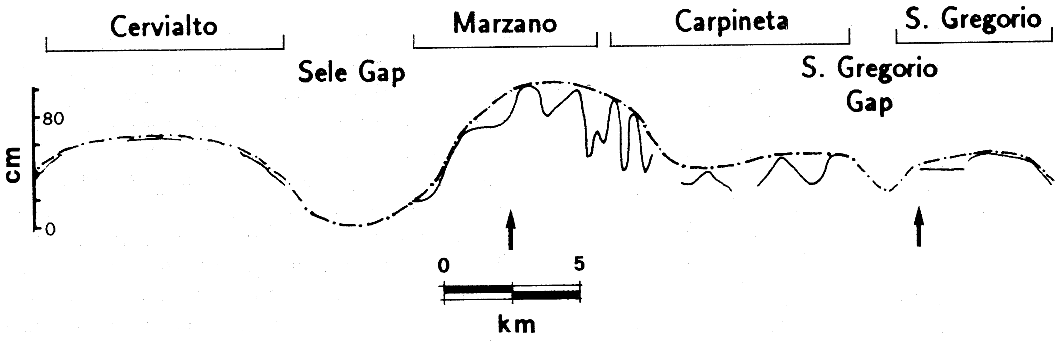

Fig. 2. Measured vertical throws along the fault scarp. The solid line indicates actual observations. The dot-dashed line represents the inferred trend prior to the scarp degradation. The arrows indicate the projection onto the profile of the location of two early mainshock subevents (from Pantosti and Valensise, 1990).

1980 scarp caused the subsidence of the central portion of Piano di Pecore relative to its natural spillway and the consequent temporary interruption of the drainage toward the Sele Valley. Paleoseismological investigations at this site (Pantosti *et al.*, 1992) revealed that flooding of Piano di Pecore has occurred repeatedly in the past; every earthquake deepened the basin, prompting quick sedimentation of deposits transported downslope from the adjacent carbonatic ridge and providing a geologic record of the displacement event.

The *Carpineta section* begins near the northern end of Mt. Carpineta at an elevation of about 1400 m, and runs continuously on its southern flank up to Piano Neurale. Between this site and Mt. Cucuzzone the scarp appears fragmented and largely degraded by intense sheep farming. The total length of this section of the scarp is about 9 km; its height varies from $(60 \div 90)$ cm to the north to $(40 \div 50)$ cm near the southern end (fig. 1, 2 and 3). The *Carpineta section* is certainly the most spectacular scarp among those produced by the 1980 earthquake. In the first 2 km, where the rupture runs along the southern flank and very close to the top of Mt. Carpineta, the fault dips toward the mountain top, and the range crest subsides relative to the valley to the southwest. Depressions up to a few meters deep and wide, together with little gullies parallel to the main slope develop in front of the scarp. As noted for Piano di Pecore, sudden damming of streams draining water from the mountain crest may provide a systematic record of surface faulting events. Occasionally the surface displacement is accommodated by small bedrock fault planes associated with the Miocene-Pliocene compressive tectonism and striking within $(15 \div 25)°$ of the scarp trend. Due to the back-dipping geometry of the fault relative to the main crest of Mt. Carpineta repeated displacement along the northern portion of this section caused the formation of a secondary rather subdued crest. By reconstructing the original morphology of the southern slope of Mt. Carpineta before the secondary crest formed we estimated that the minimum slip along the 1980 fault that is needed to create the present topographic relief at this site is about 80 m.

A 2 km gap, named *San Gregorio Magno gap*, separates the *Marzano-Carpineta scarp* from the *San Gregorio Magno scarp*. This is the southernmost section of the 1980 surface rupture and includes several scarps in and close to the Pantano di San Gregorio Magno. This is a recently reclaimed, broad, east-southeast trending depression filled with recent talus and lacustrine deposits. Two main scarp fragments are still visible in the *Pantano*. The first bounds the western side of the depression for a total length of 1.5 km; it strikes 310° and exhibits an average throw of 40 cm down to the northeast. The second starts from the middle of the Pantano and runs southeastward with increasing throw for about 1 km up to a limestone ridge. From that point it continues for about 2 km (fig. 1 and 2) before dying out at the intersection with the deep gorge of the Platano River, not far from Balvano. The orientation of this scarp fragment is 300°, with relative displacement down to the northeast. The throw

Fig. 3. View of the fault scarp on Mt. Carpineta. This 70 cm high scarp dips against the mountain slope and caused the sudden damming of temporary streams running toward the valley (the top of the range is to the left of the picture).

ranges from 0 cm at the northern end to (50÷60) cm along its middle portion (fig. 1 and 2). Several other short scarplets are still visible along the limestone ridge that bounds the northern side of the *Pantano*.

4. The source characteristics

The extent, continuity, consistency of the geometry and independence from the preexisting morphology of the 1980 scarp stress the existence of a direct link between deep and surficial deformation. The scarp can therefore be regarded as the intersection with the topography of the seismogenic fault, and the observations we collected along the scarp can be used to constrain the main source parameters of the 1980 earthquake (fig. 4).

Fault length. The total length of the scarp is about 38 km, a figure that represents a minimum for the length of the fault at depth. However the location of the two ends of the scarp coincide with two important transversal structures, the Platano gorge and the Bagnoli fault, which may mark the sites where the 1980 rupture stopped and therefore represent the boundaries of the entire fault segment. In this case the length of the scarp would become representative of the true length of the seismogenic structure, a possibility further stressed by the similarity between the geologic-geodetic and the seismometric estimates for the seismic moment (see below).

Fault strike. The overall trend of the fault shows a main zig-zagging trend with a clear change in strike corresponding with the Sele and San Gregorio Magno gaps. As noted above, the *Marzano-Valva scarp* is the closest to the instrumental epicenter and also the site where the surface effects of the earthquake were largest, both in magnitude and clarity. Therefore its geometry is likely to be representative of the entire

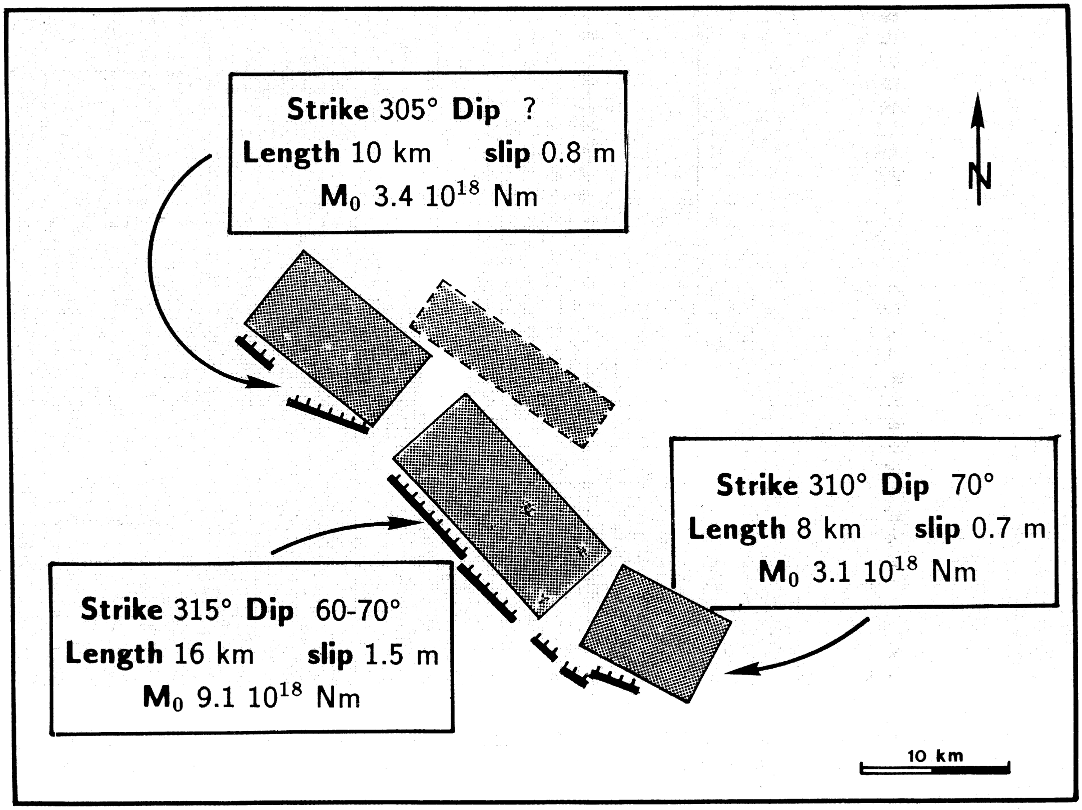

Fig. 4. Summary of relevant geologic information that was used to constrain and characterize important source parameters of the 1980 earthquake.

fault and suitable for a comparison with the rupture mechanism inferred from first-motion polarities. The 315° strike of the scarp, that also represents the average of the estimates obtained using seismological data, rotates to 308° when the entire fault is considered, reflecting the more westerly orientation of the *Cervialto* and *San Gregorio Magno scarps*.

Fault dip. Direct estimation of the fault dip from surface faulting observations is difficult. The non-cohesive behavior of the surficial rocks and the rotation of the stress axis near the surface often result in a gravity-driven response of the near-surface materials. Nonetheless properly oriented bedrock surfaces, such as those observed along the *Marzano-Carpineta scarp* and in the trail section, and the geometry of the fault exposed in the trenches opened across both the *Marzano-Carpineta* and the *San Gregorio Magno* scarps (D'Addezio *et al.*, 1991; Pantosti *et al.*, 1992), indicate a ~(60÷70)° dip to the northeast, consistent with the instrumental evidence. The narrowness of the scarp zone and the relatively short distance between the scarp and the location of the epicenter (≃5 km) support the hypothesis that the earthquake occurred along a steeply dipping plane, rupturing from the hypocentral depth to the surface. The second observation also suggests the planarity of the fault plane, as pointed out by Westaway and Jackson (1984, 1987). Based on geodetic and subordinately seismometric evidence, some studies (Bernard and Zollo, 1989; De Natale *et al.*, 1988; Pingue *et al.*, this volume) have suggested that the San Gregorio Magno section of the fault might dip 20° to the northeast rather than steeply as the remaining sections, and that dynamic faulting occurred only between about 8 and 12 km depth. This finding contrasts with observations of a clear fault scarp crossing the Pantano di San Gregorio Magno. Trenching of this scarp (D'Addezio *et al.*, 1991) has shown that it continues at depth with a (70÷75)° northeast-dipping plane. In addition, the combination of the shallow dipping geometry with the depth of the fault would make it very difficult for the rupture to propagate passively to the surface producing the observed 40 to 60 cm vertical displacement.

Fault rake. A careful search for geomorphic evidence of lateral slip along the 1980 rupture did not provide any direct or indirect proof of a significant strike-slip component, consistently with most published instrumental focal solutions (see Giardini, this volume, for a summary).

Slip. For large normal faults it is usually assumed that most of the moment is released coseismically with little or no afterslip. Geologic evaluations of the fault slip traditionally use the net scarp height, corrected for near-fault complexity (such as formation of graben-like structures, backtilting of small blocks of unconsolidated sediments). Slip is obtained from the net vertical throw corrected for the fault dip or, more rigorously, using the classical elastic-dislocation theory to calculate the scarp height expected for any given fault geometry. Using Ward and Barrientos' (1986) formulae describing the elevation changes due to a buried point source of known moment we computed a ratio 1:0.6 of slip *vs.* scarp height for a 14 km wide, 60° dipping fault buried at 1 km depth. The height of the 1980 scarp varies in the range (0÷100) cm with an average of 55 cm; for a slip-to-scarp height ratio of 0.6 this yields a mean slip at depth of 92 cm. Even though much effort has been put into reporting correct scarp heights, loss of some sections of poorly expressed or artificially degraded scarps may have occurred, and hence this estimate should be regarded as a minimum.

Moment release. The fault length and average slip estimates can be used in conjunction with an independent estimate of the fault width to compute the scalar moment globally released by the 1980 mainshock. Assuming a hypocentral depth of 12 km and a fault dip of ≃60° we estimated a fault width of ≃14 km. A 0.9 m slip on a 14 km wide, 38 km long fault embedded in a half-space with $\mu = 3.2 \times 10^{10}$ Pa yields a moment of $M_0 = 1.6 \times 10^{19}$ Nm. By combining field geologic and geodetic observations, Pantosti and Valensise (1990) proposed a total moment of 1.8×10^{19} Nm, a figure that compares well with the 2.6×10^{19} Nm estimate obtained from surface waves (Giardini, this volume). Geologic estimates of the seismic moment are intrinsically robust; an increase of M_0 of 20% would require such significant variations as 10 cm in the average scarp height, 10 km in the fault length or 3 km in fault width.

5. Conclusions

In most cases the source characteristics inferred from field observations are in good agreement with those obtained using seismometric and geodetic observations. However, some discrepancies still exist, the most important of which concerning the geometry of the *San Gregorio Magno* section of the fault and the associated coseismic slip.

In addition to supplying valuable constraints on the location, extent and geometry of the fault and on the style and magnitude of coseismic deformation, our investigations also shed light on the rupture complexity, an important characteristic of the 1980 earthquake source (Crosson *et al.*, 1986; Westaway and Jackson, 1987; Valensise *et al.*, 1989; Bernard and Zollo, 1989; Palombo *et al.*, 1989; Cocco and Pacor, this volume). Based on strong-motion analyses, different investigators recognized and located at least three main subevents that occurred within 40 seconds of the origin time. The salient features of the first two subevents (commonly referred to as 0 s and 20 s) agree very well with our observations from the *Cervialto, Marzano-Carpineta* and *San Gregorio Magno* scarps. Among these features is the location of the gaps in surface faulting, coincident with the boundaries of the fault sections that ruptured during the 0 s and 20 s subevents. Pantosti and Valensise (1990) regarded the *Sele gap* as a «relaxation-geometry barrier» (in the sense of King, 1986), a type of barrier where a sudden change in the rock properties and in the orientation of the slip vector prevents slip from accumulating but does not prevent the rupture from propagating through aseismically. Strong-motion reconstructions of the rupture process have shown that the *Sele gap* marks a site where the rupture associated with the 0 s subevent stopped for about 2 seconds (Westaway and Jackson, 1987; Bernard and Zollo, 1989; Cocco and Pacor, this volume). The *San Gregorio Magno* gap can also be associated with a «relaxation-geometry barrier», although it does not appear to coincide with any important geologic or structural discontinuity. Bernard and Zollo (1989) hypothesized that this gap may mark the boundary between the southern termination of the 0 s subevent and the northern termination of the 20 s subevent.

In contrast, no geologic verification of the last mainshock subevent (commonly referred to as 40 s) has been possible. This subevent was not strong enough to produce observable surface faulting, but it did produce sizable ground deformation such that it was positively located to the northeast of the main fault (Pantosti and Valensise, 1990; Pingue *et al.*, this volume).

Recent paleoseismologic investigations carried out along the *Marzano-Carpineta* and *San Gregorio Magno* scarps (1 and 2 in fig. 1) showed that at least four 1980-type earthquakes have occurred along this fault during the past 10 000 y and prior to 1980 (see D'Addezio *et al.*, this volume). The timing of the paleoevents that were recognized to have occurred along these two well-separated fault sections (corresponding to distinct mainshock subevents) is similar, suggesting that the 1980 rupture complexity is a permanent source feature at the time scale spanned by the paleoseismologic investigation. This would imply not only that the 1980 earthquake is *characteristic* in the sense formalized by Schwartz and Coppersmith (1984), but also that the energy tends to be radiated by the same regions of the seismogenic zone during subsequent earthquakes.

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