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New constraints on the seismic history of the Castrovillari fault in the Pollino gap (Calabria, southern Italy)

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Abstract

The Pollino Range area represents the most prominent gap in seismicity within the southern Apennines. Geomorphic and trenching investigations along the Castrovillari fault indicate that this normal fault is a major seismogenic fault within the southern part of this gap. At least four surface-faulting earthquakes have occurred on this fault since late Pleistocene age. Radiocarbon dating coupled with historical consideration set the time of the most recent earthquake as most likely to be between 530 A.D. and 900 A.D., with the possible widest interval of 530–1100 A.D. No evidence for this event has been found in the historical records, although its age interval falls within the time spanned by the seismic catalogues. Slip per event ranges between 0.5 and 1.6 m, with a minimum rupture length of 13 km. These values suggest a M 6.5–7.0 for the paleoearthquakes. The minimum long-term vertical slip rate obtained from displaced geomorphic features is of 0.2–0.5 mm/yr. A vertical slip-rate of about 1 mm/yr is also inferred from trenching data. The inter-event interval obtained from trench data ranges between 940 and 7760 years (with the young part of the interval possibly more representative; roughly 940–3000 years). The time elapsed since the most recent earthquake ranges between a minimum of 900–1100 and a maximum of 1470 years. The seismic behavior of this fault appears to be consistent with that of other major seismogenic faults of the central-southern Apennines. The Pollino case highlights the fact that geological investigations represent a potentially useful technique to characterize the seismic hazard of 'silent' areas for which adequate historical and seismological data record are not available.

Introduction

In recent years, the use of geological disciplines for the development of segmentation and recurrence models of major seismogenic fault zones, has drawn the attention of scientists to the identification of those portions of the zones that were seismically silent for a relatively long time. These are known as *seismic gaps*. The seismic gaps are of particular interest for seismic hazard assessment because they may contain the structure(s) that will next produce a large earthquake. The knowledge of the seismic behavior of the single portions (fault segments) of the fault zone nearest to and inside the gap, is critical to provide the necessary insights into which the fault segment has the highest probability of producing a large event in the near future, so that mitigation efforts can be focussed in that area.

The Pollino region is one of the most obvious seismic gaps along the central and southern Apennines seismogenic fault zone (Valensise et al., 1993; Cinti et al., 1997; Michetti et al., 1997; Valensise and Pantosti, 2001a). This is interpreted as a ∼60 km-long seismic gap because of the lack of large earthquakes (≥IXMCS) in the historical catalogues of seismicity (Boschi et al., 1997; Camassi and Stucchi, 1997; Gruppo di Lavoro CPTI, 1999) supported also by a scarce instrumental activity with small to moderate magnitude earthquakes during the past 15 years (Figure 1). The gap is separated into a northern and southern portion by the WNW-ESE-trending Pollino Range, which is the major physiographic feature in

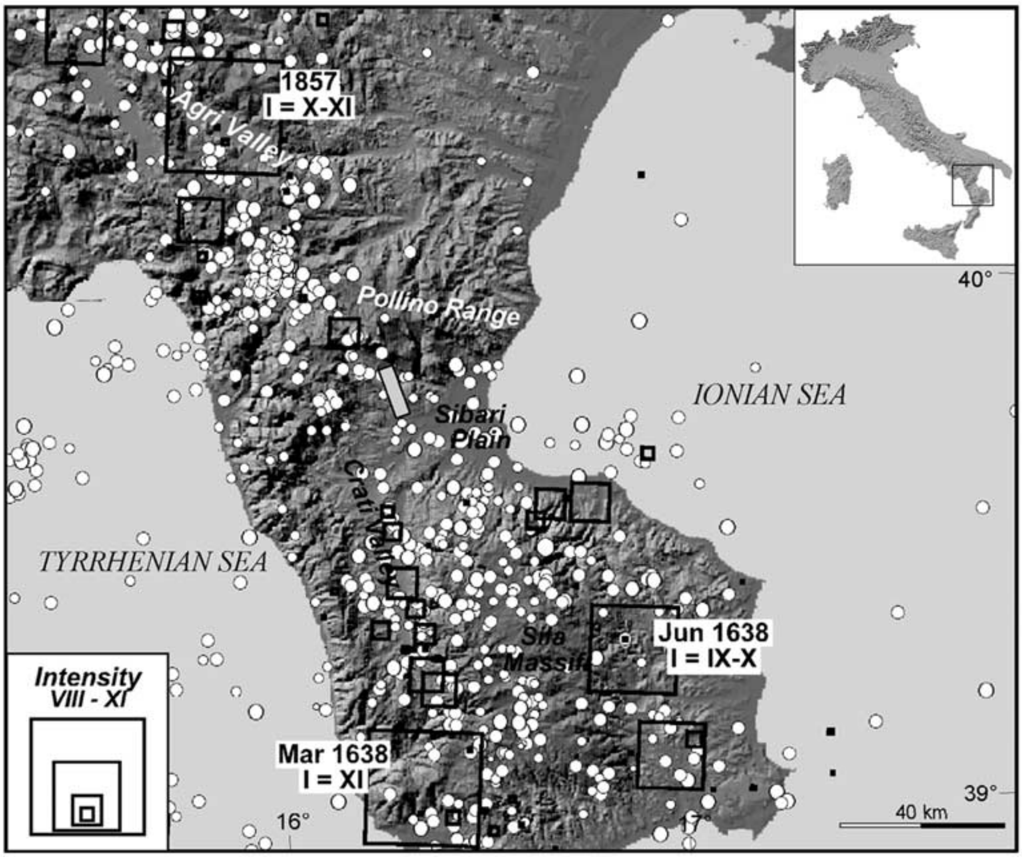

Figure 1. Distribution of historical and instrumental seismicity in southern Italy. White circles represent the instrumental earthquakes ($2 \geq M \geq 5.3$) recorded by the Istituto Nazionale di Geofisica between 1984 and 1999. Historical events (Gruppo di Lavoro CPTI, 1999) are indicated by black rectangles; year of occurrence and intensities of the major historical earthquakes are also shown. In the Pollino Range area no large historical event is reported and the instrumental seismicity is rather diffuse. The Castrovillari fault is represented by light grey rectangle.

the area. Recent geological and paleoseismological studies in the southern part of the gap indicate the presence of Middle Pleistocene and Holocene surface faulting along different faults: the Pollino fault (Michetti et al., 1997) and the Castrovillari fault (Cinti et al., 1997) (Figure 2). Despite the disagreement in defining the hierarchy of these faults, there is a consensus in the recognition of repeated seismic events during the past 30–40 Kyr and in the identification of a significant seismogenic potential. In particular, these studies recognized the occurrence of a large event during medieval times whose traces are missing in the historical records of the area. This missing record shows that, although the 2000 year-long Italian historical catalogues offer an exceptional and invaluable tool to investigate the seismicity of the Italian peninsula, they may include areas along the Apennines of spatial and temporal incompleteness. These areas may be zones of low strain rate or in contrast be just temporarily quiescent (see for example D'Addezio et al., 1995; Valensise and Guidoboni, 1995).

We focused our attention on three prominent NNW-SSE fault scarps located within the southern portion of the gap (Figures 1 and 2) to understand the true significance of the so-called 'Pollino gap'. The geomorphology of these features, firstly described by Bousquet (1973) and Chiodo (1988), and trenching at a first site (the Fonte Bellusci site, see Cinti et al., 1997) suggest they are surface expressions of a major seismogenic fault at depth, that we term the Castrovillari fault. The results from the first trenching investigation were presented in detail in Cinti et al. (1997) and are only briefly summarized in the following section 3.1. Results and conclusions from that previous study were mainly based on subsurface data relative to a single site in the middle portion of the

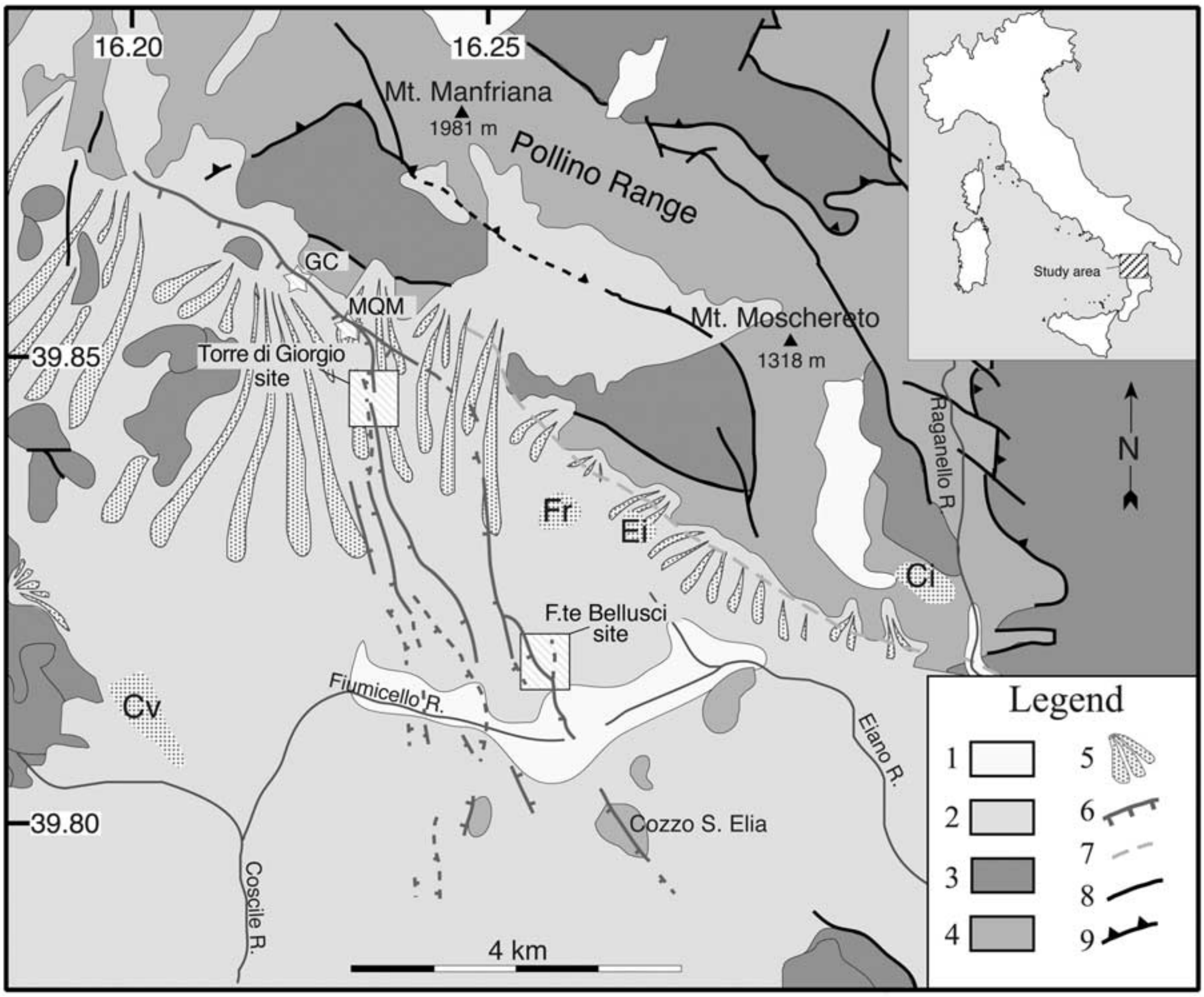

Figure 2. Schematic geological and structural map of the Pollino Range area. The location of the Castrovillari fault scarp system is shown. Boxes indicate the paleosismological sites from this paper and from Cinti et al., 1997, and stars those from Michetti et al., 1997. Legend: 1. alluvium and slope debris (Holocene); 2. marine sand and clay, gravelly-sandy alluvium and conglomerate (fan-delta), continental colluvium and alluvium (Middle-Late Pleistocene); 3. marly-silty clay and sandstone (flysch, Giurassic-Lower Cretaceous); 4. limestone-dolomite-dolomitic limestone (Triassic-Lower Cretaceous); 5. modern and active slope debris and alluvial fan; 6. Castrovillari fault scarp, dashed where inferred; 7. Pollino fault; 8. undetermined fault; 9.thrust, dashed where inferred. Abbreviations: Cv – Castrovillari; Fr – Frascineto; Ei – Eianina; Ci – Civita; MQM – Masseria Quercia Marina; GC – Grotta Carbone.

scarp system. As stated by the authors at that moment, a more complete set of data including other sections of the Castrovillari fault was required for a better reconstruction of the past activity of the fault and to define its seismogenic potential with higher reliability. Therefore, we performed further trenching at the Torre di Giorgio site, in the northern portion of the scarp system. In this paper we discuss in detail the results from this second site. In particular, the trenching data and the new information collected on the historical setting of the area provide a better control on the occurrence and size of the events along the Castrovillari fault. We also show advanced observations on the geomorphology of the fault area and comment them within a model of coseismic deformation. Finally, in the light of the results we discuss the actual potential of the Castrovillari fault for producing large earthquakes.

The surface expression of the Castrovillari fault

Detailed mapping and geomorphic analysis of the fault scarps displacing Pleistocene fan-delta deposits south of the Pollino range already described by Bousquet

(1973) and Chiodo (1988) allowed Cinti et al. (1997) to interpret them as the direct surface expression of a seismogenic active fault, named the Castrovillari Fault. Three main NNW-trending (mean orientation: N20°W) prominent scarps produce subsidence to the WSW. They are organized in a complex left-stepping en echelon pattern, and extend for a total length of 13 km. The fault trace is very complex, with local changes in strike as much as ± 20° (Figure 2). From a N40°W strike in the south, the scarps gradually change orientation to ~NS near the Pollino range, and they abruptly rotate to westward along the Pollino slope for another 3 km. This latter portion, that has a ~E-W trend, is considered by Michetti et al. (1997) as part of the Pollino fault; on the contrary, Cinti et al. (1997) consider it as part of the broad Castrovillari fault, even if it may re-utilize the western part of the pre-existing Pollino fault. The scarps displace fan-delta, fluvial, lacustrine and colluvial deposits of middle to late Pleistocene-Holocene age, and Triassic-Lower Cretaceous limestone (Figure 2). The average height of each individual scarp is 10 m, reaching a maximum of 25 m in the central portion where they cut across the flat surface of a fan-delta. In the northern portion, the height of the scarps is reduced to 0.5 m both because of burial by recent sediments and natural decrease of slip toward the segment boundaries. The scarps are steep and prominent even in soft unconsolidated sediments, and well preserved also in modern depositional and erosional environments. In correspondence of the Fiumicello river valley (Figure 2), the trace of the scarps is discontinuous and locally modelled by transverse river flows and by intense farming of vineyards. In the southern end, the geomorphic expression of the scarps system is progressively subdued; the most prominent scarp is the easternmost one, which cuts the top of Cozzo S. Elia (Figure 2) with a height of ~5 m.

The total vertical throw recorded by the fan-delta surface along the topographic profile in Figure 3a,b is about 100–150 m. The similarity of the three scarp profiles would suggest their contemporary activation instead of a possible migration of the deformation from one scarp to another. Figure 3b compares the topographic profile across the three scarps to the expected vertical changes produced by the Castrovillari fault (Valensise and Ward, 1991; Cucci and Cinti, 1998). This highlights that the present setting of the topography (1) is the result of repeated slip events on the Castrovillari fault and (2) is consistent with this fault now being the major seismogenic structure in the area. In fact, the area of maximum subsidence expected in the modelling (Figure 3a) coincides with the lowest topography of the Pleistocene deposits. On the contrary, the broad Pollino fault would produce maximum subsidence in the range foothills (inset in Figure 3a) where displaced Pleistocene deposits are found at the highest elevations. Some evidences from the drainage pattern suggest the Pollino fault does not act anymore as the main control on the evolution of the area. Presently, the Fiumicello river flows to the west; since most of its tributaries keep an opposite direction before sharply turning at the junction (Figure 3a), we hyphothesize it has recently reversed its flow direction. This effect may be related to the uplift of the foot-wall of the Castrovillari fault that would coincide approximately with the former subsidence area (hanging-wall) produced by the Pollino fault. The westward migration of the main subsidence area and the related uplift to the east, prevented the Fiumicello river to continue to flow toward E to the Eiano river (Figure 3c). As a consequence, the present capture area of the Eiano river, formerly located in a subsidence area, is now on the foot-wall of the Castrovillari fault and reduced its extension. Thus, the Pollino fault had an undoubtful major role in the past tectonics of the area and left a strong imprint on the landscape. However, magnitude and geometry of the most recent deformation suggest that at present the Castrovillari fault accomodates most of the crustal extension taking place in the area.

Trenching the Castrovillari Fault

Two trenching sites have been selected along the fault: the Fonte Bellusci and the Torre di Giorgio sites (Figure 2). The Fonte Bellusci site is located along the easternmost Castrovillari fault scarp. This site was investigated by a set of escavations in 1994 (see Cinti et al. 1997, for detailed description). Data collected during this stage of the work provided novel information on the tectonic origin, type of dislocation, and seismic history of these scarps.

Because these subsurface data are related to a single site in the middle portion of the scarp system, we chose to strenghten and integrate them with new investigations from other sites. In the Summer of 1995, we selected the Torre di Giorgio area as the most favourable site for our purpose: the recent unconsolidated alluvial sediments cropping out there were expected high potential for preserving the records of past coseismic deformations along with datable material. The Torre di Giorgio site is located along the

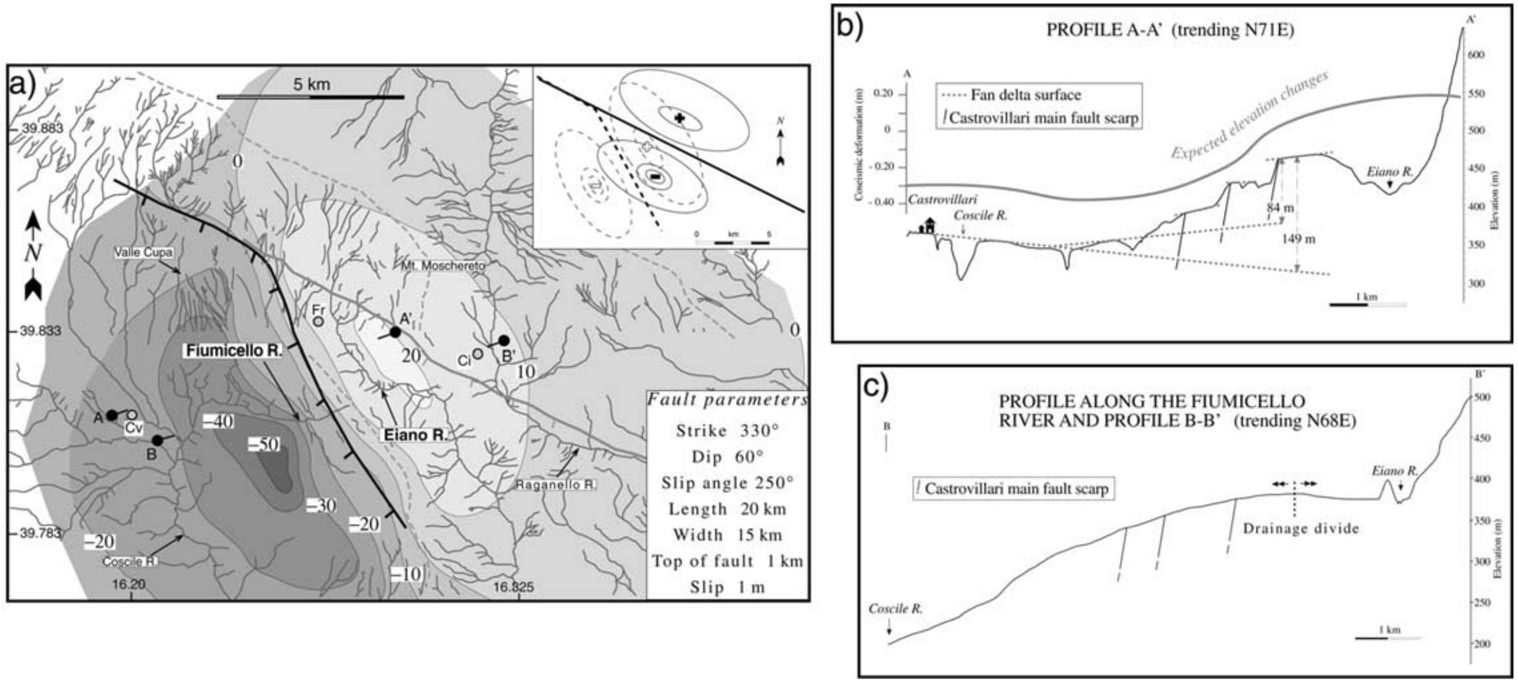

Figure 3. a) Modelling of expected elevation changes associated to the Castrovillari fault, along with drainage pattern and drainage divides of the area (grey dashed line). The easternmost fault scarp has been chosen for the modelling of the Castrovillari fault trace (black thick line). See Valensise and Ward (1991) and Cucci and Cinti (1998) for the details of the modelling. Grey solid line shows the Pollino fault. Abbreviations: Cv – Castrovillari; Fr – Frascineto; Ci – Civita. The simplified sketch in the inset shows the different field of deformation associated to the Pollino (solid lines) and the Castrovillari (dashed lines) faults. b) topographic profile transverse to the central portion of the Castrovillari fault scarp system. Maximum long-term net vertical separation of about 150 m is calculated on the relative elevation of the youngest top-set of the late Pleistocene fan-delta sequence. The location of the relief coincides with the uplift zone of deformation expected for a modelled Castrovillari-type fault (grey line); model parameters listed in Figure 3a. c) topographic profile showing the drainage divide between the Fiumicello and Eiano rivers resulting from repeated footwall uplift of the Castrovillari fault.

central scarp, in the northern portion of the system (Figure 2). In the following, first we briefly summarize the results from the Fonte Bellusci site, second, we discuss in detail the new results from the Torre di Giorgio site.

Fonte Bellusci site

Two trenches (Trenches 1 and 2) were dug across the major 200-m-wide, NW-trending step-over along the easternmost of the Castrovillari scarps (Cinti et al., 1997) (Figures 2 and 4a,b,c). Here, the fault zone is formed by a ∼3-m-high main scarp substantially modified by human activities, and several sub-parallel secondary scarps that vertically displace recent alluvial sediments, by at least 5–6 m (Figure 4a). Two more trenches (Trenches A and B) parallel to the main fault zone of Trench 1 exposed a series of unfaulted, distinct fluvial channels that did not show obvious offset associated with a horizontal component of movement on the fault. Thus, these were used for correlation of the units in the main trenches (Figure 4d). Dating of a bulk paleosol from a nearby quarry, along with stratigraphic relations, suggest that the alluvial deposits at the site are younger than ∼30,000 yr B.P.

Trench 1 was located in the central part of a seasonal stream and intercepted the two southern secondary scarps (Figure 4a). The trench walls exposed a sequence of fan-delta, lacustrine, alluvial deposits and paleosols, deformed by a series of normal and reverse high-angle faults (Figures 4b and 5). We recognized stratigraphic indicators of the formation of fault scarps, such as colluvial wedges, angular discordances, and sediments pinching out against the main faults. We also analysed features of the deformation, such as slumps in lacustrine deposits, increasing displacements with depth, upward-terminating faults, and faulted colluvial wedges. These features indicated that multiple faults formed during the occurrence of at least four surface faulting earthquakes (in Figure 5 the events are numbered starting from the most recent). The two most recent events (E1 and E2) are the best constrained in terms of stratigraphic position, faults activation and amount of slip.

Trench 2 crossed the main and a secondary fault scarp at the western edge of the stream (Figure 4a), intersecting a stratigraphic sequence similar to that of Trench 1. In this trench the human modification was so invasive that it reached a depth of as much as 1.5 m. As a consequence, some information on the faulting history is missing in the exposure. When preserved, the sediments are deformed by secondary high- and low-angle and antithetic faults formed as the result of at least three deformation events (Figures 4c and 5). Also in this trench, we found features that further helped us to define the two youngest events.

On the basis of stratigraphic relationships between Trench 1 and 2, the most recent and penultimate paleoearthquakes (E1 and E2) are interpreted as the same event (Figure 5). The minimum vertical throw produced by events E1 and E2 is of 1.2–1.6 m and about 0.8 m, respectively. Two older events were also recognized (E3 and E4), although no clear correlation between the trenches was observed. The vertical displacement produced by the third event (E3) could not be measured, whereas, displacement produced by the oldest E4 was measurable across the fault zone and is ∼0.9 m (Cinti et al., 1997). Based on sample locations with respect to the event horizons (Figure 5), radiocarbon dating of units 2 and 3 (Table 1) along with historical consideration of the region provide information on the ages of E1 and E2. In summary, the most recent earthquake occurred between 370 B.C. (Sample 103) and 1200 A.D., and probably shortly after 770 A.D. (Sample S1). Samples S5 and S4 are not considered for the age constraint because of probable contamination. The oldest age from unit 3 (Sample Z4) indicates that E2 is older than 410 B.C. The oldest events E3 and E4 occurred during the last 30000 years, which is the maximum age for the faulted alluvial sequence at this trench site (Cinti et al., 1997).

Torre di Giorgio Site

Among the three main Castrovillari scarp traces, the central one is the only feature that clearly extends to the far north to bend sharply to the west and continue along the slope of the Pollino Range (Figures 2 and 6). The Torre di Giorgio trench site is located about 700 m south of the bend (Figure 7a). Here, the main scarp trends ∼N-S, and forms a 200 m-wide right step. This step is accompanied by secondary scarp traces (Figure 7a) that considering the geometry of the scarp would suggest a minor right-lateral component of movement along the main fault. The scarp crosses the central and eastern portion of one of the late Pleistocene alluvial fans draping the slope of the Pollino Range. Repeated activity on the fault caused the interruption of a SE-flowing drainage from Valle Grande (Figure 7a); a paleostream incision descending from this valley is clearly dammed by the scarp and its bed on the upthrown block of the fault is presently

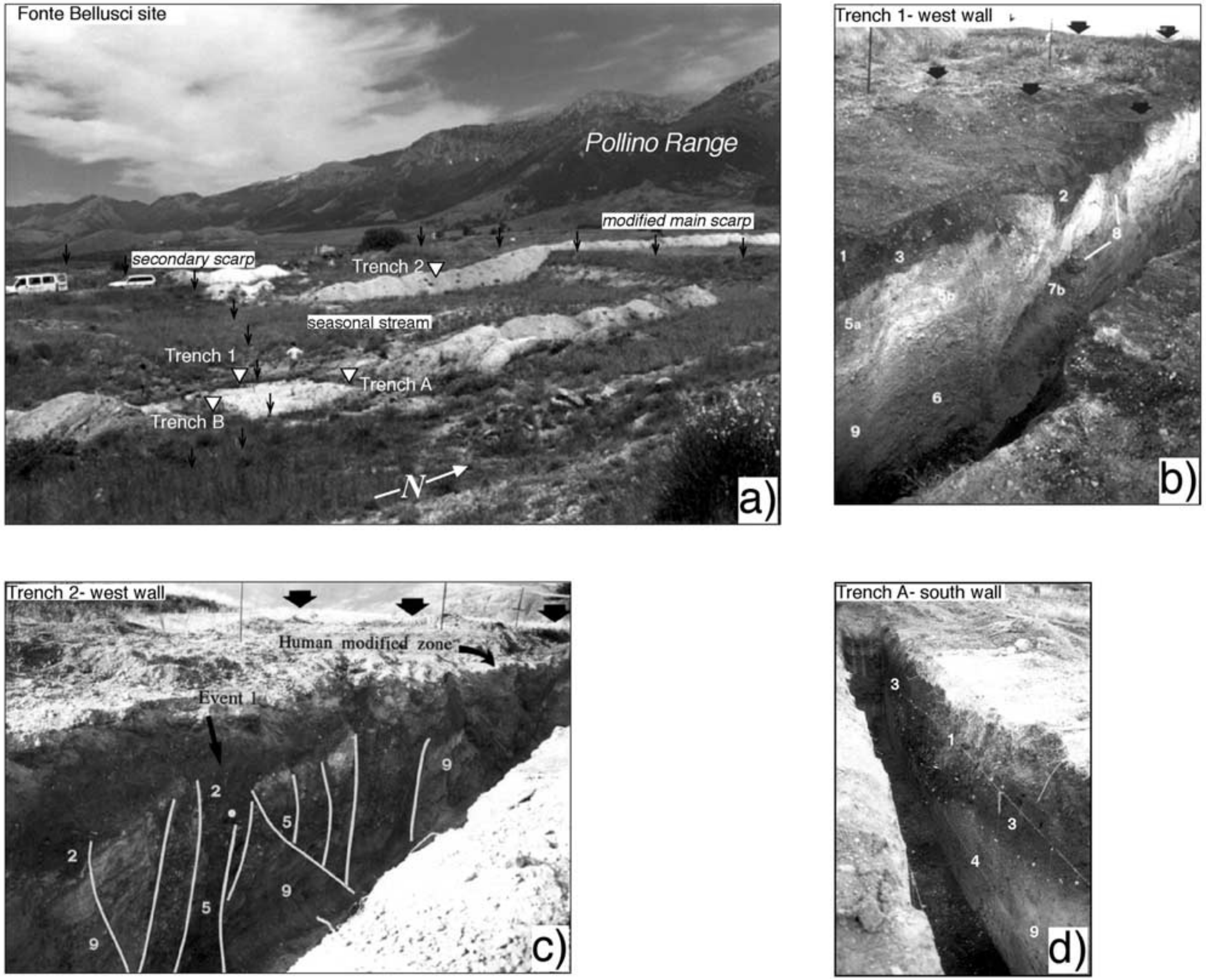

Figure 4. a) view of the Fonte Bellusci trench site. b) central part of the fault zone in Trench 1. Arrows point to the scarps; units have the same numbers of log in Figure 5. c) secondary fault zone in Trench 2; white lines mark the major fault traces, unit numbers correspond those of log in Figure 5. d) view of the unfaulted fluvial channels exposed in the fault-parallel Trench A; units were correlated to those in Trenches 1 and 2.

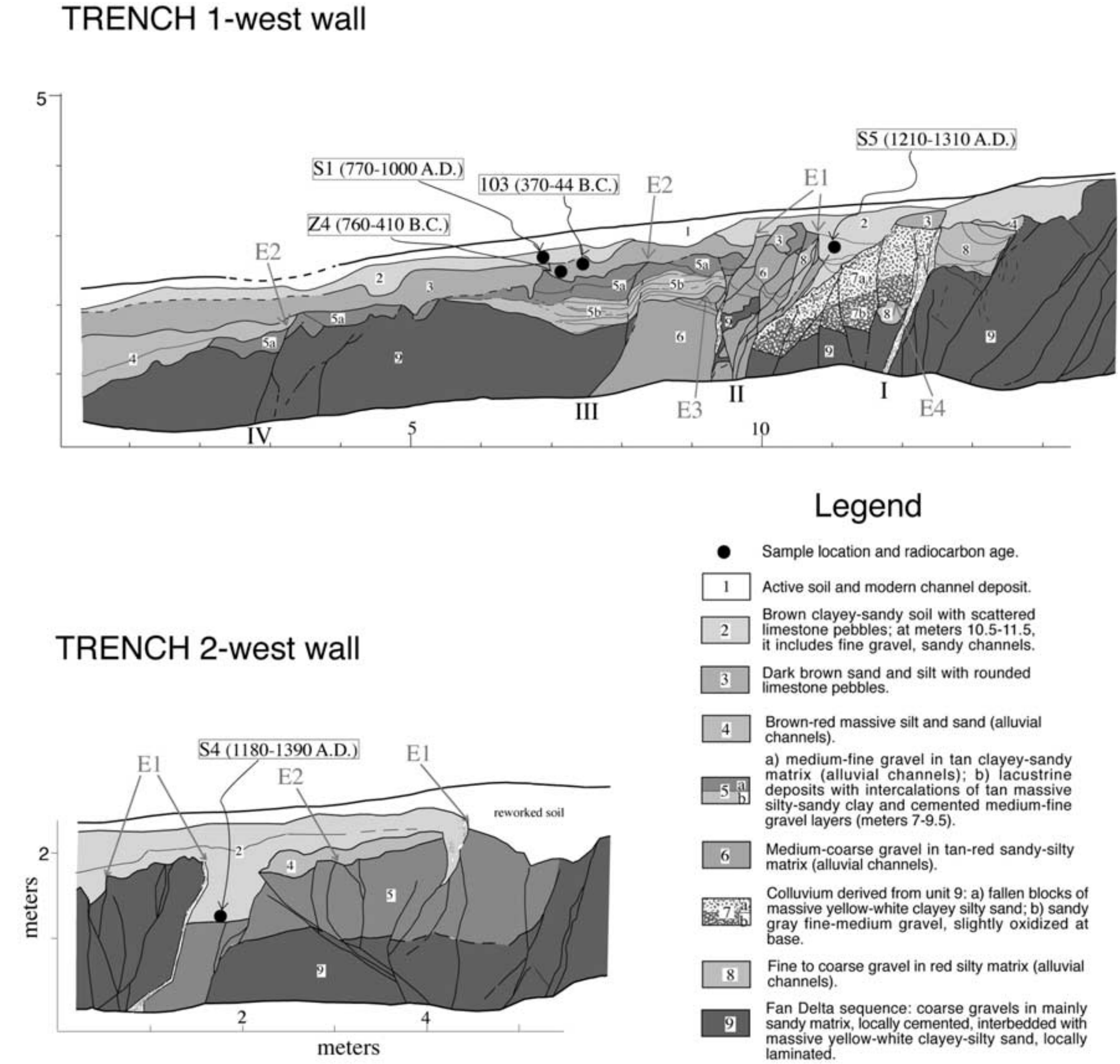

Figure 5. Simplified logs of the fault zones in Trench 1 and Trench 2 at the Fonte Bellusci site (see also Figure 4a,b and for location Figure 2). Main fault zones are indicated by Roman numerals (I to IV). E1 to E3 indicate the event horizons associated to each paleoearthquake.

abandoned. At present the seasonal drainage flows parallel to the scarp being settled in area of subsidence. A recent small alluvial fan is being formed in correspondence of the step over zone (Figure 7a).

We performed three detailed topographic profiles across the area of deformation (Figure 7b). Based on the two northernmost profiles, a value of 3.5 to 5 m for the height of the main scarp can be estimated. Unfortunately, a road runs where the third trace is located and highly modifies the main scarp preventing us from measuring the net topographic throw.

Excavations

Two trenches were excavated across the fault zone at the Torre di Giorgio site. Trench 3 has N75°E trend and intercepts the N-trending main scarp; Trench 4 is located about 100 m south of Trench 3, strikes N72°E, and crosses the lowest portion of the main scarp (Figures 6 and 7a).

Trench 3 exposed a total of about 6-m thick sedimentary sequence formed of alluvial fan, channel deposits and paleosols. Log of the north wall and description of the units are in Figure 8. In both

Table 1. Measured and dendrochronologically calibrated ^{14}C age of samples collected in the trenches (dating laboratory: Beta Analytic Inc. of Miami, Florida). Sample location and age are shown in Figures 5, 8 and 9 (except for Sample 12, which is out of the log of Trench 1). The 2σ interval and the percentage of probability distribution (in parenthesis) are given according to the radiocarbon calibration program of Stuiver et al. (1998).

Sample	Material	Site*-Trench /Unit	^{14}C Age (yr B.P.)	Cal. Age (2σ Interval)
S1	paleosol	FB-1/2	1150±60	769–1002 A.D. (97%)
S4	paleosol	FB-2/2	740±60	1182–1392 A.D. (87%–13%)
S5	paleosol	FB-1/2	740±50	1207–1315 A.D.(90%)
Z4	paleosol	FB-1/3	2460±60	764–406 B.C. (100%)
12	charcoal	FB-1/3	2430±80	783–395 B.C. (100%)
103	charcoal	FB-1/3	2150±60	365–44 B.C. (29%–70%)
Z6	organic deposit	TG-3/3b	7860±60	6861–6587 B.C. (76%)
N7	charcoal	TG-4/2d	1820±40	117–260 A.D. (86%)
NF1	charcoal	TG-4/2c	1430±70	527–693 A.D. (87%)
S11	charcoal	TG-4/2a	1280±70	642–895 A.D. (99%)

* FB = Fonte Bellusci site; TG = Torre di Giorgio site.

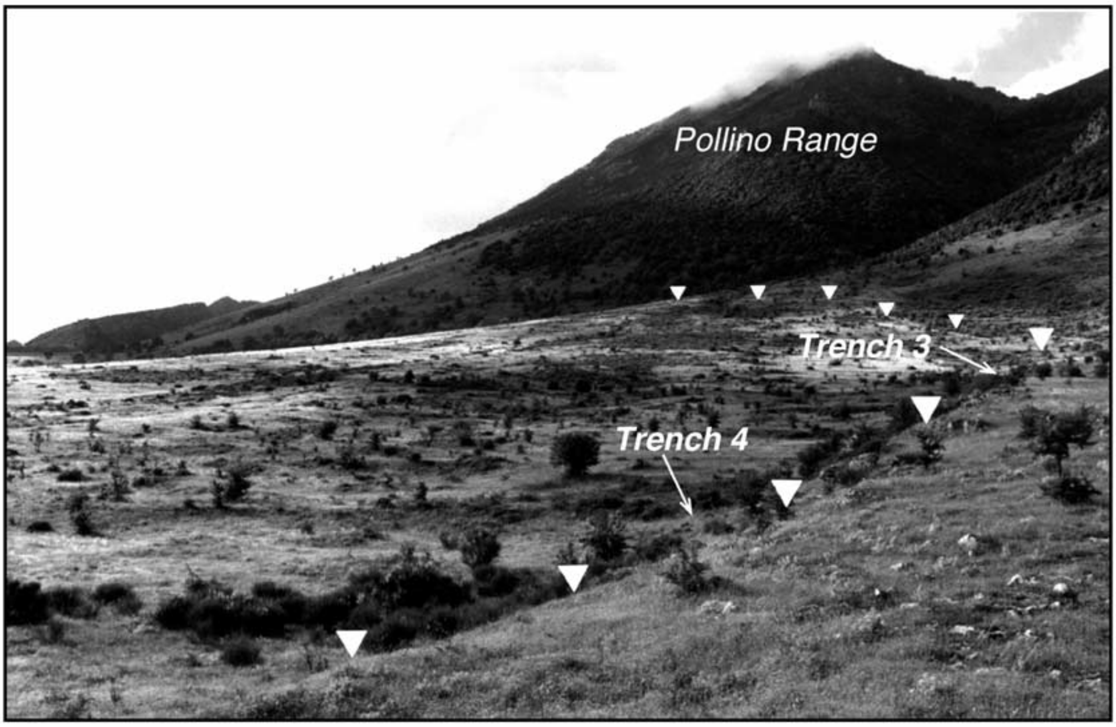

Figure 6. View of the Torre di Giorgio site (see Figure 2 for location). Triangles point to the scarp trace.

trench walls the deposits appear deformed in about 7-m-wide main fault zone located beneath the main topographic scarp. It is formed by a system of normal antithetic/synthetic and reverse high-angle faults (fault zones I-II-III in Figure 8) which bound several blocks that are tilted or back tilted. Major deformation occurs along the closely spaced fault planes of fault zone II that coincides with the abrupt surface scarp. Repeated movement on these fault planes produced the tectonic contact between alluvial fan deposits of different age (units 7 and 6 against unit 5). Minor deformation and displacement are also observed along

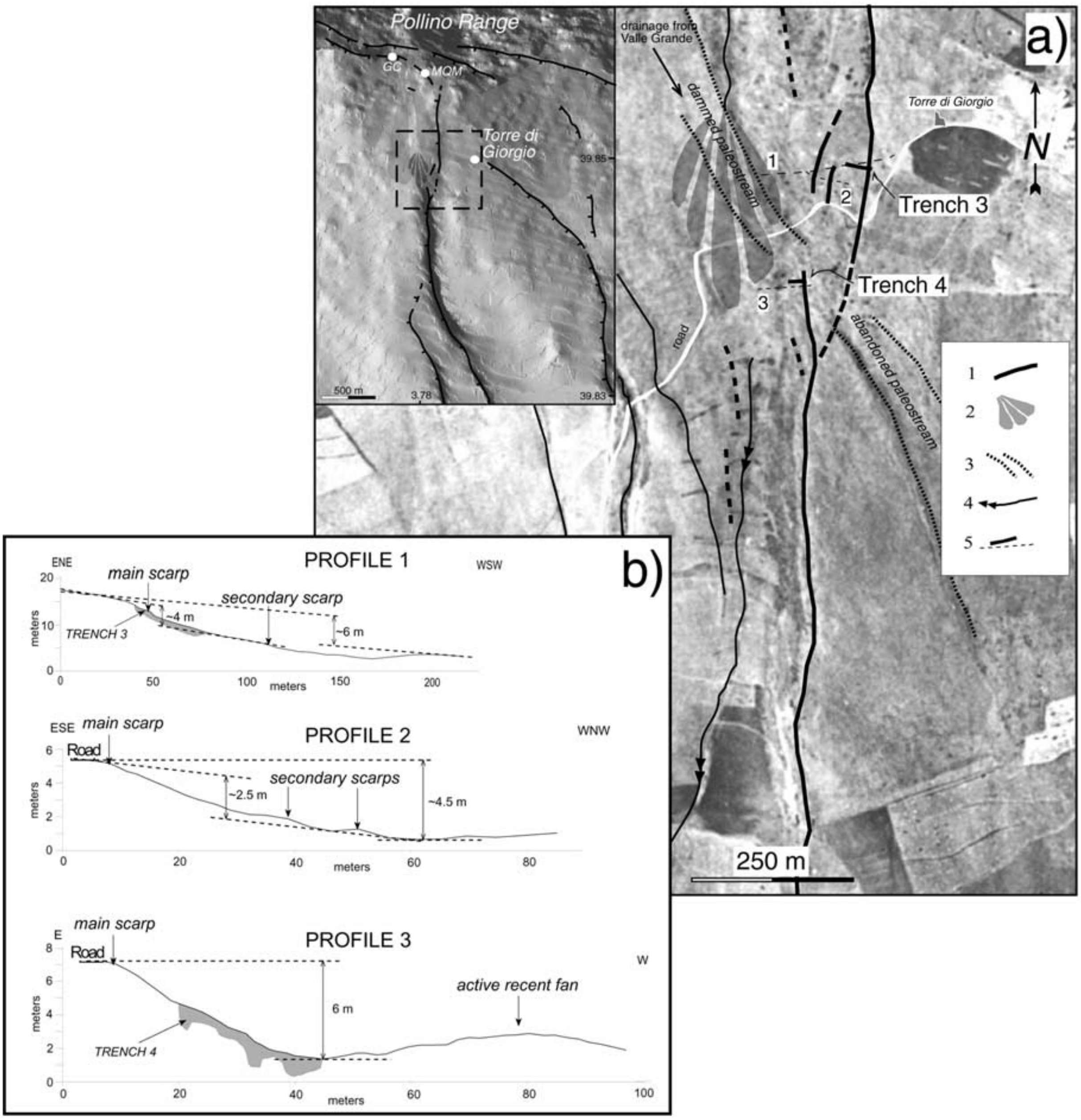

Figure 7. a) Aerial photograph of the Torre di Giorgio site (by Istituto Geografico Militare – Autorizzazione N. 5225 del 16/6/2000). Symbols: 1. scarp trace. 2. recent alluvial fan. 3. paleostream incision. 4. active drainage. 5. location of the trenches (black line) and of the topographic profiles (dotted line) shown in Figure 4b. b) Detailed topographic profiles across the fault scarp; the two northernmost profiles indicate a scarp height of about 5 meters.

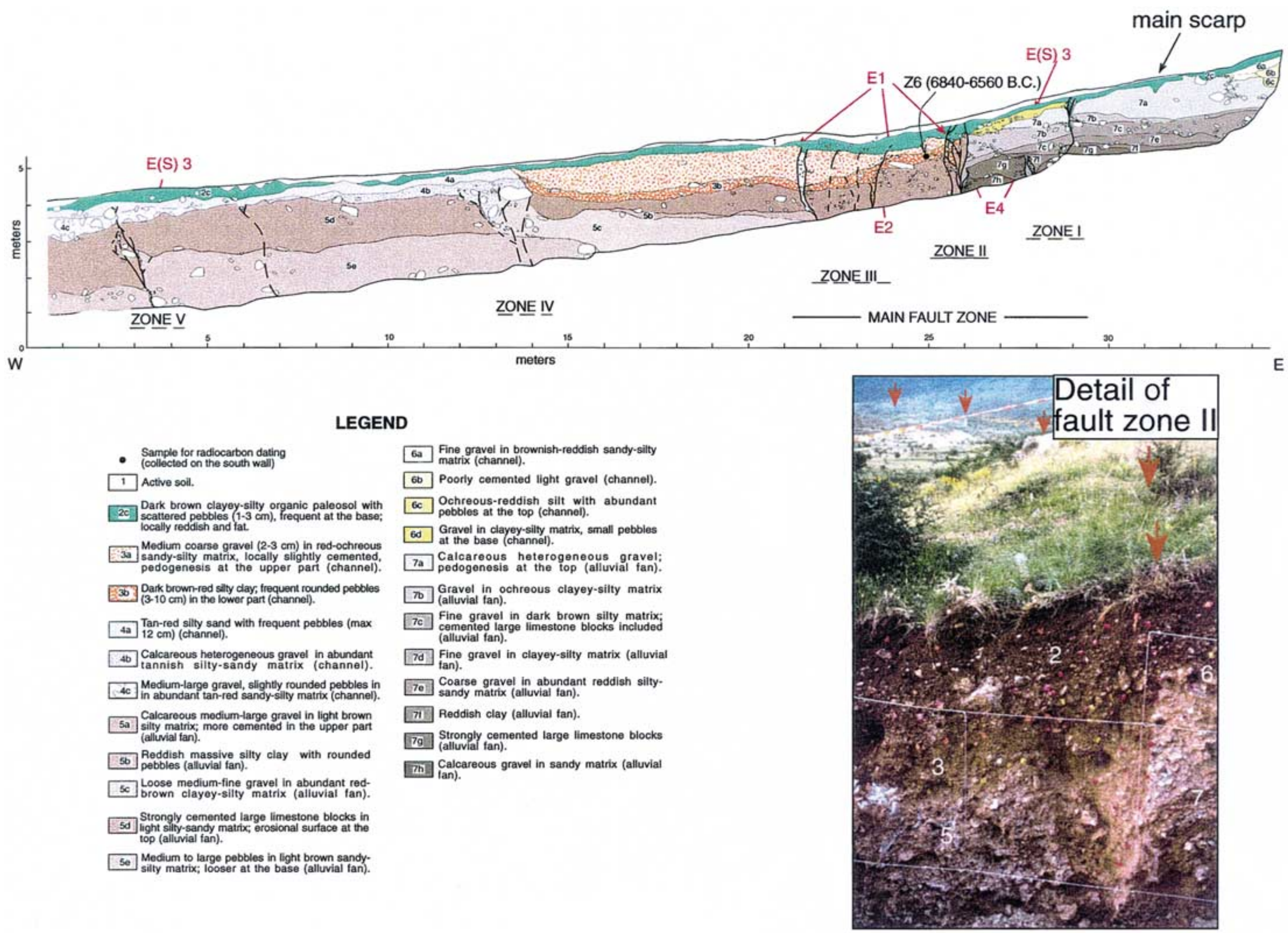

Figure 8. Log from 1:20 detailed mapping of the north wall exposed in Trench 3 at the Torre di Giorgio site (see Figures 6 and 7a for location). Fault zones are indicated by Roman numerals (I to V). Arrows indicate the event horizon recognized for paleoearthquakes. Location and reference number of the sample collected for radiocarbon dating is indicated (see Table 1), the relative age is adjusted to the nearest decade. In the photograph is a view of fault zone II which locates in correspondence of the scarp at surface (red arrows).

secondary faults and fractures (fault zones IV-V in Figure 8) in the western portion of the walls; no scarps at the surface coincide with this secondary deformation at depth. Structural and stratigraphic analysis on the whole zone of deformation highlighted relations such as increasing downward displacement, upward-terminating faults, flexed and onlapping layers, and provide evidence of at least three surface faulting earthquakes producing cumulative displacement. Most of the faults have been active during multiple events of deformation. Similarly to that observed at the Fonte Bellusci site, at this site the depositional history is controlled by the location and geometry of the coseismic scarp; in particular, the subsiding area at the base of the scarp became the preferential site for alluvial deposition after a specific event (units 3 and 4 in Figure 8).

Trench 4 is located at the eastern edge of a small active alluvial fan, about 150 m south of Trench 3 (Figure 7a). This excavation was difficult because of the presence of strongly cemented fan deposits, so that the bottom of the trench is irregular (Figure 9). The stratigraphic sequence in this trench is similar to that in Trench 3 and was divided into the same lithostratigraphic units. Exceptions exists for channel deposits of units 3 and 6 which are missing in Trench 4; here, the corresponding deposits were most likely eroded as suggested by the sharp erosional surface on the top of unit 4. The deformation observed is produced by west-dipping normal faults, and numerous fractures are also scattered within the trench walls. A general characteristic is the deposition of carbonate on fault traces and fractures, indicating important water circulation. In this trench evidence for at least three events of coseismic deformation have been found (Figure 9).

Stratigraphic relations between trench units allowed us to correlate chronologically some of the events recognized in the two trench exposures. The oldest event (E4) is observed only in Trench 3 in fault zone I where 7g is displaced by a fault trace and buried by 7f undeformed deposits (Figure 8). The top of unit 7g is interpreted as the event horizon. The penultimate event in Trench 3 produced the displacement of the sequence up to layer 3b at fault zone III. In particular, this unit shows an increase of displacement respect to the youngest deposits. Subtracting the vertical throw produced by the most recent event, the top of unit 3b across the fault zone records a vertical separation of $\sim$30 cm produced by the penultimate. This value is a minimum as calculated on a single fault active during the penultimate event, the only one where it is possible to make an estimate. Evidence for Event 2 or for an older one, is observed also in Trench 4 at fault zones II and III (Figure 9). Here several faults intersect unit 5 and displace layer 4, buried by the undisturbed paleosol 2a. The event horizon is set at the top of 4. The vertical separation is comparable to that observed in Trench 3. The most recent event (E1) produced the activation and reactivation of several fault zones in both trenches, with a general subsidence of the stratigraphic sequence of the hanging-wall up to the lower portion of unit 2c. The base of this unit records few centimeters of throw across several fault traces. Moreover, the thickness of unit 2c increases at the base of the main scarp, suggesting an accumulation of scarp derived material (from the same unit that was forming the surface at the time of the earthquake) in the subsided area. The event horizon of this event is then set within paleosol 2c. In Trench 4, the major deformation related to the most recent event is along fault zones III and IV where, similarly to Trench 3, the structures terminate within unit 2c and the lower portion of the unit represents the sudden filling of numerous open fractures. Following the event, the local sedimentary processes continued under the control of the new topographic conditions. In particular, a new alluvial channel is located exactly on the downthrown side of fault zone III. By reconstructing the relative geometries of the units before the most recent event, a total vertical throw of 0.4–0.5 m can be measured. Further evidence for cumulative displacement produced by an undefined number of events, probably including Event 4, which occurred before the penultimate event, is found in Trench 3 at fault zone II and in Trench 4 at fault zone I. At these locations units 6 and 7 are in tectonic contact with the younger alluvial deposits of unit 5. The complete lack of correlation across the fault zone prevents from estimating the total throw produced by these events of displacement. However, considering that the most recent and penultimate events produced no more than 1 m vertical displacement and that units 6 and 7 are displaced at least 4 m, this set of events should have produced at least 3 m cumulative displacement. Following this set of events the old fan (units 6 and 7) was abandoned and deposition took place only in the low area formed at the base of the scarp. This area became the preferential site for further alluvial deposition (units 4 and 3 in Trench 3).

Timing of past earthquakes

Material for radiocarbon dating, including detrital charcoals, paleosols and organic fine grained depos-

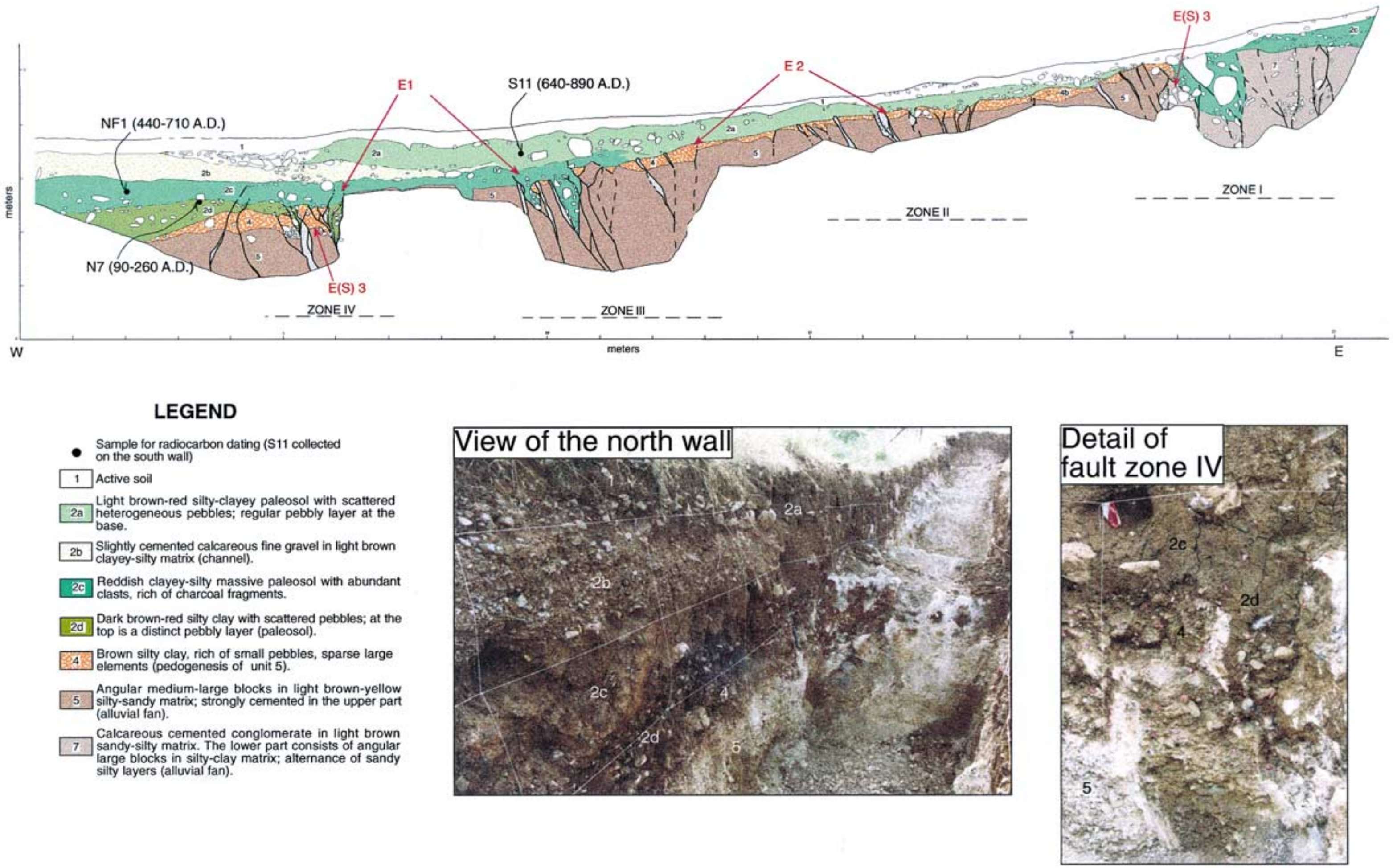

Figure 9. Log from 1:20 detailed mapping of the north wall exposed in Trench 4 at the Torre di Giorgio site (see Figures 6 and 7a for location). Fault zones are indicated by roman numerals (I to IV). Arrows indicate the event horizon recognized for paleoearthquakes. Location and reference number of the samples collected for radiocarbon dating are indicated (see Table 1), the relative ages are adjusted to the nearest decade. Photograph to the left is a view of the trench wall taken from west, units are named as in the log; photograph to the right is a detail of fault zone IV showing the deposition of carbonate on fault traces and fractures for important water circulation.

its, was found, even though in limited amount, in the sediments forming the trench walls. We use the information on age dating and event horizons (Table 1 and Figures 8 and 9) to develop estimates of the timing of the surface faulting events at the Torre di Giorgio site. The control of the timing of past earthquakes is derived from both trenches. In the following, we report the 2σ range of calibrated ^{14}C ages (Table 1) adjusted to the nearest decade. As described in the previous section, the most recent event (E1) occurred within the lower part of paleosol 2c. A sample from a burnt portion of this unit (Sample NF1) gave an age of 530–690 A.D. Since the organic carbon was from a localized fire, this date is not a proper mean residence time date related to a humic enrichment throughout the entire paleosol. Thus the dating from Sample NF1 well represents the age of the event horizon within unit 2c and sets the occurrence of E1 after 530 A.D. (event's maximum age). Charcoal S11 (640–900 A.D.) from the youngest undeformed unit 2a newly defines the event's minimum age. Using these dates the timing of E1 falls within the interval 530–900 A.D. We found correlation in terms of stratigraphic position of the event horizon and maximum age of the most recent surface-faulting event in the two different trenching sites. Using subsurface data at the Fonte Bellusci, Cinti et al. (1997) set for this event a rough maximum age of 370 B.C. and discuss its possible occurrence shortly after 770 A.D. The available datings did not allowed the authors to provide a miminum age of the most recent event that was suggested from historical observations. In this context, datings from the Torre di Giorgio improve and strenghten the estimate of the time interval of E1 along the Castrovillari fault. Regarding the upper limit of the occurrence interval, we can not exclude possible reworking of charcoal S11, so that the minimum age for E1 could be younger than 900 A.D. by an undefinable amount. On the other hand, the youngest possible time of the most recent event can not be derived from the historical catalogues of Italian seismicity (Boschi et al., 1997; Camassi and Stucchi, 1997; Gruppo di Lavoro CPTI, 1999) which, as mentioned above, do not report traces of large earthquakes in the area. However, some original historical consideration of the Pollino region suggests that the minimum age for E1 derived from paleosismological technique (900 A.D.) is reasonable and that, even in case of reworking of S11, the timing of the most recent event can not be likely set much further in time. Although we have considered the possibility of missing historical evidence of earthquakes due to scarcity of population, in this case the investigation on the history of the settlement in/around the Castrovillari village shows that the area was well settled since Roman times. The area was part of an important commercial way and definitely settled at the end of the XI century, when the villages of Castrovillari and of Altomonte (13 km further SW) were populated and flourishing centers (Russo, 1982; Lions Club Castrovillari, 1991; G. Trombetti, pers. comm.), and several churches and monastries were established under the Norman dominium. This suggests that this region was able to have a memory of destructive earthquakes around 1100 A.D. We use this age as a youngest possible age for the occurrence of the most recent large earthquake along the Castrovillari fault (530–1100 A.D.).

The top of unit 3b in Trench 3 and of unit 4 in Trench 4 represent the horizon for the penultimate event (E2). The only available age is from Sample Z6 from unit 3b (6860–6590 B.C.) that pre-dates the event's occurrence. Because this layer is a very thin organic horizon within a sequence of channel deposits, we suspect a possible inclusion of older organic material. Then, the true maximum age of E2 could be likely younger than 6860 B.C. by an unknown amount. Although unit 2d in Trench 4 directly overlies the event horizon on top of unit 4, it formed after an intense erosional process of the stratigraphy so that charcoal N7 (260 A.D.) from this unit gives an apparent very young minimum age for E2. This latter value for the penultimate event was not well constrained also at the Fonte Bellusci site (>410 B.C.), thus uncertainty on the correlation is present. However, converging the data from both sites and assuming that the event's correlation is correct, E2 occurred within the broad interval 6860 B.C.–410 B.C. This interval may be shorter if our uncertainty on the date of Sample Z6 were confirmed.

The undefined number of older earthquakes E(s) and E4 recognized at the Torre di Giorgio site deformed the alluvial fan deposits (units 5 and 7) of late-Pleistocene age, so that we can broadly frame their occurrence starting from about 300–600 ka (Colella, 1994) and before the occurrence of E2 (6860 B.C.). The different depositional environment between the two trenching sites, prevented the correlation of the trench stratigraphy as well as the comparison of the individual oldest paleoearthquakes. However, we might suppose a correlation between the two youngest paleoevents E(s) at the Torre di Giorgio site with E3 and E4 recognized at the Fonte Bellusci site during the last 30000 years (Cinti et al., 1997).

Table 2. Fault parameters of the Castrovillari fault

Minimum length (km)	Elapsed time (yrs)	Inter-event Int. (yrs)	Average recurrence Int. (yrs)	Slip per event (m)	Vertical slip-rate (mm/yr)
13–20	900–1470	940–7760*	5000–2000*	0.5–1.6	∼1 (trenching) min 0.2–0.5 (long-term)

* young part of the interval preferred.

Discussion

Evidence from the geomorphological setting of the area, trenching data combined with historical consideration and the empirical relations proposed by Wells and Coppersmith (1994), are used in the following to estimate the main seismic parameters of the Castrovillari fault (summarized in Table 2). Although uncertainties exist and mainly concerned with the dates, the following estimates can be considered as a useful reference for the behavior of the entire structure.

Length of the rupture

The similarity of the Castrovillari scarp profiles, the comparable amount of displacements associated to the paleoearthquakes recognized in the trenches, the probable age correlation of the most recent event between the two trenching sites, and the relation on average displacement vs surface rupture length (Wells and Coppersmith, 1994) suggest that the Castrovillari fault sections could have slipped in conjunction, producing a complex surface rupture 1.5–2 km wide and at least 10–13 km long. The northern termination of the Castrovillari rupture segment is related to the presence of the WNW-ESE-trending Pollino Range. This feature would act as a geometric barrier to the propagation of the rupture to the north and led to the westward deflection of the Castrovillari fault at surface which probably re-utilizes the pre-existing Pollino fault for the last 3 km (Figures 2 and 6). From this point of view, this 3 km long portion of the Pollino fault should slip along with the Castrovillari fault. This is supported also from the trenching performed by Michetti et al. (1997) at the sites Masseria Quercia Marina (MQM) and Grotta Carbone (GC) (for location see Figure 2 and inset in Figure 7a). Although the authors conclude that at these sites they have evidence for two paleoearthquakes, which occurred during the XIII and XV century, and VI and XII century, respectively, reanalysing the published trench logs (figs. 6, 7, 9 pages 76,77,80 in Michetti et al., 1997) and authors' interpretation we conclude that the most recent event on the Pollino fault portion occurred between the VI and XII century. This re-interpretation is based on the following consideration: (1) as discussed by the authors, the evidence for the most recent event at the MQM site is too weak and its size (vertical displacement < 0.1 m) is still within the uncertainties range of trenching observation to be considered truly significant to describe a paleoearthquake, (2) evidence for the most recent event at the GC site is good however no ages are available to date it, its age is assumed by the authors to be the same as the 'uncertain most recent event' at MQM, (3) even the age of the penultimate event at GC is not assessed on radiocarbon dating, but by extending stratigraphical and chronological consideration established at MQM; this event might be some millennia older than the penultimate event at MQM. Therefore our alternative interpretation is that the most recent event at GC might be possibly chronologically correlated with the penultimate at MQM, and would represent the most recent large event that ruptured this part of the fault no later than the XII century. This would be also in good agreement with the historical evidence described in the above section 3.2.2. The historical reports within this area are so well preserved that we feel confident that a large destructive earthquake on the Castrovillari/Pollino fault would not be un-reported starting from the XII century. On this base and assuming our alternative interpretation of MQM is correct, there is a consistent overlap in the ages of the most recent event at the Torre di Giorgio on the Castrovillari fault and on the portion of the Pollino fault investigated by Michetti et al. (1997). Therefore, a possible and reliable scenario is that the W-trending final portion of the rupture trace is at present part of the Castrovillari fault, and does not necessarily reflect the direct evidence of present major activity of the Pollino fault as stated by Michetti et al. (1997).

The 13-km value we indicate for the segment length from mapping and paleoseismological observations likely represents a minimum of the true fault length. The regressions of source parameters compiled by Wells and Coppersmith (1994) show that for a fault producing about 1 m of coseismic vertical displacement, it would be expected at least a 20 km-long surface rupture. If this is the case, the surface expression of the Castrovillari fault south of Cozzo S. Elia (Figure 2) might be buried by the fast modern sedimentation in the Sibari Plain (Colella, 1988). The 20-km minimum length is common for surface ruptures in the Apennines, i.e. the 1915 Fucino and the 1980 Irpinia surface faulting (Serva et al., 1986; Pantosti and Valensise, 1990) and this value is also comparable to that of the modelled major fault segments along the Apennines seismogenic belt (Valensise and Pantosti, 2001b).

Applying the Wells and Coppersmith (1994) relations to the source parameters of the Castrovillari fault, we suggest that the maximum expected earthquake magnitude for this fault ranges between 6.5 and 7.

Elapsed time

The time elapsed since the most recent earthquake (530–900 A.D.) ranges between 1100 years and 1470 years. However, if we consider the widest age interval for the timing of this event (530–1100 A.D.), the estimate for the elapsed time varies from 1470 to 900 years.

Inter-event interval

Using the preferred ages for the most recent event (530–900 A.D) and the penultimate event (6860–410 B.C.) we calculate an approximate inter-event interval for the Castrovillari fault. The minimum interval between these two earthquakes is of 940 years and the maximum interval is 7760 years, or as long as 7960 years if we use the widest age interval for the most recent event (530–1100 A.D.). The long interval results from the large uncertainties contained in the maximum age for the penultimate event that may be much younger than 6860 B.C. Thus, we suggest the youngest part of the inter-event interval as the more representative of the fault activity. On the basis of our reinterpretation of the trenches excavated by Michetti et al. (1997) (see discussion above), the penultimate event on the E-W part of the fault (Pollino fault section) occurred shortly before 2 millennia B.C. (assuming that the lower and coarser part of unit 2 of fig 9, page 80 in Michetti et al. (1997) is a scarp derived deposit). This is in agreement with the estimate of the age of the penultimate event as derived from the trenches at Torre di Giorgio and can actually help in reducing the wide age interval obtained at this site (6860–410 B.C.). If these assumptions are correct, the penultimate event that ruptured the entire fault occurred between about 2000 and 400 B.C. This would support an inter-event interval roughly ranging between 940 and 3000 years. This result is consistent with the other central and southern Apennines seismogenic fault segments which generally produce large surface faulting earthquakes with a frequency of thousands of years (Pantosti et al., 1993; Michetti et al. 1996; Pantosti et al., 1996; Galadini and Galli, 1999).

Average recurrence interval

Combining the long-term vertical slip-rate of 0.2–0.5 mm/yr, with the average slip per event of at least 1 m estimated from trenching, and assuming a periodic strain release, we estimate an average recurrence ranging between 5000 and 2000 years with the young part of the range preferred. This estimate is consistent with the inter-event interval (940–7760 years, younger part of the interval preferred) and suggests some quasi-periodic recurrence can be considered for this fault.

Slip per event and slip rate

Slip rates provide fundamental information for comparing the activity of faults. Rates for the Castrovillari fault also provide information for evaluating the rate and distribution of slip across the Apennines seismogenic belt. Slip rates represent the average rate of displacement on a fault during an interval of time. Ideally rates should represent the long-term behavior of the fault but this is not always possible to obtain, particularly in environments such as the Apennines where recurrence intervals are in the order of thousands years. However, the estimates of displacement from paleoevents, and the recurrence interval allow us to provide estimates of slip rate for the late Pleistocene-Holocene. The minimum vertical slip per event at the Fonte Bellusci site ranges between 0.8–1.6 m based on the individual events E1, E2 and E4 (Cinti et al., 1997). At the Torre di Giorgio site events E1 and E2 produced about 0.5 m slip per event, suggesting a natural decrease toward the northern segment boundary. Given the uncertainties on the estimates of the net displacements, the variations of the slip along the fault and comparing the scarps with the size of displacements produced by other faults in the Apennines, we would expect average coseismic vertical displacements of at least 1 m associated to the activity of the Castrovillari fault. Assuming that this value and the minimum inter-event interval (940 years) are representative for several earthquake cycles of the fault, we may infer a vertical slip rate of about 1 mm/yr. Because of the wide range of variability affecting the estimates of the recurrence time, this value may vary substantially. Then our preferred rates of displacement are based on the long term deformation. The minimum vertical separation across the stream bed at the Fonte Bellusci site is of 5–6 m in the past 30 ka, which yields a minimum vertical slip rate of about 0.2 mm/yr. On the other hand, the amount of vertical separation recorded by fan-delta top-set sequence (maximum age of 300–600 ka) across the entire structure is 100 to 150 m. Using these values we obtain a minimum long-term vertical slip rate of 0.2–0.5 mm/yr. The dip of normal seismogenic faults in the central and southern Apennines varies between 60° and 40°. Assuming that the dip of the Castrovillari fault also falls in this interval and using the minimum long-term vertical slip rate (0.2–0.5 mm/yr), the dip-slip rate of this fault ranges between 0.2 mm/yr and 0.8 mm/yr and the extension-rate varies from 0.1 to 0.6 mm/yr. An approximate dip-slip rate of 1.2–1.5 mm/yr and extension-rate of 0.6 to 1.2 mm/yr may be suggested provided the assumptions on the vertical slip-rate from trenching (1 mm/yr) are valid.

Conclusions

The geomorphic study and trenching on the Castrovillari fault scarps show that they are the complex but probably the contemporary surface expression of a single seismogenic fault at depth. The Castrovillari fault is 13 to 20-km minimum long, NNW striking, normal fault segment within the southern part of the Pollino seismic gap. Repeated slip on this fault occurs by successive large earthquakes during the late Pleistocene-Holocene time. The northern rupture boundary of the Castrovillari fault is defined by the WNW-ESE-trending Pollino Range which acts as a deep crustal geometric barrier arresting the rupture propagation. A peculiar feature of the Castrovillari rupture is that utilizes the crustal discontinuity produced by the pre-existing Pollino fault, inactive at present, to release the strain in its final portion. This interpretation is in contrast with that of Michetti et al. (1997). The new trenching data on this fault at the Torre di Giorgio site were analyzed and integrated with those from the Fonte Bellusci site (Cinti et al., 1997), along with a revision of the trenching results by Michetti et al. (1997) at Masseria Quercia Marina and Grotta Carbone sites (for locations see Figure 2). We believe this defines the past behavior of the Castrovillari fault in a more constrained way.

We have recognized and dated the two most recent surface faulting events produced by the Castrovillari fault. The penultimate event occurred after 6860 B.C. and before 410 B.C., young part of the interval preferred. This was tentatively constrained to about 2000–410 B.C. converging and interpreting our data and those in Michetti et al. (1997). The occurrence of the most recent event is between 530 A.D. and 900 A.D. No traces for the youngest event are found in the catalogues of historical seismicity (Boschi et al., 1997; Camassi and Stucchi, 1997; Gruppo di Lavoro CPTI, 1999). However, we collected numerous information and reports on the history of the settlement in the Castrovillari and sorrounding area (Lions Club Castrovillari, 1991; Russo, 1982; G. Trombetti, pers. comm.) which indicate the presence of nearby flourishing social and religious centers around the beginning of XII century. This essentially confirms the paleoseimologically derived minimum age of the most recent event, which cannot be reasonably younger than 1100 A.D. Thus, the absence of this event in the catalogues shows that for at least this part of Italy, they can not be considered complete, even for large earthquakes, before 1100 A.D. Although we believe it is a remote possibility, we can not completely exclude that the event is not missed but simply mislocated; this may be the case of the 951 A.D. (I=IXMCS) event, located with uncertainty immediately southeast of the Sibari Plain (Boschi et al., 1997). Assuming the catalogue is complete since 1100 A.D., the chronology of the events yields an elapsed time ranging between 1100 years (not less than 900 year) and 1470 years since the most recent event and an approximate recurrence interval for surface faulting earthquakes of 940–7760 years, likely restricted to 940–3000 years. The paleoearthquakes produced vertical slip that varies along the strike, between 0.8–1.6 at the central portion of the fault, and 0.4–0.5 m close to the northern end. Where scarp strands are parallel (particularly in the central portion) the net coseismic displacement is partitioned onto all the scarp segments. This implies that the slip values estimated at the single trenching site represent a minimum of the total displacement per event on the Castrovillari fault. We suggest this fault average coseismic vertical displacement to be at least 1 m as representative for the long-term behavior. We derived a minimum vertical slip rate of 0.2–0.5 mm/yr using the long-term displacement of geomorphic features observed both across a single scarp and the entire fault system, and inferred a vertical slip rate of about 1 mm/yr from trenching data.

The seismic parameters of the Castrovillari fault are quite comparable to those of other seismogenic Apennine faults (Valensise et al., 1993; Valensise and Pantosti, 2001a), suggesting a similar seismic fault behavior, and even that the Castrovillari fault is part of the segmented belt along the main axis of the Apennines. As also suggested by several authors (i.e. Amato et al, 1995; Frepoli and Amato, 1997; Valensise and Pantosti, 2001a), the NNW-orientation and the nearly pure normal mechanism of the Castrovillari fault indicate that the NE-SW extension observed in the Apennines, although slightly rotated toward east, is a present mechanism also in this portion of southern Italy.

Considering the uncertainties in the slip and fault length estimates, we suggest m 6.5–7.0 for the paleoearthquakes produced by the Castrovillari fault (Wells and Coppersmith, 1994). Like other areas in the Apennines, the recognition of the occurrence of a large earthquake during the past thousands years was a kind of 'surprise' because they occurred in an area were no large magnitude earthquakes are historically known. Based on the absence of strong seismicity, and considering that large earthquakes generally occur along the Apennines belt with a low frequency, the Pollino area could be interpreted as a region with a very high seismic hazard. In reality, this evaluation may vary substantially whether based on the timing of the most recent large event. Our trenching data show that the gap of large seismicity is an artefact of the historical record and that the Castrovillari fault has produced large magnitude event between 530 A.D. and 1100 A.D. However, to discriminate on the true seismic hazard associated to the fault, we need to combine the time elapsed since the most recent event to the recurrence time of the fault activity. In the Castrovillari case, if the true recurrence falls in the shorter part of the interval (940–3000), assuming a periodic strain release, and given the time elapsed (900–1470 years), the fault should be considered as a fault with potential for generating large earthquakes in the near future; on the contrary, if the true recurrence is in the longer side the hazard associated to this source is lower.

Finally, despite the apparent complexity that may characterize coseismic ruptures, our results show that geological investigations can improve definition of the seismic behavior of fault segments, particularly with regard to the expected magnitude of future events. The data derived from this type of research may represent a unique, precious and reliable contribution to the evaluation of the seismogenic potential contained in 'silent' region such as the Pollino example.

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