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New paleoseismological data from the Gran Sasso d'Italia area (central Apennines)

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[1] Paleoseismological analyses along the Campo Imperatore normal fault (CIF) in the Gran Sasso massif, which is an area characterized by the absence of significant historical earthquakes, highlight the occurrence of surface faulting after the 5th–3rd cent. BC and around the 6th–5th millenium BC. These ages agree with those reported by *Giraudi and Frezzotti* [1995] on the western tip of the CIF, thus suggesting the possible entire rupture of the 30-km-long CIF during M∼7 events. These data contribute to the re-evaluation of the seismic hazard of a large surrounding area, including the city of L'Aquila (∼100.000 inhabitants), which is located 20 km from the CIF, in the hangingwall side. *INDEX TERMS:* 7221 Seismology: Paleoseismology; 7223 Seismology: Seismic hazard assessment and prediction; 7230 Seismology: Seismicity and seismotectonics; 8107 Tectonophysics: Continental neotectonics

1. Introduction

[2] The Gran Sasso range is a massif composed by carbonate rocks and is located within the Apennine chain. Its peak is the highest (2912 m a.s.l.) among those of the Italian peninsular. Its mountainous area (about 500 km^2) is largely uninhabited, containing only a few small farm-monasteries since the Middle Ages. Therefore, no historical earthquakes which could have occurred within its slopes are reported in the seismic catalogues, the only, and recent one, being the 1950 event (Ms = 5.6, Io = 8 MCS, [*Working Group CPTI*, 1999]; Figure 1).

[3] Nevertheless, since the 1960s, tectonic movement affecting Pleistocene deposits has been identified by *Servizio Geologico d'Italia* [1963], *Demangeot* [1965], *Ghisetti and Vezzani* [1986], *Giraudi* [1988], *Carraro and Giardino* [1992] and *Jaurand* [1992]. While most of evidence of Quaternary deformation is related to Middle Pleistocene deposits (tills, alluvial and slope deposits), *Giraudi* [1988] and *Giraudi and Frezzotti* [1997] also reported displacements of Late Pleistocene alluvial fans and the presence of fault scarps affecting both the carbonate bedrock and the Late Quaternary cover. Finally, *Giraudi and Frezzotti* [1995] carried out paleoseismological studies on faults that deform Late Glacial and Holocene deposits on the northern side of the Gran Sasso massif, thus providing evidence of several-surface faulting events in the last 18.000 years.

[4] On the basis of 1:30.000-scale air-photos and field-based geomorphic mapping, we identified other potential trench-sites at Campo Imperatore (1700–1500 m a.s.l.), an intermontane basin along the southern slope of the Gran Sasso massif. We dug four trenches across a system of secondary faults that offset a post-glacial alluvial fan (Figure 2), which allowed us to identify and date Holocene faulting.

2. Seismotectonic Framework of Central Apennines

[5] Since Miocene time, the Apennine chain developed as the result of contemporaneous flexural-hinge retreat of the Adria plate (in subduction beneath Europe), the consequent back-arc opening of the Tyrrhenian basin, and the high-rate eastward migration of the thrust belt-foredeep system ([*Meletti et al.*, 2000] and references therein cited). The present state of stress of the upper crust along the chain (main NE-SW extension; see *D'Agostino et al.* [2001]) is related to the continuation of back-arc extension, with deformation occurring on normal faults, some of which were formerly thrust faults. Active extension, earthquakes and evidence of active faulting are mainly concentrated along the axial belt, close to the main topographic ridge, although *Galadini and Galli* [2000] show a widening as much as 50 km of the actively extending belt in the central part of the Apennines, between the Fucino and Gran Sasso areas (Figure 1). Here, the active faults system (NW-SE trending normal faults dipping to the SW) splits into two major systems, the eastern one (MVEF, LMF, CIF, CVF, MMF, MRF, ACF; Figure 1) and the western one (NFS, UAFS, CFCF, OPF, FF, USFS).

[6] Moreover, the Central Apennines are among the most seismically active areas in Italy, including several M > 6.5 earthquakes in the last few centuries. Almost all the destructive events have been related to the aforementioned eastern fault system [*Galli and Galadini*, 1999; *Galadini and Galli*, 2000], while others have been individuated by means of paleoseismological studies, both on the western [*Galadini and Galli*, 1999; *D'Addezio et al.*, 2001] and on the eastern system [*Giraudi and Frezzotti*, 1995; *Galadini et al.*, 1997; *Galli and Galadini*, 1999; *Galadini and Galli*, 2000].

3. Geological Setting of the Studied Area

[7] The Gran Sasso is a massif mainly composed of Mesozoic limestones and dolomites. It forms an E-W to N-S trending arcuate thrust belt, the emplacement of which ended in the Lower Pliocene [*Ghisetti and Vezzani*, 1986], and has resulted in the formation of an impressive topographic ridge dominating the landscape of the central Apennines. The onset of the extensional tectonics, which is determined by the age of the intermontane basin filling, started in the Early Pleistocene [*D'Agostino et al.*, 1997], resulting in the development of three main normal fault systems: the Assergi, Campo Imperatore and Mt. Cappucciata-Mt. San Vito (AF, CIF, CVF, Figures 1 and 2A). The latter contains three dextral en-echelon branches that cut Late Pleistocene slope deposits [*Galadini and Galli*, 2000], and are expressed by several km-long bedrock scarps. Secondary fault scarps offset Middle-Late Pleistocene lacustrine and alluvial deposits in the eastern portion of the Campo Imperatore Plain, close to the Mt. S. Vito branch [*Ghisetti and Vezzani*, 1986]. The AF is highlighted by bedrock fault scarps along which slope-derived breccias, which was deposited during the Middle and Late Pleistocene [*Vezzani et al.*, 1993], are dragged along the fault plane. The CIF and AF show a sinistral en-echelon geometry (Figure 2A), with the latter trending N120° over a

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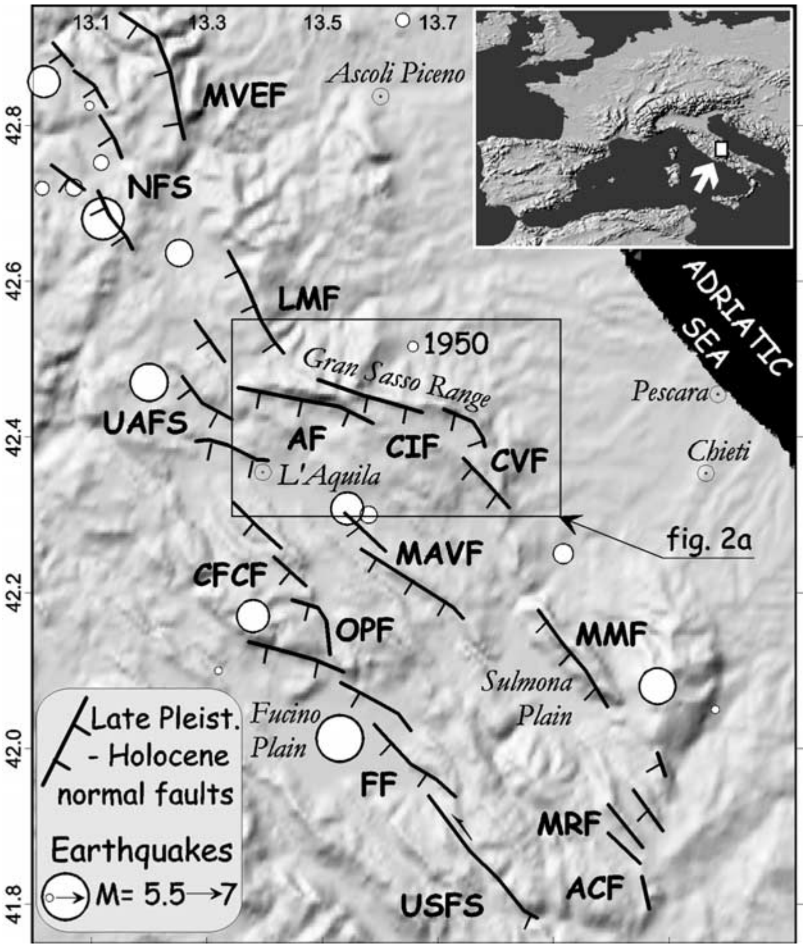

Figure 1. Primary active faults in central Apennines and associated seismicity (faults: MVEF, Mt. Vettore; NFS, Norcia; LMF, Laga Mts.; UAFS, Upper Aterno; AF, Arischia; CIF, Campo Imperatore; CVF, Cappucciata-San Vito Mts.; MAVF, Middle Aterno; CFCF, Colle Cerasitto-Campo Felice; OPF, Ovindoli-Pezza; MMF, Mt. Morrone; FF, Fucino; MRF, Mt. Rotella; ACF, Aremogna-Cinquemiglia; USFS, Upper Sangro). Modified after *Galadini and Galli* [2000].

distance of 20.5 km. The N120°-130°-trending CIF borders to the north the alluvial plain (Figures 1 and 2), and is characterized by evidence of Late Pleistocene-Holocene activity. In the western part of the plain, the branch on the piedmont area displaces Late Pleistocene-Holocene cemented slope deposits and colluvial units [*Carraro and Giardino*, 1992]. Another branch offsets the slope and the main E-W divide of the Gran Sasso Range, displacing a rocky cirque which fed a glacier during the last glacial maximum. Scarps on the flanks and bottom of the cirque formed after the last Glacial Maximum, i.e. post-18,000 years BP. To the west, beyond the topographical divide of the Gran Sasso Range, the fault offsets glacial till, colluvial, alluvial and Late Pleistocene-Holocene palustrine deposits [*Giraudi and Frezzotti*, 1995]. As mentioned before, paleoseismological studies identified four displacement events since 18,000 years BP, the most recent being younger then 4154–3381 BP (^{14}C cal. age) and being buried by colluvial units of unknown age [*Giraudi and Frezzotti*, 1995]. Based on the height of the fault scarps and on the age of the displaced deposits (18,000–13,000 years BP), *Giraudi and Frezzotti* [1995] estimated slip rates of 0.67–1 mm/yr.

[8] We focused our studies on the faults in the central part of Campo Imperatore. These faults displace a Late Pleistocene alluvial fan, and form several-hundred-m-long, WNW-ESE trending scarplets (Figure 2). This part of the plain (Figure 2) is characterized by the presence of several poliphasic alluvial fans along the northern slope, partly older than 31,500 ± 500 BP and partly younger than 17,840 ± 200 BP [*Frezzotti and Giraudi*, 1990a], and showing evidence of present activity (i.e. during heavy rainfall). Part of the plain is also filled by till deposits (pebbles and boulders in minor sandy-silty matrix), which are related to the last glacial maximum [*Giraudi and Frezzotti*, 1997] and are dissected by the present drainage net.

4. Paleoseismological Analyses

[9] Using air-photos and field surveys, we identified several possible trench-sites on the surface of an alluvial fan at the foothill of Mt. Prena, where the surface is deformed by a dozen well-preserved fault scarps (0.5–2 m high). The scarps are clustered in two groups which mainly trend WNW-ESE, and dip both north and south (see frame of Figure 2). The southern edge of the fan has a straight 20-m-high scarp facing the present alluvial plain. In agreement with *Ghisetti and Vezzani* [1986], we suspect that this scarp, although eroded and carved by several streams, could also have a tectonic origin, and faulting may have lowered the distal part of the fan below the alluvial plain. The trend of upper scarplets is slightly rotated counterclock with respect to the main CIF; the faults have a dextral component, evidenced by right-steps of the streams carved into the surface.

[10] We dug 4 trenches, Nos. 1–2 across the northern system of scarplets and Nos. 3–4 across the southern one. All trenches show

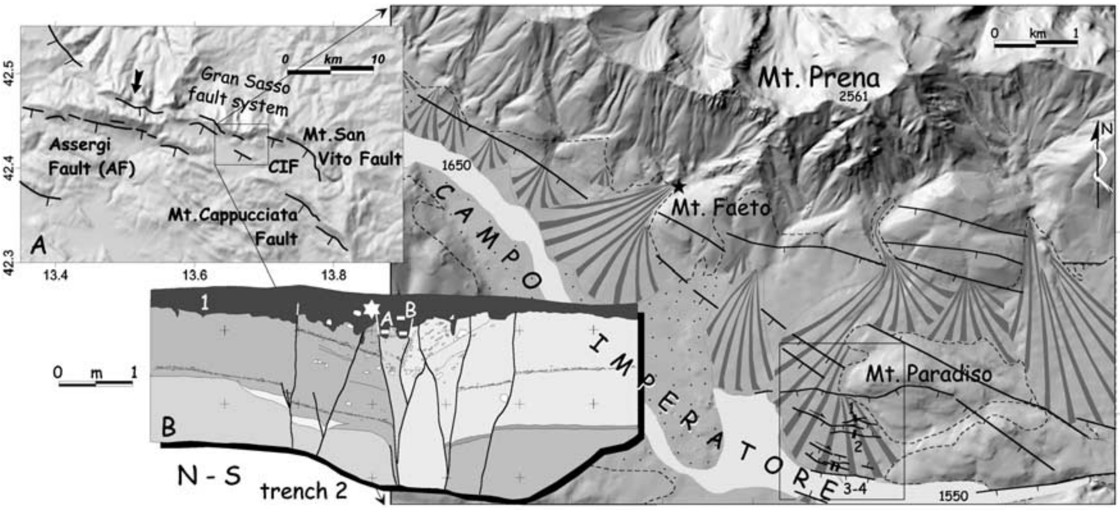

Figure 2. Shaded relief map of the central Campo Imperatore area (processed on Regione Abruzzo digital data), showing the Late Pleistocene alluvial fan system, together with the main normal faults affecting the southern slopes of the Gran Sasso ridge (bold lines). Dotted lines bound the Late Pleistocene continental deposits; dotted areas are moraines related to the last glacial maximum. Black star is the landslide near Mt. Faeto. The outlined area west of Mt. Paradiso shows the investigated area (trenches 1–4). A; active faults in the Gran Sasso area. Arrow indicates the paleoseismic site studied by *Giraudi and Frezzotti* [1995]. B: sketch of trench 2, showing the geometry of displacement of the alluvial deposits; samples A-B were dated at 2680-2310/2230–2190 BP and 2350–2290/2270–2155 BP (730–360/280–240 BC and 400–340/320–205 BC; ^{14}C cal. age); white star is the event horizon of the ultimate event.

clear evidence of displacement and dragging in all of the exposed alluvial and colluvial deposits. The geometry of the fault planes (subvertical shear planes defining "negative flower structures" features; see Figure 2B) and of the deformed deposits (e.g., thickening of strata across the fault planes, fabric and re-orientation of sediments close to the faults; Figures 2 and 3) provide evidence of both repeated faulting events and vertical and horizontal motion, as shown by the surface observations.

[11] Trenches 1 and 2, which were on the proximal part of the fan, show a continuous succession of subangular to subrounded, medium-size gravels in sandy matrix, with interbedded thin silty layers. Units are commonly separated and truncated by erosional surfaces. The upper part of the sequence contains a pedogenic brownish silty colluvium that is partly deformed.

[12] Trenches 3 and 4 (Figure 3) were on a more distal part of the fan, across a N-dipping fault. Trench 3 was dug inside a small stream channel, which is dammed by the scarp. In these trenches, the alluvial-fan succession is interbedded with sandy-silty colluvial deposits, some of which contain loess. The two sides of the fault display different alluvial sequences: in the footwall side, part of the fan dated at 31,500 ± 500 BP [*Frezzotti and Giraudi*, 1990b] outcrops (units 8–9), while in the hangingwall side, according to our dates, the deposits are mainly Holocene in age. Also here, a thick brownish-black andosol (unit 1) caps the stratigraphical sequence. Eleven ^{14}C dates constrain the age of the upper part of the succession as being deposited in the last 7000 years BP (alluvial in the hangingwall side and colluvial and pedogenetic in both sides).

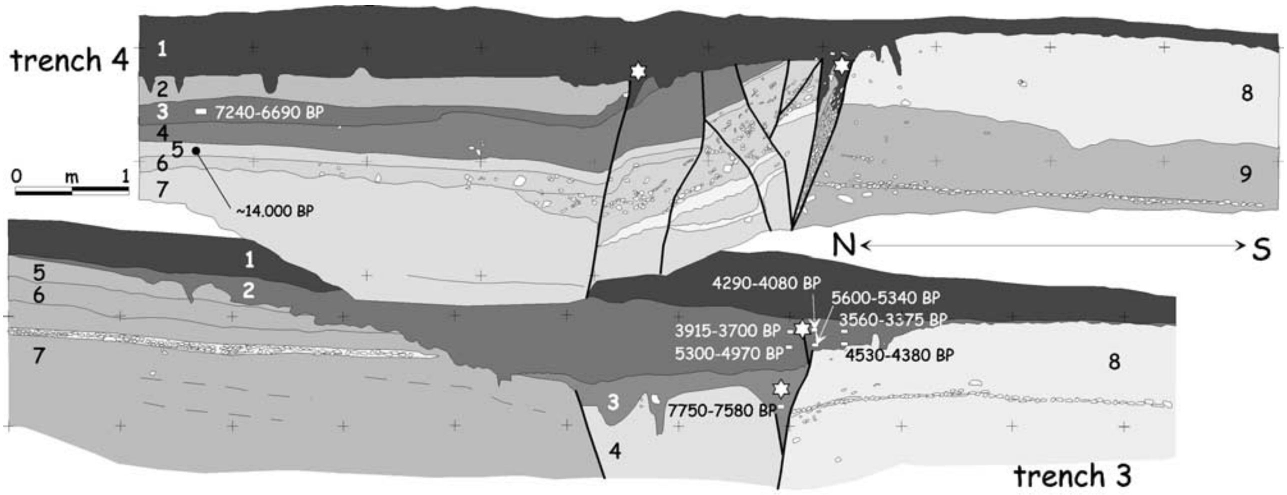

Figure 3. Simplified diagram of trenches 3 and 4. White stars in trench 3 denote event horizons for the most recent and a previous event. Labels (1–9) do not indicate the same units in the two trenches.

[13] As for the faulting history, we found evidence of the youngest surface-rupturing event in trench 2, where the pedogenic brown colluvium deposited on the alluvial succession is displaced (Figure 2B, unit 1). The event is younger than 2680–2310/2230–2190 BP and 2350–2290/2270–2155 BP (^{14}C cal. age of samples A-B in unit 1). This rupture can be recognized also in trench 3, as the event that displaces brown colluvial deposits dated 3560–3375 BP (^{14}C cal. age; unit 2 in Figure 3). A previous event, which we cannot say to be the penultimate (due to the presence of several erosional surfaces), is also evident in trench 3, where a yellowish sandy-silty colluvium is displaced (and successively eroded in the footwall; unit 3 in Figure 3). It is younger than 7750–7580 BP (^{14}C cal. age of unit 3), but older than 5300–4970 BP (^{14}C cal. age of bottom of unit 2; Figure 3). Even if we can presume the occurrence of other previous events, which are indicated by the greater amount of the offset and by the fabric of the older deposits across the fault planes, we cannot provide further chronological constrains to them.

[14] These data agree with those of *Giraudi and Frezzotti* [1995]. Their most recent and penultimate events (younger than 4154–3381 BP and between 6573–5893 and 7336–6616 BP, respectively; ^{14}C cal. ages) correspond with ours, while their previous events (around 13,000–16,000 and shortly after 18,000 BP) could be expressed by the older deformation that we observed on faults in the trench. Moreover, in the Campo Imperatore area, the age of the "penultimate" event might also be constrained by dating a possible seismically-induced landslide located north to Mt. Faeto (Figure 2, black star). Here, far from the hillslope, a huge mass of boulders buries a paleosol dated 7979–7717 BP ^{14}C cal. age [*Giraudi and Frezzotti*, 1997].

[15] A minimum vertical slip-rate can be estimated by the offset of dated deposits. Unit 3 in trench 4 has a minimum offset of 0.8 m, while unit 5 (a pink loess whose age is about 14 kyr BP; [*Frezzotti and Giraudi*, 1990a, 1990b] has a minimum offset of 1.1 m (Figure 3). Moreover, the top of the alluvial fan outcropping in the footwall side, which is younger than 31,500 ± 500 BP [*Frezzotti and Giraudi*, 1990a, 1990b], has a minimum offset of 2.7 m. All these offsets yield a minimum slip-rate of 0.1 mm/yr on this secondary antithetic fault, that must be at least doubled because of the presence of the northern system (investigated by trenches 1–2). To this amount we must add the offset of the fan surface related to the southernmost and highest fault-scarp (>15 m, assumed age of 31,500 ± 500 BP: slip rate 0.48 mm/yr), which yield a total minimum vertical slip-rate of 0.68 mm/yr. This rough value is very close to that obtained by *Giraudi and Frezzotti* [1995] on the western tip of the CIF.

5. Conclusions

[16] We dug four trenches in the Campo Imperatore area, an intermontane basin growth in the hangingwall of the CIF, that show evidence of repeated surface-faulting events which occurred during the Holocene on a branch of the CIF system. The synthetic and antithetic faults offset a Late Pleistocene-Holocene alluvial fan, being highlighted by scarp on the fan surface. The most recent surface-rupture occurred close to the 5th–3rd cent. BC, and a previous event occurred around 6th–5th millenium BC. Our dates are consistent with those of *Giraudi and Frezzotti* [1995] on the western tip of the fault, hence suggesting the probable rupture of the entire length of the CIF (about 30 km; [*Galadini and Galli*, 2000]) during single earthquakes. On the basis of the empirical relationships between surface-rupture length and magnitude [*Wells and Coppersmith*, 1994], we infer that the magnitude of large earthquake associated to the CIF is close to 7.

[17] This result yields an important implication in terms of seismic hazard for the town of L'Aquila (∼100.000 inhabitants), which is only 20 km away from the CIF. Magnitude 7 earthquake would likely cause widespread damage in the town and surrounding region.

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