5. Castrovillari (CS). Earthquake-induced ground ruptures and paleoseismology in the Mt. Pollino Area

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Introduction

The visit to the Mt. Pollino fault generated mountain front will be described using the paper by Michetti A.M., Ferreli L., Serva L. and Vittori E. (1997), *Geological evidence for strong historical earthquakes in an "aseismic" region: the Pollino case (southern Italy)*, Journal of Geodynamics, 24, 1-4, 67-86.

ABSTRACT

The Pollino Range is the southernmost segment of the Southern Apennines, at the boundary with the Calabrian Arc. While several strong earthquakes (magnitude 6.5 - 7.0) occurred in the nearby regions, apparently the Pollino area has known no historical evidence for seismic events of magnitude > 5. We carried out an airphoto interpretation and a field survey of the Pollino fault (the major Quaternary normal fault of the area) in order to geologically characterize the seismic potential of this structure. We dug two sets of trenches across fault scarps within the apex of latest Pleistocene to Holocene alluvial fans at Masseria Quercia Marina (MQM) and Grotta Carbone (GC) sites, in the central segment of the southern Pollino Range front. At both sites we identified two surface faulting events affecting the alluvial fan deposits and two overlaying colluvial units of historical age. The penultimate event produced a vertical offset of 80-90 cm at GC and 50-60 cm at MQM; while the last event produced a vertical offset of 40-50 cm at GC and few centimeters at MQM. Based on field observations and range front morphology, we hypothesize that the two historical earthquakes reactivated at least the entire length of the Masseria Marzano - Civita segment of the Pollino fault (rupture length about 18 km). For such events, the comparison with surface faulting earthquakes in the Apennines and abroad indicates a magnitude of 6.5 - 7.0. Therefore, the maximum potential earthquake and the seismic hazard of the Pollino area is significantly larger than that suggested by the available historical seismic catalogue.

Purpose and scope of the study

The Pollino Range is the southernmost segment of the Southern Apennines, at the boundary with the Calabrian Arc. Crustal extension has shaped these regions during the Quaternary with a system of tectonic basins (e.g., Bousquet, 1973; Ciaranfi *et al.*, 1983; Westaway *et al.*, 1989; Scandone *et al.*, 1992; Valensise *et al.*, 1994; Fig. 1) and is also active today as shown by seismological data (cf. Gasparini *et al.*, 1985). While several strong earthquakes (Intensity X MCS or greater, i.e. about magnitude 6.5 to 7.0; Postpischl, 1985; Boschi *et al.*, 1995; Camassi and Stucchi, 1996; Fig. 1) occurred nearby, seemingly the Pollino area has known no historical evidence for seismic events of Intensity greater than VII MCS (cf. Valensise and Guidoboni, 1995), i.e. about magnitude 5 (yet, for low Intensity events along the Pollino fault, see Magri and Molin, 1979).

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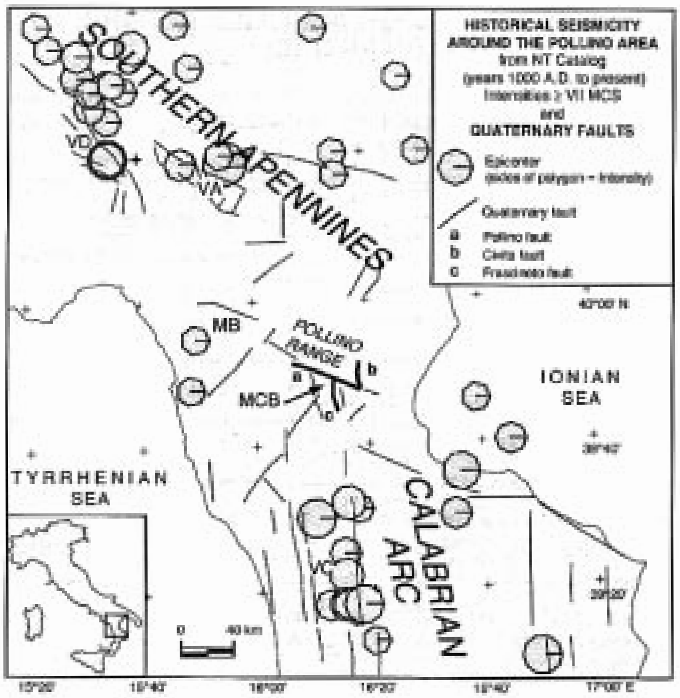

Fig. 1. Main Quaternary faults (from our own data and from Bousquet, 1973; Bosi, 1987) and historical seismicity (according to Postpischl, 1985, and Camassi and Stucchi, 1996; Intensity is given in the MCS, Mercalli-Cancani-Sieberg scale) in the area between the Apennines and the Calabrian Arc. Magnitude estimates provide values of 7 for I = XI and of 6.1 to 6.6 for I = X (Postpischl, 1985); note the lack of events with Intensity > VII near the Pollino Range, whereas faults marked "a", "b", and "c" do show evidence of recent surface faulting events. The Vallo di Diano (VD), Val d'Agri (VA), Mercure Basin (MB), Morano - Castrovillari Basin (MCB), and Valle del Crati (VC) are the main Quaternary extensional basins (e.g. Bousquet and Gueremy, 1968; 1969; Lippman-Provansal, 1985; Ascione et al., 1993; Russo and Schiattarella, 1993; Tortorici et al., 1995), corresponding (with the exception of MB and MCB) to the main historical seismogenic structures.

However, the Pollino fault, that is the major neotectonic structure of the area ("a" in Fig. 1; see also Figs 2 and 3), shows evidence of late Quaternary faulting with the same style (normal), and at least the same (but probably a larger) amount, than that observed in the neighboring seismogenic structures (e.g., Bousquet and Gueremy, 1969; Bosi, 1987; Russo and Schiattarella, 1993; Ghisetti *et al.*, 1994; Tortorici *et al.*, 1995; Fig. 1). It is reasonable to assume that in the seismotectonic environment of the Central-Southern Apennines and Calabrian Arc, major Quaternary normal faults do represent the surface expression of seismic sources capable of strong events (magnitude 6.5 to 7.0; e.g. Michetti, 1994; Vittori, 1994; Tortorici *et al.*, 1995); the lack of documented creep along either the Pollino fault and any other normal fault within the Central and Southern Apennines rules out the occurrence of significant aseismic slip.

Therefore, this apparent disagreement between geological and seismological data may have two explanations: (1) the seismic potential is higher than that suggested by the historical record and the last strong earthquake occurred in pre-historical times, since then the Pollino region being seismically quiescent; or (2) the last strong earthquake is historical but unrecog-

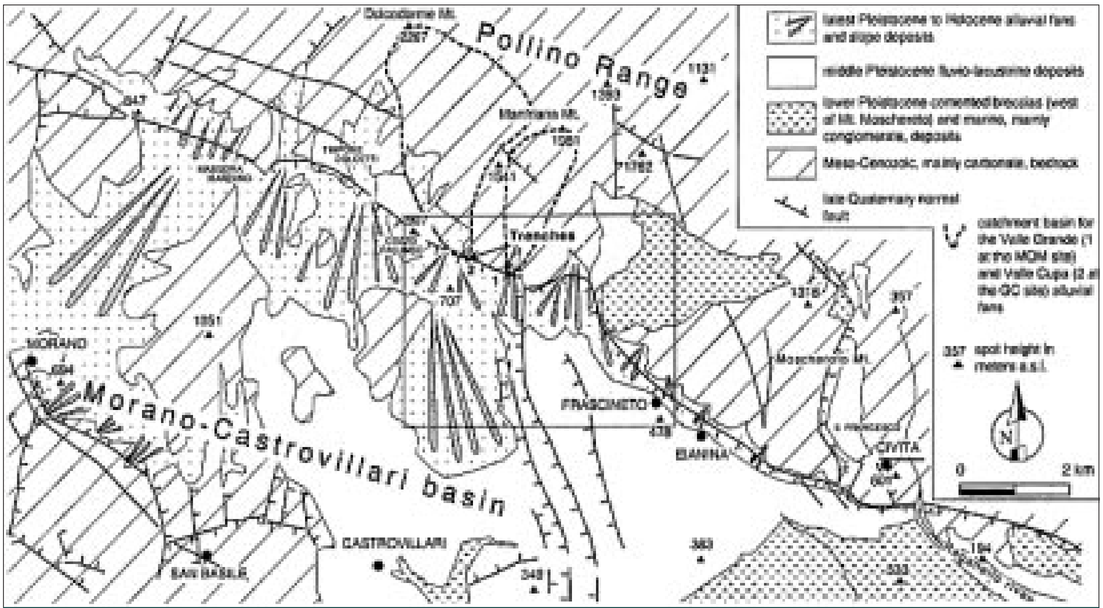

Fig. 2. Geologic map and late Quaternary faults of the Pollino region. Inset shows the location of Fig. 4

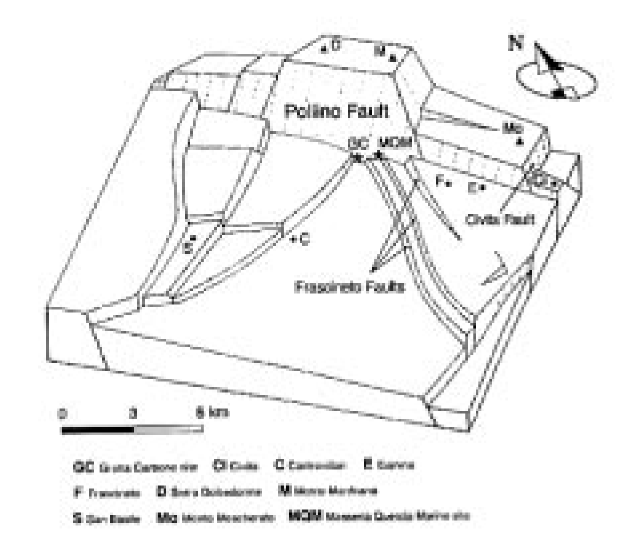

Fig: 3. Block diagram showing the structural relations in the Pollino region, near Castrovillari (after Bousquet, 1973, modified); dotted lines show the maximum dip on fault planes; the represented marker is the top surface of the lower Miocene. Post-lower Miocene vertical displacement on the Pollino fault reaches a maximum of ca. 3000 m, while post-lower Pleistocene vertical displacement reaches a maximum of ca. 400 m. Based on available geomorphic and structural data, since the beginning of the Quaternary extensional phase the N-S trending faults in the Castrovillari basin are interpreted as release faults (sensu Destro, 1995) confined within the hangingwall of a major active normal fault, the Pollino fault; likewise, cross faults developed in the Pollino fault footwall. In particular, recent activity is concentrated on the Civita and Frascineto faults.

nized, the catalogue is not complete, and the seismicity of the Pollino region is similar to that of the nearby areas. These hypotheses imply completely different scenarios for earthquake hazard characterization.

To address this issue, we firstly carried out field survey and airphoto interpretation along the range front generated by the Pollino fault, the related second-order faults (like the Frascineto cross faults, within the Pollino fault hangingwall, and the Civita fault, within the Pollino fault footwall; "b" and "c" in Fig. 1; Figs 2 and 3) and over the Morano-Castrovillari basin (Fig. 1), and then selected two sites for exploratory trenching across the Pollino fault. In this paper we summarize the results of our analyses in the Pollino region, and discuss the evidence for historical paleoseismicity. The initial findings from these investigations are described in Ferreli *et al.* (1994) and Vittori *et al.* (1995).

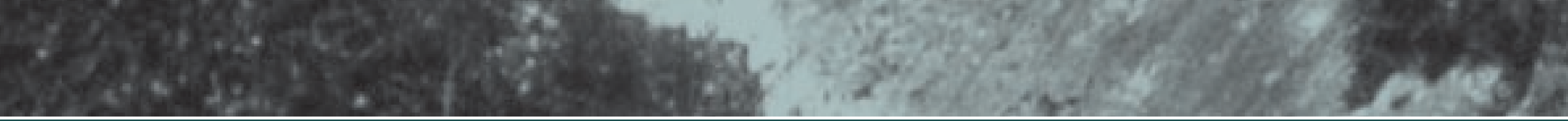

Table 1 – Radiocarbon samples

Samples	$d^{13}C$	Laboratory reported Radiocarbon Age[a], ^{14}C years B.P.	Calibrated Radiocarbon Age [b] (cal years at 2s)	Location [c] and Description
POL 2	-27,6	575 ± 210	1270-1615 A.D. (680-335 B.P.)	MQM1, top unit 1, wood
POL 4	-24,9	2470 ± 85	780-405 B.C. (2730-2355 B.P.)	MQM1, bottom unit 2, TOC [d] from colluvial soil
POL 6	-25,6	1030 ± 80	955-1150 A.D. (995-800 B.P.)	MQM1, top unit 2, TOC from colluvial soil
POL 7 *	-24,1	1451 ± 53	595-655 A.D. (1355-1295 B.P.)	MQM1, unit 2, charcoal
POL 8	-25,2	modern age		MQM1, unit 1 filling an open fissure, TOC from colluvial soil
POL 9	-24,4	1550 ± 75	425-610 A.D. (1525-1340 B.P.)	MQM2, unit 2, TOC from colluvial soil
POL 15	-24,5	2385 ± 75	750-390 B.C. (2700-2340 B.P.)	GC1, unit 2, TOC from colluvial soil
GC 1	-26.7	1355 ± 110	435-975 A.D. (1515-975 B.P.)	GC2, unit 2, TOC from colluvial matrix of debris
GC 2	-25.3	3705 ± 165	2565-1630 B.C. (4515-3580 B.P.)	GC2, unit 2, TOC from colluvial matrix of debris
GC 3	-25.1	5380 ± 130	4460-3950 B.C. (6410-5900 B.P.)	GC2, unit 2, TOC from colluvial soil
GC 4	-23.5	3240 ± 150	1880-1055 B.C. (3830-3005 B.P.)	GC2, unit 2, TOC from colluvial soil
GC 7	-23.2	4985 ± 90	3970-3635 B.C. (5920-5585 B.P.)	GC2, unit 2, TOC from colluvial soil
GC 8	-27.1	6095 ± 200	5435-4535B.C. (7385-6485 B.P.)	GC2, unit 2, TOC from colluvial soil
GC 11	-26.4	5075 ± 185	4330-3385 B.C. (6280-5335 B.P.)	GC2, unit 2.F3, TOC from colluvial soil
GC 13	-25.9	5840 ± 185	5215-4332 B.C. (7165-6280 B.P.)	GC2, unit 3.C, TOC from colluvial soil
POL 10	-25,0	19470 ± 395		colluvial soil within the alluvial fan deposits at Cava D'Atri, sampled at a depth of 6 m, TOC
POL 11	-25,6	14260 ± 200		colluvial soil within the alluvial fan deposits at Cava D'Atri, sampled at a depth of 3 m, TOC
POL 12	-25,6	25330 ± 1380		colluvial soil within the alluvial fan deposits at Cava A, sampled at a depth of 7 m, TOC
POL 14	-24,3	25915 ± 465		charcoal-rich colluvial soil within the alluvial fan deposits at Masseria Marzano, sampled at a depth of 5 m, TOC

[a] Radiocarbon analyses by GEOCHRON Laboratory, Cambridge, Massachusetts, USA.
[b] Age calibration calculated (cal) following Stuiver and Becker, 1993.
[c] Samples collected, for instance, at Masseria Quercia Marina site, trench 1, are marked as MQM1; Figs 2 and 4 show the map location of the sampling sites.
[d] TOC is for total organic carbon
* AMS dating

The Pollino fault

The Pollino region is part of the northwest-southeast trending Apenninic Chain built up as a thrust-and-fold belt essentially during the upper Miocene to lower Pleistocene (e.g. Royden *et al.*, 1987; Patacca *et al.*, 1992; Ghisetti *et al.*, 1994). Previous studies indicate that the Pollino fault firstly evolved in a compressional regional environment and was characterized by significant amount of both horizontal and vertical offset (Bousquet, 1973; Monaco, 1993; refer to Ghisetti *et al.*, 1994, for a critical summary of the pertinent literature).
At present, the Pollino fault is a WNW-trending structure (Fig. 2) characterized by an impressive range front with more than 1400 m of relief. The fault hangingwall hosts the Morano-Castrovillari basin, whose sedimentary filling reaches its maximum thickness (about 600 m of upper Pliocene to lower Pleistocene marine sequence plus about 300 m of middle Pleistocene to Holocene continental deposits; see Russo and Schiattarella, 1993, and references herein) against the fault plane. The N-S trending and antithetic faults in Figure 2, generated as second-order structures of the Pollino fault, also display clear evidence of late Quaternary activity. Our own data and previous structural and geomorphological studies (e.g. Bousquet and Gueremy, 1969; Bousquet, 1973; Russo and Schiattarella, 1993) clearly demonstrate that the

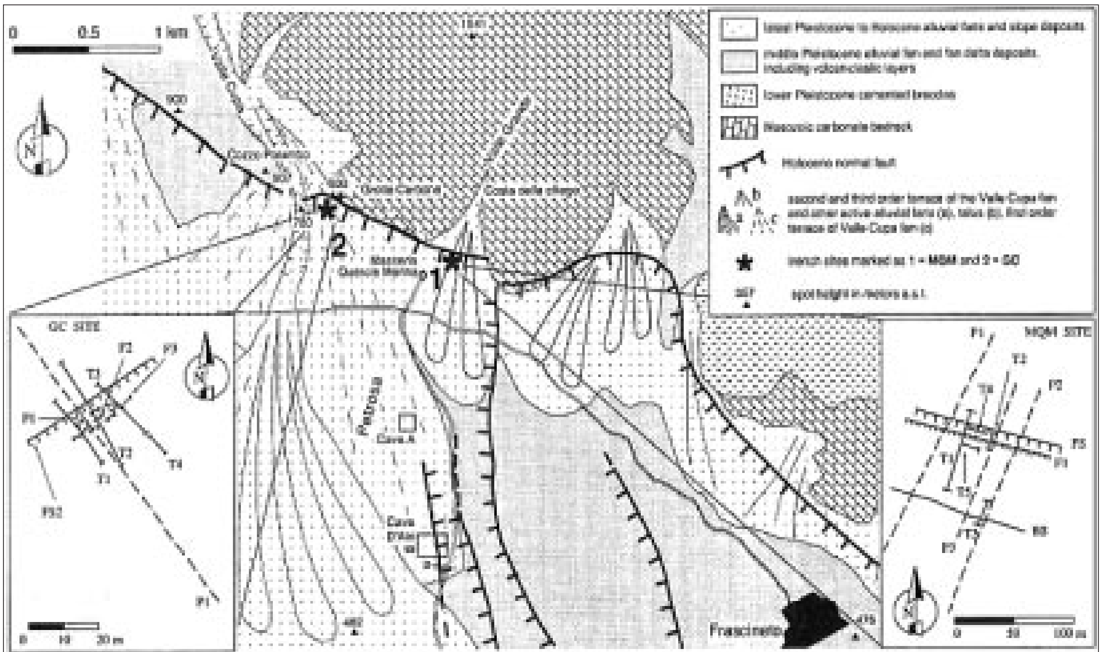

Fig. 4: Map of the trench sites area. Insets show detailed map of the trench sites: P) trace of the topographic profiles shown in Figs. 5 and 8; T) trench; F) fault; FS) fault scarp edge; BS) break in slope marking the boundary of the backtilted sector of the alluvial fan at MQM as illustrated in Fig. 5.

Pollino fault dominates the recent evolution of the region. Comparison of Figures 2 and 3 illustrates the hierarchy of active tectonic structures in the area. While part of the vertical offset is probably linked to pre-rift tectonic phases, inception of Quaternary extensional tectonics activated the Pollino fault as a major, purely normal fault. Consequently, the Morano-Castrovillari basin developed in the subsiding hangingwall of the Pollino fault, and second-order cross faults (Civita and Frascineto faults) formed. In particular, the Frascineto faults are typical *release faults* observed to form in the hangingwall of normal faults to accommodate extension along the strike of the dominant fault segment (Destro, 1995; Roberts, 1996). In the current stress field acting in the southern Apennines (e.g., Cello *et al.*, 1982) the above structural relations are the result of a NE- SW extension and of a strong regional uplift (cf. Bousquet, 1973; Ciaranfi *et al.*, 1983; Gasparini *et al.*, 1985). The nearby Mercure Basin (MB in Fig. 1; cf. Bousquet and Gueremy, 1968; Bousquet, 1973) shows a very similar setting, controlled by aspectacular WNW-trending active fault representing the extension of the Pollino structure; this demonstrates that the Pollino fault belongs to the main active and segmented normal fault system of the Southern Apennines (Fig. 1).

The nature of the Pollino fault is also corroborated by data from Ferreli *et al.* (1994), showing no evidence for significant strike-slip offsets in middle Pleistocene to Holocene landforms and deposits along the faults in Figure 2. The above data also allowed us to confirm the amount of late Quaternary normal displacement evaluated by Bousquet and Gueremy (1969) and Russo and Schiattarella (1993) along the Pollino fault and related minor faults (such as the Civita and Frascineto faults). Latest Pleistocene to Holocene displacement is apparent on the entire fault trace mapped in Figure 2. In particular, at Masseria Marzano fan deposits younger than 25,915 ± 465 ^{14}C years B.P. (sample POL 14, Table 1) are dragged and faulted, and similar relations exist near Timpone Dolcetti, as already illustrated by Bousquet and Gueremy (1969). Between Eianina and Civita, the range front base is oversteepened over a two km long section by a fresh limestone fault scarp showing associated features (non-karstified fault planes, thickening of Holocene talus against the fault planes, faulted Pleistocene breccias) typically observed along historical earthquake scarps in the Mediterranean region (e.g., during the 1915 Fucino earthquake, Serva et al., 1988; or the 1981 Corinth earthquakes, Jackson *et al.*, 1982; cf. Stewart and Hancock, 1994, and references herein).

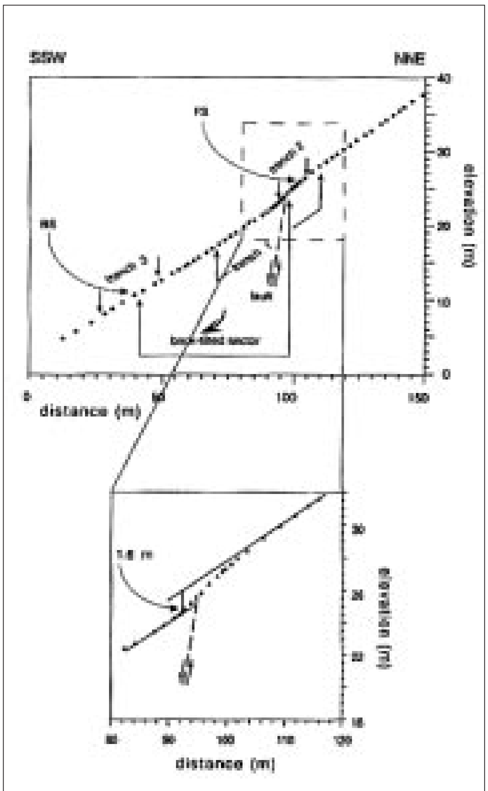

Fig. 5. Topographic profile at MQM (see location in Fig. 4); elevations relative to an arbitrary datum. Note the back-tilting of the alluvial fan deposits; no antithetic fault was found in trench 3, dug across its lower boundary (BS). The vertical displacement of 1.6 m across the main fault scarp (FS) is therefore greater than the net vertical tectonic offset at this site.

Ferreli et al. (1994) describe fault scarps affecting the apex of two adjacent young alluvial fans (Figs 2 and 4) at Masseria Quercia Marina (MQM) and Grotta Carbone (GC). Since it is reasonable to assume that the faulting history at these sites elucidate the most recent movements of at least the entire Masseria Marzano – Civita segment of the Pollino fault (about 18 km long), and this fault clearly controls the active tectonics of the whole area, we surveyed and trenched both the MQM and GC fault scarps in order to recognize evidence of the last surface faulting earthquakes.

Trench walls were mapped at 1:20 scale, and samples were collected for ^{14}C dating (Table 1) and soil analyses (P. Lorenzoni and M. Raglione, written comm., 1995). Since the stratigraphy of the trenches shows remarkable correspondences, we correlated the mapped units using the same unit numbers.

Masseria Quercia Marina site

The Pollino Range area, whose relief varies from more than 2200 m (Monte Pollino) to almost the sea level (Raganello River valley floor; Fig. 2), has a mountain-mediterranean climate characterized by 1000 - 1500 mm/yr of precipitation and 5 - 15° C of average temperature; at elevations higher than 1500 m the snow permanently covers the soil from December to March. The range front is essentially carved in carbonate rocks. This is the same geographic and lithologic setting of other intermountain tectonic depressions in the Apennines, like the Rieti basin and the Fucino basin in Central Italy (cf. Michetti *et al.*, 1995; Giraudi, 1995), where the latest Pleistocene to Holocene climatic history appears to be quite similar (e.g. Palmentola *et al.*, 1990). The latter features are relevant for interpreting the stratigraphy, morphology and faulting at MQM and GC sites.
The Valle Grande fan has a relatively small surface (Fig. 4) where active deposition still occurs during rare alluvial events; the present-day channel is not deeply entrenched. The deposition rate was much higher during the last glacial period, when the top of the Pollino range hosted significant glaciers (Palmentola et al., 1990) and the forest cover was completely removed from the slopes (cf. Watts, 1985). The scarp at MQM is very well preserved for most of its length within the fan surface, suggesting a very recent age of faulting. At the trench site the fault scarp is 1.6 - 1.8 m high, however, backtilting does amplify the net vertical displacement (Ferreli et al., 1994; see Fig. 5). Figure 4 shows the location of the trenches at MQM. The fol-

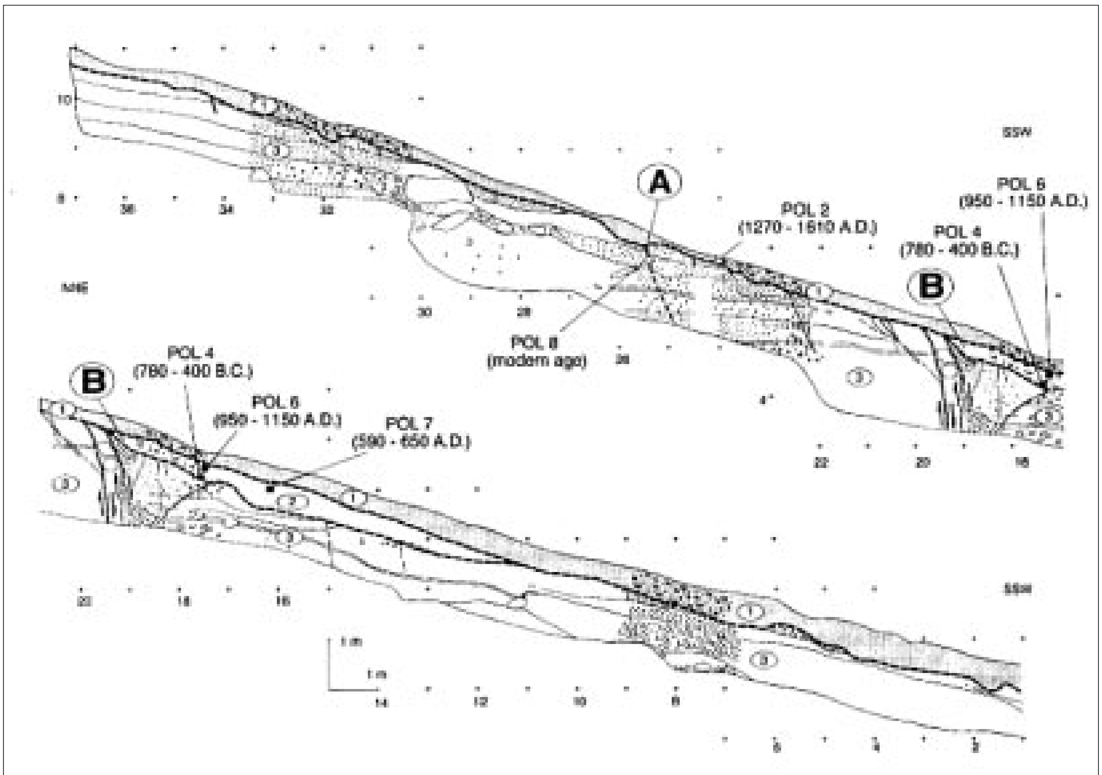

Fig. 6. MQM site, log of the eastern wall of trench 1 near the fault zone; the normal fault plane (marked by arrows) trends N108° and dips 70°S . Note location (black dots) and age (see Tab. 1) of samples (POL 2, etc.) collected for radiocarbon dating. Two main erosional surfaces (marked by bold dashed lines) separate the mapped depositional units (marked by encircled numbers): 1) upper colluvial soil, 10YR 3/2; 2) lower colluvial soil, 2,5YR 3/4; 3) bedded alluvial fan deposits made of carbonate clasts. A and B mark the evidence for the last and penultimate paleoseismic event.

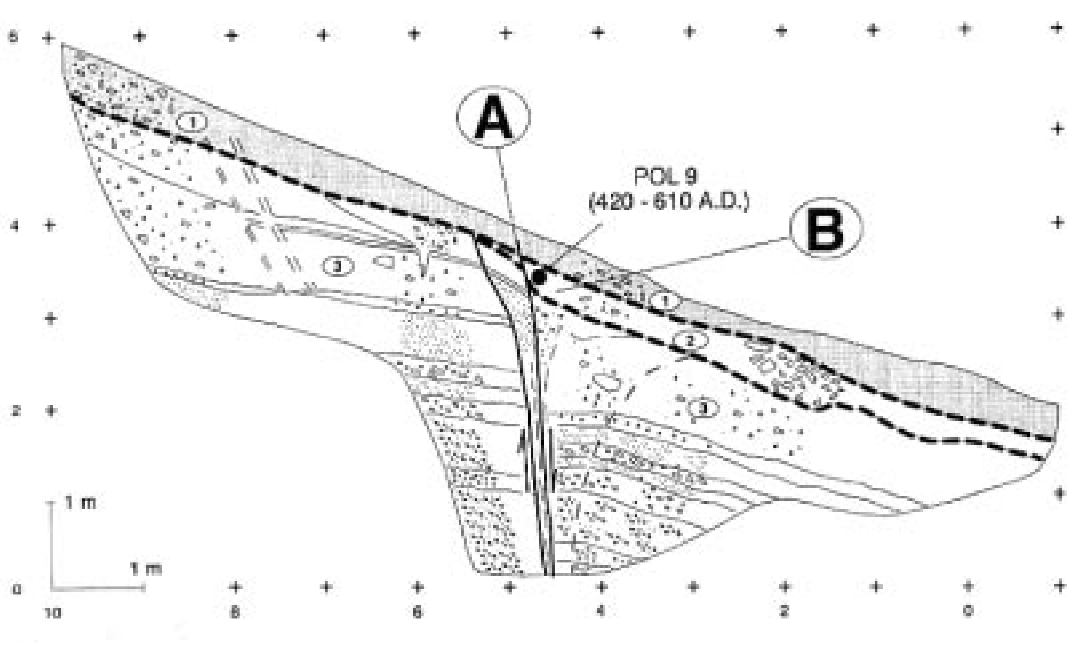

Fig. 7. MQM site, log of the eastern wall of trench 2; the fault plane has the same attitude as in trench 1. Symbols as in Fig. 6.

lowing discussion is based on data from trenches 1 and 2 (Figs 6 and 7) that illustrate evidence for past surface faulting events.

The fault plane visible in the trenches affects the fan deposits and two overlaying colluvial soils. The lower colluvial soil (unit 2 in Figs 6 and 7) thickens toward the fault plane, and is preserved only in a 8 m section of the fault hangingwall in trench 1 (Fig. 6). This indicates that when unit 2 was at the ground surface a movementof the fault, that we indicate as event B in the following (see Figs 6 and 7), produced rejuvenation of the scarp, and backtilting of the hangingwall. An erosional phase then removed unit 2 from the footwall and most of the hangingwall before deposition of unit 1. While we lack correlative units on both sides of the fault, the top of the alluvial sequence (top of unit 3 in Figs 6 and 7) indicates a displacement from event B of about 0.5 to 0.6 m; since the texture of unit 2 near the fault does not show evidence for the retreat of a big free face, this value can be seen as a reasonable approximation.

In trench 2 the fault also displaces a few centimeters of the upper colluvial soil (units 1.1 and 1.2), which also fills an open fracture in trench 1 (see "A" in Figs 6 and 7). On the whole, evidence for a fault movement younger than event B at this site is based on small effects, and we were at first very cautious about its interpretation. After finding a much more convincing evidence at GC, we now think that these effects may confidently be regarded as the fossil record of the last faulting event, i.e. event A.

Radiocarbon dating of charcoal from trench 1 (sample POL 7, see Table 1) shows that the deposition of unit 2 occurred in a time span comprised between 590 - 650 A.D. or later (the radiocarbon dates reported in the text and figures are the calibrated ages from Table 1 adjusted to the nearest decade), thus suggesting that the age of event B is younger than the VI century A.D. A similar timing is also corroborated by dating of total organic carbon (TOC) from unit 2 (POL 4, POL 6 and POL 9 in Figs 6 and 7), the corresponding ages being in agreement with stratigraphy and dating of wood from unit 1 (POL 2 in Fig. 6). This indicates that, despite the inherent uncertainty associated with the colluvial nature of this unit, the age of its organic matter correctly reflects the age of deposition at this site. Since unit 1 is the present-day soil, contamination from modern organic matter complicates accurate ^{14}C dating. However, dating of POL 2, while showing a wide age range due to the penetration of rootlets in the analyzed wood sample, suggests that the deposition of unit 1 originated before 1270 - 1610 A.D.; this is also the minimum age for event B. Pedological analyses indicates that the upper undisplaced section of unit 1 required at least 2 - 3 centuries to form (P. Lorenzoni and M. Raglione, writ. comm., 1995). To summarize, the time intervals comprised between the VI and XII century A.D. (for event B) and the XIII and XV century A.D. (for event A) represent our best estimate of earthquake dates at MQM.

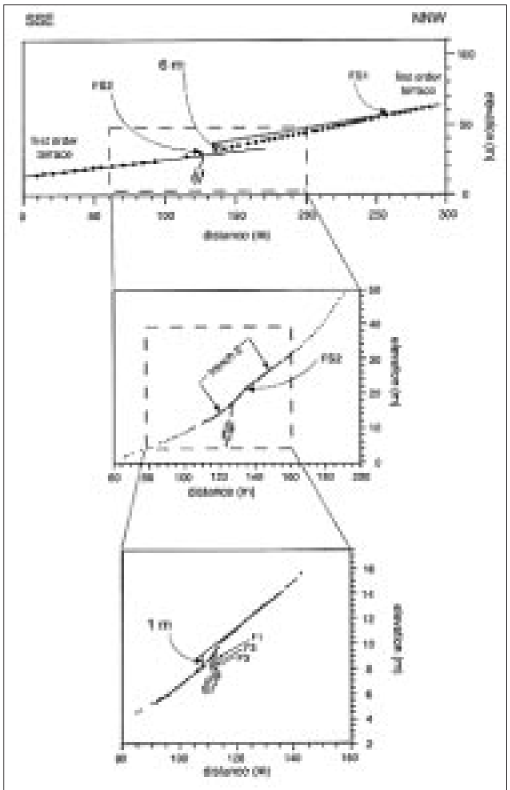

Fig. 8. Topographic profiles at GC (see location in Fig. 4); elevations relative to an arbitrary datum. Symbols as in Fig. 5. The upper profile includes both the main scarp (FS1) and the trenched scarplet at its base (FS2); the lower profiles were performed with increasing detail along the same trace.

Grotta Carbone site

The Valle Cupa fan has a catchment basin much wider than the Valle Grande fan (Figs 2 and 4), and this explains their different Pleistocene to Holocene evolution. While the Valle Grande fan has a regular surface with a feeble channel incision, the Valle Cupa fan displays three orders of recent terraces. Radiocarbon dating of colluvial soils (samples POL 10 and POL 11 from Cava D'Atri; and POL 12 from Cava A; ages in Tab. 1, locations in Fig. 4) beneath the first order surface in the piedmont belt strongly suggests that the corresponding phase of fan development started during the last Glacial stage and ended at about 14 kyr ago. For example, this is in very good agreement with the late glacial evolution of the Majelama fan in the Fucino area, in a similar geomorphic setting (e.g. Frezzotti and Giraudi, 1992); thus suggesting a common climatic control on this depositional phase.

The deposition rate during this phase at Cava A was higher than 0.6 mm/yr, and most likely higher than the corresponding vertical slip rate of the Pollino fault. This indicates that during this phase there was no fault scarp at GC, that is at the Valle Cupa fan apex. We assume that in the footwall of the Pollino fault the inception of fan apex entrenchment and, therefore, of displacement of the first order terrace surface, occurred at about 14 kyr B.P. Observations from trench exposures, however, show that at GC, that is in the Pollino fault hangingwall, the alluvial fan sedimentation continued until about 6 kyr ago (shortly after the deposition of unit 3.C and the dating of sample GC 13; Fig. 9); hence, downslope of GC the first order surface age increases with the distance from the range front fault. Topographic survey demonstrates that the first order surface offset at the main GC scarp (FS1 in Figs 4 and 8) is at least 6 m. Since we assume that the age of this surface in the Pollino fault footwall is about 14 kyr B.P., this yields a minimum vertical slip rate of 0.4 mm/year. This is consistent with the slip rate obtained from the GC trenches. The offset of the 7160 - 6280 yr old colluvial soil of unit 3.C (Figs 9 and 10; sample GC 13, Table 1) is greater than 2.5 m, yielding a minimum vertical slip rate of 0.35 - 0.4 mm/yr.

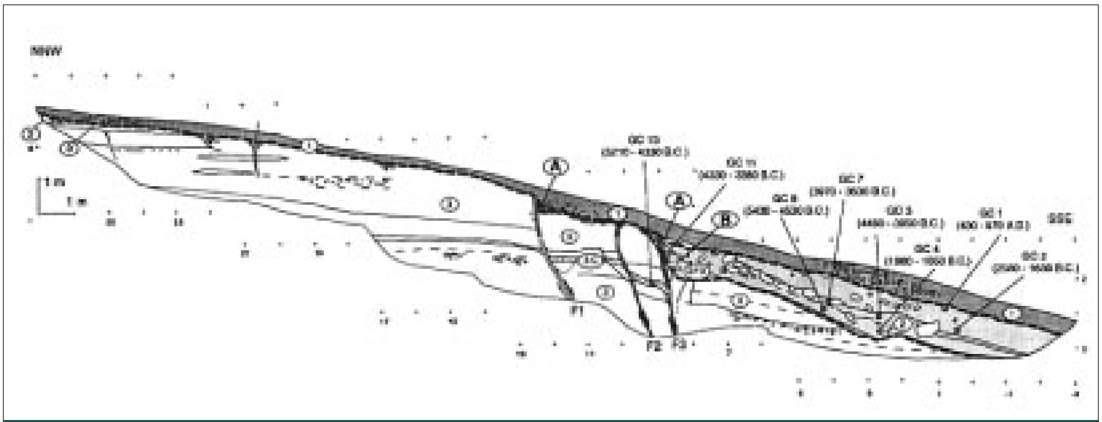

Fig. 9. GC site, log of the eastern wall of trench 2. The normal fault zone (fault planes F1, F2 and F3 are marked by arrows) has an average trend of N77° and dip of 70°S; however, the fault planes are not parallel to each other, as shown in Fig. 4. Note location (black dots) and age (see Tab. 1) of samples (GC 1, etc.) collected for radiocarbon dating. Two main erosional surfaces (marked by bold dashed lines) separate the mapped depositional units (marked by encircled numbers): 1) upper colluvial soil, 5YR between 2,5/2 and 3/3; 2) slope deposits including colluvial soils between 5YR 4/6 and 7,5YR 4/6, containing volcanic minerals, in the lower part, and carbonate debris in the upper part; 2.F3) colluvial wedge at the base of unit 2 near the fault plane F3; 3) bedded alluvial fan deposits made of carbonate clasts; 3.C) colluvial soil. A and B mark the evidence for the last and penultimate paleoseismic event.

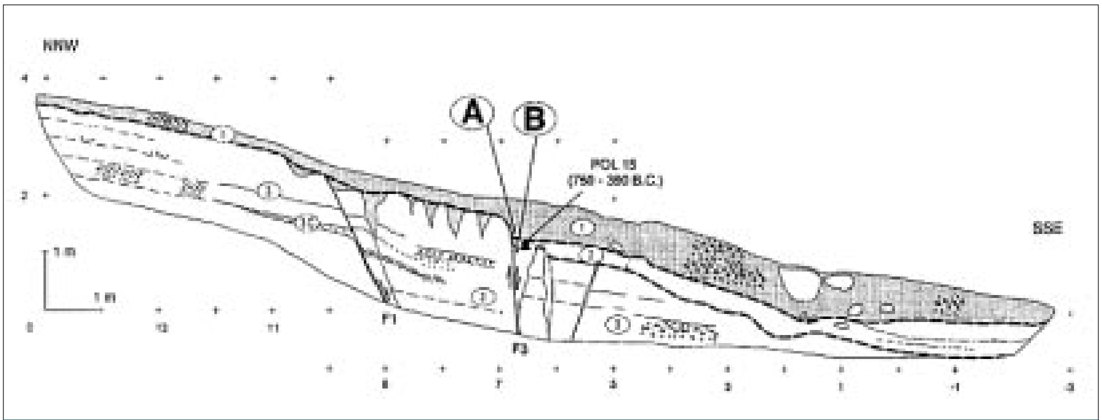

Fig. 10. GC site, log of the eastern wall of trench 1. Symbols as in Fig. 9.

A fresh scarplet located at the toe of the main scarp (FS1 in Fig. 8) marks the most recent fault movements at GC (FS2 in Figs 4 and 8). In the following we focus on observations from trench 1 and 2, dug across FS2, since these revealed the best record of past surface faulting earthquakes (Figs 9 and 10). The stratigraphy illustrates the final phase of the alluvial deposition, including a remarkable colluvial soil (unit 3.C), followed by two episodes of erosion and subsequent colluvial and slope deposition (Figs 9 and 10). The trenches exposed a normal fault zone composed of three listric discontinuity planes; only the fan deposits (unit 3) are clearly offset at each plane. The cumulative displacement of unit 3.C is significantly greater than that of the overlaying unit 2, evidence of faulting event(s) sealed by the first erosional phase.
Unit 2 is a slope deposit made of tephra-derived colluvial soils in the lower part and carbonate debris in the upper part. In trench 2 the lower part of unit 2 thickens close to the fault (Fig 9). The surface between unit 3 and unit 2 clearly indicates a degraded fault scarp free face, buried by the colluvial wedge of unit 2.F3. The height of this paleoscarp suggests that the causative event (event B, Fig. 9) produced a vertical displacement of about 0.8 - 0.9 m at F3; this is in good agreement with observations from trench 1 (Fig. 10). Moreover, in trench 2 at

F3 unit 2.F3 and unit 1 are affected by a younger faulting event (event A, Fig. 9) with a 0.1 m throw. Unit 1 is displaced by additional 0.2 - 0.3 m at F1. The cumulative vertical displacement for event A is therefore 0.3 to 0.4 m. This is consistent with the 0.4 - 0.5 m displacement estimated in trench 1 at F3 from the degraded fault scarp free face buried by unit 1 (Fig. 10).
Earthquake dates are not well constrained at GC because of 1) the lack of charcoal samples, and 2) the uncertainty involved in the interpretation of total organic matter dating from colluvial soils (see Table 1). Samples GC 3 and GC 4 show a chronostratigraphic reversal; sample GC 13, collected within the alluvial sequence (Fig. 9), has a ^{14}C age younger (see GC 8 in Fig. 9) or only slightly older (see GC 3, GC 7 and GC 11 in Fig. 9) than samples collected within the colluvial soils of unit 2. Furthermore, despite the similitude in the trench stratigraphy and pedologic features, most of the samples from unit 2 at GC appear to be significantly older than the corresponding samples at MQM. This different organic matter age and distribution in colluvial soils, that we interpret as correlative, may be explained by taking into account the different geomorphic setting at MQM and GC. The trench site at GC is near the first order terrace edge and 20 m above the present-day valley floor. The age of sample GC 13 clearly suggests that channel entrenchment took place shortly after 6 kyr B.P. The subsequent colluvial deposition at GC derives only from the nearby slopes, as also demonstrated by clast lithology and soil analyses (P. Lorenzoni and M. Raglione, writ. comm., 1995). In the Central Apennines, the major Holocene phase of soil development, forest expansion and slope stability occurred at 8 to 6 kyr B.P. (cf. Giraudi and Narcisi, 1995), about the same age range of samples GC 3, GC 8, GC 11, and GC 13 (Fig. 9). We therefore suggest that the organic matter produced during that phase was subsequently stored in the soils uphill from GC; this aged organic matter was then recycled at least twice in the trench stratigraphy, i.e. during the deposition of unit 3.C and during the deposition of unit 2. This reconstruction is consistent with typical features of colluvial deposition along Apennines carbonate mountain slopes (Giraudi, 1995; Michetti *et al.*, 1995; Frezzotti and Narcisi, 1996). For instance, a sharp climatically-controlled phase of soil erosion and re-deposition with stratigraphic inversion across a fault scarp has been documented by Lorenzoni *et al.* (1993) in the Rieti basin.
Based on the above considerations, we believe,that radiocarbon dates of unit 2 samples at GC record the age of the original organic matter, that is older than the age of the corresponding beds. Conversely, the internal consistency and the lack of reversals for ^{14}C ages at MQM strongly suggests that the active alluvial fan environment, where input of organic matter derives from periodical erosion of the whole catchment basin, allows satisfactory TOC dating. Therefore, to assess the age of faulting events at GC we follow the same chronological frame established at MQM, and interpret event A and event B as occurred in the same period at both sites.

Discussion and conclusion

Paleoseismic analysis at MQM and GC sites, located south of the Pollino Range, demonstrates that the Pollino fault ruptured during two historical surface faulting earthquakes. At both sites there is no evidence for significant lateral components of motion neither from displaced landforms nor from trench exposures, thus showing that the Pollino fault has had a mainly normal style of surface faulting. Our investigations and literature data strongly suggest that faults mapped in Figure 2 are presently acting as normal faults capable to produce surface displacement during strong earthquakes; indeed, Holocene reactivation has been proved for the Pollino, Frascineto and Civita faults (Ferreli *et al.*, 1994; Cinti *et al.* 1995a; in the latter, the Frascineto faults are referred to as "Castrovillari fault"). However, the structural and geomorphic setting definitely demonstrates that the master fault of the Pollino seismogenic structure is the Pollino fault (cf. Cinti *et al.*, 1995b).

Field observations and published data (Bousquet and Gueremy, 1969; Bousquet, 1973; Russo and Schiattarella, 1993; Ferreli *et al.* 1994) clearly show that the recognized events can be confidently associated with a rupture length of at least 18 km (Masseria Marzano - Civita segment, Fig. 2). Coseismic displacement from trench mapping is consistently larger at GC (0.8 - 0.9 m for event B, 0.4 - 0.5 m for event A) than at MQM (0.5 - 0.6 m for event B, less than 0.1 m for event A), in agreement with the suggested continuity of fault rupturing between the two sites. These features are coherent with contemporary surface faulting occurred in the Central and Southern Apennines (Serva *et al.*, 1988; Pantosti and Valensise, 1990) and corresponding paleoseismic evidence (Pantosti *et al.*, 1993; Michetti *et al.*, 1996), suggesting earthquake magnitudes ranging between 6.5 and 7.0 for both events A and B.
Although the ages from unit 2 at GC appear unsatisfactory, radiocarbon dating suggests that event B at MQM took place in the early Middle Ages, our best estimate being VI to XII century A.D. Radiocarbon dating and soil analyses also provide a basis for estimating the age of event A, our preferred range being XIII to XV century A.D. This is also in agreement with the very young faulted landforms. Main result of our study is, therefore, that two strong earthquakes are missing or unrecognized in the historical record of the Pollino region (cf. Valensise and Guidoboni, 1995, for a discussion of the available historical sources); accordingly, hypothesis (2) from the introduction appears to be the correct one. In other words, the present situation in the Pollino region might be similar to that of the Fucino basin before the 13.01.1915, magnitude 7, earthquake; i.e. the seismic catalogue until 1914 shows only subdued seismicity for this area, while paleoseismological studies (cf. Michetti *et al.*, 1996; Galadini *et al.*, this volume) found convincing evidence of strong historical events.

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North Calabria - 1783 and 1905 earthquake-triggered landslides

G. Chiodo[1], L. Merenda[1] and M. Sorriso-Valvo[1]

Most significant effects on the environment of several historical destructive earthquakes occurred in Calabria (Southern Italy) are briefly discussed.
As a preliminary result of a long-yterm study, a chronogical list of the Calabrian sites in which certain signs of sismo-induced landslides orderly have been reckonned, is produced. The data base so built also contains data on the seismic events as cause of the movement, on the geological, morphological and geothecnical features of the involved sites, and the information extracted by the historical sources. In the cases in which we have carried out the investigation on the ground, the database contains informations on typology of the movement according to the classification of Varnes (1978) and a synthetic evaluation of the damage.
Here we describe results derived from the study of three destructive earthquakes happened in Calabria in the 1638, 1783 e 1905 AD. The last two earthquakes will be illustrated, as data for 1638 event are poorly reliable. Two localities with seismo-induced landslides by this earthquakes will be visited during workshop, S. Lucido and Martirano Lombardo, north Calabria.

Itinerary of 2001 September 25 excursion.

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1 - The March 23, 1783 earthquake

The 28th March, 1783 earthquake was one of the most destructive earthquakes of Calabrian region in historical times.
This earthquake was the last of the five strongest earthquakes occurred in the period February-March 1783 (Tab. 1), that were part of a seismic period continued for about four years from 1783 to 1786. The total number of casualties, including those due to the epidemic waves and other aftershocks, reached 35.000 (Vivenzio 1783).

The first three earthquakes involved an area located in Southern Calabria (the Gioia Tauro plain) and Messina Straits. In the last strong earthquake of 28 March, the epicentral area migrated northwards in the Catanzaro area.

Tab.1: Table of the 1783 Earthquake of Calabria; I_0 = seismic intensity at the epicentre; I_{max} = maximum observed seismic intensity. *M* = derived magnitude. Data from CPTI Working Group, 1999

Major 1783 earthquake	I_0	$I\ max$	M_m
1783/02/05	XI	XI	7.1
1783/02/06	IX	X	5.8
1783/02/07	X-XI	X-XI	6.8
1783/03/01	VIII-IX	IX-X	6.0
1783/03/28	X	XI	6.6

The distribution of intensity of the 1783 28th March in the central part of Calabria is shown in Fig.1a. The geographic distribution of phenomena most probably related to earthquake-induced landslides is shown in Tab. 2 and Fig. 1b.

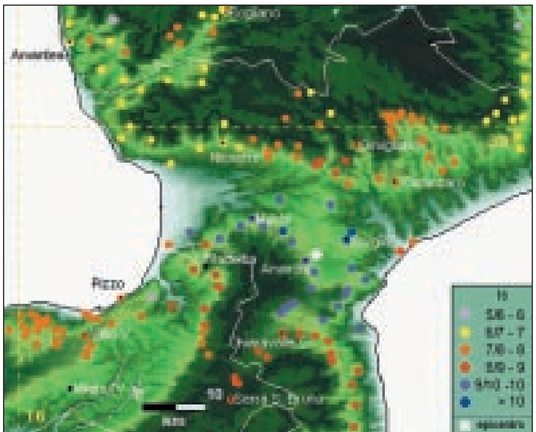

Fig. 1a. Distribution of intensity (March 28, 1783 earthquake). (Camassi & Stucchi, 2000)

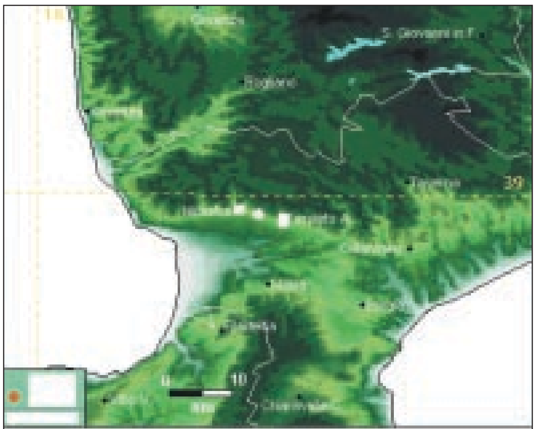

Fig. 1b. Landslides (*frane* in the legend) triggered by March 28, 1783 earthquake.

Table 2 - Sites with landslides and their distance from epicentre (March 28, 1783 earthquake)

Sites	Distance from epicentre	Sites	Distance from epicentre
Aiello Serra	4	Maida	12
Altilia (CS)	43	Marano Marchesato	53
Amato	15	Marcellinara	13
Borgia	2	**Martirano**	**36**
Caraffa	7	Pedace	53
Di Catanzaro		San Floro	4
Carolei	55	**San Lucido**	**70**
Cortale	7	San Mango	36
Girifalco	7	San Sostene	19
Laurignano	60	Squillace	3.5
Figline V.	49	Vallelonga	25

2 - The 1905 earthquake

The 8th September, 1905 earthquake was one of the most destructive earthquakes in XX[th] Century, in Italy. The cities and villages damaged by the earthquake were 326. Casualties totalled 600, and 300,000 people remained without cover.

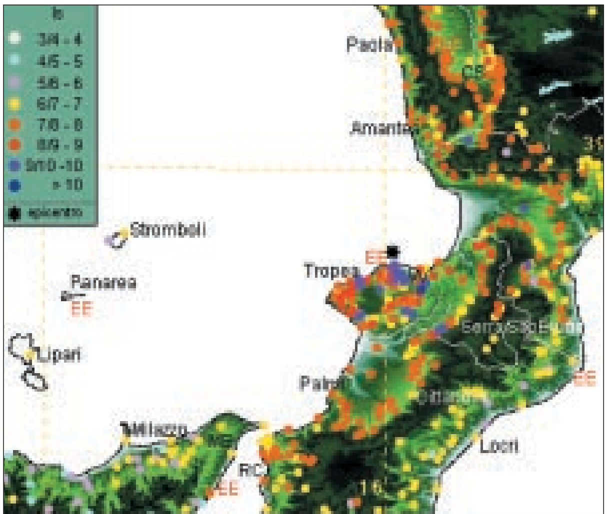

Fig.2a. Distribution of intensity (September 8, 1905 earthquake). In (Camassi & Stucchi,2000)

In the CPTI working group, 1999 report, the most recent publication on strong Italian earthquakes, it is reported an intensity of XI on the Mercalli scale, and a magnitude of 7.1 with the epicentre located offshore, in the S. Eufemia Gulf (Fig. 2a).

Table 3 – Sites with landslides and their distance from epicenter of 1905 earthquake.

Sites	Distance from epicentre	Sites	Distance from epicentre
Acri	90	Guardavalle	48
Aiello Calabro	40	Majerato (Angitola)	12
Amaroni	32	Marcellinara	40
Amato	35	**MARTIRANO**	**38**
Belmonte Calabro	42	Mileto	20
Briatico Vecchio	10	Parghelia	16
Caraffa di Catanzaro	38	Ricadi	24
Caulonia	57	Rosarno	32
Cessaniti	10	San Floro	39
Cirò	110	San Gregorio di Ippona	14
Cleto	38	San Leo Diruto	12
Conflenti	38	San Martino di Finita	80
Conidoni	10	Santa Sofia d'Epiro	88
Cortale	30	Seminara	50
Curinga	22	Stefanaconi	12
Dinami	28	Tiriolo	44
Feroleto Antico	34	Triparni	10
Filandari	16	Tropea	18
Gerocarne	24	Vallelonga	24
Gizzeria	26	Vena (VV)	12
Fitili	14	Zungri	16

The distribution of the 8th September of 1905 intensity is very irregular and the localisation of the epicentre from macroseismic data has been so far much debated.
In the sites near the Mt. Poro area, and in few more sites into and near the Savuto River Valley, the intensity reached higher value when compared with the nearby localities; in the same sites, contemporary reports indicate the presence of landslides occurred contemporaneously and shortly after the earthquake, but it is not clear what was the real space-time relationship between seismic event and instability phenomena. We could note that some phenomena are replicas of landslides occurred during earthquakes dating since 1600.

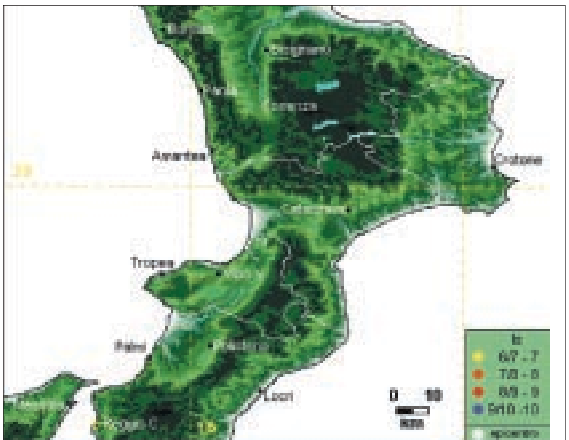

Fig. 2b. Landslides (*frane* in the legend) triggered by the 1905 earthquake. White lines are the province boundaries.

The distribution of intensity of the 1905, March 9th in the central part of Calabria is shown in Fig. 2a. The distribution of landslides most probably triggered by the earthquake is shown in Fig. 2b.

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The ancient large land-slide of Mount Martinella – San Lucido (CS), in the calabrian coastal chain, and its reactivation by the calabrian earthquakes of 1783

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Studies of landslides distribution carried out many years ago (1980 – 1990) in the Calabrian "Catena Costiera" (Coastal Range), have shown that landslide phenomena of various type, age and degree of activity were widely diffused throughout the entire Range; often they are of quite considerable dimension.

A large landslide phenomenon, located on the western side-slope of the Tyrrhenian Coastal Range, developed from an elevation of about 1100 - 800 m a.s.l., over a length of 5 km and an average width of 2-3 km (with an area of about 10-15 km^2), in the area of Mt. Martinella – Falconara Albanese and San Lucido (province of Cosenza).

Evidence of numerous events of general and paroxysmal activation ("diastrofic movements") have been recognised. One of these reactivations is certainly correlated with the 1783 Calabrian earthquakes, occurred between February 5th and March 28th (Fig. 1). Currently, the slope movement is believed not to be exhausted; indeed, it still causes strong marine erosion, together with stability problems to important infrastructure facilities, such as the state road SS.108 and the railway, as well as to urbanised areas rather densely populated.

The Coastal Range is composed of calcareous-dolomitic nappes of the Apennine Chain, tectonically overlain by metamorphic rocks belonging to the nappes of the Calabrian Alpine Chain; in some places the former units crop out in tectonic windows.

Conspicuous and rapid uplift occurred in the Range, particularly during the Quaternary, through a wide distribution of faults and joints, producing the present "horst" configuration comprised between the "grabens" of the Crati valley and Tyrrhenian basin. Tortonian to Quaternary sedimentary sequences overlie the eastern and western flanks of the Range; these are also to be found at high altitude.

In the Middle-Lower Pleistocene, as a consequence of a left transcurrent fault (with a NNE direction) crossing the Falconara Albanese-San Lucido area, these units were affected by tectonic deformation of "pull-apart" type, which was probably re-activated by ancient earthquakes and by the 1783 tremors as "lateral spreading" and associated typology of more superficial "complex" landslides and flows.

Gneiss and underlying phyllites make up the basement of the landslide area. These are overlain by Miocene formations (conglomerate, sandstone and limestone) and Pleistocene continental conglomerate. Deep ruptures and dislocations are to be observed in these formations, also produced by mass movements.

Events of the year 1783

According to the chronicle of the times, from Autumn 1782 till the end of January 1783 "continual and intense" rainfalls in Calabria caused landslides and floods throughout the entire region (Sarcone, 1784).

[1] CNR-IRPI, Cosenza

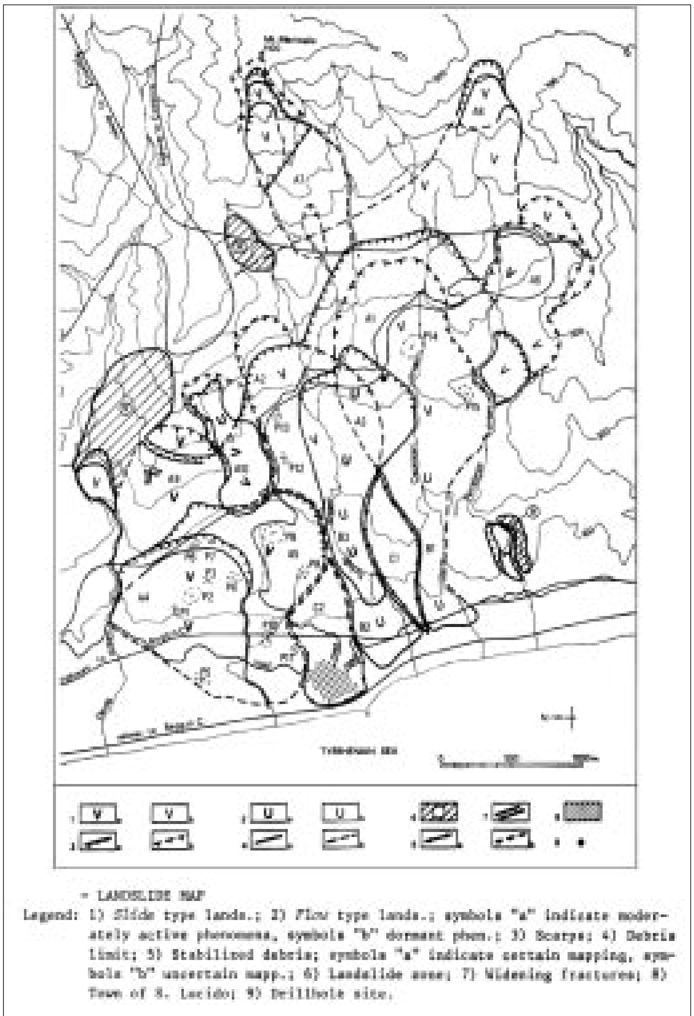

Fig. 1. The S. Lucido landslide.

Since no quantitative data obviously exist, it is impossible to establish whether, and to what extent, the circumstances were all that exceptional. The existing evidence does however point to a flooding stage accompanied by a widespread triggering of slope movements.
While the stability of slopes was in these precarious conditions, the climax of one of the most devastating periods of seismic activity ever experienced in Calabria occurred: between February 5th and March 28th 1783 the five principal seismic shocks which hit the region ranged in intensity from IX to XI degrees MCS. These shocks, which primarily involved the area south of the 39th parallel, caused tens of thousands of victims and altered the morphology of the zone to such an extent that several hundreds of lakes were formed along the streams dammed by landslides (Cotecchia *et al.*, 1969; Iaccarino, 1978).
According to Sarcone (1784) ground movements started in the San Lucido area towards the end of December 1782, accelerated during January 1783 and finally became disastrous in February, after the first strong earthquake shock happened.
A committee from the "*Reale Accademia delle Scienze e delle Belle Lettere del Regno di Napoli*" (Royal Academy of Science and Arts of the Kingdom of Naples), which was led by Sarcone himself, sailed for Calabria in the following month of April.

The aim of the expedition was to:
i) check the extent of the damage;
ii) revise the maps of the region;
iii) examine the problem of how to drain the landslide lakes.
The Neapolitan scientists carried out a survey of the San Lucido area on April 12th and 15th 1783. They ascertained that the ground was still in movement and found what they describe in detail in their report as a "total disaster" (Sarcone, 1784). Draughtsmen employed by the committee prepared a very interesting map of the area which, albeit presenting some problems of interpretation, essentially corroborates our own survey (fig.1.b, North Calabria - 1783 and 1905 earthquake-trigged landslides).
It seems worth mentioning two other points which can be deduced from Sarcone's report:
i) the slope movements, in so far as they are described, appear to belong to the class of "*complex landslides*", as defined by Varnes (1978) in the upper part of landslide, followed by "*flows*" type downslopewards. This fully agrees with our data.
ii) accoprding to the description of the sliding materials, at depth it is of the same type as those encountered from 9m to 68m in our exploratory drillholes.
Unfortunately, the language used in the report is not always perfectly clear and some uncertainties arise. It is however clear that the committee members understood the inherent instability of the area. which they attributed to its lithology and geomorphic setting. They also appear to have understood the accelerating effect that an earthquake has on landslides.
Since then, two centuries have passed. Nowadays the area is rather densely populated: in addition to the town itself, it is dotted by many houses and small farms. Moreover, two highways, one important railway (two until few years ago), roads, aqueducts and power lines pass through or close to it. All this accounts for social and economic importance for this ancient and large landslide.

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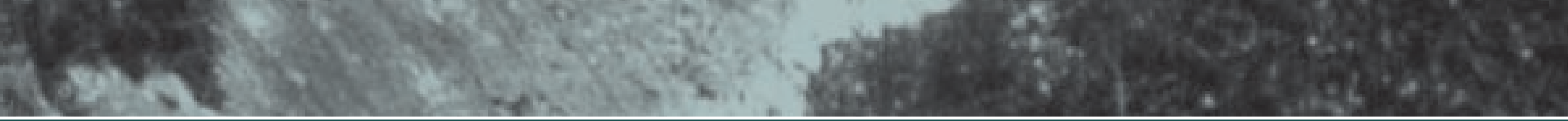


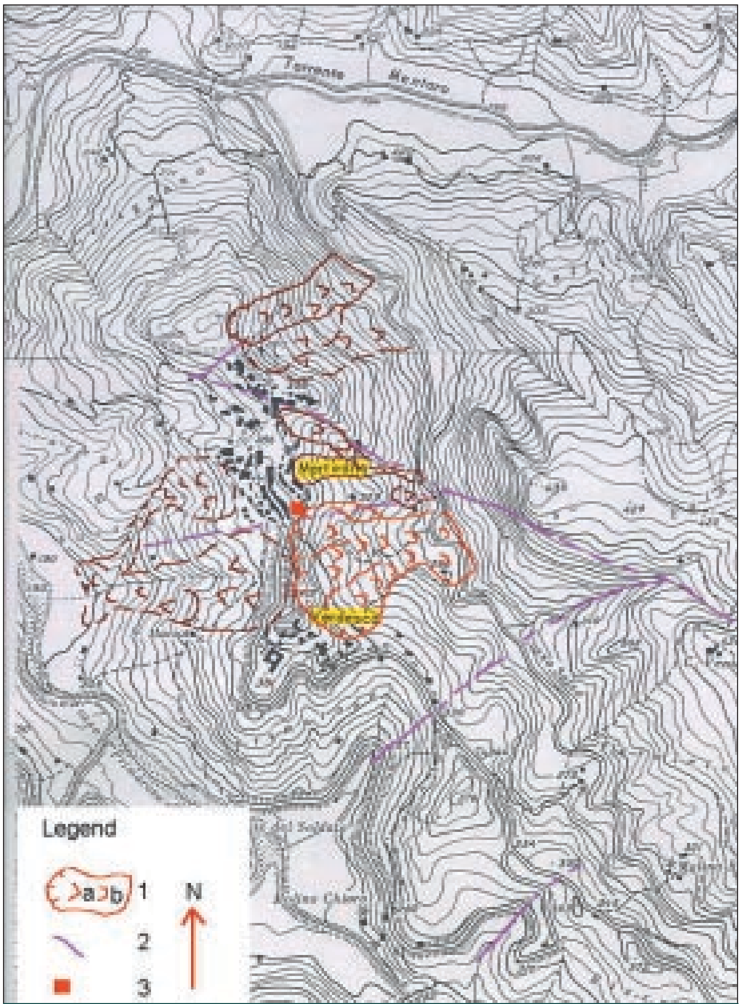
Martirano (CZ). Landslide reactivated by the 1638 and 1905 earthquakes

Martirano Lombardo is a village settled in the river Savuto valley, north-west Calabria, on the top of hill with steep slopes.
The Geology of the site is rather complex: Upper Miocene sands and sandstones lye unconformably over allochtonous terranes made of Jurassic limestone overlying Paleozoic phyllites and granite belonging to the Alpine Units. Landsliding affets a great part of the hill (Fig. Next page).
This area suffered several historical earthquakes, that destroyed Martirano at least eigth times. The last three events occurred in 1638, 1783 and 1905 (see table bellow).
Landslides were reported in occasion of all three earthquakes, but it is certain which landslides moved only for 1638 and 1905 events.
After the 1905 event the village was split in two: part of people remained in the ancient village, part moved to the new Martirano Lombardo site. The new site is the one visible from the A3 freeway.
From the reports on the 1905 earthquake, it appears that an entire side of the village, named Verdesca, was completely destroyed by a large landslide (table below: *"...una frana fece precipitare in basso un colle...(oriente)...con tutte le abitazioni"* = "a landslide knocked down a hill....(east)...with all the houses,...". The same zone was involved by a landslide during the 1638 earthquake (*sdrucciolando in ruine* = rolling down in a mess).
This landslide is recognisable today. It is shown in Plate 1 (provided separately from this text), where the main geomorphologic features of the old Martirano zona are displayed.
In 1638, liquefaction phenomena occurred in the river Savuto alluvial deposits; these phenomena produced deep depressions and ground craks, from which sulphur-stinking steam was ejected.
Today, the old village is still suffering problems due to mass-movement.

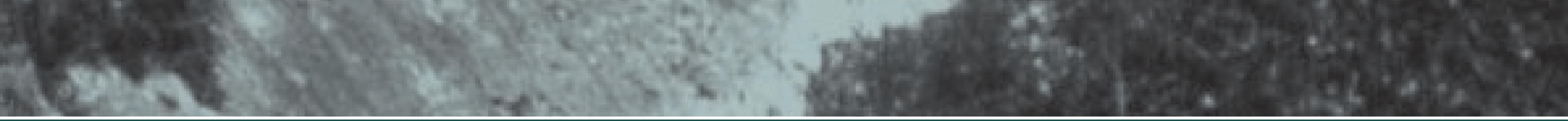
HISTORICAL SEISMICALLY-TRIGGERED LANDSLIDES IN MARTIRANO (CALABRIA)

Date/ I Max	I Site	Transcription	Source
1638-03-27 XI	XI	*"Parte del monte della città si squarciò dall'un fianco, e **sdrucciolando in ruine** occluse il corso del fiume Bisanto, e dall'altro lato, dove declina in pianure, e fremendo vi scorre il fiume Acherone, hoggi volgarmente Savuto, s'aperse la terra in vaste voragini e in pozzi profondi; esalandone fuori le fetide nebbie di solfo, per oltraggiar il medesimo cielo, e palesar in Calabria un verace Acheronte. Pochi mesi da poi io mi condussi, per officio civile verso quel buon prelato, e per osservar di presenza gli effetti strani del terremoto….."*	D'Orsi (1640) Di Somma (1641)
1783-03-28 XI	VII	Il territorio si trova sconvolto dà movimenti……	Vivenzio (1784)
1905-09-08 X-XI	X	*"La montagna si squarciò in più punti, e ne scaturirono getti di acqua bollente…"* *"**Una frana fece precipitare in basso un colle** soprastante da questo lato (oriente) con tutte le abitazioni, sicchè passare era pericoloso tanto da sopra, quanto nel precipizio ch'era di sotto* *[…] mi aiutarono a passare per quella striscia larga 20 cm e per buoni 20 metri che s'era formata sul cedevole terreno, mentre sotto di noi s'apriva un abisso …"* ***"** Infine quasi tutte le vittime (16 su 17 morti) furono nella frazione Verdesca […] fondate su una molassa miocenica molto franabile…"*	Rizzo (1907) Cotroneo (1905) Mercalli* (1906)

[1] CNR-IRPI, Cosenza



The Martirano area. The landslide in red is the one reported as triggered off by the 1638 and 1905 earthquakes.
Symbols of the Legend: 1 = landslide; a = earth/rock slide; b = earth flow; 3 = stop site.



The seismicity of Martirano area

Prof. I. Guerra[1]

The figures accompanying these notes (Fig. 1) represent at different scales two areas, both centred in Martirano, and the instrumental seismicity resulting from the catalogue of the Geophysical Laboratory at the Calabria University. Seismic foci have been located by using mainly the data acquired by the Regional Seismic Network of Calabria, managed by this laboratory, and those published by all the other scientific institutions operating in the area, first of all the Italian National Institute of Geophysics.
The full square identifies the Martirano's location, while the open circles correspond to the epicentres located since 1986 up to May 2001, selected on the basis of the precision of their focal parameters. Only earthquakes at depths less than 40 km have been retained. The magnitude of the shocks is generally very low. If one accepts the definition of micro-earthquakes as the shocks characterised by magnitude less than 3.0, the two maps are better called microseismicity maps.
Seismic events prior to 1986 have not been taken into account because the quality of the instrumental parameters in the years preceding the eighties in not finer than the corresponding locations by typical macroseismic methods.

The instrumental seismicity recorded in Calabria in the last years shows, particularly on the maps at small scale, several clusters of epicentres that allow to identify some areas characterised at the present by a more intense seismic activity. The correlation between tectonic structures responsible for the great historical earthquakes and the present-day instrumental microseismicity observed on a span shorter than twenty years is not an obvious matter. It results particularly questionable in Calabria, where the main seismogenic structures are quiescent since nearly a whole century, after the paroxysmal activity in the years 1783-1908. It is supported however by the observation that the areas with denser seismic clusters coincide with those where the amount of the released seismic energy more frequently in the last years has exceeded the perceptibility threshold.
With these limitations, the present-day micro-seismicity maps indicate that no cluster of the presently more intense seismic activity is located near Martirano. This site falls in a relative seismicity minimum, so that the hypothesis is strengthened that the effects of the earthquakes of March 27, 1638 and September 8, 1905 had their severity enhanced there by factors related to local geological-geomorphological conditions.

This statement is supported by the results of the analysis of the macroseismic filed carried out at the Geophysical Laboratory. The work involved the fitting of the macroseismic field resulting from contemporary historical chronicles to the well-known Blake's law on the attenuation of the seismic intensities. In spite of the simplicity of the numerical model and the contrasting complexity of the geological structures, the agreement between experimental data and theoretical model came out very strict. The intensity X of the MCS scale assigned to Martirano in this study is greater than the theoretical value corresponding to the best-fit model, so that this datum represents a positive anomaly of the macroseismic field. Of course, the anomaly could be much more pronounced repeating the same analytical procedure by using the intensity values assigned in the Catalogue of Strong Earthquakes in Italy by Boschi et al. (1995): these authors infact assign to Martirano the degree XI of macroseimic intensity.

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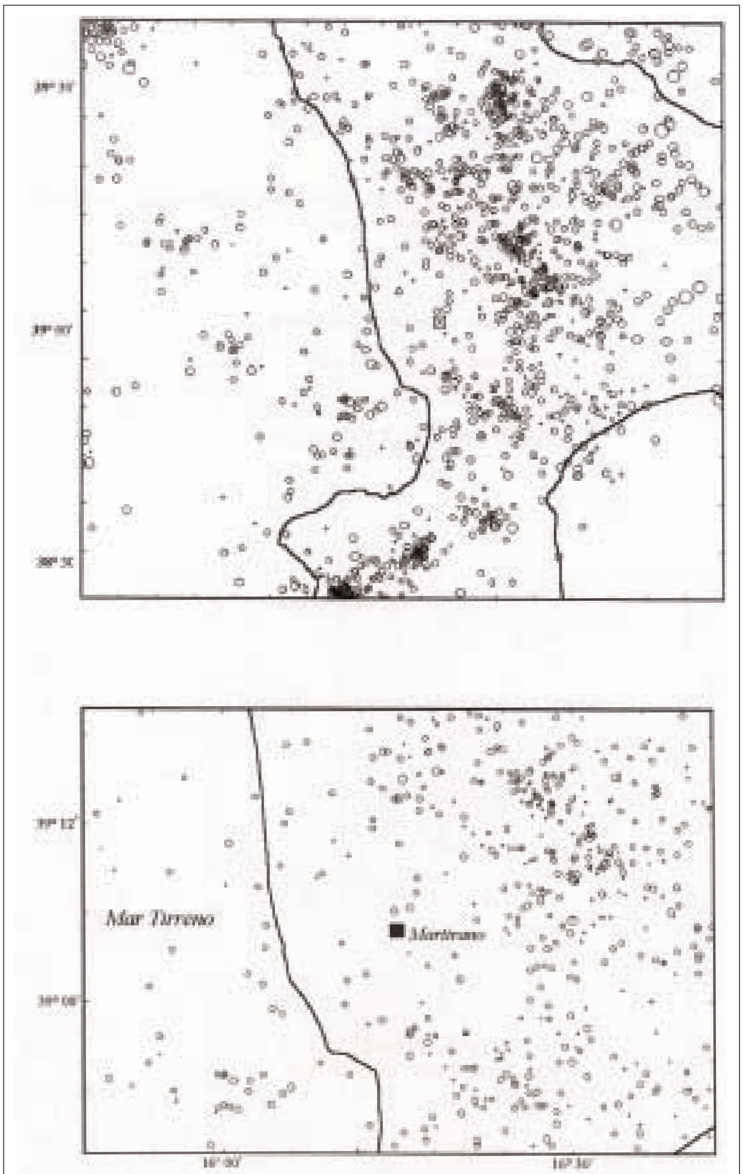

Fig. 1. Instrumental seismicity resulting from the catalogue of the geophisical Laboratory at the Calabria University

The same algorithms have been successively applied to the macroseismic observations of the 1905 earthquake. On the basis of the results obtained in this case, it is impossible to fit the data to the Blake's and other common mathematical models. It is noteworthy that the unusual space distribution of the macroseismic effects was already noticed by contemporary authors like Baratta and Mercalli. However, the strong positive anomaly of the intensity at Martirano in this case is evident in the same observational data. Again according to Boschi et al. (1995) intensities of the degree X or greater were observed in fifteen sites: fourteen are located on the Mt Poro promontory; the last is just Martirano, well away from all the others.

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