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The 1998-1999 Pollino (Southern Apennines, Italy) seismic crisis: tomography of a sequence

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Abstract
In 1998-1999 a seismic sequence occurred in the Southern Apennines, after the moderate size (m_b=5.0) 9th September 1998 Pollino earthquake. It lasted about 14 months and was clearly localized to the sole north-west area of the main shock epicenter. Its peculiarity consisted in sudden changes of activity from a series of normal faults with Apenninic (NW-SE) trend and transfer, presumably strike slip, faults with Antiapenninic (NE-SW) and E-W trend. The complexity of the behavior and the different orientations of the activated systems suggest that the area acts as a hinge between the NW-SE trending Southern Apennines and the locally N-S trending Calabrian Arc.

Key words *seismic sequences – stress field evolution – Southern Apennines – Calabrian Arc – Pollino Chain*

1. Introduction

Earthquakes play a fundamental role in depicting the ongoing geological processes because they make possible the location of the active structures and the characterization of the stress and strain fields. Therefore the occurrence of seismic events becomes the occasion for clarifying tectonic relationships in areas of increased interest. This is especially true when they hit areas of moderate seismicity, where even a magnitude 5.0 event can furnish significant information on the geodynamical regime and in particular where the boundaries between tectonic major domains are not well defined.

For these reasons we focus on the seismic sequence that followed an earthquake located on the western slope of the Pollino Chain (Southern Italy). This seismic event occurred on 9th September 1998 and caused some damage in several towns and villages located in the mesoseismal area (Galli *et al.*, 1998), attaining a maximum intensity of VII MCS.

The whole sequence was confined to the upper 15 km of the crust and involved the sedimentary cover of the region where two important contacts exist. At the surface there is the boundary between the Apenninic Chain and the Calabrian Arc; more in depth there is the limit between the Adriatic and the African plate. These contacts are not yet well understood either at subduction on crustal levels.

2. Geodynamic setting

From a geodynamic viewpoint, Southern Italy is divided into two regions. The southern-

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most one, the so-called Calabrian Arc, is the area where the Ionian lithosphere still subducts beneath the Tyrrhenian Sea; the subduction is characterized by an eastward rollback (*e.g.*, Malinverno and Ryan, 1986; Doglioni *et al.*, 1996). North of the Calabrian Arc there are the so-called Southern Apennines that constitute the accretionary prism of the Adriatic plate subduction (*e.g.*, Doglioni *et al.*, 1996, and references therein); on the basis of geological evidence the hinge of this subduction has been migrating northeastward up to the Pliocene; at present it is thought to be quiescent. These two geodynamically separated regions meet in the Pollino Chain (fig. 1a,b). This latter, broadly shaped as a triangle due to its short E-W extension, is bordered to the south by the Sibari Plane, to the north-east by the Metaponto plane and to the west by the Mercure Basin.

The main structural lineaments shown in fig. 1a,b are taken from Valensise and Pantosti (2001).

It is noteworthy that the tectonic style of the Southern Apennines is broadly dominated by a NE-SW oriented tensile stress field (Amato and Montone, 1997) that generates a series of normal fault systems with longitudinal trend. They are usually recognized to dip northeastward and are displaced by shear fault systems with Antiapenninic trend. The southernmost normal system that exclusively yields this feature is the Agri Valley, bordered to the south by the Policastro Gulf-S. Arcangelo Line.

The extensional systems are characterized by large earthquakes. According to the CPTI catalogue (Gruppo di Lavoro CPTI, 1999), the main known seismic event in the Agri Valley is the 1857 earthquake that caused over 10000 ca-

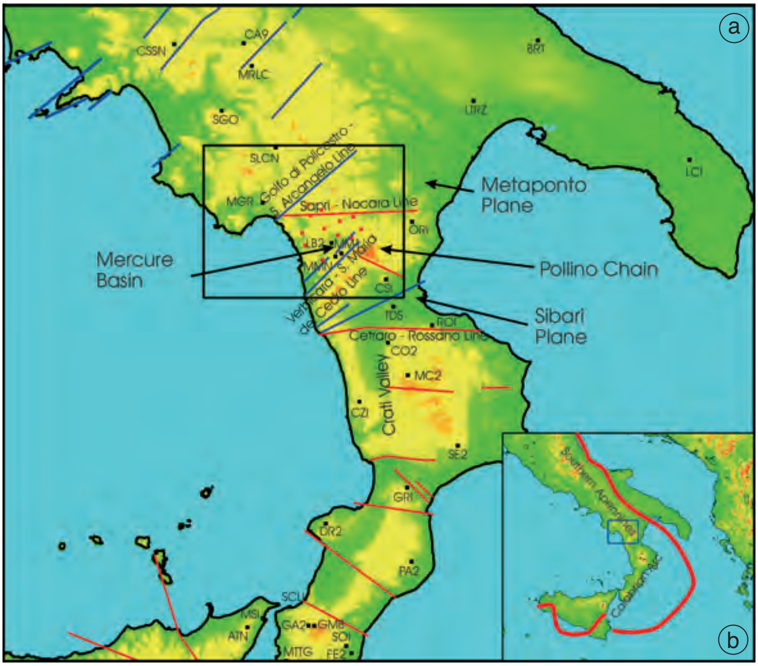

Fig. 1a,b. a) Relative position of the investigated area with respect to the location of the thrust belt. b) Main structural lineaments according to Valensise and Pantosti (2001) and seismic stations in Southern Italy. Blue lines: Apenninic features; red lines: other tectonic features; black squares: permanent seismic stations; red squares: temporary seismic stations.

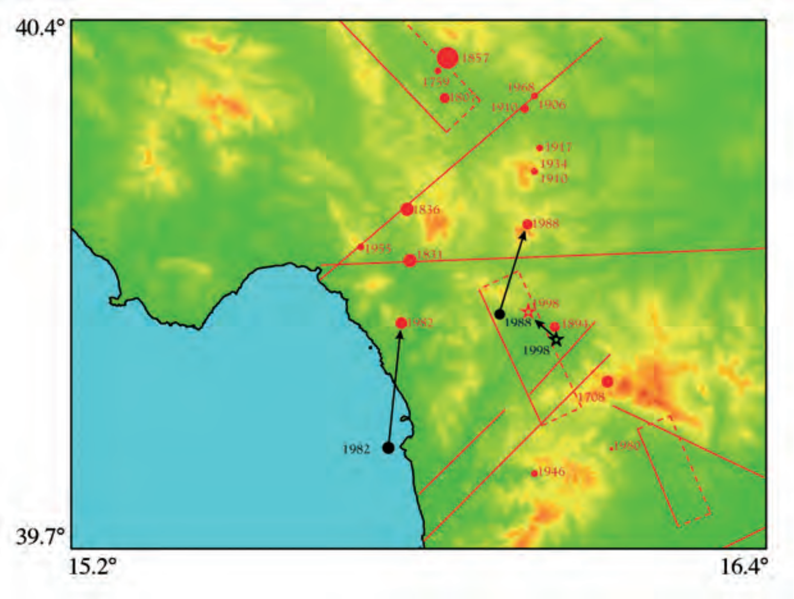

Fig. 2. Historical seismicity (red circles, radius increasing with macroseisimic intensity), main tectonic lineaments (solid red lines), reported active faults on the base of geological evidence (dashed red rectangles – intersection with the surface, solid red). Black circles show instrumental locations of the 1982 and 1988 seismic events and their relative dislocation with respect to the macroseismic epicentres. The star refers to the 1998 main event (sources: Gruppo di Lavoro CPTI, 1999; Valensise and Pantosti, 2001).

sualties (fig. 2). This is the famous «Great Neapolitan Earthquake», that is considered the starting point of the modern seismology, because of the in-depth inspection of its effects and of the subsequent first attempt of a quantitative interpretation of macroseismic observations carried out by Mallet (1862) on behalf of the Royal Society of London.

The Calabrian Arc in its northern portion has an almost North-South trend. It is also apparently characterized by extensional activity oriented along its axis: this is testified by the graben structure of the Crati Valley (fig. 1a,b) and the fault plane solutions of the two seismic events of February 20, 1980, the strongest ones in the last few decades (Cello *et al.*, 1982). In the same area E-W trending lineaments exist too, that probably displace the extensional systems in a similar manner to what happens in the Southern Apennines, even though there is scant geological evidence (Finetti and Del Ben, 1986; Moretti and Guerra, 1997; Moretti, 2000; Valensise and Pantosti, 2001). The Cetraro-Rossano line represents the northern boundary of the area where Calabrian Arc tectonic features are exclusively observed. The Calabrian Arc showed in historical times earthquakes of such an energetic level that it has to be considered among the regions with highest seismic risk in the world.

The Pollino Chain and the strictly adjacent areas represent a minimum of the seismic activity in terms of moment release along the ridge of the Italian Peninsula. They are characterized by the occurrence of a relatively large number of events, all however of moderate size. Maximum intensities, observed in 1831, 1836, 1894 never attained severity higher than degree VIII on the MCS macroseismic scale. From the tectonic point of view, the boundaries of the area can be identified with the Policastro Gulf-S. Arcangelo Line to the north and with the Cetraro-Rossano Line to the south: in between these limits both trends, Antiapenninic and east-west, coexist generating a complex surface tectonic pattern. One open question is whether they are still active at the present time throughout the whole area.

The 1998 seismic sequence followed an earthquake that occurred in the Mercure Basin, immediately to the northwest of the Pollino Chain, in an area broadly comprised between the Policastro Gulf-S. Arcangelo Line and the Verbicaro-S. Maria del Cedro Line.

It is noteworthy that aside from the 1831, 1836 and 1894 events, in more recent years the area suffered damaging earthquakes only in 1982, 1988 and 1998 (Esposito *et al.*, 1988; Gasparini and Tertulliani, 1988; Galli *et al.*, 1998). It is quite obvious on the basis of the huge shift between the instrumental and macrosesimic epicentres observed in these occasions (fig. 2), that historical locations might be misleading (Moretti *et al.*, 1994): they can give a hint on the level of activity in the area but not on the tectonic setting.

3. Data acquisition and treatment

Around the Pollino Chain several seismic stations belonging to different organizations operate. Among these there are the National Centralized Seismic Network of the Istituto Nazionale di Geofisica e Vulcanologia, Rome (INGV) and the Calabria University Seismic Network. Data useful for its seismographic monitoring are also acquired by Osservatorio Vesuviano (Naples), presently a section of INGV. The stations active in 1998 are drawn in fig. 1a,b.

Soon after the main shock of 9th September, 1998 the above described network was integrated by 14 temporary seismic stations that were installed all around the mesoseismal area. In particular, 6 REFTEK acquisition systems managed by INGV remained active up to mid October. The other temporary stations, belonging to the University of Calabria, remained active up to 20th December 1998, but two are still in activity (LB2 and MM1). These stations were six Lennartz Mars-88/FD, one locally engineered telemetered digital seismograph, and one analogic Sprengnether MEQ-800 (fig. 3).

Because of the elongated shape of the Italian Peninsula, it is often quite difficult to obtain an optimal azimuthal coverage. Since the temporary network operated only for a short span

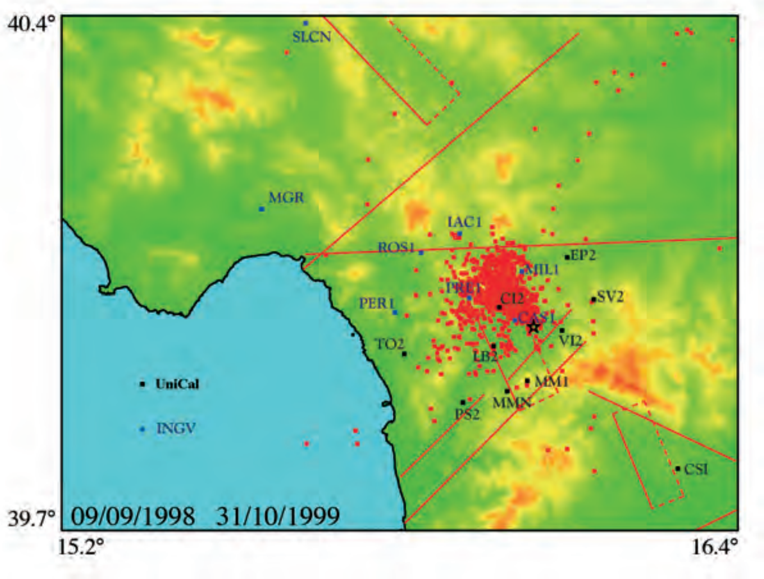

Fig. 3. Event locations throughout the seismic sequence and seismographic stations. Blue squares: INGV stations; black squares: University of Calabria stations.

of time, it was necessary to verify whether the locations obtained on the basis of the permanent network only could be considered satisfactory enough for an in-depth investigation of the whole sequence.

To perform the check, the envisaged procedure was to select a subset of events with azimuthal gap and number of available arrival times respectively below and above given threshold values. The successive step was the comparison of their locations obtained using separately the data from the permanent and the temporary network.

As a result, we verified that by using the preferred velocity model, the locations of events with gaps up to 200° and a minimum set of 10 available readings, almost never differed by more than 6 km, with the overwhelming majority falling within a 3 km difference (fig. 4). This procedure finally led to the selection of 881 events from September 1998 to October 1999 (fig. 3).

The process of hypocentral location required the treatment of phase arrivals recorded both at the temporary network installed in the aftermath of the main event, and at the regional networks – INGV and University of Calabria – that operated in the area (stations within 150 km from the main shock). This imposed a complex procedure to design a velocity model that could satisfy both data sets.

The regional model is a 3D model – SLAB5 – developed at the Geophysical Laboratory of Calabria University (Guerra, 1998) that consists of a 30 × 30 km horizontal grid extending down to the depth of 550 km. It proved to yield a good match for the whole Calabrian Arc and surrounding regions (Bruno *et al.*, 1999). This was then integrated with an *ad hoc* model of the epicentral area that essentially resulted in a 1D description (fig. 5), to be inserted in the 30 × 30 km grid of the regional model.

The epicentral area model was initially derived by extrapolation of seismic refraction data available in the surrounding regions (Colombi *et al.*, 1973; Morelli *et al.*, 1975; Milano *et al.*, 1989) and further refined by an iterative procedure of rms minimization. This process resulted in a family of possible models out of which we selected our preferred solution. The criteria we applied were:

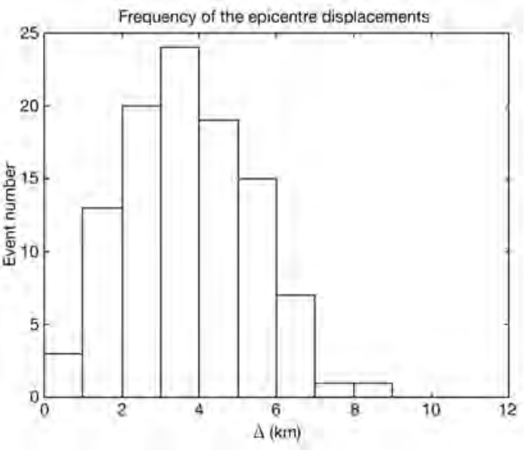

Fig. 4. Histogram of the event frequency with respect to the epicentre displacements as obtained using separately temporary and permanent network data.

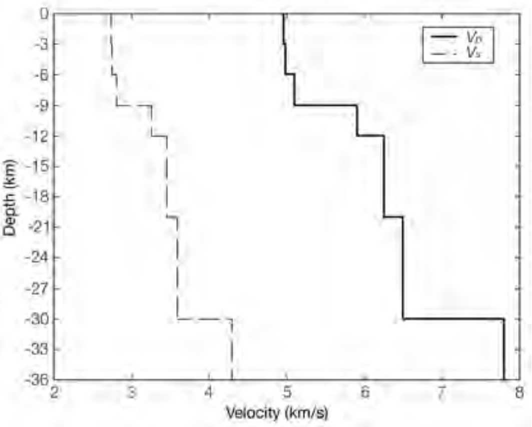

Fig. 5. Local velocity model.

– Depth distribution of the events consistent with the structural asset of the area, located between the nearby Tyrrhenian Sea and the axis of the Apennine mountain chain.

– Pronounced clustering of the aftershocks.

To better focus possible fault planes activated during the sequence, the method proposed by Bossu (2000) was applied. It is based on the assumption that being 2σ the 95% confidence

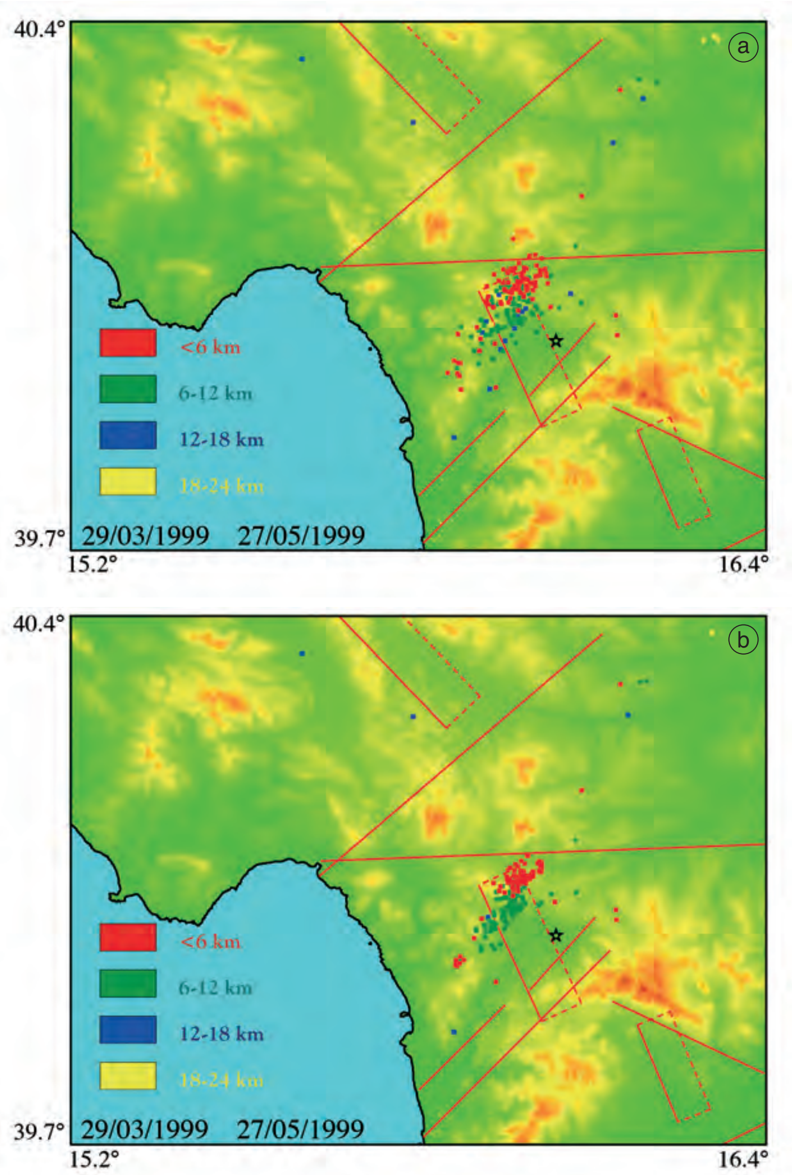

Fig. 6a,b. Comparison of the surface distribution of the epicentres a) before and b) after the application of the Bossu (2001) method. Here and in the following figures, colours correspond to different depth ranges.

interval of an hypocentral location, it is possible to substitute the location of a given event with that arising by the average locations of all the events that fall within the confidence interval, without any net gain or loss of information. As an example, hypocentral locations of the events that occurred in spring 1999 are reported in fig. 6a,b before and after the application of the Bossu method: in both cases hypocenters tend to align along an Antiapenninic trending direction but this trend is better evidenced in the second case.

4. The 1998 event and the sequence

The main event took place on 9th September 1998 at 11:28:00.9 UTC. Its localization is

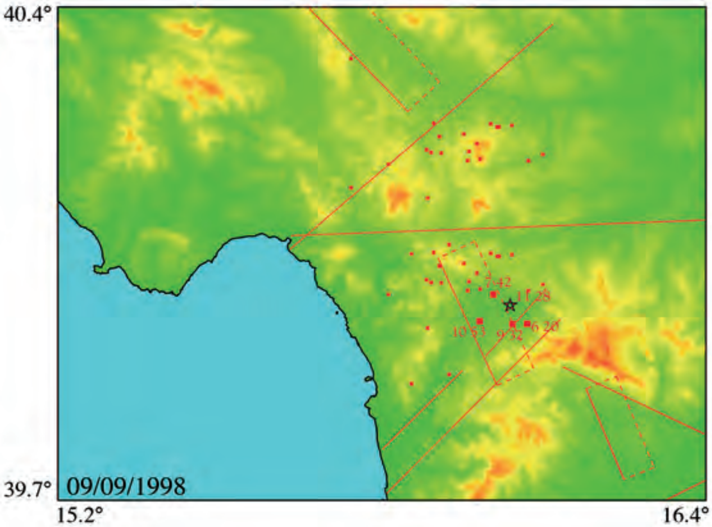

Fig. 7. Events observed on 9th September 1998. The star refers (in the following figures too) to the main event (at 11.28 UTC), larger squares to the foreshocks (with relative UTC timing), smaller squares refer to aftershocks locations.

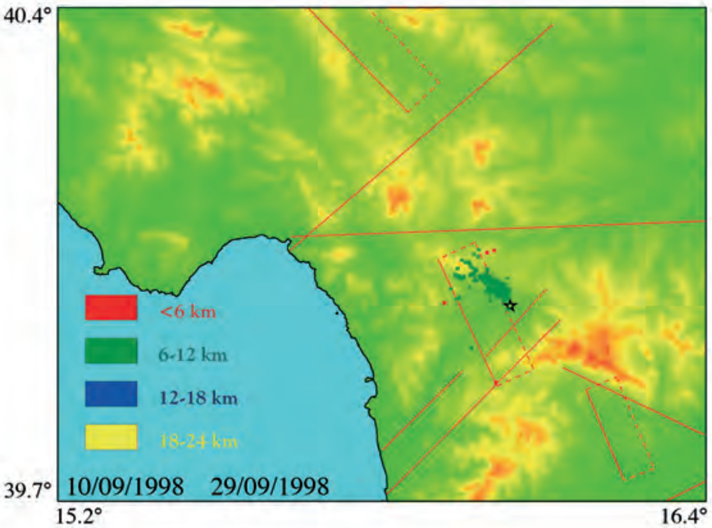

Fig. 8. Event locations in the time interval 10/09/1998-29/09/1998.

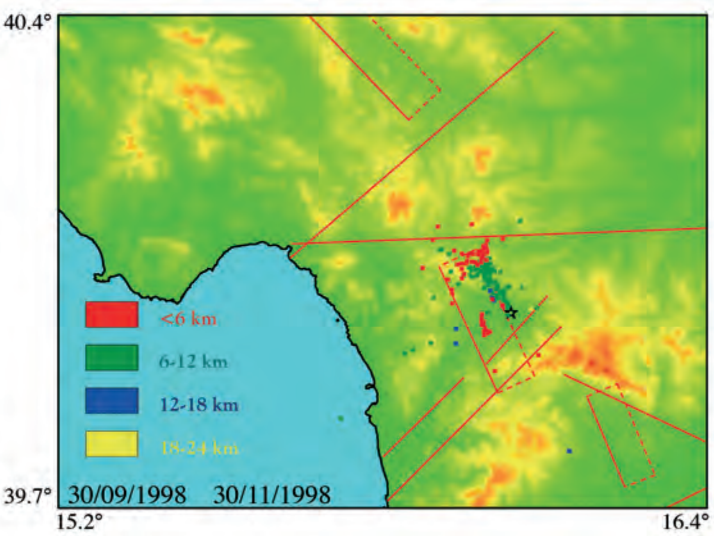

Fig. 9. Event locations in the time interval 30/09/1998-30/11/1998.

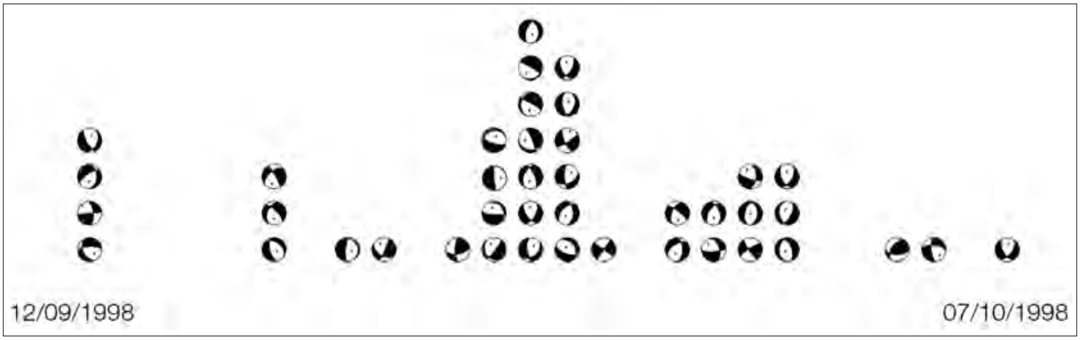

Fig. 10. Fault plane solutions for 41 selected aftershocks in the time interval 12/09/1998-07/10/1998. FPS for events in the same day are in an unique column, at height increasing with time.

39.9811°N ± 1.3 km, 16.0499°E ± 1.9 km, at the depth of 14.3 ± 4.3 km. Magnitude estimates vary widely – *e.g.*, BJI (M_S=5.6), ISC (M_S=5.2, m_b=5.3), NEIC (M_S= 5.2, m_b=5.2), MOS (M_S= =5.3, m_b=5.9), ROM (m_d=5.0). The mean of the values arising from the records at the stations of the Calabria University Seismic Network is m_L=5.0. It is noteworthy that the Harvard CMT catalogue reports a moment release of $3.26*10^{24}$ dyne cm, corresponding to a M_w= =5.6: this high value from teleseismic recordings in association with the lower value from regional ones, suggests a relatively low spectral corner frequency.

It is also important to observe that the focal mechanism derived by the CMT inversion yields a normal faulting event with Apenninic trend and a rather significant minor to major double couple ratio. The centroid time is set at about 5 s after the nucleation time. This is a quite long delay for a moderate sized earthquake and might indicate a rather complex rupture process.

The time evolution of the energy release prior to the main shock was also rather remarkable. In the two months preceding the main event, almost no activity was observed in a wide area surrounding the epicenter of the main shock event: the catalogue of the Seismic Network of the Calabria University reports in the area represented in fig. 3 only 4 shocks, all with $m_L \leq 2.8$. On 9th September 1998 a burst of foreshocks occurred (fig. 7). The first and largest one was an $m_d = 3.7$ event at 6:20 UTC. Other foreshocks occurred at 7.42, 9.32, 10.53 UTC. There was another feature that differentiated the event spatial distribution throughout the first day of activity with respect to the rest of the sequence: both the foreshocks and the first few aftershocks were distributed in a rather wider area that embodied the main shock. From 10th September onward, the aftershocks occurred within a narrower area located to the NNW of the main event location (fig. 8).

The activity that can be ascribed to the sequence lasted up to October 1999. However after June 1999 the decrement of energy release was significant. As a consequence, the Bossu method can be applied only up to the end of May 1999. On this basis, taking into account the time evolution of the hypocentral location, the sequence can be divided into five major phases.

The first lasted about 20 days (fig. 8). During this period most of the activity was concentrated along a narrow NNW-SSE elongated area at depths between 6 and 9 km. This first phase was therefore compatible with the focal mechanism of the main event.

The second phase (fig. 9) went through the end of November 1998. During this period the hypocenters delineate a fault plane that dips to the south and meet the surface in correspondence of the Sapri-Nocara Line. The hypocenters appear to lay along an E-W oriented plane with a low dipping angle that makes hard a straightforward interpretation of the space distribution. The relatively few stable fault plane solutions that could be obtained (fig. 10) by using first arrivals polarities, show a prevalence of extensional focal mechanisms with a significant number of strike slip events: only one reflects a locally compressive stress field. The inhomogeneous orientation of the stress axes suggests that the area behaved as a transfer zone.

The third phase (fig. 11) lasted through the end of January 1999 and coincided with the activation of a shear plane dipping southwest-

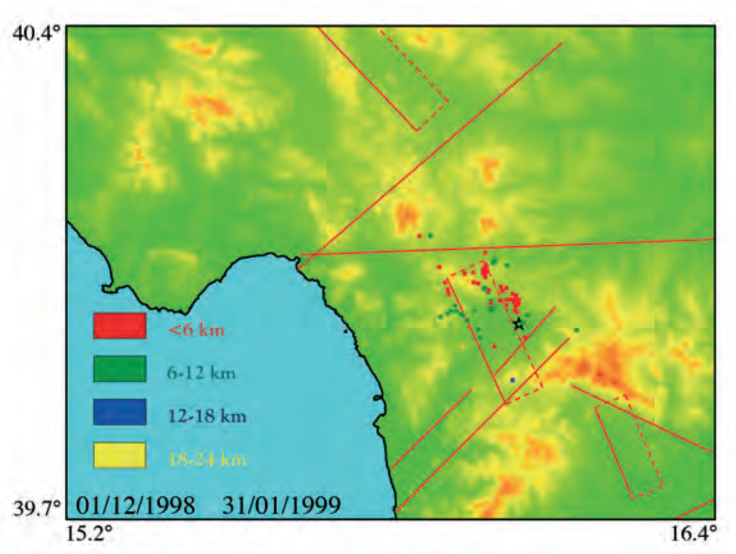

Fig. 11. Event locations in the time interval 01/12/1998-31/01/1999.

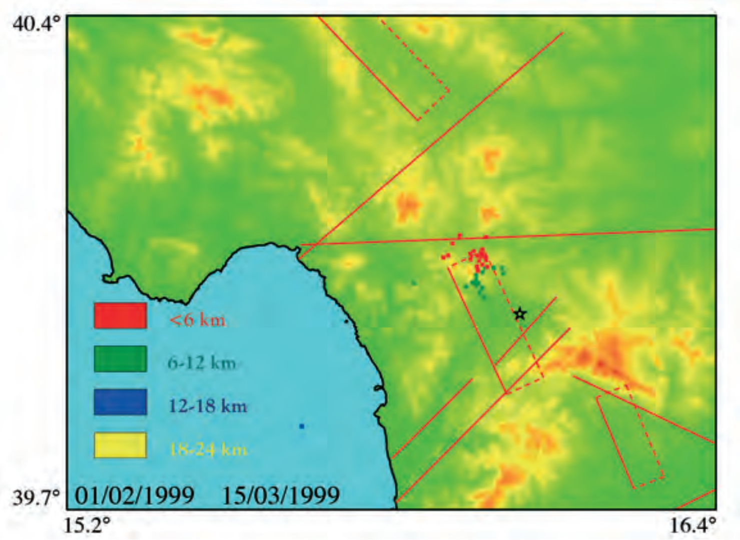

Fig. 12. Event locations in the time interval 01/02/1999-15/03/1999.

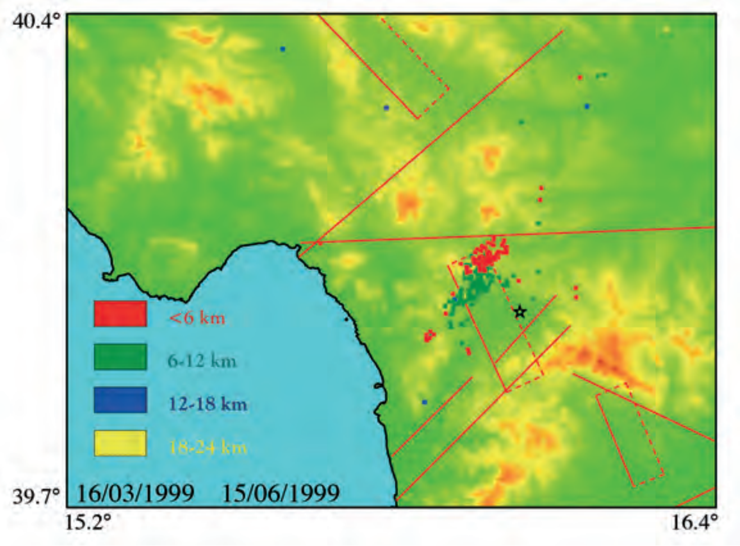

Fig. 13. Event locations in the time interval 16/03/1999-15/06/1999.

wards. This is in sharp contrast with the geological observation of a northeastward dipping fault plane (Valensise and Pantosti, 2001). Its peculiarity is a sort of activity gap at depths of 7-8 km.

The fourth phase (fig. 12) lasted till mid March 1999. It marked a return to the same regime as the second phase, with an E-W trending plane that was dipping southward. The activity level undergone an evident decrease.

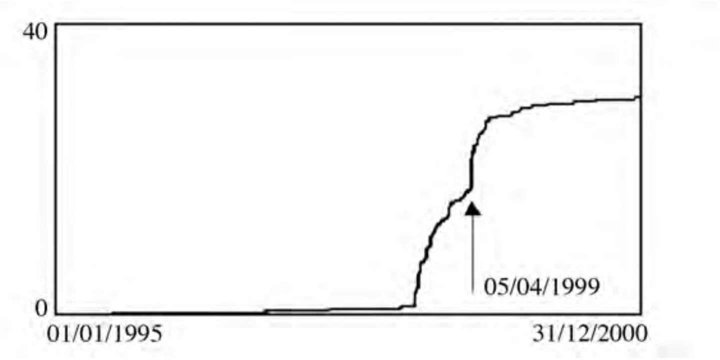

Fig. 14. Cumulative moment release (dyne·cm$*10^{20}$) in the investigated area as resulting by considering all the events with the exclusion of the main shock. m_d values have been converted to moment applying the relation by Selvaggi *et al*. (1997). Arrow marks the starting date of the last phase of the seismic sequence.

The fifth and last phase (fig. 13) was characterized by a noticeable increment of seismic activity. The tectonic element activated in this case shows an Antiapenninic trend, already envisaged by Moretti *et al*. (1994). Its main feature was the southwestward deepening of hypocenters that suggests a coexistence of activity with that of the south dipping fault observed during the second and fourth phase.

To characterize the time evolution of the energy and moment release, we show in fig. 14 the cumulative moment obtained by applying the relationship between magnitude and seismic moment proposed by Selvaggi *et al*. (1997). The plot accounts for earthquakes with epicenter in the area represented in the preceding figures according to the catalogue of the Geophysical Laboratory of Calabria University since 1997, excluding however the main shock of 9th September 1998 in order to enhance the variation before and after the begin of the sequence. Arrow marks the starting date of the above described last phase. Remarkable features are the perfectly flat trend in the years preceding the sequence and the sharp jump corresponding to the fifth phase.

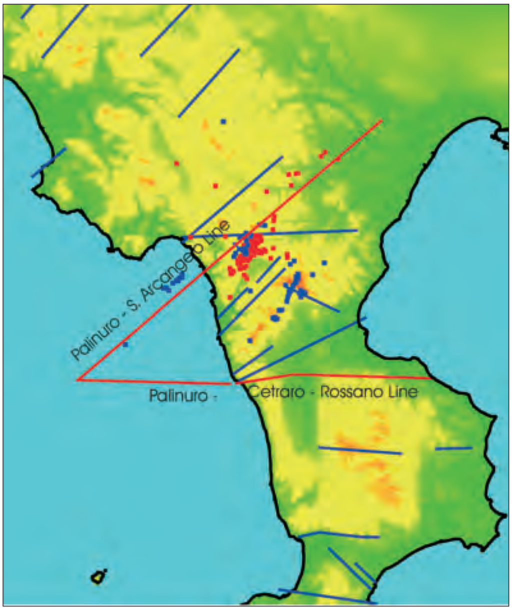

Fig. 15. Scheme of the proposed limit of the hinge between the Southern Apennines and the Calabrian Arc at crustal levels.

5. Conclusions

We observe that the major tectonic features along the whole Apenninic ridge are directed mostly in directions parallel and perpendicular to the axis of the chain and are referred to as Apenninic and Antiapenninic elements respectively. Analogously, south of the Pollino Chain, the most evident tectonic features are directed

NS and EW: since in its northern sector the Calabrian Arc is directed NS, they result respectively parallel and perpendicular to the strike of the arc. Therefore we can define them calabrian and anti-calabrian.

The seismic sequence started on 9th September 1998 on the western slope of the Pollino Chain shows the alternate activation of tectonic elements characterized by different strike and dip, that seems to well agree with the location at the contact between different major geological domains, in such way that the characteristics of both them are evidenced: Apennic, Antiapenninic and Anticalabrian, the latter being represented by the Sapri-Nocara Line.

The atypical character of the studied area is demonstrated by the southwestward dipping trend of the shear plane activated in the third phase of the seismic sequence, contrasting with that of the major Apenninic normal structure that typically deepens northeastward.

The peculiar features of the area, classifiable in the typology of transfer zones due to their heterogeneity, are also confirmed by the wide variety of focal mechanisms observed on each lineament.

The major features include the E-W trending fault that was activated throughout the second and the fourth phase of the sequence and the Antiapenninic fault that was activated throughout the last phase. From the moment release point of view, they seem to be the major transfer structures at the hinge between the Southern Apennines and the Calabrian Arc. This is particularly true with regard to the Antiapenninic fault, whose activation at the end of the sequence, was characterized by the most intense moment release. Its existence had already been suggested by Moretti *et al.* (1994). On the basis of a few dense microearthquake sequences both at sea and on land, these authors identified an Antiappeninic trending lineament on the prolonging of that activated in the last phase of the 1998-1999 sequence (fig. 15). At the time, they hypothesized the existence of a major feature that would extend for over 100 km from the submerged Palinuro volcano up to the Upper Sinni Valley (S. Arcangelo Basin).

The observations described in the present work seem to confirm this model, so that the lineament can be more correctly called Palinuro-S. Arcangelo Lineament. It is intersected in proximity of Palinuro volcano by another major lineament, the Palinuro-Cetraro Line (Finetti and Del Ben, 1986; Moretti *et al.*, 1990) and its land expression, the Cetraro-Rossano Line. Since this lineament represents the southern limits where apenninic features can be observed, it turns out that the system composed by the Palinuro-Sant'Arcangelo Lineament and the Palinuro Cetraro-Rossano Line is with highest probability the one that acts as hinge between the Southern Apennines and the Calabrian Arc at crustal levels.

A hint to further analysis to be carried on in future works arises by the coincidence of this surface lineament with the area where a sharp variation is found in the regime of seismic energy release by intermediate and deep earthquakes in the Southern Tyrrhenian Sea.

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