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Seismicity and stress field in the Sannio-Matese area

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In this study we discuss the available data on seismicity and focal mechanisms in the Sannio-Matese area in order to obtain information on the stress field acting in the area. Background seismicity of the area is characterized by isolated events, with magnitude generally less than 2.5, on which is superimposed a swarm and seismic sequence activity of low magnitude (max magnitude 4.1). The epicentral distribution of both isolated events and seismic sequences, disclose NE-SW striking active faults that fall in between the fault segments of the large historical earthquakes which occurred in the area. The available information on the stress field deducible from the focal mechanisms of the area agrees that a general extensional stress regime is acting. Locally both NE-SW and NNW-SSE extensions are observed. The large scale stress regime deduced from the focal mechanisms of strong instrumental earthquakes which occurred in the Apennines supports the local NE-SW extension but cannot explain the normal movements related to a NW-SE extension. The local longitudinal extension observed, supported by GPS data, can be explained utilizing large scale geodynamic models.

3.1. Introduction

The estimation of tectonic stress is important to contribute to geodynamic studies. Since 1980, detailed analyses have been carried out for the Apennines Chain studying strong instrumental main and related aftershocks but the potential for reconstructing tectonic regimes based on weak earthquakes has not been exploited. Earthquake focal mechanisms are among the most valuable sources for assessing the state of stress of the Earth's crust. On a regional scale and using sparse earthquake data, previous studies agree that most of the Apennines are dominated by extension perpendicular to the NW-SE trend of the mountain belt. This stress regime is also extended in small areas of the Apennines Chain like the Sannio-Matese area where no strong earthquakes recently occurred.

The Sannio-Matese area (figs. 3.1 and 3.2) is situated in the northern sector of the Southern Apennines Chain between 41°-42° north and 13°50′-15° east. During the historical period, strong earthquakes, seismic swarms, and sequences of tectonic origin (lasting from a few days up to several months) struck the area. Notable historical earthquakes with I_0>X MCS, separated by long periods of relative quiescence, occurred in 1456, 1688, 1702, 1732, 1805 (fig. 3.1); seismic sequences of low magnitude also occurred in 1885, 1903, 1905 and, recently, in 1990 and in 1997-1998.

Seismicity of the Sannio-Matese area is, at present, characterized by the occurrence of low-energy seismic sequences and swarms but their role in the geodynamic context is a matter of debate. Seismic swarms occur in a variety of geologic environments. For example, they are common in volcanic areas. In this case the immediate influence of magma and ground water (*i.e.* intrusion to the fault), and peculiar inhomogeneity of crustal structure can explain the occurrence of swarms. Outside volcanic areas other mechanisms are required. Some swarms are thought to be produced by the formation of new faults and others may be related to fault creep. In a recent study Toda *et al.* (2002) argue that swarms are simply an elevated level of background seismicity caused by a sustained increase in stress rate.

In this study we address the question of whether the present stress field revealed by the large earthquakes at regional scale is the same observed by low-magnitude seismic sequences and swarms in the Sannio-Matese area, or whether local deviations exist. We review and discuss the instrumental seismicity and focal mechanisms of low magnitude events occurring in the study area to infer information on the stress field. We emphasize that recent seismological studies disclose a significant local deviation from the large scale stress field in this sector of the Southern Apennines.

3.2. Geological setting

The Apennines Chain is a thrusting belt developed in Neogene times by progressive northeastern migration. A back-arc basin, the Tyrrhenian Sea, is associated with the migration of the thrusts. Intense deformations during the Pliocene and Pleistocene occurred (Scandone *et al.*, 1990). In the central sector of the chain the deformation regime is characterized by predominant NE-SW extension responsible for the formation of NW-SE striking normal faults along which large historical earthquakes occurred (Valensise and Pantosti, 2001). The Sannio-Matese area (figs. 3.1 and 3.2) is a part of the chain and its geological evolution is rather complex. Prevalent uplift since the Pleistocene has been reported by many authors (*e.g.*, Ciaranfi *et al.*, 1983). In particular, the prevalent deformation regime has been created by predominant NE-SW and subordinate NW-SE extension along lineaments with Apenninic/anti-Apenninic directions (NW-SE/NE-SW) (Patacca and Scandone, 1989). The Matese Massif is a carbonate structure intersected by a main system of WNW-ESE trending tectonic structures and subordinate meridian/parallel structures trending N-S and E-W. The Sannio Mountains, located to the east of the

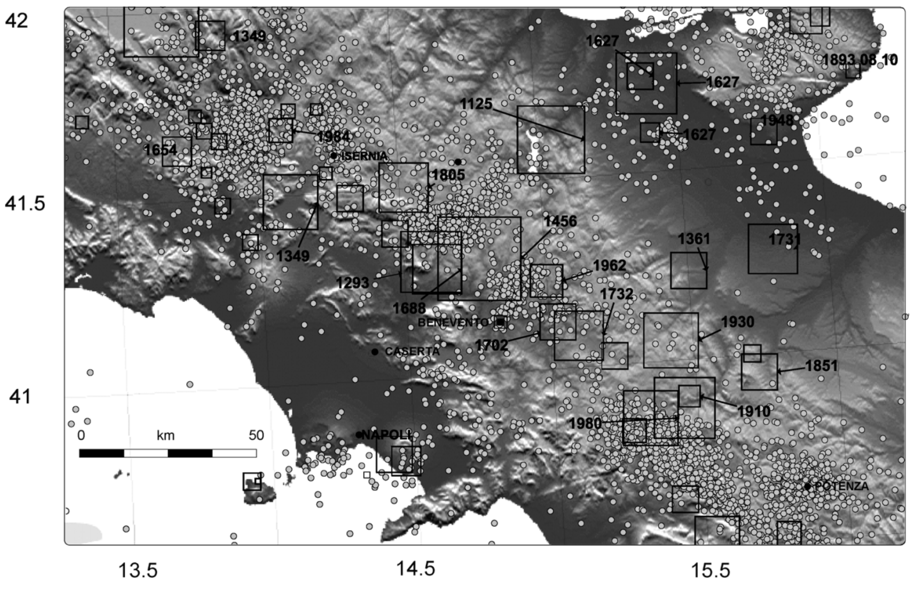

Fig. 3.1. Map of Southern Apennines. Seismicity from the historical catalog is indicated with large squares (Boschi *et al.*, 1997). The instrumental seismicity during 1983-2000 is indicated with small squares (Barba *et al.*, 1995).

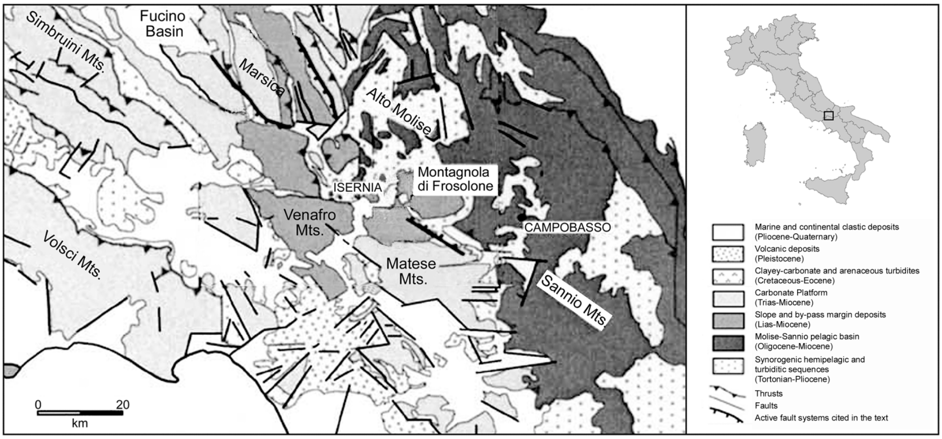

Fig. 3.2. Simplified geological map and fault systems of the area (re-drawn and modified after Di Bucci *et al.*, 2002).

Matese Massif, represent the sector of the Apenninic Chain that slopes down to the Bradanic Foredeep. These mountains are mainly formed by terrigenous deposits cut by minor normal faults. The Sannio Mountains and the Matese Massif are divided by a N-S to NW-SE elongated morphological depression.

3.3. Stress field in the Southern Apennines from focal mechanisms of strong earthquakes

The Southern Apennines are one of the most interesting seismic regions in Italy due to the presence of the largest main shocks and the occurrence of earthquake sequences and swarms. The spatial distribution of the historical and recent instrumental earthquakes (*i.e.* 1980, $M=6.9$; fig. 3.1) shows that in this portion of the Apennines the strongest earthquakes occur within a relative narrow zone about 50 km wide along the axis of the chain between Molise and Basilicata regions. Available fault plane solutions of both strong ($M>5$) and low magnitude ($M<4$) events (Gasparini *et al.*, 1980, 1985; Selvaggi *et al.*, 1997; Frepoli and Amato, 2000) show a prevalence of normal dip-slip solutions with planes striking NW-SE, along the chain axis. The T-axes of these focal mechanisms are sub-horizontal and follow a prevailing NE-SW strike whereas P-axes are sub-vertical. These observations, as well as structural data (Hyppolite *et al.*, 1994), suggest that the NW-SE faults along which the most recent strong earthquakes occur (*i.e.* 1962; 1980; fig. 3.1) move in response to an extensional active stress regime characterized by a NE-SW oriented $\sigma 3$. On the contrary, along NE-SW striking faults present in the area (Oldow *et al.*, 1993), isolated and low-magnitude seismic sequences ($M<4.0$) cluster (Valensise and Pantosti, 2001).

Geophysical data show that the extensional active stress regime characterized by a NE-SW oriented $\sigma 3$ is observed also in other portions of the Apennines Chain. For example, the moment tensor for the $M_w>4.2$ events of the seismic sequence which occurred in 1997-1998 in the Northern Apennines (Colfiorito) shows that earthquakes are characterized by normal faulting with NE-SW tension axis (Ekström *et al.*, 1998). Therefore, on a regional scale all the Apennines Chain seems to be dominated by extension perpendicular to the NW-SE trend of the chain. This stress regime is extended also in areas in which no detailed geophysical information is available like the Sannio-Matese area. This area is considered a transition zone between the Central and Southern Apennines (Di Bucci *et al.*, 2002) and a change in the seismic source's distribution is hypothesized (Valensise and Pantosti, 2001). The focal mechanisms of the recent instrumental strong earthquakes ($M>5.5$) which occurred at the border of this area in 1962 (Ariano Irpino earthquake; fig. 3.1) and 1984 (Val Comino-Val di Sangro area; fig. 3.1) are consistent with the NE-SW extension. Since no instrumental data for the last strong earthquake (1805) to occur in the area are available, no information on the stress field can be inferred even though the location of this event is certain and accurate reconstruction of isoseismal is available (Postpischl, 1985). Therefore, information on the stress field of the Sannio-Matese area, at present, can be deduced only by focal mechanisms of the background seismicity and from the recent seismic sequences in the area.

3.4. What we know about the seismicity and focal mechanisms in the Sannio-Matese area

Although instrumental seismicity in the Sannio Matese area has been monitored since 1975, reliable estimates of earthquake locations and focal mechanisms of low magnitude events have been possible only since 1990, when the Italian National Seismic Network was integrated by a local network operating in the area (Federici *et al.*, 1992). Temporary digital seismic stations have also been installed in the area in recent years for short time periods for a dedicated seismic survey or immediately after the beginning of seismic sequences.

Data from INGV instrumental catalogue show that the seismicity of the area is characterized by sparse isolated earthquakes whose epicentral distribution is shown in fig. 3.1. Foci are within the first 15 km of the crust. Seismicity is located prevalently around the Matese Massif and in proximity of the places where the 1990 and 1997-1998 seismic sequences occurred (fig. 3.1). The low magnitudes of the isolated events, generally less than 2.5, do not allow reliable focal mechanisms to be computed because the events are recorded by a low number of seismic stations.

Further characterization of the seismicity between 1990 and 2000 can be deduced from previous seismological studies. Alessio *et al.* (1996) analysed the seismic sequence that occurred in the area between April and July 1990 making use of five portable digital three-component stations to support the few permanent seismic stations running in the area. Between April and July 1990 about 1000 events, with magnitude ranging between 1.0 and 3.6, were recorded. The epicentral distribution of 370 well located events, clustered in a small area close to the town of Benevento, shows a concentration along an anti-Apenninic direction (NNE-SSW). Hypocentral distribution of the events is quite homogeneous from the surface to 15 km of depth without meaningful alignments. The 19 fault plane solutions of this sequence, constrained with at least 7 reliable P-wave first motions, do not show a predominant type of faulting motion. However, the distribution of the T-axes shows a fairly good alignment along a NE-SW direction whereas the P-axes appear to be rather scattered.

Federici *et al.* (1992) analyzed the seismicity occurring in the area between 1991 and 1992, mainly characterized by isolated low magnitude events ($M_d<2.5$) and typical swarm pattern. The major seismic episodes were two swarms in June 1991 and in March 1992 in the same area as the 1990 sequence. The first was constituted by about 20 events with $1.0<M_D<2.0$. The second was the most intense. About 260 events, with M_D greater than 1.5 were recorded in about 30 h and the strongest events had magnitude 3.7. 50 fault plane solutions, constrained with at least 8 P-wave first motions and related to events located in the whole area, show a prevalence of normal faulting motion but inverse faulting motion can also be recognized. In particular, the fault plane solutions of the events located near Benevento, in the same area where the 1990 sequence occurred, show normal faulting motions whereas inverse faulting motion occurs in a restrict area located west of Campobasso.

Milano *et al.* (1999, 2002) analyzed the seismic sequence that occurred in 1997-1998. The seismic activity, the strongest one in the last 20 years in the study area, started with a $M=4.1$ event and was characterized by the alternation of intense activity and relative quiescence periods. The seismic

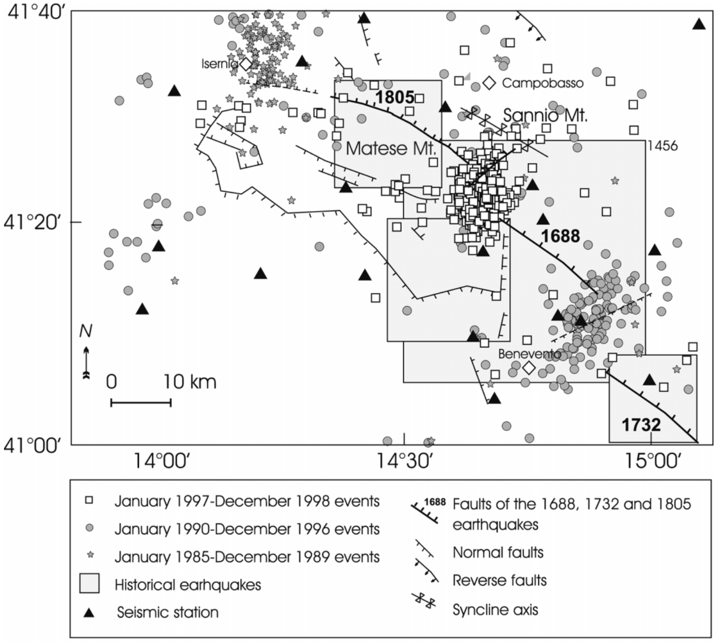

Fig. 3.3. Main structural lineaments of the Sannio-Matese area (data from CNR-PFG, 1983) and well constrained relocated seismicity occurred during 1985-1998. Faults of historical earthquakes are from Boschi *et al.* (1997). The cluster near Benevento (circles) represents the 1990-1992 seismic activity whereas squares represent the 1997-1998 seismic sequence. Stars are the January 1985-December 1989 events.

energy release behavior shows, in the period of intense activity, the typical swarm pattern: a huge number of events of similar magnitude, without a distinct main shock, clustered in space and time. Between March 1997 and March 1998 about 4000 micro-earthquakes, with magnitude ranging between 0.8 and 4.1, were recorded by the permanent seismic networks operated by INGV and OV. Only about 25 events had $M > 3.0$. The hypocentral distribution of about 600 well located events (Milano *et al.*, 2002) shows that seismic activity is clustered along a nearly vertical plane striking NNE-SSW and dipping toward east. The sequence originates in a restricted area of about 140 km^2 that is highly fractured and dissected by at least three main systems of normal faults with Apenninic, anti-Apenninic and E-W directions (fig. 3.3). The epicentral distribution suggests that this sequence took place along the NE-SW structures recognizable in the area that mark the geological transition between the Matese Massif and the Sannio Mountains. 106 best-fit, double-couple focal mechanisms of this sequence, computed by means of the FPFIT algorithm and constrained by at least 10 *P*-wave polarities, show a prevalence of normal dip-slip solutions with fault plane NNE-SSW striking. The *T*-axes distribution shows a prevalence of sub-horizontal axes NNW-SSE striking whereas sub-vertical *P*-axes are recognizable.

3.4.1. What we know about the strain field

In the past 30 years several inversion codes have been developed in order to obtain information on the stress field, which is the most consistent with a heterogeneous set of focal mechanism data

(Angelier and Mechler, 1977; Gephart and Forsyth, 1984; Angelier, 1990; Gephart, 1990; Albarello, 2000). These methods provide the directions of the principal stresses, $S1$, $S2$ and $S3$ and a ratio of their magnitudes $\sigma 1$, $\sigma 2$, $\sigma 3$. To have reliable information to apply the above methods, it is necessary to have data from many well constrained focal mechanisms. When no well constrained data are available, information on the stress field can be deduced approximately.

Federici *et al.* (1992) computed the average orientations of the $S_{H\max}$ utilizing data from 50 focal mechanisms related to sparse events which occurred in 1991 and 1992 in the Sannio-Matese area. They performed a stereographic representation of the *P*- and *T*-axes since the orientations of the *P*-, *T*- and *B*-axes can be considered an approximation of the principal stress axes. The $S_{H\max}$ (fig. 3.4) show alignment in Apenninic (W-SE), E-W and NNE-SSW directions. The coexistence of these different directions in a restricted area indicates the occurrence of large heterogeneity in the strain field.

Milano *et al.* (2002) first applied inversion codes to obtain information on the stress field acting in the area. They determined the stress orientations by inverting the focal mechanisms of the 1997-1998 sequence using the Angelier technique (1990). This method minimizes the angles between the slip vector $\boldsymbol{s}$ and the computed shear stress τ using a least square procedure. Like other inversion methods (*e.g.*, Gephart and Forsyth, 1984), Angelier's method determines four of the six independent components of the stress tensor.

To better constrain the kinematics of the brittle deformation, Milano *et al.* (2002) applied the inversion method to 59 focal mechanisms, constrained by at least 15 polarities, belonging to the sequence. The results indicate that the deformation regime that generated this sequence is heterogeneous. However, 64% of the whole data set is compatible with a constrained normal stress field characterized by a sub-horizontal NNW-SSE striking $\sigma 3$ and by a subvertical $\sigma 1$ (fig. 3.4). The distribution of the nodal planes shows a maximum consistent with a NW dipping, NE-SW striking plane. This information, as well as the hypocentral distributions, indicate that the 1997-1998 seismic se-

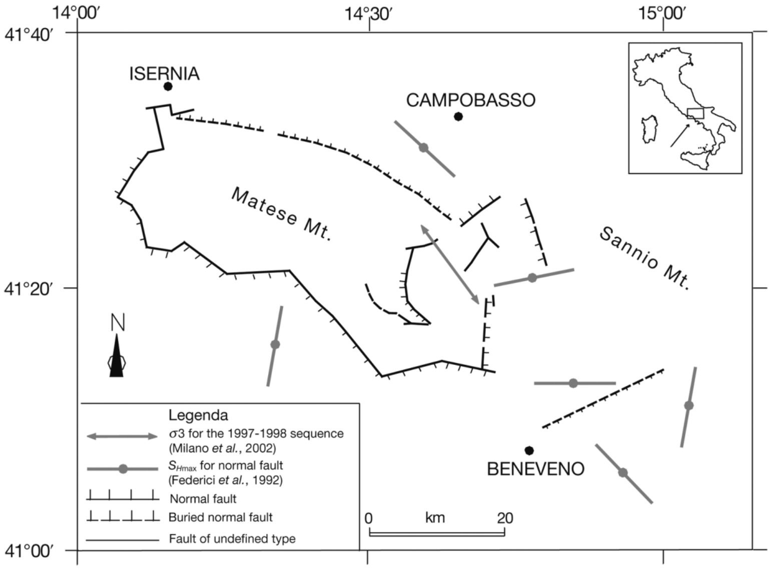

Fig. 3.4. Spatial distribution of the average directions of the $S_{H\max}$ (from Federici *et al.*, 1992) and direction of the $\sigma 3$ for the 1997-1998 sequence obtained from the inversion of the focal mechanisms (from Milano *et al.*, 2002).

quence mainly developed along normal fault NNE-SSW striking and moving in response to an extensional NNW-SSE stress regime.

3.5. Discussion and conclusions

The results of the above studies characterize background seismicity in the Sannio-Matese area as isolated events on which is superimposed a swarm and seismic sequence activity is superimposed. The isolated events, with magnitude generally less than 2.5, occur scattered in the area without any particular alignment, and concentrated in the places where the seismic sequences occurred; foci are within the first 15 km of the crust. The epicentral distribution of the 1990 and 1997-1998 seismic sequences, the swarm episodes of the 1991-1992 and the location of the isolated events, disclose NE-SW striking active faults. These faults fall in between the fault segments of the large historical earthquakes (figs. 3.1 and 3.3). In particular, the 1990 sequence and the swarm episodes of 1991-1992 fall in between the fault segments of the 1688 and 1732 historical earthquakes; the seismicity of the 1997-1998 seismic sequence is concentrated between the fault segments of the 1688 and 1805 historical earthquakes and overlaps the NE-SW striking faults that separate the Sannio Mountains from the Matese Massif.

Recent tomographic studies performed in the area (Chiarabba and Amato, 1997; Bisio *et al.*, 2004) show two high *Vp* regions in the upper crust that extend between 6 and 12 km in depth. These high *Vp* regions, 20 to 40 km in length, are located close to the 1688 and 1805 fault segment, and close to the 1688 fault segment, and are characterized by scarce seismicity, it being concentrated at their borders. As evidenced by Bisio *et al.* (2004), the high *Vp* regions can be interpreted as high strength materials able to store large stress, representing the main asperities (Foxall *et al.*, 1993; Zhao and Negishi, 1998). At present the seismic activity in the Sannio-Matese area concentrates prevalently at the tips of the fault segments that nucleate the large historical earthquakes in the area. The location of these tips coincides with the NE-SW striking faults along which the seismic sequences occurred.

The kinematics of the NE-SW striking faults is not related only to the regional stress field. The focal mechanisms of the 1990 sequence (Alessio *et al.*, 1996), and those of the 1991-1992 seismicity (Federici *et al.*, 1992) are consistent with NW-SE striking rupture planes. These focal mechanisms, showing a prevalence of dip-slip solutions with NE-SW striking *T*-axes, agree with the stress regime deduced by the focal mechanisms of strong earthquakes of the Southern Apennines. On the contrary, the results of the stress analysis of the 1997-1998 focal mechanisms are consistent with a well constrained normal stress field characterized by a subvertical $\sigma 1$ and sub-horizontal NNW-SSE striking $\sigma 3$. The distribution of the nodal planes (Milano *et al.*, 2002), showing a maximum in the NE-SW direction, agrees with the local geology which shows the occurrence of a NW dipping NE-SW striking fault in the area of the 1997-1998 seismicity (fig. 3.3). The normal movements of the NE-SW faults as detected by the 1997-1998 sequence support the hypothesis that longitudinal extension within the Apennines Chain occur. Recent GPS data (Serpelloni *et al.*, 2001) recorded in the area also disclose an extension parallel to the chain axis in the Apennines Chain. The well-known NE-SW extension in the Apennines, supported by seismological data, breakout analysis and GPS measurements (Montone *et al.*, 1999; Frepoli and Amato, 2000; Anzidei *et al.*, 2001), cannot explain the normal movements recognized along the NNE-SSW ruptures of the 1997-1998 seismicity.

Larger scale geodynamic models (*e.g.*, Oldow *et al.*, 1993; Doglioni, 1996), suggest that the extensional processes occurring in the Southern Apennines are due to a) the eastward migration of the chain (the NE-SW extension) and b) the progressive curvature and thinning of the chain (the NW-SE extension). The a) extension is responsible for the NW-SE faults while the b) extension causes movement of the NE-SW striking faults. Using these geodynamic models, Milano *et al.* (2002) interpreted the local deviation of the stress field, observed for the 1997-1998 sequence, with respect to the large scale ones. In particular, they proposed that i) the deformation due to the eastward chain migration within the inner sectors of the Apennines Chain is focused along NW-SE striking normal faults, which are responsible for the largest earthquakes (Valensise and Pantosti, 2001), and ii) the deformation related to the progressive chain curvature is focused along NE-SW striking normal faults.

In conclusion, the seismological data available for the Sannio-Matese area well characterizes the background seismicity. Nevertheless, they do not put constraints on the stress field acting in the whole area. The little available information on the stress field of the area agrees that a general extensional stress regime is acting, but locally both NE-SW and NNW-SSE extensions have been observed. Further geophysical investigations are therefore required. The concentration of seismic events on the tips of the fault segments responsible for the strong earthquakes indicate that seismic release concentrates in these tip zones. In this context we cannot *a priori* exclude that the seismic sequences occurring in the area represent precursory activity for future large earthquakes.

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