Seismicity at the border between the Southern and Central Apennines (Italy): a review

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ABSTRACT We review the instrumental seismicity at the boundary between the Southern and Central Apennines with the aim of detecting the active structures and clarifying the seismotectonic framework of this area of the chain. Single events with M<3.0, low magnitude (M<4.0) seismic sequences (1997–1998 and 2001), and swarms (1999, 2000 and 2005) characterize the seismicity of this area. Earthquakes occur within the upper 15 km of the crust, prevalently aligning along the Apennine Chain in a NW–SE axis. Strain analyses indicate that these events are related to the main NE–SW extension processes that affect the Apennine Chain. They are concentrated in the following areas: (a) south of the seismogenetic source responsible for the 1915 destructive earthquake (2000 swarm), (b) between the faults of the 1984 and 1805 destructive events (2001 sequence), and (c) between the faults of the 1805 and 1688 events (1997-1998 seismic sequence). The 1999, 2000 and 2005 swarms occurred along the so-called Ortona-Roccamonfina alignment, which is the NNE-SSW belt separating the Central Apennines from the Southern ones. The distribution of these swarms and the focal mechanisms indicate the presence of active NE–SW faults related to a local NW-SE extension. This direction of extension was also observed in the 1997–1998 and 2001 sequences. The location of the NE–SW striking faults, responsible for the seismic swarms, suggest that some segments of the Ortona–Roccamonfina line may be a rupture response to both the NE–SW regional extension of the Southern Apennines, and to a NW–SE striking longitudinal extension. Our data indicate that the seismicity of the Apennines at the boundary between the central and southern sectors is related to both the eastward migration of the chain (the NE-SW extension) and to its progressive curvature and thinning (the NW-SE extension). The NE-SW extension is responsible for the major earthquakes whereas the lower energy seismicity is related to the NW-SE extension.

1. Introduction

Geophysical and geological investigations carried out in the last 25 years have shown that present-day tectonics of the Apennine Chain is characterized by seismic events with magnitude between 2.5 and 6.9. The events are concentrated along the chain axis (Fig. 1) and occur, mainly, along NW-SE striking normal faults whose kinematics are controlled by a NE-SW extension (e.g., Montone *et al*., 2004). The foreland of the Apennines is characterized by moderate-sized seismic sequences (e.g., 1990-1991 Potenza, M_w=5.2; 2002 Molise, M_w=5.7) developed on E-W

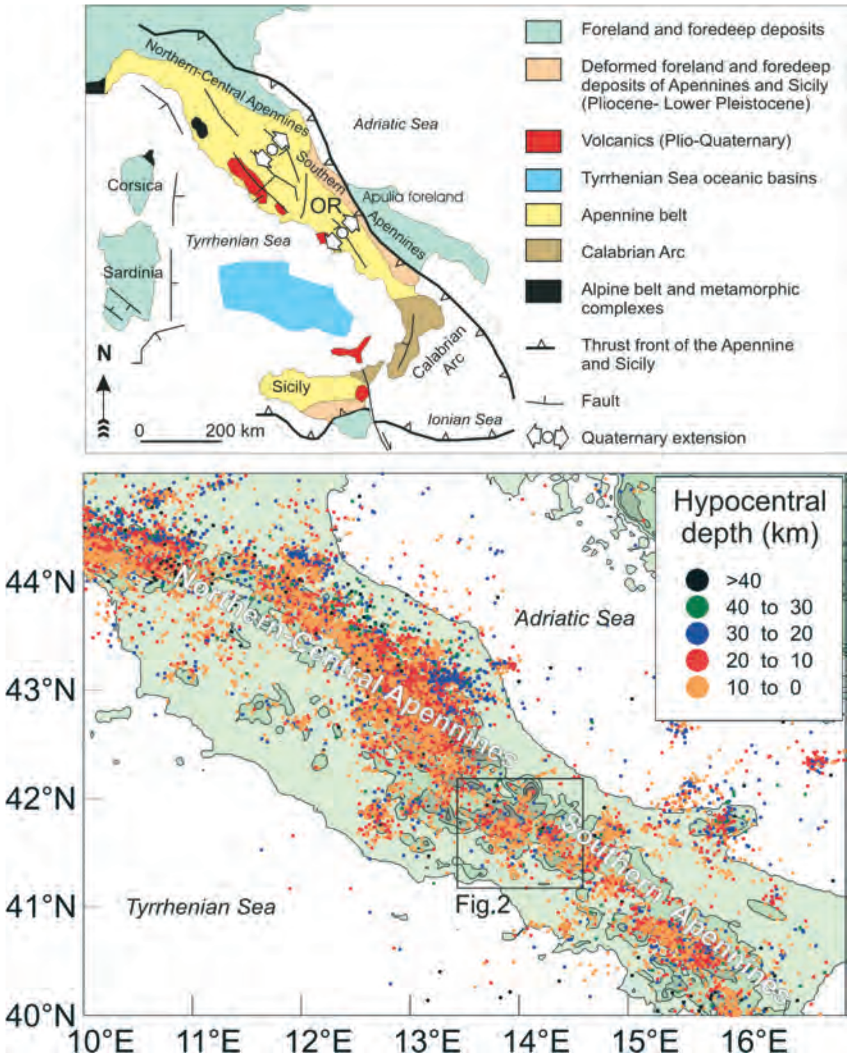

Fig. 1 - Top: structural scheme of Italy (modified from Bruno *et al.*, 2000). OR is the acronym of the Ortona-Roccamonfina line, which separates the Southern Apennines from the Northern Apennines. Bottom: epicentral distribution of events that occurred between 1981 and 2002 in the Northern and Southern Apennines (data from Castello *et al.*, 2005). The location of Fig. 2 is also reported.

striking, strike-slip faults (Di Luccio *et al.*, 2005).

The best documented instrumental, large (1980 Irpinia, M_s=6.9) and moderate (1997 Umbria-Marche, M_s=5.9) earthquakes of the Southern and Central Apennines show a fracture process linked to a NW-SE normal faulting but with a complex aftershock distribution (Chiaraluce *et al.*, 2003; Amoruso *et al.*, 2005). The above-mentioned characteristic has also been observed for a moderate seismic sequence that occurred in the border zone between the Central and Southern Apennines (1984 Abruzzo-Lazio earthquake, M_s=5.5). This sequence that occurred between the NW-SE striking seismogenic sources of the 1915 event [M_w=7.0, Fucino Fault System, Galadini and Galli (1999, 2000)] and the 1805 earthquake (M_w=6.6, North Matese Fault System, Galli and Galadini, 2003) (I_o=X-XI MCS; Working Group CPTI, 2004), was characterized by a NNE-SSW aftershock distribution, possibly related to the interaction between a main NNW-SSE normal fault and an ENE-WSW second-order, transfer fault (Pace *et al*., 2002). The presence of active NE-SW striking faults in the Central-Southern Apennines has already been reported by geological and geophysical investigations (e.g., Oldow *et al*., 1993; De Luca *et al*., 2000; Valensise and Pantosti, 2001; Milano *et al*., 2002), but their location and role in the present-day tectonics of the area are still poorly investigated and a matter of debate. According to Oldow *et al*. (1993), the NE-SW striking faults move in response to a second-order longitudinal extension of the Southern Apennines that could be due to the progressive curvature and thinning of the chain.

Therefore, a detailed study of the local instrumental seismicity may provide more useful information towards the understanding of the seismological framework of this region. Earthquake fault plane solutions are valuable sources for assessing the deformation acting in an area and, as a consequence, can give a contribution towards a better understanding of present-day tectonics. The little historical data available and the poor information on the background seismicity have not allowed us, so far, to identify the seismogenic structures responsible for moderate and low magnitude seismic sequences occurring on the border between the Southern and Central Apennines (hereafter SCAT). On the other hand, the significant increase of seismic stations belonging to the Italian Telemetered Seismic Network (ITSN) of the Istituto Nazionale di Geofisica e Vulcanologia (INGV) in the last 10 years, made it possible for us to perform detailed studies on instrumental seismicity. In order to have a general overview of the SCAT, we summarize the main results obtained from previous studies in this area.

2. Geological and geophysical overview

The Apennine Chain consists of tectonostratigraphic units related to different palaeogeographical domains. The chain is arranged in two main arches (Patacca and Scandone, 1989): the arcuate Central-Northern Apennines and the NW-SE striking Southern Apennines (Fig. 1). In the Central-Northern Apennines, the innermost Liguride/Sicilide Units are tectonically superimposed, from the Late Oligocene onwards, on the Apennine carbonate units of the Apulian palaeomargin (Patacca and Scandone, 1989; Patacca *et al*., 1990). Folds and thrusts were involved the Triassic–Miocene carbonate successions and the Neogene–Quaternary foreland and fore deep basins. The Plio–Quaternary thrust system controls the structural elevation of carbonates in the Central Apennines.

The SCAT is characterized by the NNE–SSW striking Ortona–Roccamonfina (hereafter OR) tectonic line [Fig. 2; Locardi (1982)]. According to Patacca *et al*. (1990), this feature represents a 20 to 40 km-wide crustal decoupling zone. West of it, the Apulia carbonate platform is involved in the shallower thrusting, whereas 3 km-thick terrigenous thrust sheets cover the Apulia units [Fig. 1; Mostardini and Merlini (1986); Corrado *et al*. (1997)] eastwards. According to Vai (2001), the OR is not well defined at the surface, consisting of a NNE–SSW, laterally discontinuous thrust-to-oblique system, which acts as a lateral ramp for the Central Apennine thrusts (Fig. 2).

The Sannio-Matese area is located SE of OR. The Matese Massif is a NW-SE elongated structure that consists of Trias-to-Miocene carbonates (Fig. 2). Matese is intersected by WNW-

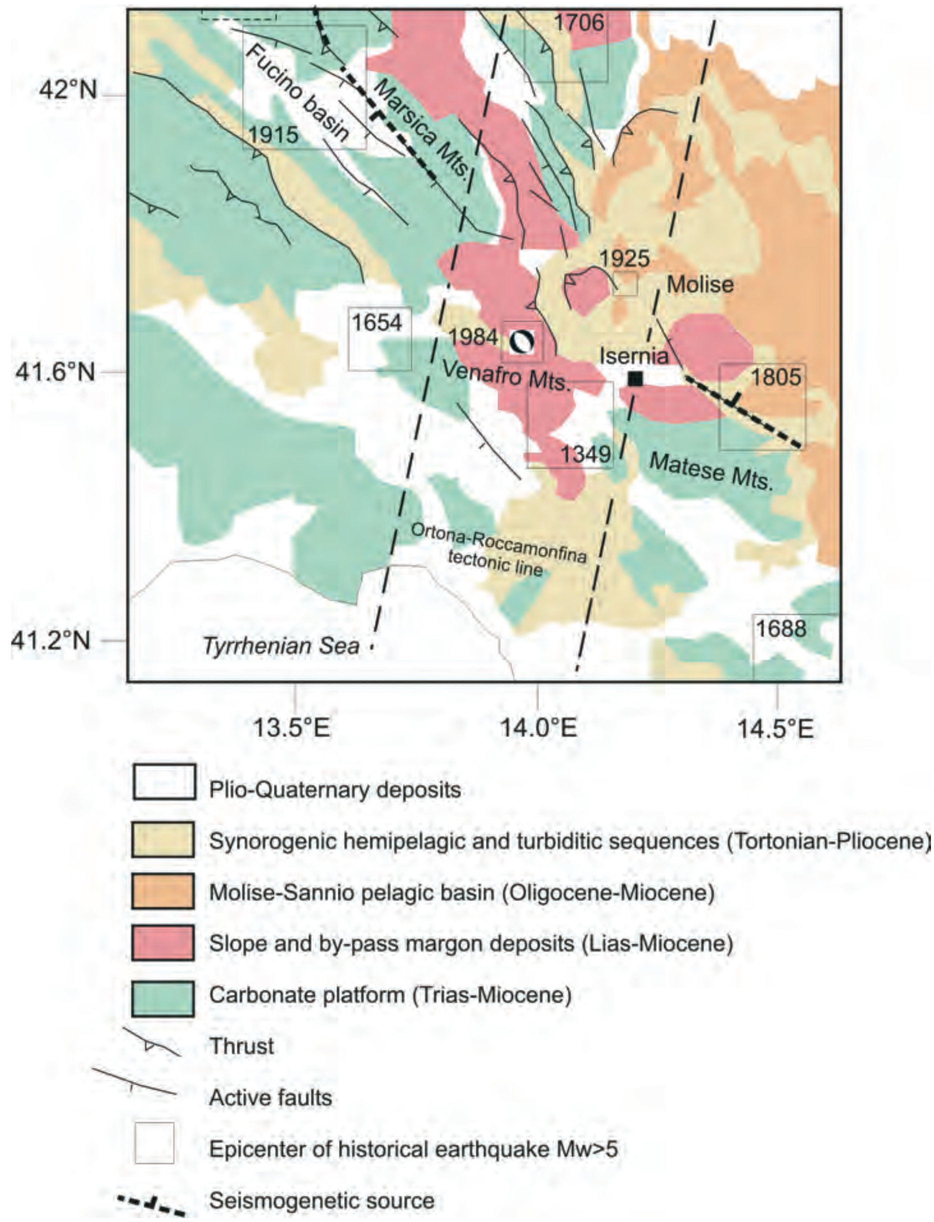

Fig. 2 - Simplified geological sketch map of the border between the Northern and Southern Apennines (location in Fig. 1). Redrawn with modifications from Di Bucci *et al*. (2002) and Milano *et al*. (2005). Epicenters of historical earthquakes and seismogenetic sources are from Working Group CPTI (2004). The location of the Ortona-Roccamonfina (OR) line is also reported. The focal mechanism of the 1984 earthquake is from Pace *et al*. (2002).

ESE trending faults and bounded by NW-SE and E-W striking faults. The Sannio Mountains are located east of the Matese Massif and consist of Oligo-Miocene terrigenous terrains. The Sannio Mountains and the Matese Massif are separated by a N-S to NW-SE elongated valley. The present-day geological evolution of the Sannio-Matese sector is characterized by an uplift occurring from the Pleistocene and associated to an extensional strain. Prevailing NW-SE striking faults and minor NE-SW faults are recognizable (e.g., Patacca and Scandone, 1989; Galadini *et al*., 2000; Di Bucci *et al*., 2002).

Destructive earthquakes with IX<I_o<XI in 1456, 1349, 1706, 1805, and, more recently, in 1915 [Fig. 2; Working Group CPTI (2004)] affected the area. These earthquakes occurred along NW-SE striking, normal faults related to the NE-SW extension responsible for the present-day deformation of the Apennines (e.g., Galli and Galadini, 1999; Serpelloni *et al*., 2001; Di Bucci *et al*., 2002; Pace *et al*., 2002; Papanikolau *et al*., 2005 and reference therein). According to Di Bucci *et al*. (2002), the SCAT zone could be regarded as a main structural boundary representing a mechanical barrier to the propagation of rupture of the NW-SE active fault systems across the central and southern segments of the chain.

3. Present-day seismicity

The instrumental seismicity of the Apennine Chain has been monitored since 1975, but reliable estimates of earthquake locations and focal mechanisms, mainly for low magnitude events, were possible only after 1990, when the ITSN was increased. The last revised instrumental catalogue based on the ITSN data shows that seismicity in SCAT concentrates along the Apennine Chain axis [Fig. 1 bottom; Castello *et al*. (2005)]. The almost NE-SW cluster in SCAT corresponds to the most relevant seismic sequence that occurred in 1984 (Fig. 1, bottom). This sequence was characterized by two distinct main shocks (M_S=5.8 and M_S=5.2) and by a complex aftershock distribution.

A detailed overview of the present-day SCAT seismicity can be obtained considering the results of recent studies (Milano *et al*., 1999, 2002, 2005, 2008). In these studies, the seismic events, between latitude 41°10' – 42°10' N and longitude 13°30' – 14°30' E, have been relocated after accurate re-picking of P- and S-phases in the digital waveforms recorded by the ITSN and after integrating the data set with other data recorded by temporary digital stations installed in the area. For the reliability of the focal depth, only events with a minimum of five P-wave and four S-wave readings were relocated by means of the standard HYPO71 algorithm (Lee and Lahr, 1975) making use of a 1-D velocity model (Milano *et al*., 2005). The maximum error location on a horizontal position and depth are 2 km and 2.5 km, respectively; the maximum rms value is 0.45. The main characteristics of the seismicity can be summarized as follows.

The epicenter distribution relative to the time interval 1996-2006 (Fig. 3) shows that the seismic activity in the SCAT is poorly diffused. With the exception of two seismic sequences that occurred in 1997-1998 and 2001 (purple blue and dark yellow, respectively), the seismicity is prevalently constituted by single events. Seismic swarms, constituted by a few tens of events clustered in time and space, also occurred in 1999, 2000 and 2005 (Fig. 3). The magnitude of the events, evaluated from the duration of the seismograms, is between 1.5 and 2.5 and almost all events with magnitude greater than 2.5 occurred during the bursts of activity in correspondence to the seismic sequences and swarms. Single events occur prevalently along the NW-SE axis of the Apennine Chain and are concentrated in three main zones: (a) southeast of the Fucino basin, (b) between the Venafro and Molise areas, and (c) east of the Matese Mountain (see Figs. 2 and 3). The hypocentral distribution along the NW-SE (B-B') and the SW-NE (A-A') cross-sections

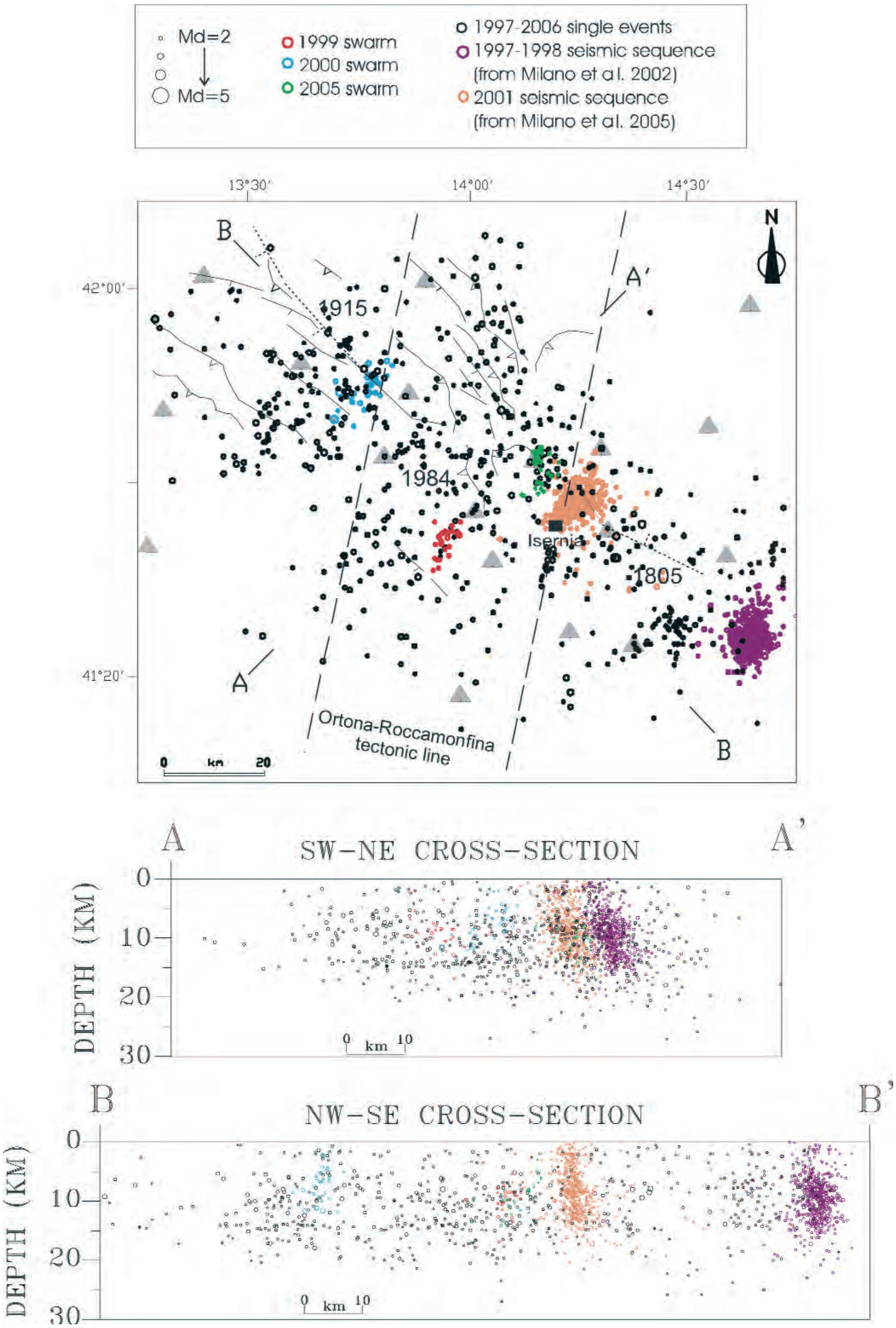

Fig. 3 - Top: epicentral distribution of the relocated events occurring in the study area between 1996 and 2006. Triangles represent the mono- and three-component seismic stations within the study area. Bottom: hypocentral distribution of the seismicity on SW-NE (A-A') and NW-SE (B-B') oriented cross-sections (the horizontal scale equals the vertical scale). Faults and seismogenic sources are from Fig. 2.

(Fig. 3, bottom) shows that the seismic events occur prevalently within the upper 15 km of the crust with a gentle deepening of foci towards the northeast, towards the foreland.

The events of the 1999 swarm ($M_{D\,max}$= 2.9) are NNE-SSW aligned and almost all hypocentres are between 8 and 13 km deep (red circles in Fig. 3). The epicenters of the 2000 swarm ($M_{D\,max}$ = 3.8) are aligned in a NE-SW direction and the hypocentral distribution shows a gentle deepening towards SW from the surface to a depth of about 12 km (blue circles; Fig. 3). The location of this swarm is close to the source of the 1915 earthquake. The 2005 seismic swarm ($M_{D\,max}$ = 2.6) occurred NW of the 2001 seismic sequence (green circles in Fig. 3). The epicentral distribution of this swarm shows a rough NNE-SSW alignment and the hypocenters are confined to between 8 and 12 km.

As concerns the seismic sequences that occurred in 1997-1998 and 2001, the 1997-1998 seismic activity started on March 20, 1997 with an M_D=4.1 event and was characterized by alternating periods of more intense activity with relatively short quiescence ones. The seismic energy release behaviour shows the typical swarm pattern during the period of intense activity: 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 but only about 25 events had M_D>3.0. The hypocentral distributions of about 900 well located events (Fig. 3, purple-blue circles) show that the seismicity is clustered along a nearly vertical plane striking NNE-SSW and dipping eastwards. The sequence originates in a restricted area that marks the geological transition between the Matese Massif and the Sannio mountains. The hypocentral distribution suggests that this sequence developed along NNE-SSW structures.

The 2001 seismic sequence started in January without a distinct main shock but with an increase in seismicity both in number and magnitude of events. The sequence lasted nine months and was characterized by several phases of concentration of activity in both time and space. Also this sequence shows the typical behaviour of swarms being characterized by some tens of events of similar magnitude without a distinct main shock and clustered in space and time. The time periods of the main swarms activity occurred between the end of February and the end of April, in the last 10 days of May, and between the second decade of June and the end of September. The magnitude of the events ranges from between 1.5 and 2.5 and increasing slightly to 3.0 in the time periods of major swarm activity. The epicentral distribution shows that almost all the events are located NE of Isernia in an area of about 140 km^2 and are roughly aligned along a NNE-SSW direction (Fig. 3, dark yellow circles). Hypocentral distributions of about 600 well located events depict a quite homogeneous distribution from the surface down to a depth of 15 km and cluster along a plane striking N33°E and dipping 84° towards east. It is worth noting that this sequence occurred in the same area already struck by a low magnitude seismic sequence that occurred in 1986 (Alessio *et al*., 1990).

4. Focal mechanisms and strain field

In order to obtain information on the strain field at SCAT, Milano *et al*. (1999, 2002, 2005, 2008) computed fault plane solutions by means of the standard technique [FPFIT; Reasenberg and Opphenheimer (1985)]. Results from focal mechanisms were processed following the

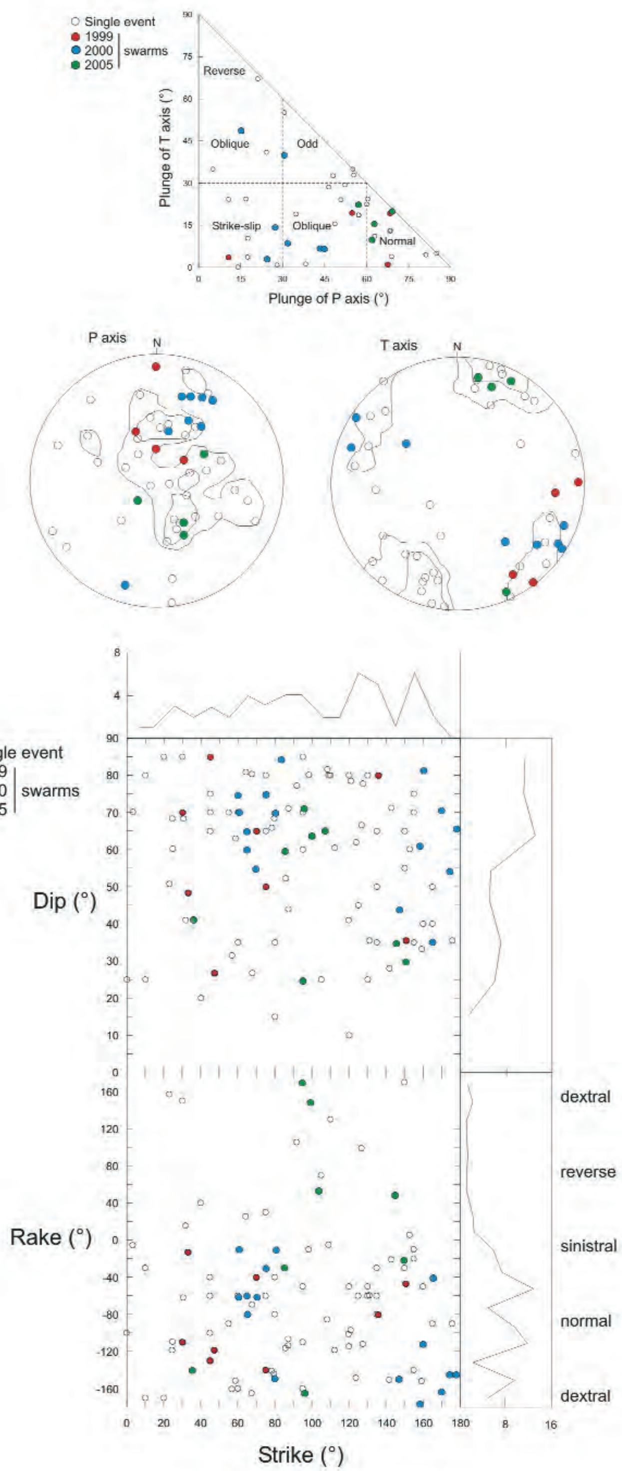

Fig. 4 - Main results of the strain analysis based on 52 fault plane solutions relative to both single events and seismic swarms occurring in the time period 1996-2006.

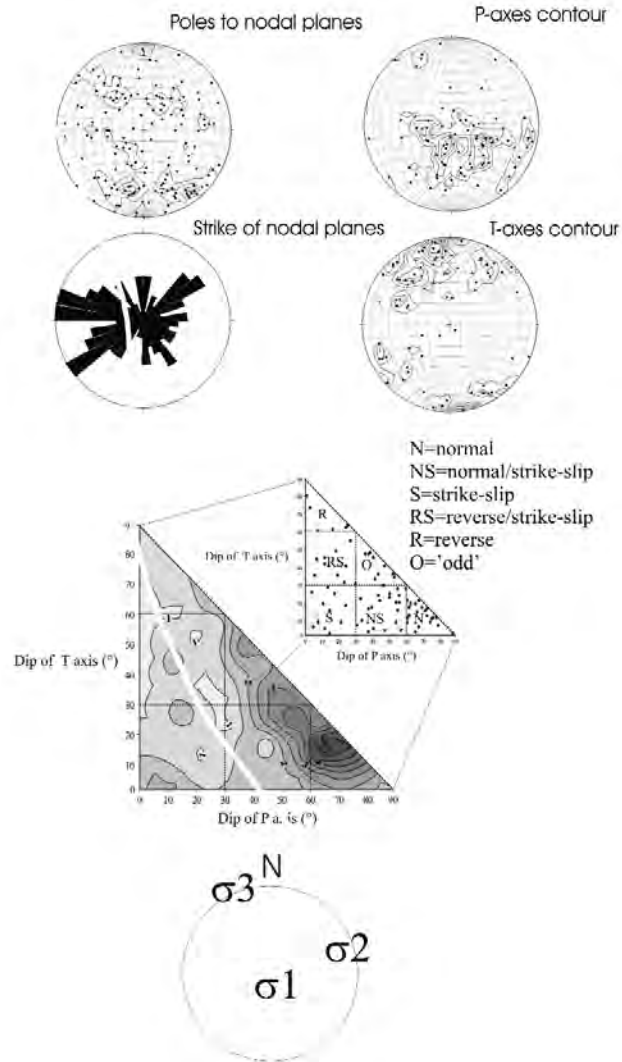

Fig. 5 - Main results of the strain analysis based on 106 focal mechanisms relative to the 1997-1998 seismic sequence. σ1, σ2, σ3 represent the orientation of the principal stress axes resulting after inversion of 59 out of 106 focal mechanisms constrained by at least 15 polarities.

approach of Marrett and Allmendinger (1990, 1991) for the analysis of faults and focal mechanisms, by utilizing a triangle diagram in which the dip angle (plunge) of the T-axes vs. the dip angle of the P-axes are reported, and by analyzing the P- and T-axes pole distributions and the strike and dip direction of nodal planes vs. rake.

The focal mechanisms of 30 single events which occurred between 1996 and 2006 fall mainly in the fields of normal, oblique (strike-slip/normal), and strike-slip deformation whereas data from the 1999 and 2005 swarms concentrate in the normal and oblique fields and those from the 2000 swarm in the oblique (strike-slip/normal) and strike-slip fields (Fig. 4). The distribution of the sub-vertical to oblique P-axes of single events (Fig. 4) shows two maxima at N150°E and N10°E and a dispersion toward N100°E. The preferred strike of the sub-horizontal T-axes (Fig. 4) is NE-SW, and a secondary maximum occurs NW-SE. The P-axes of the 1999 and 2005

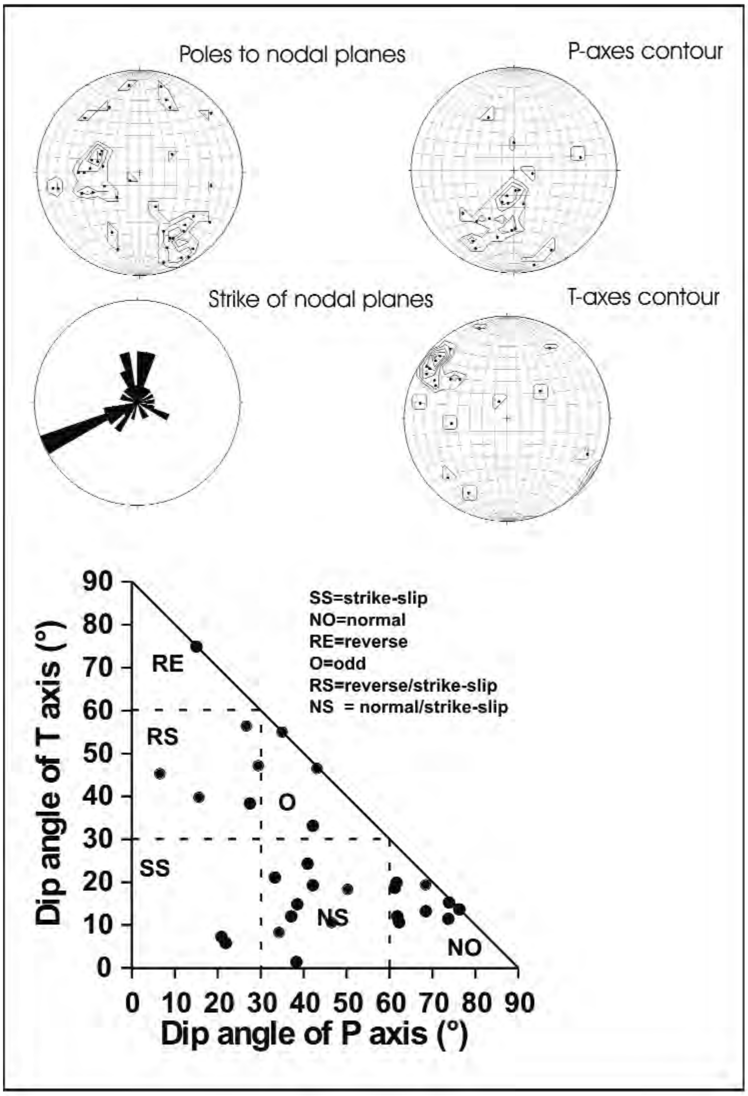

Fig. 6 - Main results of the strain analysis based on 30 fault plane solutions relative to the 2001 seismic sequence.

swarms show a distribution consistent with that of the single events. On the contrary, the P-axes of the 2000 swarm, that strike mainly between N10°E and N30°E, are characterized by a lower plunge (~30°). NE-SW is also the prevailing strike of the T-axes of the 2005 swarm. The preferred distribution of the T-axes of the 1999 and 2000 swarms is NW-SE. Nodal planes (Fig. 4) of the single events show two preferred strikes at N130°E and N160°E, and dip between 60° and 70°. The distribution of the rake is consistent with prevailing normal-to-oblique sinistral and dextral slips. The strike of the few 1999 nodal planes concentrates between N30°E and N70°E, whereas that of the 2000 swarm is between N50°E and N80°E. The planes of the 2005 events preferentially strike between N80°E and N100°E. The rake of the 1999 and 2000 swarms show a distribution consistent with strike-slip-to-normal movements. The nodal planes of the 2005 swarm are characterized by a widespread distribution of rake without preferred slips.

With regard to the 1997-1998 seismic sequence, the number of computed focal mechanisms led us to apply inversion codes in order to constrain the kinematics of the brittle deformation of the sequence. The inversion technique by Angelier (1990) was applied to 59 out of 106 focal mechanisms, constrained by at least 15 polarities. This method minimizes the angles between the slip vector s and the computed shear stress τ using a least square procedure. Like other inversion methods (e.g., Gephart and Forsyth, 1984), the Angelier's (1990) method determines four of the six independent components of the stress tensor. The results indicate that the deformation regime that generated this sequence is heterogeneous. 64% of the whole data set is compatible with a well constrained normal stress field characterized by a sub-horizontal NNW-SSE striking $\sigma 3$ and by a subvertical $\sigma 1$ (Fig. 5). 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, indicates that the 1997-1998 seismic sequence mainly developed along a normal fault NNE-SSW striking moving in response to an extensional NNW-SSE stress regime.

Data reported in Fig. 6, related to the focal mechanisms of the 2001 sequence, indicate that the strain field is heterogeneous. However, 18 focal mechanisms on 30 are characterized by normal and oblique (normal/strike-slip) solutions, whereas the remnant 12 mechanisms are widespread in the fields of the RE, RS, SS and O solutions. Anyway, the kinematics of the deformation were identified by considering the best constrained focal mechanisms (20 events). The distribution of the P-axes (Fig. 6) shows a maximum at N210°/75° (strike/dip), whereas the distribution of the T-axes (Fig. 6) shows a well-defined maximum at N315°/10°. This configuration indicates that most of the deformation of the 2001 seismic sequence is consistent with a normal strain field characterized by a NW-SE striking extension. Poles to nodal planes (Fig. 6) point out two maxima consistent with NE-SW striking planes dipping toward NW, and N-S to NNE-SSW striking planes dipping towards east, suggesting that NE-SW and N-S to NNE-SSW striking ruptures occurred. The strike of nodal plane vs. rake diagram (Fig. 6) shows that the deformation occurred along NE-SW-striking faults dipping toward NW and characterized by prevailing normal movements. The N-S to NNE-SSW ruptures show dextral-to-oblique (normal/dextral) movements that are consistent with a prevailing NW-SE extension.

5. Discussion and conclusions

The 1997-2006 SCAT seismicity was characterized by single events with M_D< 3.0, low magnitude seismic sequences (1997-1998 and 2001), and swarms (1999, 2000, 2005) with foci within the upper 15 km of the crust. The epicentral distribution of the relocated seismicity (Fig. 3) shows that many events are located along a NW-SE direction, according to the NW-SE trending seismic belt of the Apennines Chain (Fig. 1, bottom). For these events, the preferred distribution of the sub-vertical P axes and of the subhorizontal, NE-SW striking T axes as well as the NW-SE strike of nodal planes, suggest that this seismicity is related to the large-scale present-day extensional strain field affecting the chain. Single events are concentrated: (1) south of the seismogenic source responsible for the 1915 earthquake (Fucino Fault System), where the 2000 swarm occurred; (2) between the sources of the 1984 and 1805 events (the Barrea Faults and the North Matese Fault System, respectively), where the 2001 sequence developed; (3) between the sources of the 1805 and 1688 events, where the 1997-1998 seismic sequence concentrated. The location of these spatially concentrated single events and the results of the strain analysis suggest that ruptures may be related to the activation of NE-SW striking faults located transversally to the NW-SE seismogenic sources responsible for the 1984, 1915, 1805 and 1688 major events. The normal-to-oblique movements of the NE-SW striking faults could reflect the occurrence of a secondary NW-SE extension in the Southern Apennines.

The 1999, 2000 and 2005 swarms and the 2001 seismic sequence occurred along the NNE-SSW OR line. The epicentres of the 2005 swarm align NNE-SSW and the results of the strain analysis show T-axes striking NE-SW. As a consequence, this swarm is due to the main NE-SW extension acting in the Southern Apennines. Results from the hypocentral distribution and from the strain analysis clearly show that the 1999 and 2000 swarms and the 2001 sequence occurred on NE-SW to NNE-SSW seismogenic structures moving in response to a NW-SE extension. This kinematic picture is found also southeast of OR, between the NW-SE striking seismogenic sources responsible for the 1805 and 1688 major events, where the 1997-1998 seismic sequence occurred. This seismic sequence puts in evidence prevailing N-S to NNE-SSW striking ruptures and a NNW-SSE extension. Therefore, the 1999 and 2000 swarms and the 1997-1998 and 2001 seismic sequences are due to the secondary longitudinal extension affecting the chain.

In summary, the 1997-2006 single events at the boundary between the Central and Southern Apennines are mainly due to the NE-SW regional extension of the chain, whereas about one third of the earthquakes are related to the second-order longitudinal extension. The 1999, 2000 and 2005 swarms and the 2001 seismic sequence occur along the OR alignment and their epicentral distributions clearly depict NNE-SSW to NE-SW trends. As a consequence, these swarms and the sequences developed on segments belonging to the OR structural line, suggesting that this system is partly reactivated with normal movements. Therefore, some small segments of OR are seismically active and move in response to both the NE-SW regional extension of the Southern Apennines (2005 swarm), and to the NW-SE striking longitudinal extension (1999 and 2000 swarms and the 2001 sequence). It is worth noting that the southern, offshore tip of the OR line, which is located along the Tyrrhenian coast (Fig. 1), is considered to be inactive from Pliocene times (Bruno *et al*., 2000).

Large-scale geodynamical models (e.g., Oldow *et al*., 1993; Doglioni, 1996) suggest that the extensional processes occurring in the Apennines are due to the eastward migration of the chain, and to the progressive curvature and thinning of the chain. The eastward migration of the chain is responsible for the NW-SE faults along which major earthquakes occur, whereas the curvature and thinning of the chain could cause activity on the NE-SW striking faults. Following this model, in the transition zone between the Central and Southern Apennines the deformation due to the eastward chain migration concentrates along the NW-SE faults that are responsible for the largest earthquakes, whereas that related to the chain curvature concentrates along NE-SW faults, responsible for the lower energy, seismic activity.

Finally, the seismic sequences and swarms cluster close to or in between the main NW-SE normal fault sources responsible for the $I_0 \geq$X MCS historical earthquakes (1688, 1805, 1915) that, are presently locked (they lack earthquakes clearly aligned on them). However, in the case of a large earthquake on the NW-SE trending normal faults, the rupture might continue on the next segment via the second-order NE-SW trending faults (Pace *et al*., 2002).

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