4. Discussion and conclusions

The goal of this study was to report all the fault plane solutions of small earthquakes that occurred in Southern Italy in recent years and discuss their tectonic significance. This can be done with a qualitative comparison of these results with independent information, first of all the fault plane solutions of larger earthquakes which yield the regional deformation pattern, and other stress indicators. A quantitative analysis of the strain field derived from these earthquakes is beyond the scope of this paper, and would be hardly significant due to the sparse sampling of the micro-earthquake data set. From the trends and plunges of *P*- and *T*-axes of the focal mechanisms analyzed in this work and of those previously available, we infer the existence of regions characterized by homogeneous seismic attitudes with short wavelength variations superimposed.

We observe a widespread NE-SW extension in the Southern Apennines, including the Gargano and Northern Apulia sector. Extension also dominates in some regions of Southernmost Italy, like Northern Calabria and in the Messina Strait. We find evidence for active compression in Sicily, ~ N-S directed in the Aeolian Islands-Northeastern Sicily sub-region, and WNW-ESE directed in the western half of the island.

Focal mechanisms calculated in this paper for earthquakes in the Southern Apennines are in large part normal and strike-slip solutions. Generally, the tensional axes of these mechanisms are oriented NE-SW (fig. 6a,c). This is in close agreement with the average direction of the minimum horizontal stress inferred by Montone *et al.* (1997) from breakout directions, which is N44°E (± 20°) in the entire Southern Apenninic sector, from the Tyrrhenian coastal region to the Adriatic foreland. The average direction of tensional (*T*) axes of fault plane solutions of earthquakes that occurred in the Southern Apennines between 1962 and 1995 is also N44°E (± 27°), according to Montone *et al.* (1997). This estimate includes focal mechanisms derived both from CMT solutions and polarity data of moderate to large ($4 < M < 7$) earthquakes, and those of small earthquakes presented in this paper. Although the scatter of *T*-axes is high (circular variance ~ 27°), the striking correspondence with the minimum horizontal stress directions (S_{hmin}) obtained from breakout analysis strongly supports the idea that the whole region is dominated by NE extensional stress associated with normal faulting. It is worth noting that if the assumption of the horizontal components of the stress tensor corresponding to *P*- and *T*-axes of fault plane solutions can sometimes be misleading (McKenzie, 1969), in the case where dip-slip solutions dominate this assumption is acceptable (the horizontal projections of the principal stresses and of *P*- and *T*-axes should correspond).

Mesostructural data in the Southern Apennines suggest a change in the stress field probably in the Middle Pleistocene (Hippolyte *et al.*, 1994). Hippolyte *et al.* (1995) hypothesize that the NE extension in the Southern Apennines is confined into the upper 10-15 km depth, that is in the entire brittle crust composed of the stack of thrust-sheets detached from the underlying Apulian basement. Interpreted seismic reflection lines in Southern Italy (Mostardini and Merlini, 1986) give no clear evidence of the active NE extension, probably due to the already mentioned young age of the present-day stress field (0.7-0.6 Ma). Active strain and stress indicators, like focal mechanisms and breakouts in deep wells (Amato *et al.*, 1995) together with field observation of active faulting (Pantosti *et al.*, 1993) and mesostructural analysis (Hippolyte *et al.*, 1994) have given sufficient information of this extension. Taking into account the instrumental and historical seismicity since 1650 A.D. and assuming widespread normal faulting, Westaway (1992) estimated the seismic deformation rate along the Apenninic belt from seismic moment summation, finding that the extensional velocity perpendicular to the Southern Apenninic belt is as high as 5 mm/yr around 41°N of latitude.

Other estimates of the extension rate were obtained by Jackson and McKenzie (1988) who find 2.1 mm/yr by seismic moment summation of events with $M_s > 6.0$ in a time window of 73 years (1908-1981). This deformation rate is similar to that found by Anderson and Jackson (1987) (2.5 mm/yr) using smaller-magnitude events relative to a shorter period (21 years). Pondrelli *et al.* (1995) found a lower value (1.7 mm/yr) from the summation over 16 years (1977-1992) using only CMT solutions. A recent study by Hunstad and England (1999) based on triangulation measurements over one century demonstrated that the maximum rate of extension across the Apennines is no higher than about 3 mm/yr.

The new data presented here corroborate the hypothesis that the regional stress in the Southern Apennines is dominated by NE extension and predominant normal faulting, and demonstrate that the microseismicity can be used to predict the style of faulting in a given region, and thus to predict the rupture mechanism of large seismogenic faults at least at a regional scale. This is particularly important for regions with large historical earthquakes, but where no strong earthquakes occurred in the last century, and therefore no fault plane solutions are available. For the Southern Apenninic belt the absence of reverse solutions in the data set of the past 8 years is remarkable (fig. 6a-d). A few strike-slip solutions are present in the belt around latitude 40.5-41.5N. This region includes the area of Benevento-Campobasso, where the strike-slip solutions have NE trending *T*-axes, in agreement with the S_{hmin} directions of borehole breakouts. In this region, heterogeneous fault plane solutions of microearthquakes have been calculated by Federici *et al.* (1992) and Milano *et al.* (1999), and suggest significant deviations from the regional stress due to local sources.

Also the Gargano sector, in the Adriatic foreland, is characterized by normal and strike-slip solutions. *T*-axes of these solutions are generally E-W or NE-SW oriented (fig. 6a,c). The neotectonic structures of this area are consistent with the deformation style provided by the new seismological data presented in this work. Most of the mapped normal faults active in Quaternary times in the Gargano promontory are NW-SE oriented except for the E-W Mattinata Fault (Bigi *et al.*, 1983). The fault plane solutions presented here show no clear evidence that the E-W faults are active. It must also be noticed that the hypocentral depths of earthquakes in this region are around 15-25 km, and therefore these earthquakes may not be directly related to surface tectonic structures.

A few thrust fault solutions are present in the Central Apennines and along the outer margin of the Calabrian arc. In the Central Apennines focal mechanisms are heterogeneous probably due to the complex structural setting of the region, which represents the boundary between the northern and the Southern Apenninic arc and where stress rotations were also observed from breakout analysis (Montone *et al.*, 1997). On the Tyrrhenian side (latitude ~ 41.5 and longitude ~ 14.0), the normal solutions appear as a continuation of the extensional regime detected in the Southern Apennines and, to the north, of the extension observed in the internal sector of the Northern Apenninic arc (Montone *et al.*, 1995; Frepoli and Amato, 1997). On the Adriatic side of the Central Apennines, the few strike-slip and thrust solutions show heterogeneity in *P*- and *T*-axes orientation. This sector is dominated by Pliocene thrust structures (Bigi *et al.*, 1983) which appear to be inactive today at least from earthquake data. In the Southern Apennines, the end of the thrust activity is documented by the widespread uplift and tilting of the entire belt and foredeep since 0.7 Ma (Cinque *et al.*, 1993; Cascella *et al.*, 1997). The new data presented here confirm that this entire region is affected by NE-SW oriented extension and normal faulting, as indicated by the large earthquakes and borehole breakouts (Amato and Montone, 1997).

In the Ionian off-shore of the Calabrian arc, the only two thrust solutions computed in this work show NW-SE *P*-axes (figs. 6b and 8c), parallel to the *P*-axes orientation of strike-slip earthquakes in the same sector. This could be due to a still active (though slow) convergence between the Ionian lithosphere and Calabria. Considering the fault plane solutions of earthquakes located in the Ionian lithosphere of the Tyrrhenian subduction zone (between 40 and 165 km depth), the active convergence is also suggested by the *P*-axes orientation (see figs. 5a and 6 in Frepoli *et al.*, 1996), which trend NW-SE along the dip of the slab.

The NE-SW extension of the Southern Apennines is detected as far south as the Northern Calabrian arc along the Ionian side. Southern Calabria and the area around the Messina Strait is characterized by heterogeneity in *T*-axes dis-

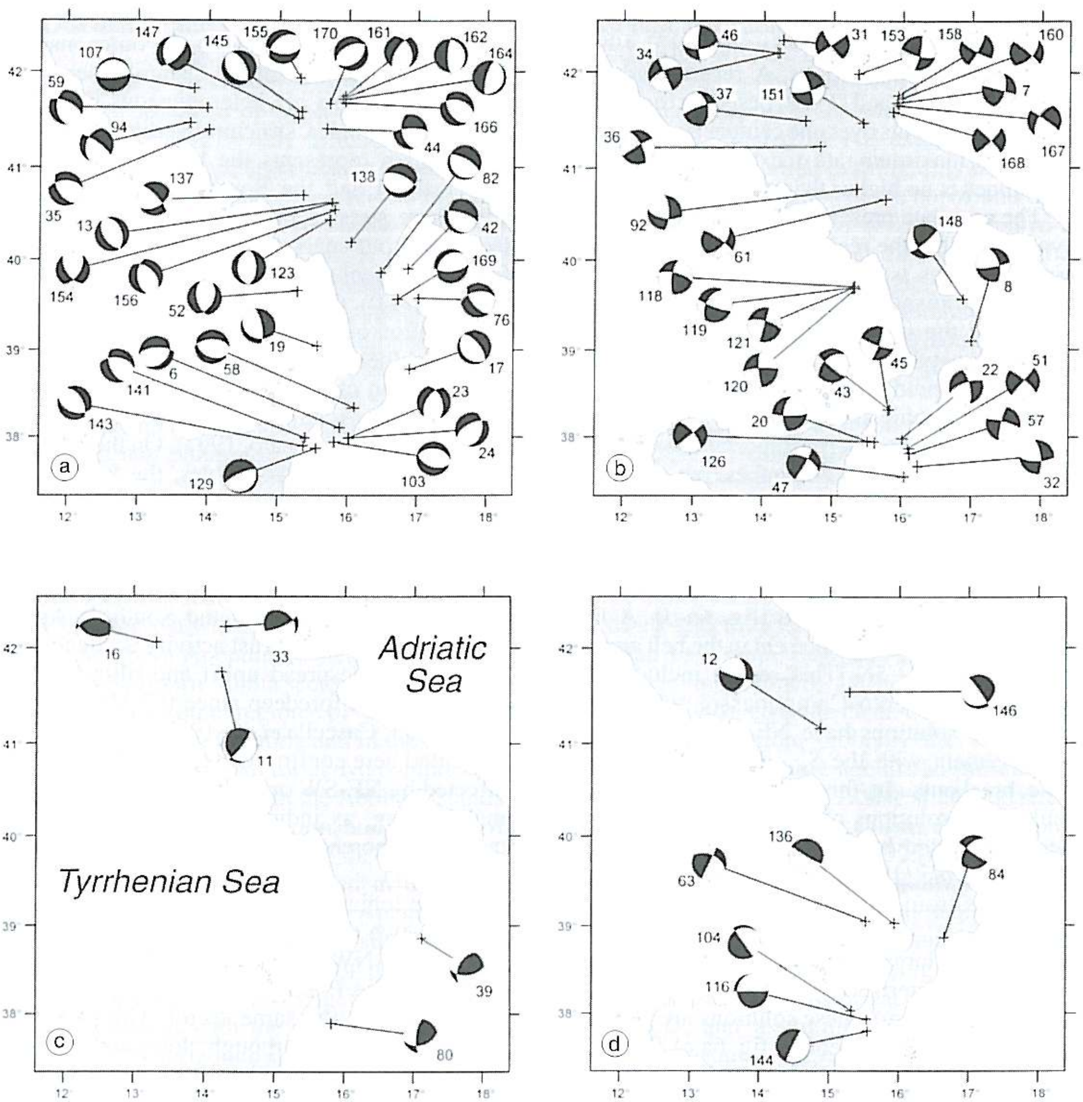

Fig. 8a-d. Focal mechanisms of the Southern Apennines and Calabrian arc divided into different stress categories according to Zoback (1992): a) normal-fault solutions (NF-NS categories); b) thrust-fault solutions (TF-TS); c) strike-slip solutions (SS); d) unknown category fault-plane solutions (U). The numbers in the first column of table I are indicated next to each focal solution.

tribution of normal and strike-slip solutions. This area, as well as the Southern Apennines, is characterized by strong uplift since Middle-Late Pleistocene (Cosentino and Gliozzi, 1988; Westaway 1993). The lack of earthquake fault plane solutions in Central Calabria (figs. 2a,b and 6a-d) in the period analyzed in this study may be due to the poor network geometry (fig. 3). Nonetheless, the surface tectonic structures reveal active normal faulting and uplift in the region

(Bigi *et al.*, 1983; Westaway 1993). Uplift rate is ~ 1 mm/yr in Calabria, and is lower in Sicily and in the Apulian foreland with values around 0.2-0.3 mm/yr. Westaway (1993) and Hippolyte *et al.* (1994) argue that the recent uplift in the Southern Apennines, in particular in the Calabrian arc where the uplift rate is higher, is the result of an isostatic rebound due to the detachment of the subducted lithosphere beneath this region in agreement with the tomographic results of Spakman *et al.* (1993). The large wavelength of the uplift trend in Southern Italy and in the Calabrian arc, observed through the study of marine terraces and shorelines (Bordoni and Valensise, 1998), also suggests that the Southern Apennines rise is driven by a deep-seated mechanism. Other tomographic studies (Amato *et al.*, 1993; Selvaggi and Chiarabba, 1995; Cimini and De Gori, 1997; Lucente *et al.*, 1999) and accurate locations of intermediate and deep earthquakes (Frepoli *et al.*, 1996) show no clear evidence of slab detachment in the Southern Tyrrhenian subduction zone. Moreover, numerical modeling of this region (Giunchi *et al.*, 1996) shows that a slab detachment would cause a subsidence at the surface just over the subduction hinge. Giunchi *et al.* (1996) also argue that the uplift in Calabria could be explained with a slab retreat process. Conversely, in the case of the Southern Apennines, the presence of a detached slab, or alternatively of a less dense subducted lithosphere, is suggested by seismic tomography and the lack of subcrustal earthquakes (Amato *et al.*, 1993; Lucente *et al.*, 1999).

The difference in the deep structural setting of Calabria and Southern Apennines could explain the observed different state of stress in the crust and the style of seismic activity (widespread extension in Southern Apennines, extension in the belt and active convergence in the foredeep of Calabria), as inferred from the earthquake focal mechanisms described in this paper and from previous studies (Hippolyte *et al.*, 1994; Amato and Montone, 1997).

Beneath the Northern-Central Apennines, the Pliocene flexuring of the Adriatic plate seems to stop during the Quaternary according to Kruse and Royden (1994) who argue that this could be related to a diminution of forces acting on the subducted slab, like downward directed forces due to the slab weight.

Focal mechanisms in Sicily are generally coherent with the convergence between the European and the African plates, which trends ~ NNW-SSE according to Argus *et al.* (1989). Also fault plane solutions of earthquake with $M > 2.5$ recorded by the Sicilian and Calabrian local networks and shown by Neri and Wyss (1993) and Caccamo *et al.* (1996) are consistent with this convergence.

In the Aeolian Islands and Western Sicily, thrust fault and strike-slip solutions are prevalent (figs. 7a-d and 9a-d). However, the N-S compression detected in the Aeolian Islands is in contrast with the Plio-Pleistocene extensional stuctures in this region. This result could suggest a very recent inversion of the stress regime, or a complexity due to the active volcanism. A comparison of some of the solutions obtained in this paper for the Aeolian Islands with those obtained for the same events by Barberi *et al.* (1999) with local data reveals that the determination of focal mechanisms with both regional and local data is a difficult task, due to the lack of dense networks and good coverage of the focal sphere, which cause poorly constrained solutions. However, we also note that, although some of the solutions differ in terms of nodal planes, the P and T axes have similar orientations.

It is interesting to note that in this region the ~ N-S compression is observed above the subducting Ionian lithosphere (see fig. 10), as well as in the adjacent region off-shore Northern Sicily, as evidenced by CMT solutions (fig. 2a). In this area, although intermediate and deep earthquakes are not recorded (fig. 10), there is evidence of past subduction from seismic tomography. Conversely, the direction of P-axes rotate in the adjacent regions of Central and Western Sicily and Southern Apennines, where earthquakes occur in the stack of thrust sheets constituting the belt. It is difficult to establish whether the WNW-ESE compression observed in Central and Western Sicily is a widespread feature due to the regional stress or a local perturbation, because the few data available are scattered in a large area.

Another open problem is the relationship between the N-S compression observed in North-

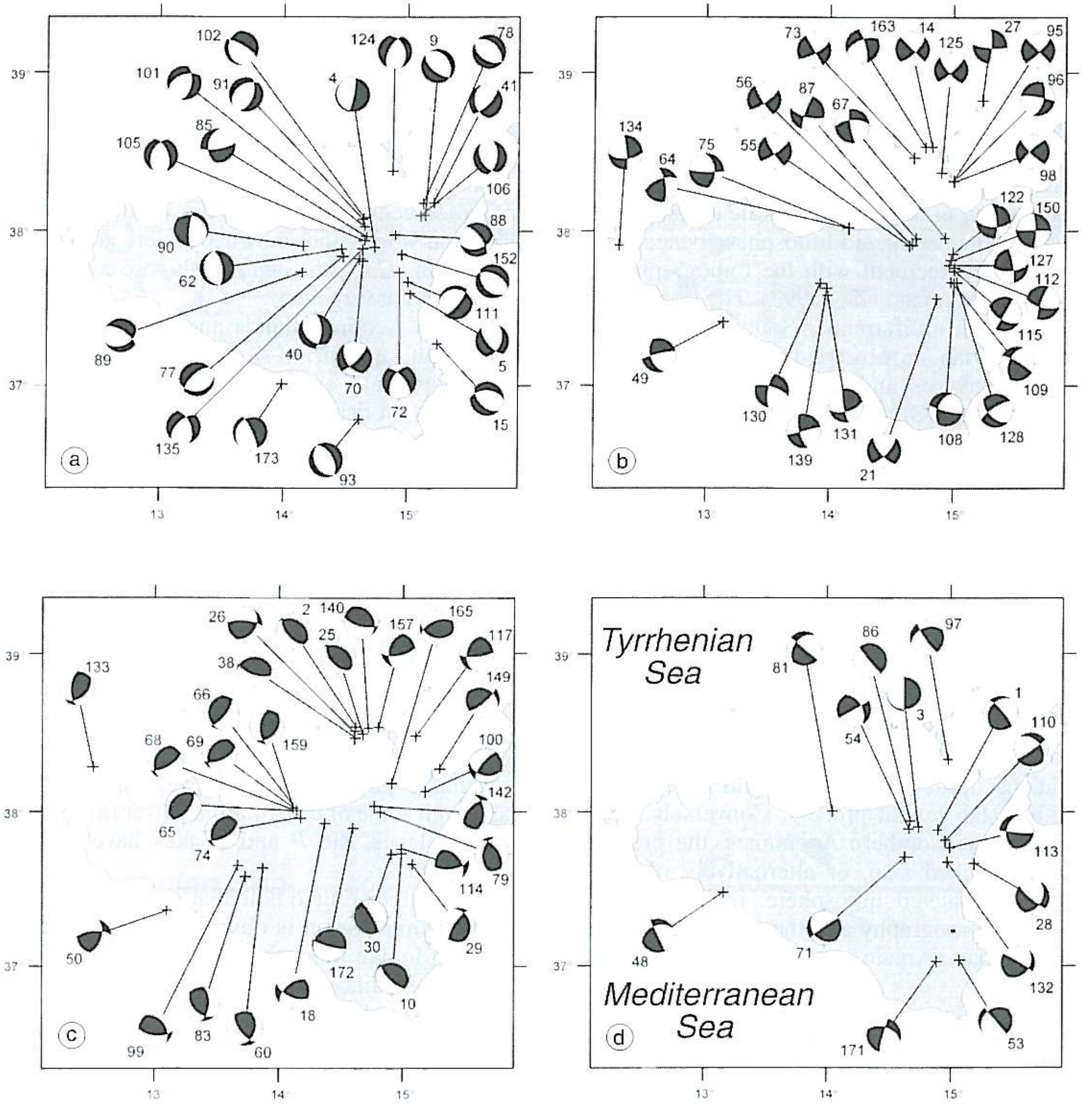

Fig. 9a-d. Focal mechanisms of the Sicilian region divided into different stress categories according to Zoback (1992): a), b), c) and d) as in fig. 8a-d. The numbers in the first column of table I are indicated next to each focal solution.

eastern Sicily and the normal faulting in the Messina Strait, as that associated with the 1908 destructive earthquake (M_S 7.1; De Natale and Pingue, 1991; Valensise and Pantosti, 1992). Looking at small earthquakes in this area (figs. 6a-d and 7a-d), it appears that the normal faulting earthquakes are located in the plate overlying the Ionian slab, where the slab is sub-horizontal and starts to bend (fig. 10). The 100 km depth contour line in fig. 10 marks the abrupt change in the slab dip. The normal faulting earthquakes in Calabria and in the Messina Strait

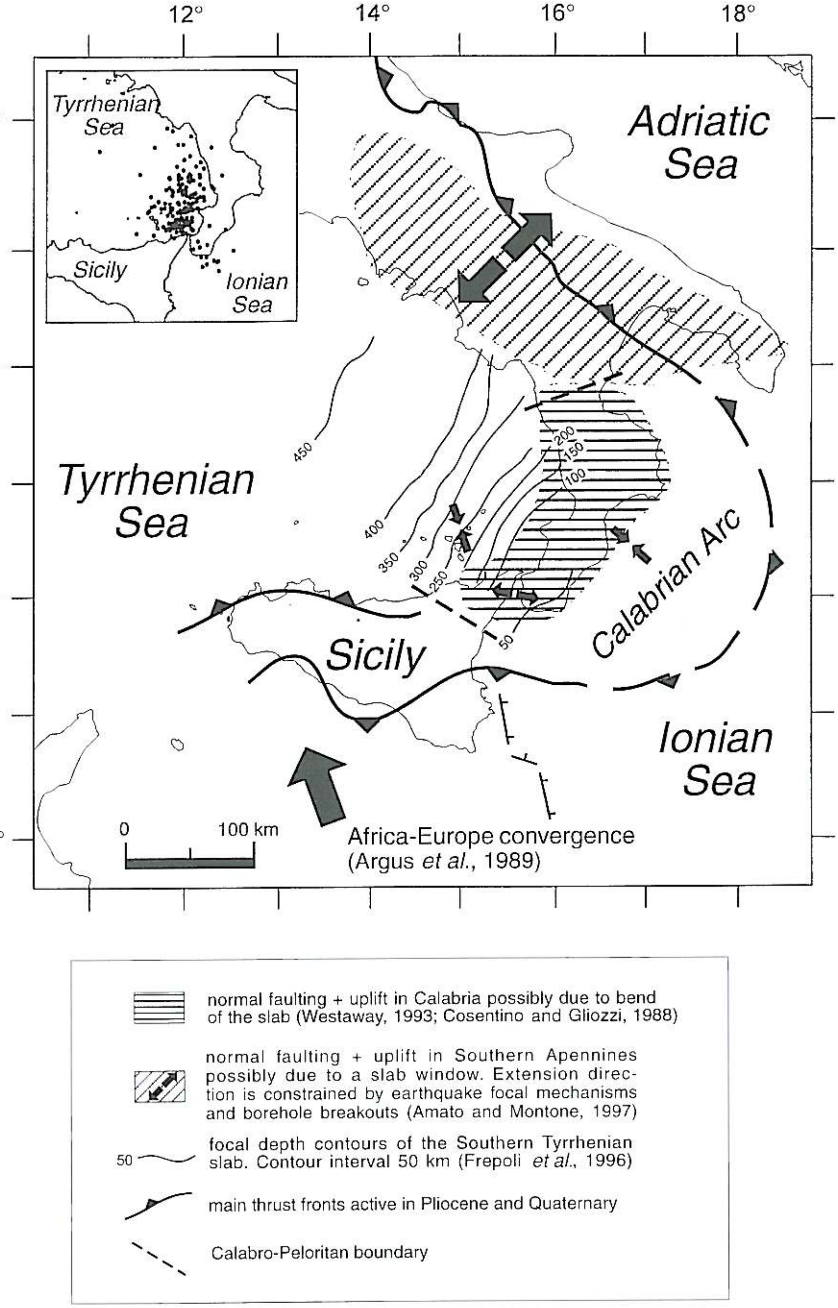

Fig. 10. Schematic outline of the main geodynamic features of Southern Italy. In the upper left box is shown the epicentral distribution of 185 intermediate and deep Southern Tyrrhenian earthquakes selected from Selvaggi and Chiarabba (1995) for the period 1988-1994.

are located just above and slightly behind this line. This suggests that the slab geometry and dynamics control the deformation of the crust in this region.

In this paper, we have shown that the distribution of fault plane solutions of background seismicity earthquakes is helpful in delineating the main seismotectonic provinces of Italy, also in comparison with other data (large earthquakes, borehole breakouts, active fault data, etc.). Of course, due to the small size of these earthquakes, the fault plane solution of each single earthquake may not directly reflect the regional stress. However, both the internal consistency of these data in large regions and the coherence with other data suggest that these small earthquakes also yield useful information on the large scale processes. The availability of more and more detailed microearthquake data and a more accurate knowledge of the crustal structure will contribute in the future to better constrains the seismotectonics of this complex region.

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