Crustal and deep seismicity in Italy (30 years after)

Alessandro Amato, Claudio Chiarabba and Giulio Selvaggi
Istituto Nazionale di Geofisica, Roma, Italy

Abstract
The first modern studies of seismicity in Italy date back to the late 60's and early 70's. Although with a sparse seismic network available and only a few telemetered short-period stations, significant studies were carried out that outlined the main features of Italian seismicity (see, *e.g.*, Boschi *et al.*, 1969). Among these studies, one of the most important achievements was the reconnaissance of a Wadati-Benioff zone in Southern Tyrrhenian, described for the first time in detail in the papers of Caputo *et al.* (1970, 1973). Today, after three decades of more and more detailed seismological monitoring of the Italian region and tens of thousands earthquakes located since then, the knowledge of the earthquake generation processes in our country is much improved, although some of the conclusions reached in these early papers still hold. These improvements were made possible by the efforts of many institutions and seismologists who have been working hard to bring seismological research in Italy to standards of absolute quality, under the pivoting role of the Istituto Nazionale di Geofisica (ING). From the relocation of about 30000 crustal earthquakes and detailed studies on intermediate and deep shocks carried out in the last few years, we show that seismic release in peninsular Italy is only weakly related to the Africa-Eurasia convergence, but rather is best explained by the existence of two separate subduction/collision arcs (Northern Apennines and Southern Apennines-Calabria-Sicily). The width of the deforming belt running along peninsular Italy is 30 to 60 km, it is broader in the north than in the south, and the two arcs are separated by a region of more distributed deformation and stress rotations in the Central Apennines. Along the belt, the reconnaissance of regions of continuous and weak release of seismic energy, adjacent to fault areas which are currently «locked» (and therefore are the best candidates for future earthquakes) is another recent important achievement of the prolonged detailed seismic monitoring of our territory, which will provide in the future more and more precise indications of where earthquakes will strike. In addition, the accurate location of hundreds of intermediate and deep earthquakes beneath the two arcs has recently provided (together with seismic tomography results) new hints on the tectonic setting of Italy and its evolution over time, on the relations between deep processes and crustal stress, and ultimately on the mechanisms of earthquake generation in our country.

Key words *seismicity – seismotectonics – Italy*

1. Introduction

The Italian peninsula is one of the most active regions of the world. Although large ($M \sim 7$) destructive earthquakes are not as frequent as in other regions, its enormous cultural and archeological heritage renders the Italian territory one of the most hazardous in the world. All the devastating earthquakes of this century, from the 1908 Messina-Reggio until the 1980 Irpinia event, have struck a country and a scientific community which were not prepared for such disasters. Many things have changed since then, including a seismological data base which is continuously updated and provides important basic inputs for predicting where and how future large earthquakes will most likely occur. The data recorded by a modern seismological network are the first tool that Earth sci-

Mailing address: Dr. Alessandro Amato, Istituto Nazionale di Geofisica, Via di Vigna Murata 605, 00143 Roma, Italy; e-mail: amato@ing750.ingrm.it

entists can use (in combination with the historical information) to identify seismically active structures and possibly recognize locked faults prone to incipient rupture. In this paper, we describe what has been done in this field in Italy in the past three decades, even though it is only in the past 15 years that a good seismic network has collected data with a sufficient density and a homogeneous technical standard and geographical coverage.

In this contribution, we describe the main achievements obtained in the 80's and 90's in delineating the distribution of crustal, intermediate and deep seismicity in Italy with the aid of a modern seismological network, like the national network of the ING. The huge amount of data collected in the past three decades (but mostly in the last 15 years) has been the spur for a wide variety of studies, which includes: the detailed location of many thousands of crustal earthquakes every year (Cocco *et al.*, 1993; Chiarabba and Selvaggi, 1997), the accurate delineation of the Tyrrhenian subduction zone (Frepoli *et al.*, 1996), the identification of a relic subduction in the Northern Apennines (Selvaggi and Amato, 1992), the tomographic study of the lithosphere-asthenosphere structure and its important geodynamic implications (Amato *et al.*, 1993; Selvaggi and Chiarabba, 1995; Alessandrini *et al.*, 1995; Mele *et al.*, 1996; Chiarabba and Amato, 1997; Cimini and De Gori, 1997); a good knowledge of the state of stress in the crust (Frepoli and Amato, 1997; Montone *et al.*, 1997).

Here, we show the most recent results relative to the distribution of the seismicity in the crust, which allows to identify the region where the seismic deformation is taking place and, comparing to what we know from the damaging patterns of historical earthquakes, where we can expect future large earthquakes. For this purpose, more than 30000 crustal earthquakes have been relocated with an optimized velocity model and appropriate location parameters (see Chiarabba and Frepoli, 1997). Also, we describe the most updated pictures of both the Southern Tyrrhenian subduction zone (Frepoli *et al.*, 1996) and the past subduction/continental collision setting of the Northern Apennines (Selvaggi and Amato, 1992).

2. Tectonic setting and earthquake occurrence in peninsular Italy

The present shape and seismicity distribution of the Italian peninsula and Sicily (fig. 1) reflect the Neogene and Quaternary evolution of the Central Mediterranean. In a context of general convergence between two main plates (Africa and Eurasia), the development of subduction and collision processes in the late stage of the Tethys consumption in the Mediterranean has been strongly controlled by the inherited paleogeography (Dercourt *et al.*, 1986; Dewey *et al.*, 1989). Remnants of the oceanic lithosphere have determined the progressive slab retreat in several regions of the Mediterranean basin in different times, leading to the formation of several arcs and back-arc basins (see, *e.g.*, Malinverno and Ryan, 1986; Patacca and Scandone, 1989). Today, many of these regions are clearly evident from morphological, geological and seismological features, and they differ from each other because they represent different evolutionary stages of subduction, sinking, continental collision processes. Besides other examples of the Mediterranean like the Betic-Alboran basin, the Aegean, the Pannonian basin, not described here, in Italy we observe four different examples of the differential evolution of such subduction/collision arcs. These are:

a) The Alpine arc, with evidence of past subduction (from geology and seismic tomography) but no intermediate and deep seismicity, because the process stopped several million years ago.

b) The Northern Apennines, where subduction of the oceanic lithosphere was followed by continental collision and possibly by subduction or sinking of continental lithosphere: evidence of this is found in subcrustal earthquakes (Selvaggi and Amato, 1992) and seismic tomography (Amato *et al.*, 1993; Spakman *et al.*, 1993).

c) The Calabrian arc, with clear evidence of a long, continuous slab of oceanic lithosphere as long as at least 500 km and possibly much more than this (Caputo *et al.*, 1970, 1973; Gasparini *et al.*, 1985; Anderson and Jackson, 1987b; Spakman *et al.*, 1993; Selvaggi and

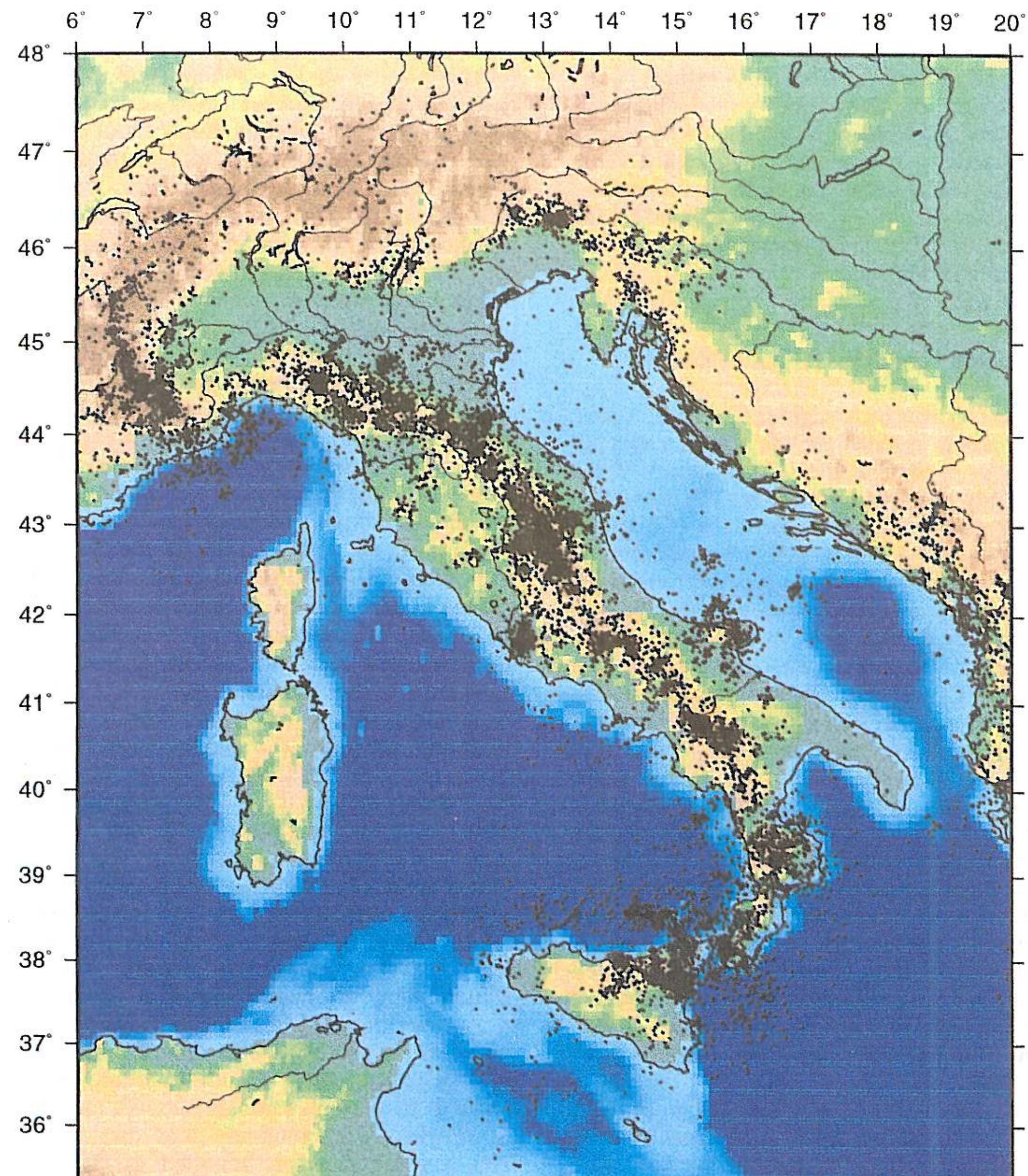

Fig. 1. Epicentral map of the relocated earthquakes in the period 1975-1997. The seismicity is mainly concentrated beneath the Apenninic belt, defining two main arcs (Northern Apennines and Calabrian arcs) and a zone of distributed deformation in between.

Chiarabba, 1995; Frepoli *et al.*, 1996; Lucente *et al.*, 1997 among many others).

d) The Southern Apennines, where a detached slab (or, alternatively, subduction of a less dense lithosphere) is documented by earthquake activity and seismic tomography. Here, a widespread crustal extension is inferred by earthquake fault plane solutions (Anderson and Jackson, 1987a) and present-day stress data (Amato and Montone, 1997).

3. Crustal seismicity in peninsular Italy

The constant increase in the number of seismic stations installed in the past decades allowed us to outline the basic features of the seismicity distribution in Italy. The relocation of more than 30 000 earthquakes (Chiarabba and Selvaggi, 1997) which have occurred in the period 1975-1997 have been performed using the program *Hypoinverse* (Klein, 1989), a 1D velocity model taken from Chiarabba and Frepoli (1997), and restrictive weights which filter-off the seismic phases recorded at distances larger than 200 km from the epicenter and with *P*-wave residuals larger than 0.6 s. From this huge data set, about 16 000 earthquakes with hypocentral errors lower than 4 km in horizontal and vertical coordinates are selected and discussed (fig. 1). It must be reminded that the estimation of depth parameters suffers for not uniqueness, due to the network geometry. The improvement in the seismic monitoring of Italy is well evident if we look at the earthquakes located in three subsequent time intervals of 7 years, from 1975 to 1982, from 1983 to 1990, and from 1991 to 1997 (fig. 2a-c).

The distribution of seismicity shown in fig. 1 is helpful to outline the main features of seismic release in Italy, keeping in mind that the analyzed time window is very short (only 20 years) compared to typical repeat times of large faults (hundreds or thousands years). The distribution described here has the advantage that it is mainly based on a homogeneous network of seismic stations (the national network of the ING) which uses the same type of seismometers, data transmission and storage, and a common waveform synchronization procedure. The main disadvantage of such network is the relatively large station spacing (typically between 20 and 70 km) and the consequent inability to constrain well the hypocentral depths of crustal earthquakes. For this purpose, the availability in many regions of Italy of dense local networks, either permanent or temporary, is fundamental to know important parameters of the earthquake generation process, such as the thickness of the seismogenic layer, the fault plane solutions of small earthquakes, and the space-time distribution of microseismicity. These aspects are not described in this paper, but the data used to locate the earthquakes of figs. 1 and 2a-c include data from local networks.

Three main seismic provinces can be delineated across the Italian peninsula based on the crustal seismicity distribution (fig. 1, see also Gasparini *et al.*, 1985): a) the Tyrrhenian belt, with shallow (0-7 km) and small magnitude ($M < 4.5$) earthquakes, mostly concentrated in the vicinity of the Quaternary volcanoes and the geothermal areas of Tuscany, Latium, and Campania; b) the Apenninic belt, characterized by stronger (M up to 7) and deeper events (0-20 km), generally with normal (subordinately strike-sip) focal mechanisms; and c) the Adriatic foredeep, where thrust and strike-slip fault plane solutions are generally observed, but only in the Northern Apennines. The lower level of seismicity visible in some regions (fig. 1) in some cases is due to very weak or aseismic deformation (like Sardinia), but it may be also due to a lower density of seismic stations (Central Alps), to smaller magnitude events, or to a combination of both (as in Tuscany). In the following section, we describe the seismicity distribution within the three different domains as seen by the national network (and local stations which routinely send data to the ING and are therefore reported in the bulletins), but also using information obtained from temporary arrays or microseismic networks.

The Tyrrhenian Quaternary Volcanic belt, extending from Tuscany to Campania, is affected by frequent seismic swarms that can last from a few days up to years. Local seismic networks operating in the region during the past

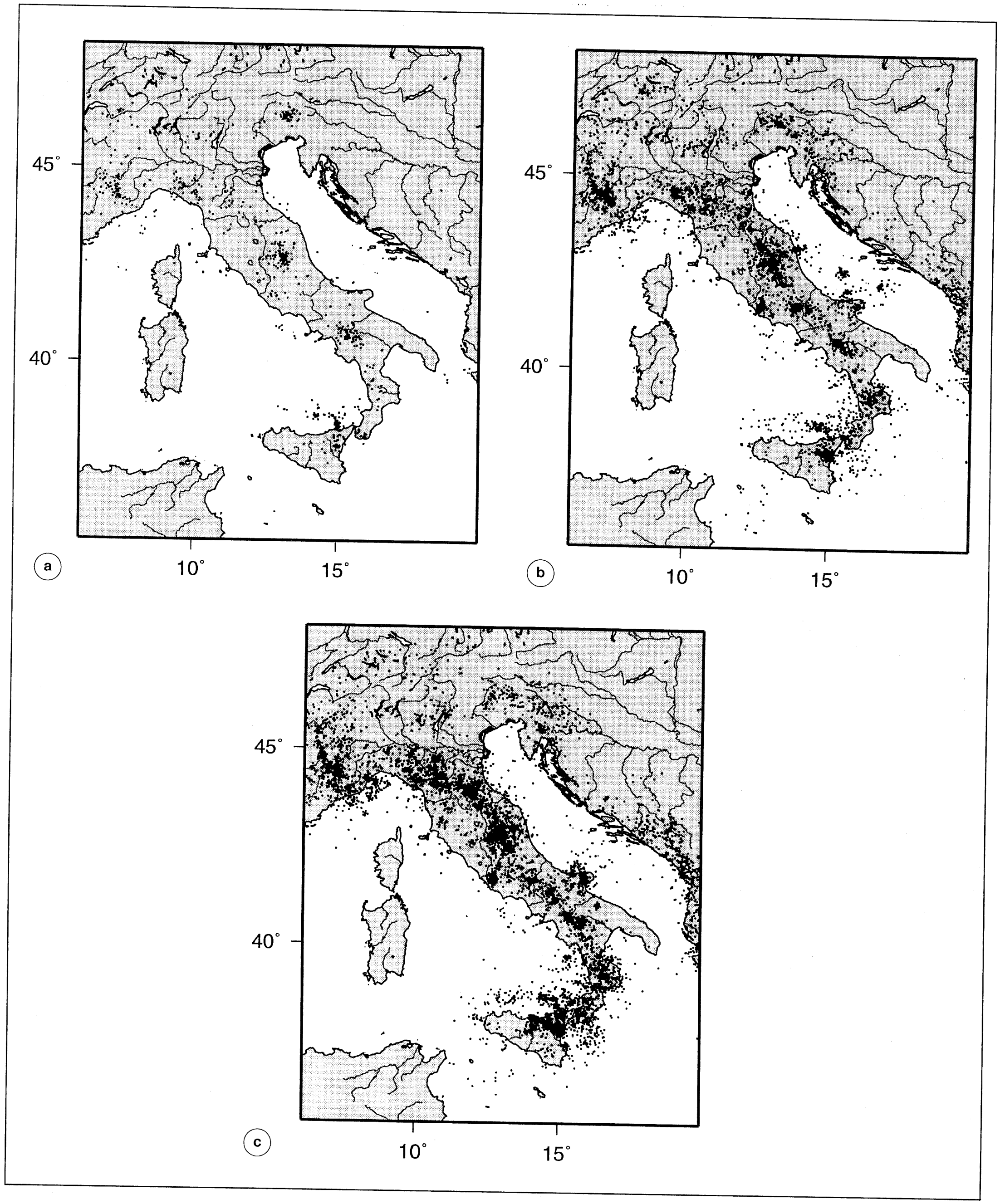

Fig. 2a-c. Epicenters of relocated earthquakes in three different time intervals: a) 1975-1982; b) 1983-1990; c) 1991-1997. Note the significant increase of located events from the early '80s to the present, due to the strong improvement in the national seismic network.

20 years have located several thousands of small earthquakes. The very low seismicity of this region appearing in fig. 1 is due to the poor coverage of the national network and to the lack of data from local networks included in the published bulletins (though microseismic networks do exist). Common features of earthquake occurrence within these areas are a maximum magnitude that seldom exceeds 4.5, shallow hypocentral depths (moslty confined in the upper 7 km of the crust), swarm-like behaviour, and hypocenters confined in small crustal volumes. The depth distribution of seismicity in this region is controlled by the high thermal gradient and by the presence of magmatic/hydrothermal systems in the upper crust which often generate episodes of ground uplift. The role played by magmatic processes and fluid pressure in the earthquake generation for this volcanic province remains an open problem.

Along the Apenninic belt, the seismicity distribution delineates two distinct seismic areas (fig. 1), which differ for the total moment released, for the largest magnitude observed, and for the faulting mechanisms. An offset in the seismicity distribution in the central sector of the belt was pointed out by Cocco *et al.* (1993). This region does not appear as a single fault zone, but as a zone of diffuse seismicity that geologically corresponds with the boundary between the northern arc (in Umbria) and the carbonate platform of the Central Apennines. Here the seismicity is sparse, less frequent than in Umbria, but with large historical earthquakes and therefore a high seismic hazard. The seismicity distribution indicates that the large «geologic» faults which played a major role during the Apenninic build-up, like for instance the Olevano-Antrodoco and the Ortona-Roccamonfina lines, are no longer active, at least as far as the seismic deformation is concerned. Another interesting feature of the boundary region between the northern and southern arc is the stress rotation observed both at the outer front of the belt, around latitude 43°N (Montone *et al.*, 1997), and within the belt where NW-SE extension is suggested by fault plane solutions of recent crustal earthquakes (Frepoli and Amato, 1997).

The northern arc is characterized by moderate magnitude events, that barely exceed M 6. Here, the seismicity follows an arcuate belt convex toward the Adriatic sea. Earthquakes are clustered underneath the axis of the Apenninic chain. Within this arcuate belt three main distinct sequences occurred in the past 20 years; the m_b 5.9 Norcia earthquake in 1979 (Deschamps *et al.*, 1984), the m_b 5.2 Perugia earthquake in 1984 (both with normal faulting mechanism), and the m_b 5.1 Parma event in 1983, with a predominant reverse mechanism. The seismicity recorded during these seismic sequences, monitored by local networks in the former two examples, shows some relation with previously known geologic structures. Conversely, the background seismicity appears as isolated shocks or swarm sequences occurring within small crustal volumes and not clearly related to any specific structure, indicating that the deformation in this sector of the Apenninic arc is diffuse, although in a relatively narrow belt. The width of this seismically deforming belt is about 50-70 km wide (perpendicular to the chain), and generally corresponds with the maximum elevation of the chain (Selvaggi *et al.*, 1997). The average hypocentral depths of the earthquakes in the Northern Apennines are larger than those of the central and southern portions of the belt.

Figure 3a is a vertical section of hypocenters across the Northern Apennines. Most of the seismicity occurs in the upper 20 km of the crust beneath the Apenninic belt (around x = 200 km in fig. 3a). Another cluster is evident more to the east (x = 300-350), that corresponds to deformation in the Adriatic foredeep. From the analysis of fault plane solutions of crustal earthquakes Frepoli and Amato (1997) pointed out the concomitant existence of extension in the back-arc region and compression at the outer front, a feature typical of the entire Neogene-Quaternary evolution of the Northern Apennines. A few sub-crustal earthquakes (down to 110 km depth) are also evident (fig. 3a) and will be discussed below.

The Southern Apennines, where the largest earthquakes occur, are characterized by a narrow seismic belt, NW-SE striking and 30 to

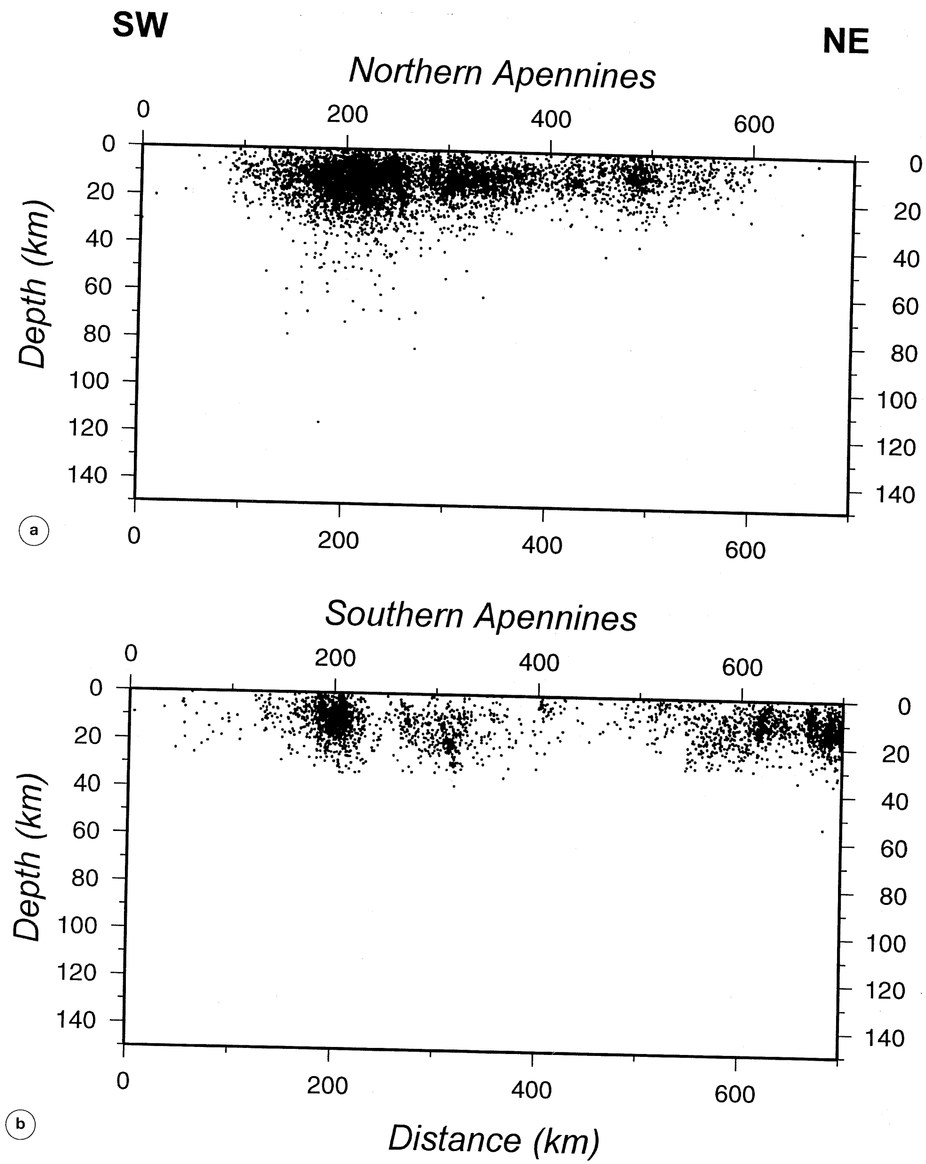

Fig. 3a,b. Vertical sections of earthquakes across the Northern (a) and the Southern (b) Apennines. Earthquakes are mainly concentrated beneath the belt. Note the subcrustal seismicity in the Northern Apennines.

50 km wide. In the past 20 years several earthquakes with magnitude larger than 5 occurred in this region, particularly the M_s 6.9, 1980 Irpinia earthquake. In this area the seismicity is clustered either along the major fault segments (for instance, aftershocks of the 1980 event), or it identifies the boundary between adjacent, possibly laterally offset, segments of the main Southern Apennines seismic belt, as previously suggested by Valensise *et al.* (1994). Accord-

ing to this, the zones along the belt that have been hit by large historical earthquakes but do not show seismic release today (zones of quiescence) have to be considered as the most hazardous regions of the Apennines. Among these, the Benevento-Sannio-Matese region (source region of the 1688 and 1732 events), north of the 1980 Irpinia fault, and the Val d'Agri fault zone, source region of the 1857 earthquake. Figure 4 compares the 1975-1997 seismicity distribution with the approximate geometry of the main faults of the Central-Southern Apennines, in a vertical section running from the Ionian coast throughout the entire peninsula. The position of the faults in fig. 4 is constrained by macroseismic data (Boschi *et al.*, 1995) while their vertical extent is not meaningful (most of these faults have probably ruptured the entire seismogenic layer). The approximate fault lengths are determined from seismic moment estimates (Castello, 1997), assuming a constant strain drop (ratio between displacement and fault length, see Kanamori and Anderson, 1975). Most of the faults of the Southern Apenninic belt appear to be almost aseismic (fig. 4), except for the 1980 fault, marked by diffuse aftershock activity and the 1561 fault, over which many shocks of the 1990 and 1991 sequences of Potenza are projected. Some boundary regions between adjacent segments are well depicted by the background seismicity, like the one between the 1688 and the 1805 source regions. Also evident from fig. 4 are a few zones of diffuse seismicity, like Umbria and the region between the 1805 and the 1915 faults (including the source area of the M_B 5.5 Latium-Abruzzi earthquake in 1984).

Figure 3b shows the hypocentral distribution of earthquakes across the Southern Apennines. Earthquakes occur in the upper 20 of the crust, and subcrustal seismicity is absent. Two main seismic areas are identified, one underneath the Apenninic belt (x = 200 km in fig. 3b), the second beneath the Apulian foreland (x around 300 km), particularly the region around the Gargano promontory (fig. 1). The seismicity of the Southern Apenninic belt is characterized by predominant normal faulting earthquakes. Contrary to the northern arc, the Adriatic foreland has a very low seismicity. Borehole breakout data show that the foredeep

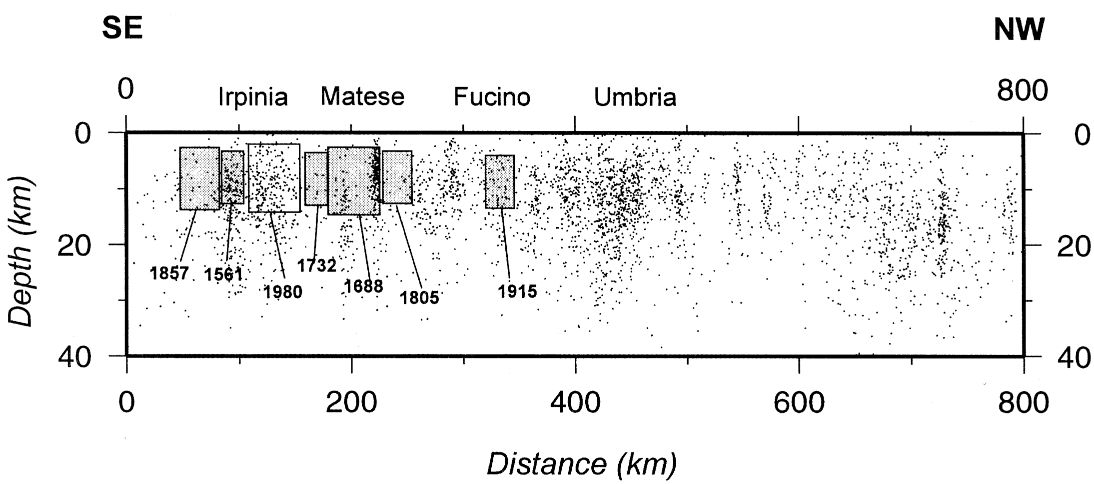

Fig. 4. Vertical section of earthquakes along the apenninic belt. Earthquakes located within a ± 25 km wide zone are plotted. The main fault segments which ruptured during large historical earthquakes hypothesized (gray square) or observed (white square) are shown. The numbers indicate the year of the last historical earthquake for each segment.

is also undergoing extension perpendicular to the trend of the Apennines, even though the stress regime is not well defined as in the belt (Amato and Montone, 1997).

4. Intermediate and deep seismicity in Italy

Only in two regions of Italy there are earthquakes below the crust located by the national network of the ING, namely the Southern Tyrrhenian and the Northern Apennines (fig. 5), with a large difference in the maximum depth (~ 400 km in the former, ~ 100 in the latter). While the existence of a subduction process in the Tyrrhenian region was proven by seismological data many years ago (see, *e.g.*, Caputo *et al.*, 1970, 1973), Northern Apenninic subduction had been hypothesized mainly based on geological data (Patacca and Scandone, 1989; Doglioni, 1991, among many others). The existence of a subcrustal seismicity, though of low energy, has strengthened this hypothesis and allowed the geometry of the lithosphere at depth to be constrained (Selvaggi and Amato, 1992).

The Southern Tyrrhenian subduction zone is the region of the Italian peninsula of highest seismic energy release, with many $m_b \sim 5$ earthquakes recorded each year. During this century, the largest earthquake ($m_b = 7.1$) occurred on April 13, 1938 at 290 km depth. Tens of intermediate and deep earthquakes occur yearly. Looking at the distribution of large earthquakes located between 1911 and 1970 with data from regional and teleseismic stations, Caputo *et al.* (1970, 1973) identified a Wadati-Benioff zone dipping from the Calabrian arc to NNW with a dip of about 60°. More recent studies, based on a longer and more detailed sesimological record, were then carried out by Gasparini *et al.* (1985), Anderson and Jackson (1987b) and Giardini and Velonà (1991), among many others. The good coverage of regional seismic stations achieved by the ING in the past decade has provided new insight of the seismic processes in the Tyrrhenian slab (Frepoli *et al.*, 1996). Figure 6a-d shows the location of intermediate and deep earthquakes selected among those located by the national network of the ING between 1988 and 1995 (see also Selvaggi and Chiarabba, 1995). Earthquakes between 40 and 100 km depth are located beneath the Ionian Sea and the Calabrian arc, delineating a subhorizontal seismic zone that may represent the subducting Ionian plate. The deep seismicity is mainly concentrated in a narrow area (approximately 200 km across and 70 km thick) offshore the Calabrian arc with an average dip of 70° to the northwest.

Lateral variations along the slab are well evident if we compare the deep structure in proximity of the Southern Apennines (fig. 6b) with that of the Calabrian arc (fig. 6c,d). In the former profile, a clear gap of seismicity is observed between 100 and 200 km depth, suggesting the existence of a detached slab below the southernmost portion of the Apennines. This generally agrees with what was proposed by Amato *et al.* (1993) from seismic tomography results, that this section of the Apenninic belt is a sort of «slabless» window. Consistently, northwest of Calabria, no intermediate and deep seismicity is recorded for about 250 km along the belt (see fig. 5). On the contrary, the seismicity distribution of the Tyrrhenian subduction in Calabria does not indicate any clear detachment in the slab (fig. 6c,d).

A sparse, low magnitude subcrustal seismicity also affects the Northern Apenninic arc, north of latitude 43°N (Selvaggi and Amato, 1992). The subcrustal earthquakes of the Northern Apennines (figs. 3a and 5) are mainly located slightly to the southwest of the axis of the chain, following the bend of the Northern Apenninic arc. These deep events have magnitudes generally lower than 4.5 (although these values might be underestimated) and are generally not followed by aftershock activity. These earthquakes occur in a southwestward thickening wedge dipping about 40° from the Adriatic towards the Tyrrhenian Sea down to a depth of 100 km. As hypothesized by Selvaggi and Amato (1992), this seismicity may indicate the geometry of the Adriatic continental lithosphere beneath the Northern Apennines, the present remnant of a longer subducted slab which is imaged by seismic tomography (Amato *et al.*, 1993; Spakman *et al.*, 1993).

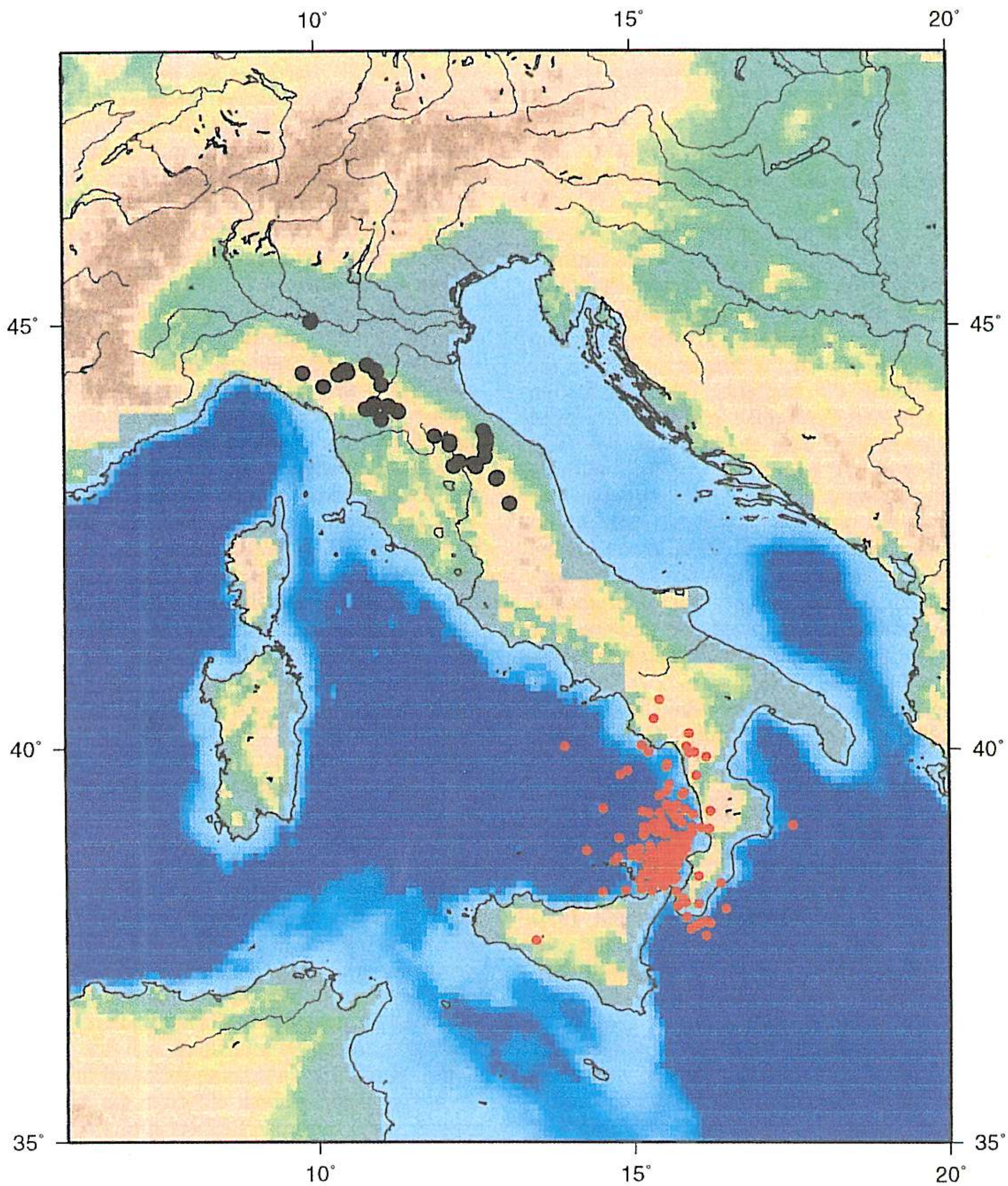

Fig. 5. Epicentral distribution of subcrustal seismicity in Italy. Subcrustal earthquakes are located both between 35 and 110 km depth beneath the Northern Apennines (black dots), and between 35 and 500 km depth beneath the Calabrian arc (red dots).

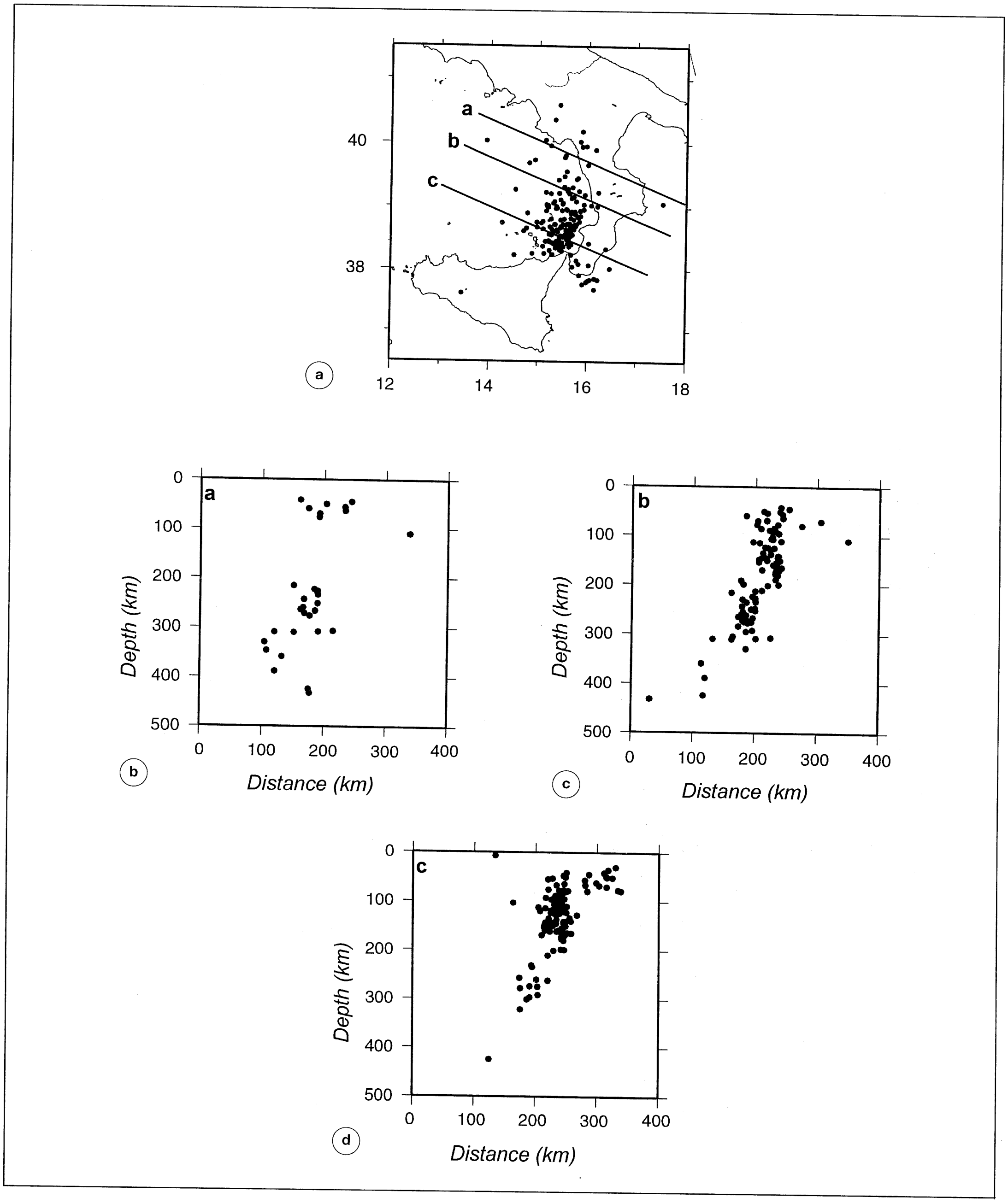

Fig. 6a-d. The intermediate-depth and deep seismicity of the Southern Tyrrhenian subduction zone in the map and in three WNW-ESE vertical sections. Earthquakes help to constrain the geometry of the descending Ionian slab, identifying a gap between 100 and 200 km in the northernmost sector, close to the Southern Apennines. Earthquakes within ± 50 km are plotted.

5. Conclusions

The relocation of about 30000 earthquakes recorded by the national network of the ING between 1975 and 1997, including intermediate and deep shocks located in the Northern Apennines and Southern Tyrrhenian, allowed us to infer that the seismic release in peninsular Italy is only weakly due to the relative convergence of Africa and Eurasia. Only in Northeastern Italy (Friuli) and part of Sicily does the seismic deformation seem to accommodate north-south (or NNW-SSE) convergence between Africa and Eurasia. In the rest of Italy, the seismic activity reflects the existence of two separate arcs (Northern Apennines and Southern Apennines-Calabria-Sicily) which represent different stages of evolution of incomplete subduction and continental collision between microplates. The two arcs have undergone a different tectonic evolution in Neogene and Quaternary times and the seismic deformation observed today reflects this difference, in terms of deformation rates (one order of magnitude higher in the south), maximum magnitude expected (larger in the south), and faulting mechanisms. The width of the deforming region is of a few tens of kilometers, it is more diffuse in the north than in the south, and the two arcs are separated by a region of more distributed deformation and stress rotations, corresponding to the carbonate platforms of the Central Apennines. The complex shape of the deforming belt as outlined by the earthquake distribution marks the active plate boundary in this region of the Central Mediterranean, and follows the deformation of the crustal stack of the Apenninic thrust sheets above the subducting (or sinking or retreating) Adriatic and Ionian lithosphere.

Along the belt, the identification of regions characterized by continuous and low seismic energy release, adjacent to fault areas which are currently «locked» (and therefore are the best candidates for future earthquakes) is another recent important achievement of the prolonged detailed seismic monitoring of our territory, which in the future will provide indications of where earthquakes will strike. To date, the data recorded in the 22-year time span by the national seismic network of the ING, and where available those of local networks, already allow us to depict the regions of the Apenninic belt which are accumulating stress. The comparison of these data with the information contained in the historical record demonstrates that a good instrumental catalogue, even if relative to a period which is much shorter than a seismic cycle, is a valuable tool that provides useful information for seismic hazard and earthquake prediction studies.

Furthermore, the accurate location of hundreds of intermediate and deep earthquakes beneath the Italian region, together with results of seismic tomography, has recently provided new important information on the deep tectonic setting of Italy and of its evolution over time. The analysis of hundreds of present-day stress indicators carried out in the past few years is bringing new constraints for geodynamic modelling, and suggests that a close relationship exists between deep processes and crustal stress. The wide variety of studies briefly summarized in this paper demonstrate that the continuous recording of seismological data with modern instruments greatly contribues in unraveling the complex tectonic evolution of the Italian region and in shedding light on the mechanisms of earthquake generation in our country.

REFERENCES

ALESSANDRINI, B., L. BERANZOLI and F.M. MELE (1995): 3D crustal *P*-wave velocity tomography of the Italian region using local and regional seismicity data, *Ann. Geofis.*, **38**, 189-211.

AMATO, A. and P. MONTONE (1997): Present-day stress field and active tectonics in southern peninsular Italy, *Geophys. J. Int.*, **130**, 519-534.

AMATO, A., B. ALESSANDRINI, G.B. CIMINI, A. FREPOLI and G. SELVAGGI (1993): Active and remnant subducted slabs beneath Italy: evidence from seismic tomography and seismicity. *Ann. Geofis.*, **36** (2), 201-214.

ANDERSON, H.J. and J. JACKSON (1987a): Active tectonics of the Adriatic region, *Geophys. J. R. Astron. Soc.*, **91**, 937-987.

ANDERSON, H.J. and J. JACKSON (1987b): The deep seismicity of the Tyrrhenian Sea, *Geophys. J. R. Astron. Soc.*, **91**, 613-637.

BOSCHI, E., M. CAPUTO and G.F. PANZA (1969): Stability of seismic activity in Italy, with special reference to

Garfagnana, Mugello, and Forlivese, CNEN, RT ING, 24.
BOSCHI, E., G. FERRARI, P. GASPERINI, E. GUIDOBONI, G. SMRIGLIO and G. VALENSISE (1995): Catalogo dei Forti Terremoti in Italia dal 461 a.C. al 1980, *Istituto Nazionale di Geofisica* - SGA, pp. 973.
CAPUTO, M., G.F. PANZA and D. POSTPISCHL (1970): Deep structure of the Mediterranean Basin, *J. Geophys. Res.*, **75**, 4919-4923.
CAPUTO, M., G.F. PANZA and D. POSTPISCHL (1973): New evidences about the deep structure of the Lipari arc, *Tectonophysics*, **15**, 219-231.
CASTELLO, B. (1997): Distribuzione di momento sismico lungo la catena appenninica dal 1983 al 1996 e confronto con possibili strutture sismogenetiche, *Tesi di Laurea*, Università degli Studi «La Sapienza», Roma.
CHIARABBA, C. and A. AMATO (1997): Crustal velocity structure of the Apennines (Italy) from *P*-wave travel time tomography, *Ann. Geofis.*, **39**, 1133-1148.
CHIARABBA, C. and A. FREPOLI (1997): Minimum 1D velocity models in Central and Southern Italy: a contribution to better constrain hypocentral determinations, *Ann. Geofis.*, **40**, 937-954.
CHIARABBA, C. and G. SELVAGGI (1997): Sismicità strumentale degli ultimi 22 anni in Italia: nuove determinazioni ipocentrali, magnitudo e rilascio di momento sismico, *Int. Publ. ING*, No. 590.
CIMINI, G.B. and P. DE GORI (1997): Upper mantle velocity structure beneath Italy from direct and secondary *P*-wave teleseismic tomography, *Ann. Geofis.*, **40**, 175-194.
COCCO, M., G. SELVAGGI, M. DI BONA and A. BASILI (1993): Recent seismic activity and earthquake occurrence along the Apennines, in *Recent Evolution and Seismicity of the Mediterranean Region*, edited by E. BOSCHI *et al.* (Kluwer Academic Publisher, The Netherlands), 295-312.
DERCOURT, J., L.P. ZONENSHAIN, L.E. RICOU, V.G. KAZMIN, X. LE PICHON, A.L. KNIPPER, C. GRANDJACQUET, I.M. SBOTSHIKOV, J. GEYSSANT, C. LEPVRIER, D.H. PECHERSKY, J. BOULIN, J.C. SIBOUET, L.A. SAVOSTIN, O. SOROKHTIN, M. WESTPHAL, M.L. BAZHENOV, J.P. LAUER and J. BIJU-DUVAL (1986): Geological evolution of the Alpine Thetys belt from the Atlantic to the Pamir since Lias, *Tectonophysics*, **123**, 241-315.
DESCHAMPS, A., G. IANNACCONE and R. SCARPA (1984): The umbrian earthquake (Italy) of 19 September 1979, *Ann. Geophysicae*, **2** (1), 29-36.
DEWEY, J.F., M.L. HELMAN, E. TURCO, D.H.W. HUTTON and S.D. KNOTT (1989): Kinematics of the Western Mediterranean, in *Alpine Tectonics*, edited by M.P. COWARD, D. DIETRICH and R.G. PARK, *Geol. Soc. London, Spec. Publ.*, 265-283.
DOGLIONI, C. (1991): A proposal for the kinematic modelling of W dipping subduction. Possible applications to the Tyrrhenian-Apennines system, *Terra Nova*, **3**, 423-434.
FREPOLI, A. and A. AMATO (1997): Contemporaneous extension and compression in the Northern Apennines from earthquake fault plane solutions, *Geophys. J. Int.*, **129**, 368-388.
FREPOLI, A., G. SELVAGGI, C. CHIARABBA and A. AMATO (1996): State of stress in the Southern Tyrrenhian subctudion zone from fault-plane solutions, *Geophys. J. Int.*, **125**, 879-891.
GASPARINI, C., G. IANNACCONE and R. SCARPA (1985): Fault-plane solutions and seismicity of the Italian Peninsula, *Tectonophysics*, **117**, 59-78.
GIARDINI, D. and M. VELONÀ (1991): Deep seismicity of the Tyrrhenian sea, *Terra Nova*, **3**, 57-64.
KANAMORI, H. and H.J. ANDERSON (1975): Theoretical basis of some empirical relations in seismology, *Bull. Seismol. Soc. Am.*, **65** (5), 1073-1095.
KLEIN, F. W. (1989): HYPOINVERSE, a program for Vax computers to solve for earthquake location and magnitude, *USGS Open File Rep.*, 89-314, 6/89 version.
LUCENTE, F.P., C. CHIARABBA, G.B. CIMINI and D. GIARDINI (1997): Tomographic images to trace the trench-arc system evolution in the Italian region, *Geophys. J. Int.* (in preparation).
MALINVERNO, A. and W.B.F. RYAN (1986): Extension in the Tyrrhenian sea and shortening in the Apennines as results of arc migration driven by sinking of the lithosphere, *Tectonics*, **5**, 227-245.
MELE, G., A. ROVELLI, D. SEBER and M. BARAZANGI (1996): Lateral variations of P_n propagation in Italy: evidence for a a high-attenuation zone beneath the Apennines, *Geophys. Res. Lett.*, **23**, 709-712.
MONTONE, P., A. AMATO, A. FREPOLI, M.T. MARIUCCI and M. CESARO (1997): Crustal stress regime in Italy, *Ann. Geofis.*, **40** (3), 741-757.
PATACCA, E. and P. SCANDONE (1989): Post-Tortonian mountain building in the Apennines. The role of the passive sinking of a relic lithospheric slab, in *The Lithosphere in Italy*, edited by A. BORIANI, M. BONAFEDE, B.G. PICARDO and G.B. VAI, *Acc. Naz. Lincei*, Roma, 157-176.
SELVAGGI, G. and A. AMATO (1992): Intermediate depth earthquakes in the Northern Apennines (Italy): evidence for a still active subduction?, *Geophys. Res. Lett.*, **19**, 2127-2130.
SELVAGGI, G. and C. CHIARABBA (1995): Seismicity and *P*-wave velocity image of the Southern Tyrrhenian subduction zone, *Geophys. J. Int.*, **121**, 818-826.
SELVAGGI, G., B. CASTELLO and R. AZZARA (1997): Scalar seismic moment distribution of Italian seismicity (1983-1996): seismotectonic implications for the Apennines, *Ann. Geofis.* (submitted).
SPAKMAN, W., S. VAN DER LEE and R. VAN DER HILST (1993): Travel-time tomography of the European-Mediterranean mantle down to 1400 km, *Physics Earth Planet. Inter.*, **79**, 3-74.
VALENSISE, G., D. PANTOSTI, G. D'ADDEZIO, F.R. CINTI and L. CUCCI (1994): L'identificazione e la caratterizzazione di faglie sismogenetiche nell'Appennino Centro-Meridionale e nell'arco Calabro: nuovi risultati e ipotesi interpretative, in *Atti del XII Convegno GNGTS*, CNR, Roma, 24-26 November 1993.