Active and remnant subducted slabs beneath Italy: evidence from seismic tomography and seismicity

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Abstract
A complex, nearly continuous subduction system exists beneath the Italian region. Seismic tomography images, computed starting from the digit waveforms of teleseisms recorded at the National Seismic Network (RSNC) of the ING, show high-velocity anomalies beneath the Alps, the Apennines and the southern Tyrrhenian Sea. These anomalies are interpreted as remnants of oceanic or continental subducted lithosphere. In order to constrain the geometry of the subducted slabs, we compared the tomographic images to the sub-crustal seismicity recorded in the past decade. The results are somewhat controversial, though some clear evidence emerges: a) in the southern Tyrrhenian sea, a high-velocity zone as deep as $\sim (400 \div 500)$ km is associated with a frequent seismicity. The strongest velocity anomaly and the largest concentration of earthquakes are approximately coincident (between $\sim$ 200 and $\sim$ 400 km); b) in the upper mantle beneath the Alps, a broad high-velocity region is apparently aseismic; c) in the northwestern portion of the Apennines, a strong high-velocity anomaly is observed in the upper $\sim (200 \div 250)$ km. We found that subcrustal earthquakes as deep as $\sim$ 90 km do occur in the same region. They are located beneath a zone of abundant crustal seismicity and approximately define a 45° dipping plane from the Adriatic to the Tyrrhenian. The high-velocity anomaly becomes weaker and deeper moving southeastward along the Apenninic chain. Based on these observations, we argue that a) the previously hypothesized subduction in southern Tyrrhenian is substantiated by the existence of the northwestward dipping high-velocity anomalies, although the pattern of seismicity and velocities in the upper mantle is more complicated at depth $\geq$400 km. b) The Alpine lithosphere-asthenosphere system is characterized by the presence of wide lithospheric roots, interpreted as an old, aseismic, remnant slab of the Tethyan (Mesogean) ocean, underthrusted beneath the Adriatic microplate. c) In the northern Apennines, a remnant portion of oceanic lithosphere that escaped the former Alpine subduction, is probably sinking underneath Tuscany. The absence of high-velocity anomalies and of subcrustal seismicity beneath the central Apennines confirms that an important lithosphere-controlled discontinuity separates the northern from the southern Apennines. It may be due to a «slab window» in the central Apennines, caused for instance by an irregular geometry of the two colliding plates, by the stretching of the subducted lithosphere generated by the increasing curvature of the arc over time, or by an anomalously hot asthenosphere in the Tyrrhenian margin of central Italy.

1. Introduction

The existence of positive seismic velocity anomalies in the upper mantle is generally interpreted as the effect of «cold» oceanic lithosphere which penetrates a «warmer», «softer», lower-velocity asthenosphere. On the contrary, low-velocity regions are preferably associated with regions of (partially) molten rocks, as beneath volcanoes. If we accept these concepts to be valid for central Mediterranean, we must believe that a complex, nearly continuous subduction system exists beneath the Italian region.

As known, the Mediterranean region is a complex plate boundary between the Eurasian and the African continental plates. These two main relatively undeformed plates interacted for millions of years, giving rise to a mosaic of smaller blocks or microplates. The formation of the Alpine system in the Italian region started approximately in the upper Cretaceous, when the displacement vector between Africa and Eurasia changed from a sinistral movement to an approximate north-south compression (Dewey *et al.*, 1973; Le Pichon *et al.*, 1977). The oceanic lithosphere that formed in western Mediterranean before the compression (the Tethyan, or Mesogean, ocean, see, *e.g.*, Dercourt *et al.*, 1986) must have been absorbed by subduction, collision, or any other mechanism (Philip, 1988).

It is generally agreed that the Alpine chain formed formerly by consumption of oceanic lithosphere (Panza and Mueller, 1979; Laubscher, 1984; Dal Piaz and Polino, 1989), and afterwards by continental collision. No intermediate or deep earthquakes are presently recorded beneath the Alpine arc, suggesting that subduction or deep continental collision is no longer active.

The only region with active subduction in central Mediterranean is the southern Tyrrhenian, where intermediate and deep earthquakes are presently recorded (McKenzie, 1972; Ritsema, 1979; Gasparini *et al.*, 1982; Anderson and Jackson, 1987), with an associated volcanic island arc (Barberi *et al.*, 1973) (fig. 1).

The presence of active or remnant slabs and lithospheric roots beneath the Apennines is today a matter of discussion among Earth scientists. According to some authors, the northern Apennines formed by subduction, at least in the northern sector (Reutter, 1981; Malinverno and Ryan, 1986; Royden *et al.*, 1987; Philip, 1988; Beccaluva *et al.*, 1989). In the following sections, we will discuss recently reported seismic data that show a weak seismicity located in the upper mantle (up to $\sim$ 90 km depth) beneath northern Apennines. This evidence substantiates the hypothesis of subduction in this region.

In order to constrain the geometry of subducted portions of oceanic or continental lithosphere, we have computed the velocity anomalies in the upper mantle of Italy (up to the depth of 500 km) by means of teleseismic tomography. For this goal we have used high-quality data from the digital database of the Istituto Nazionale di Geofisica.

Most of the studies on the deep structure in Italy since the 50's were based on DSS (Deep Seismic Sounding) data, that revealed a strongly inhomogeneous crust beneath our region (see for instance Giese and Morelli, 1975, Cassinis *et al.*, 1979; Mueller, 1982; Nicolich, 1989; Roeder, 1990). The study of deeper structures, obtainable by teleseismic delay times, started only in the early 80's, when the number of permanent seismic stations increased and tomographic techniques became available (Aki *et al.*, 1977). Scarpa (1982) calculate a velocity model up to 360 km depth using the ACH technique applied to *P* and *PKP* arrival times taken from bulletins. Only some general features were detected by these inversions (a strong contrast between a low-velocity Adriatic region and high velocity in NW and NE Alps, northern Apennines, and southern Tyrrhenian), probably due to the poor data quality.

A lithospheric thickening up to 200-250 km depth beneath the Alpine chain was also suggested by Calcagnile *et al.* (1979) and Panza and Mueller (1979) from surface wave dispersion analysis, and by Babuška and Plomerová (1990) from teleseismic tomography. Lithospheric roots were also detected beneath northern Apennines by Babuška and Plomerová (1990), from the analysis of teleseismic residuals, while an anomalous (high velocity) upper mantle was revealed underneath Tuscany by Panza (1984).

More recently Spakman (1988, 1990) obtained a velocity model for the upper-mantle structure beneath the whole Mediterranean region by inverting a large number of regional and teleseismic data using a $(1\times1)^\circ$ block size. Spakman's models show an almost continuous belt of high velocities at different depth beneath Italy, from the Alps to the Tyrrhenian sea, which he interpreted as subducted oceanic lithosphere.

Our contribution aims to a more precise identification of the positive velocity anomalies beneath Alps, Apennines, and Tyrrhenian sea, previously described. Furthemore, we compare the velocity anomalies in the upper mantle with the seismicity recorded in the past decade beneath our region (see also Cimini *et al.*, 1990; Amato *et al.*, 1991; Selvaggi and Amato, 1992; Amato *et al.*, 1993).

2. Data and methods of analysis

To compute travel time residuals, and then

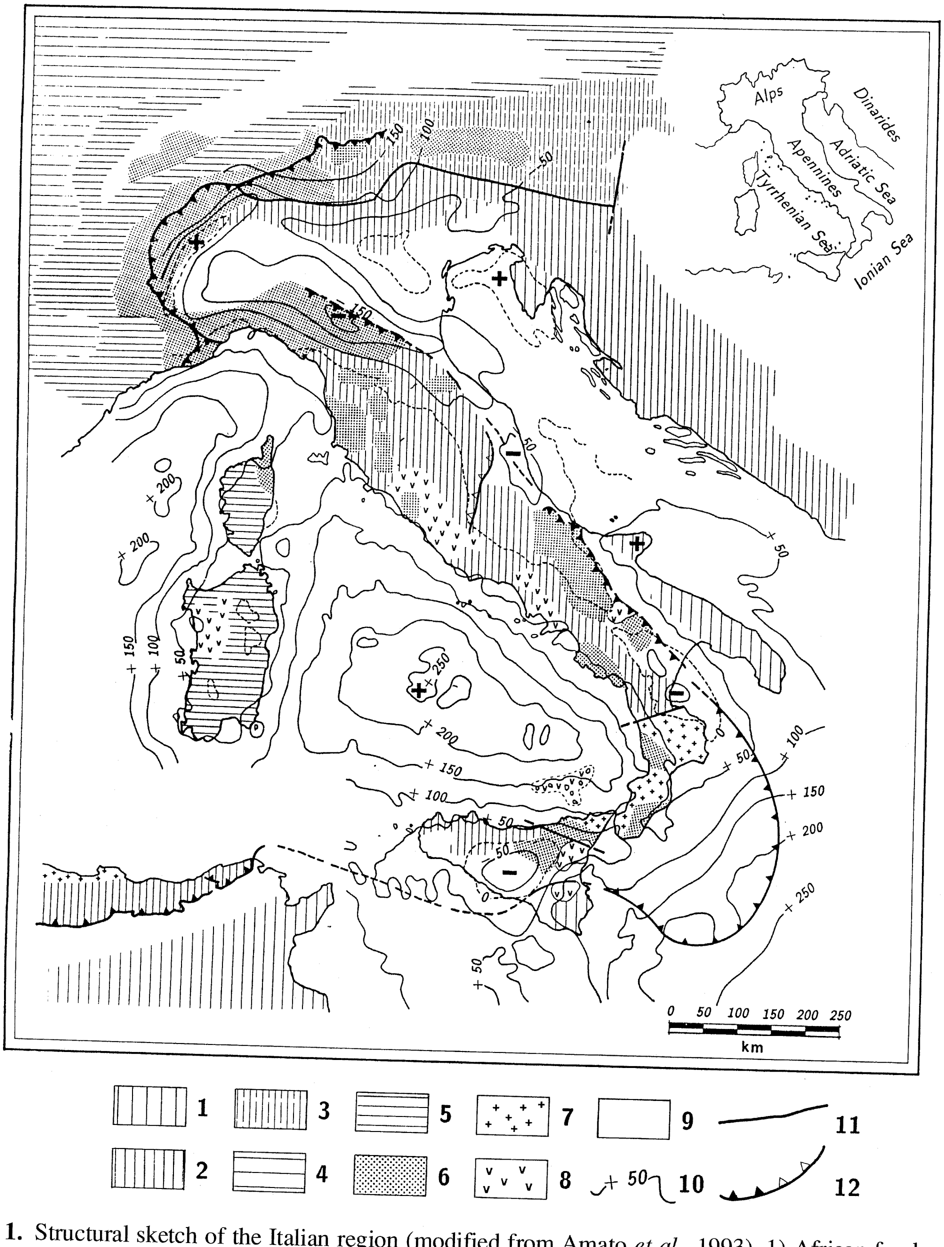

Fig. 1. Structural sketch of the Italian region (modified from Amato *et al.*, 1993). 1) African foreland; 2) deformed African continental margin; 3) Austroalpine nappes; 4) European foreland; 5) deformed European continental margin; 6) oceanic remnants (ophiolites, oceanic sediments – Ligurides, Sicilides, etc.); 7) «internal massifs» (metamorphosed Alpine and pre-Alpine complexes); 8) volcanic complexes (includes both the Tertiary volcanism of Sardinia and the Quaternary volcanism of Tuscany, Latium, Campania, and Sicily); 9) terrigenous sediments of the late and post-orogenic phases; 10) Bouguer gravity anomalies; 11) important tectonic lines with uncertain meaning (*i.e.* Insubric Line in the Alps); 12) main thrust front system of Alps and Apennines (solid triangles) and boundary between the northern and central Apennines (open triangles).

tomographic images, we used the digital waveforms of teleseismic events recorded by the RSNC of the Istituto Nazionale di Geofisica (ING) between 1988 and 1990. In that period the ING network consisted of 64 stations (fig. 2) equipped with mostly vertical short-period seismometers, linked to the central observatory in Rome by telephone lines and radio telemetry.

We used 123 teleseisms in the distance range $(25 \div 100)°$ (*P* phases) and 25 *PKP* events ($\Delta \geq 110°$), that provide about 4000 arrival times. The NEIC (National Earthquake Information Center of the U.S. Geological Survey) locations of the *P* events are shown in the polar diagram of fig. 3. We observe a predominance of events in the northeastern sectors, corresponding to the Pacific belt from the Aleutian arc to the Philippine Islands, and with the mountain belt from Caspean Sea to the Himalayan region. Events from other regions, such as the mid Atlantic Ridge, Bolivia, Trinidad, Malawi, and eastern Kazakh (nuclear explosions), provide a good azimuthal coverage. We computed the arrival times of each teleseismic signal performing digital band-pass filtering, amplitude and time scaling, and visual correlation of digital waveforms. The picking is done either on a first-break, a peak, a trough, or a zero-crossing (Alessandrini *et al.*, 1989).

Before applying the ACH inversion technique (Aki *et al.*, 1977) to our data, we performed a detailed analysis of the travel time residuals, determined as the difference between the observed travel time and the reference or theoretical travel time (Herrin, 1968), after correction for station elevation. In order to reduce the errors due to hypocentral mislocation and to Earth model approximation, we analyzed the distribution of relative residuals, obtained by subtracting from the absolute residual the network average residual for each event.

The analysis of relative residuals provides a first qualitative estimate of velocity anomalies at depth (Cimini *et al.*, 1990; Amato *et al.*, 1993). We show in fig.4 the distribution of relative residuals obtained for the Italian stations, grouping the direction of approach of teleseismic wavefronts in eight 45° sectors. The values plotted in the eight maps represent the mean relative residuals for events within the 45° azimuthal window minus the mean *P* residuals for all azimuths which is shown in the central map.

Figure 4 emphasizes the presence of strong-velocity heterogeneities beneath many regions of Italy. Specifically, the Alps, the northern Apennines, and the Calabrian arc, show a consistent pattern of negative residuals which moves as the direction of the incoming teleseismic wavefront changes. The directions showing early arrivals (SE for the northwestern Alps, SW for the northern Apennines, NW for the Calabrian Arc) indicate the presence of high-velocity anomalies, which may be generated by subducted oceanic lithosphere, as we discuss later on. In contrast, positive residuals (indicating low-velocity anomalies) may be determined by a «normal» asthenospheric layer, with no «lithospheric roots» or subducting slabs. This is the case of the Adriatic microplate and of Sicily (see fig. 4). For the latter, we observe strongly positive residuals for southern incoming wavefronts, indicating the presence of a wide low-velocity anomaly. It is worth noting the coincidence between the large positive residuals (fig. 4) and a gravimetric minimum in central Sicily (fig.1).

We inverted the *P* and *PKP* relative residuals using the ACH technique, originally developed by Aki *et al.* (1977) and subsequently improved by Evans (1986). Following this method we specified the starting model with homogeneous constant velocity layers divided into a grid of rectangular blocks.

Considering the observed travel time anomaly of a single ray as the result of the cumulative effect of velocity perturbations on different ray segments, we computed a velocity perturbation for each block, relative to the assumed initial velocity.

Details of the inversion procedure applied to the Italian region are described in Cimini *et al.* (1990) and Amato *et al.* (1993). These papers show how important is the choice of a reference velocity model and of the Earth parametrization within the target volume (number and size of blocks, starting velocities, etc.), and in the analysis of the resolution and covariance matrices. This analysis allows an evaluation of the quality of the tomographic images (Aki *et al.*, 1977; Evans and Achauer, 1993).

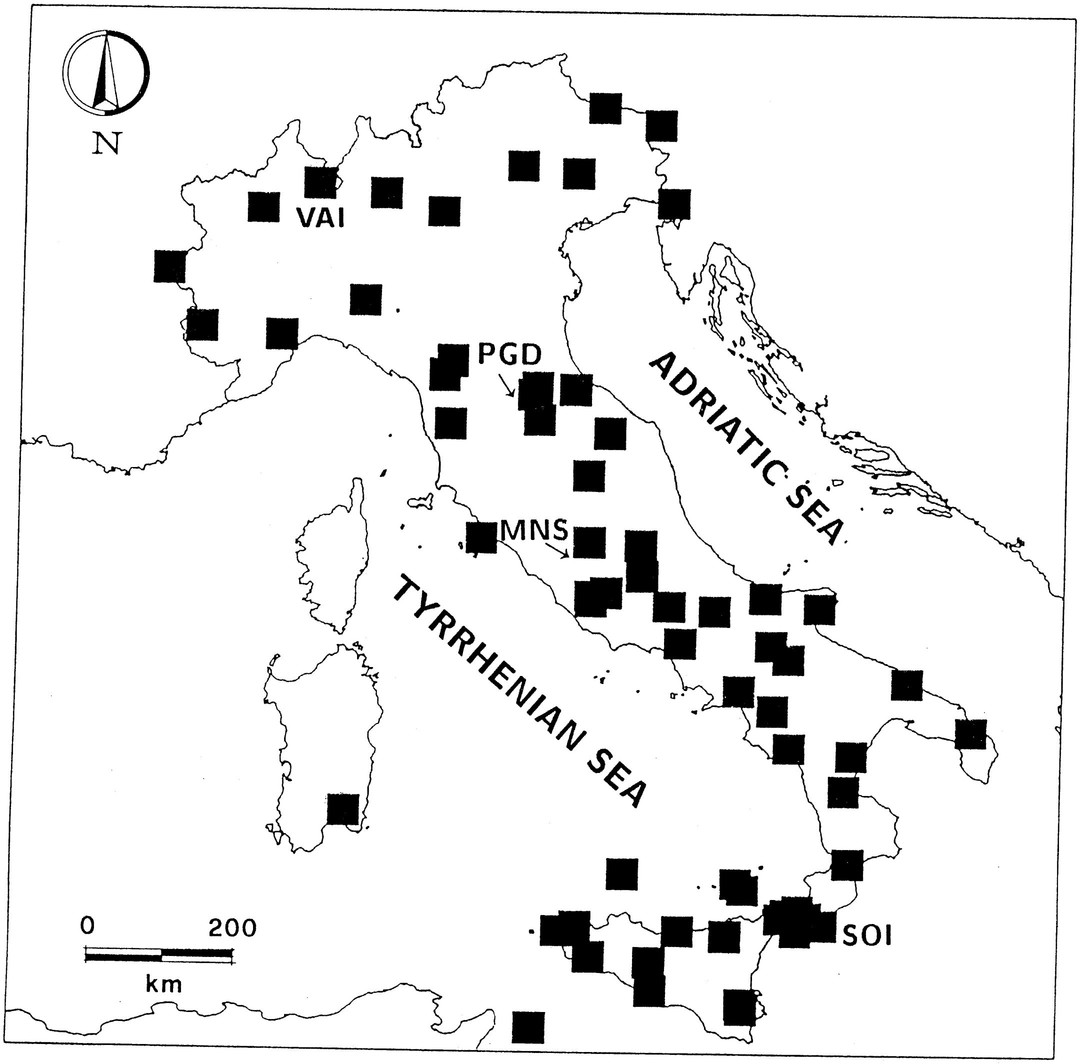

Fig. 2. Station distribution (solid squares) of the National Seismic Network (RSNC) of the Istituto Nazionale di Geofisica (ING). The data are telemetered by telephone lines and radio links and digitized at the ING, in Rome.

3. Velocity anomalies in the upper mantle of Italy

We show here a model with five layers from the base of the Moho to 530 km depth (fig.5 and 6). Other models relative to the Italian region are shown in Cimini *et al.* (1990) and Amato *et al.* (1991 and 1993).

The model shown in fig.5 consists of «pseudo-blocks» obtained by averaging from nine different inversions, each obtained shifting the grid one third of the block size in x and y directions (Evans, 1986). This is useful to mimimize the artifacts due to an inappropriate model parametrization, as when an anomaly of about the same wavelength of the modeled blocks is located close to a vertical boundary (see Evans and Achauer, 1993).

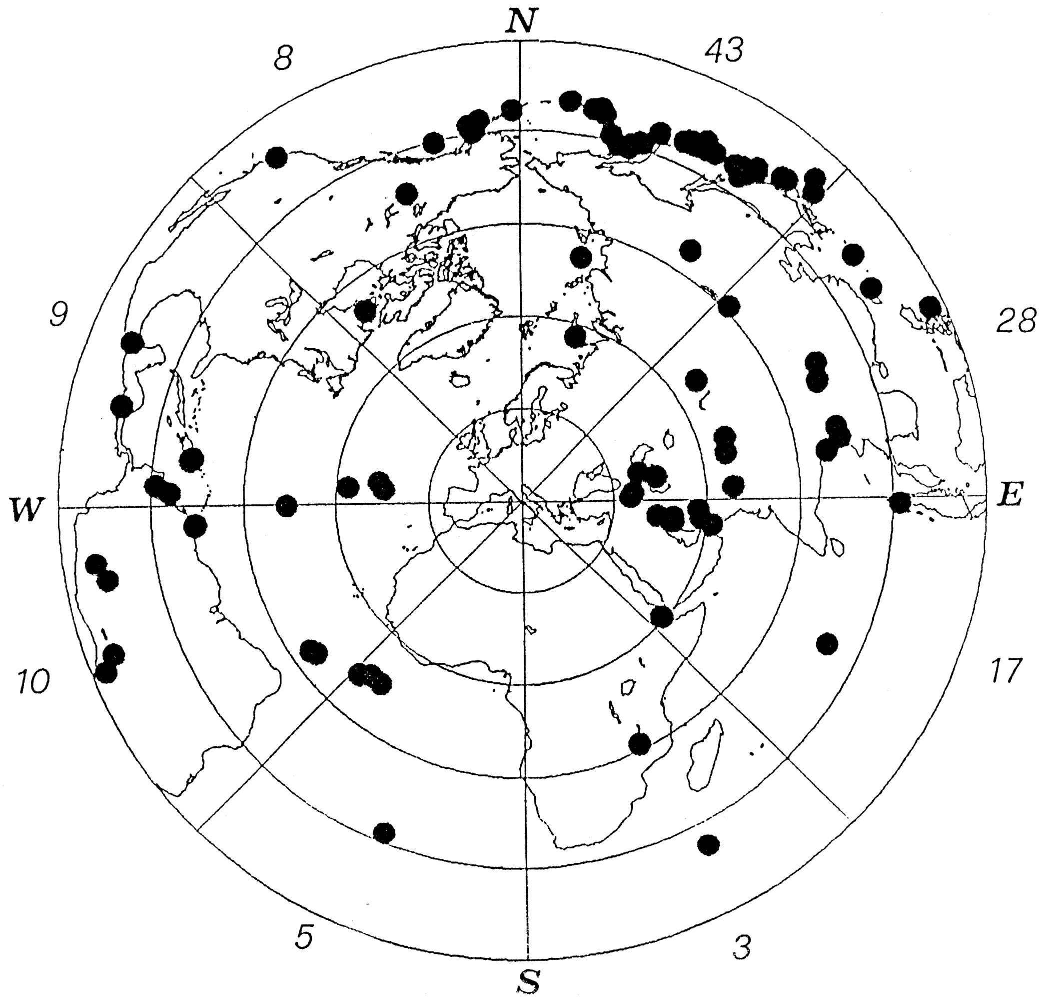

Fig. 3. Polar diagram centered in Rome showing the distribution of the *P* teleseisms (solid dots) analyzed in this study. The numbers are the events recorded for each of the eight 45° sectors.

Figure 5 shows that the main anomalies are located beneath the western Alps, the nothern Apennines, the southern Tyrrhenian (high velocities), and in the Adriatic region and Sicily (low velocities). The Alpine anomaly is not associated with sub-crustal seismicity, whereas beneath both the northern Apennines and the southern Tyrrhenian intermediate and deep earthquakes do occur near the high-velocity anomalies. In the deepest part of the model ((400÷500) km) the high- velocity anomaly is located close to the Tyrrhenian coast, south of Rome (fig. 5e)), and apparently joins the two anomalies observed in the shallower layers beneath the northern Apennines and the southern Tyrrhenian sea (fig. 5c), d)). This deep high-velocity anomaly approximately corresponds with the region where some of the deepest Tyrrhenian earthquakes were recorded, as that occurred near the town of Gaeta (12/27/1978, h~400 km) (Giardini and Velonà,

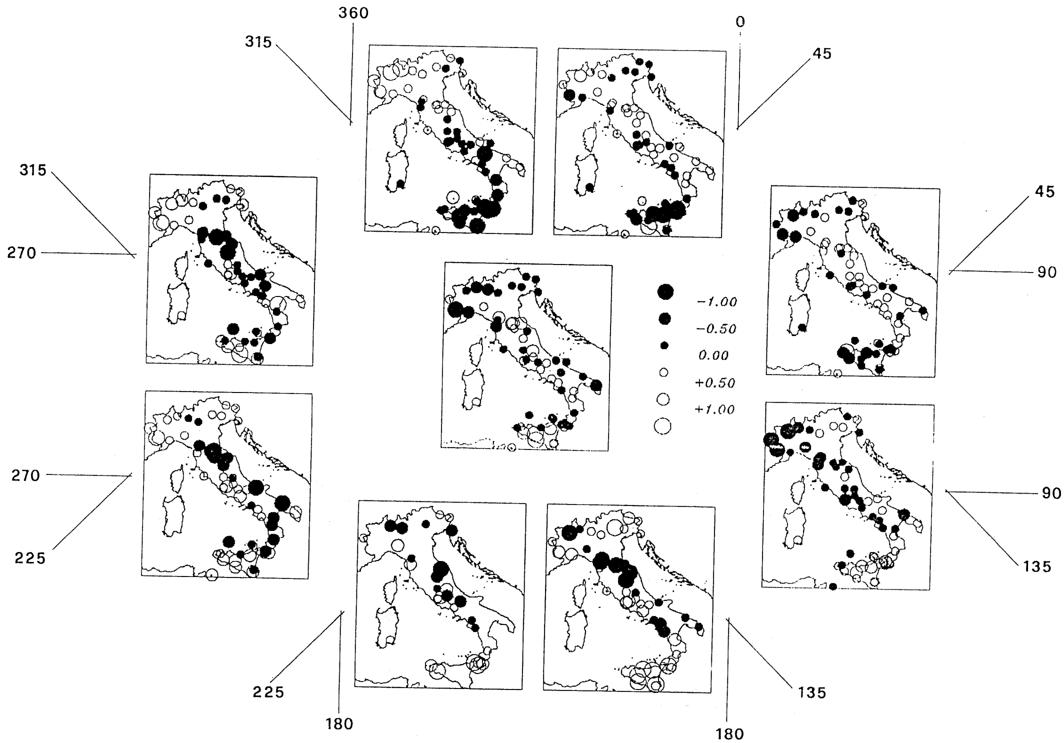

Fig. 4. Distribution of P relative residuals for the eight 45° sectors (see fig.3). The values plotted in each figure are the average for each sector subtracted by the global mean $((0 \div 360)°)$. Note the strong azimuthal dependence in many regions of Italy.

1991). This furtherly substantiates the hypothesis of the presence of a subducted lithospheric slab beneath this region.

The strong high-velocity zone in the northern Apennines (fig.5) is of more difficult interpretation, as no intermediate or deep earthquakes had previously been observed in this region. Nonetheless, there is some geological (Reutter, 1981; Malinverno and Ryan, 1986; Royden *et al.*, 1987; Philip, 1988) and geochemical (Beccaluva *et al.*, 1989; Civetta *et al.*, 1989) evidence that the northern Apennines formed by subduction of oceanic and/or continental lithosphere. An anomaly in the upper mantle of Tuscany was observed both by Panza (1984), from surface wave dispersion analysis, and by Babuška and Plomerová (1990) beneath northern Apennines from P delays. High velocities beneath the Apennines, although deeper or shifted to the east from their location in our model, were also computed by Spakman (1988, 1990). The seismic data discussed in the following section help in the interpretation of the tectonic evolution of this region.

4. Intermediate and deep seismicity in Italy

It is well known that in the southern Tyrrhenian Sea several intermediate and deep earthquakes occur, and that the distribution at depth of these earthquakes (fig.6b)) delineates a continuous Wadati-Benioff zone from the surface down to 500 km depth (McKenzie, 1972; Anderson and Jackson, 1987; Giardini and Velonà, 1991 among many others). The intermediate and deep seismicity of the southern Tyrrhenian Sea is mostly concentrated in the depth range $(250 \div 350)$ km, whereas a rarefaction of hy-

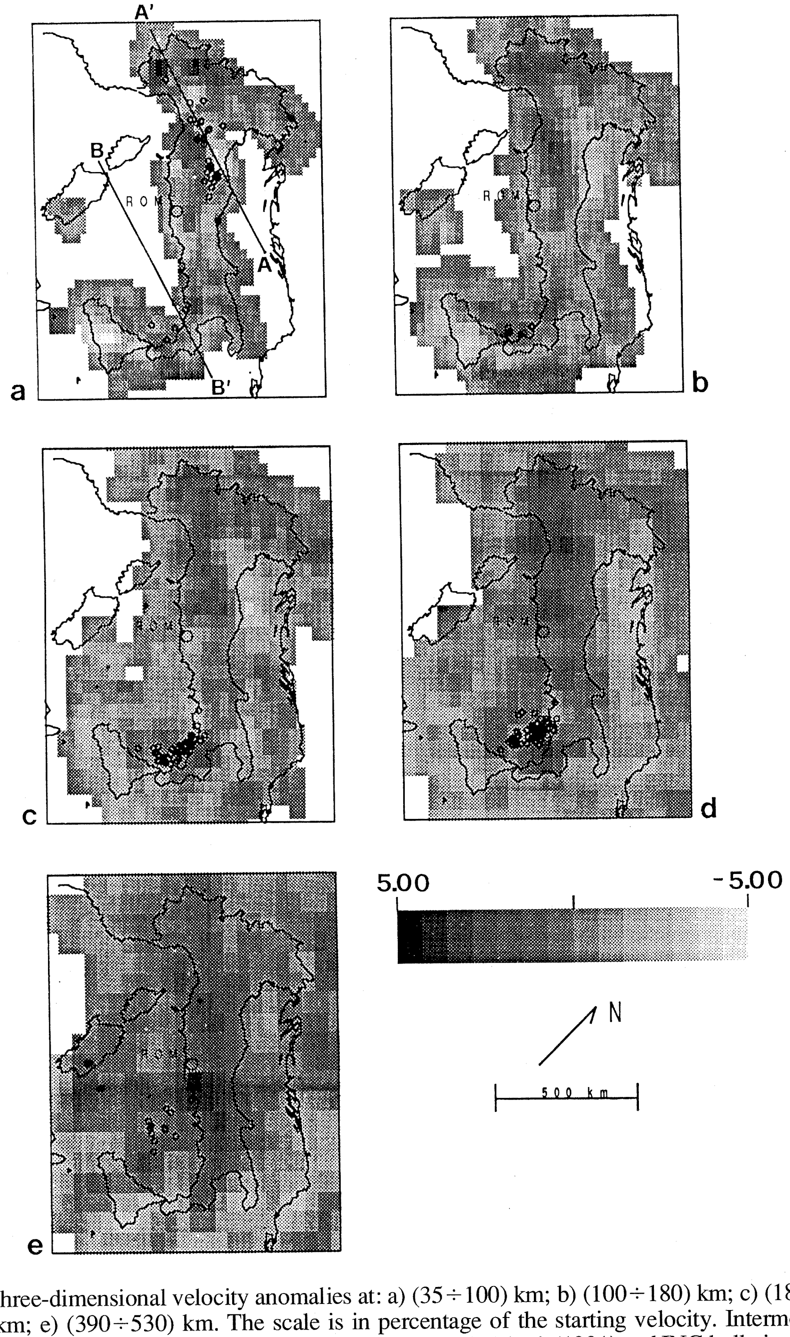

Fig. 5. Three-dimensional velocity anomalies at: a) (35÷100) km; b) (100÷180) km; c) (180÷270) km; d) (270÷390) km; e) (390÷530) km. The scale is in percentage of the starting velocity. Intermediate and deep earthquakes of the Tyrrhenian (open circles) from Giardini and Velonà (1991) and ING bulletins are also shown. The Apenninic earthquake locations are from the ING bulletins of the period 1984-1991 (only the sub-crustal earthquakes are plotted).

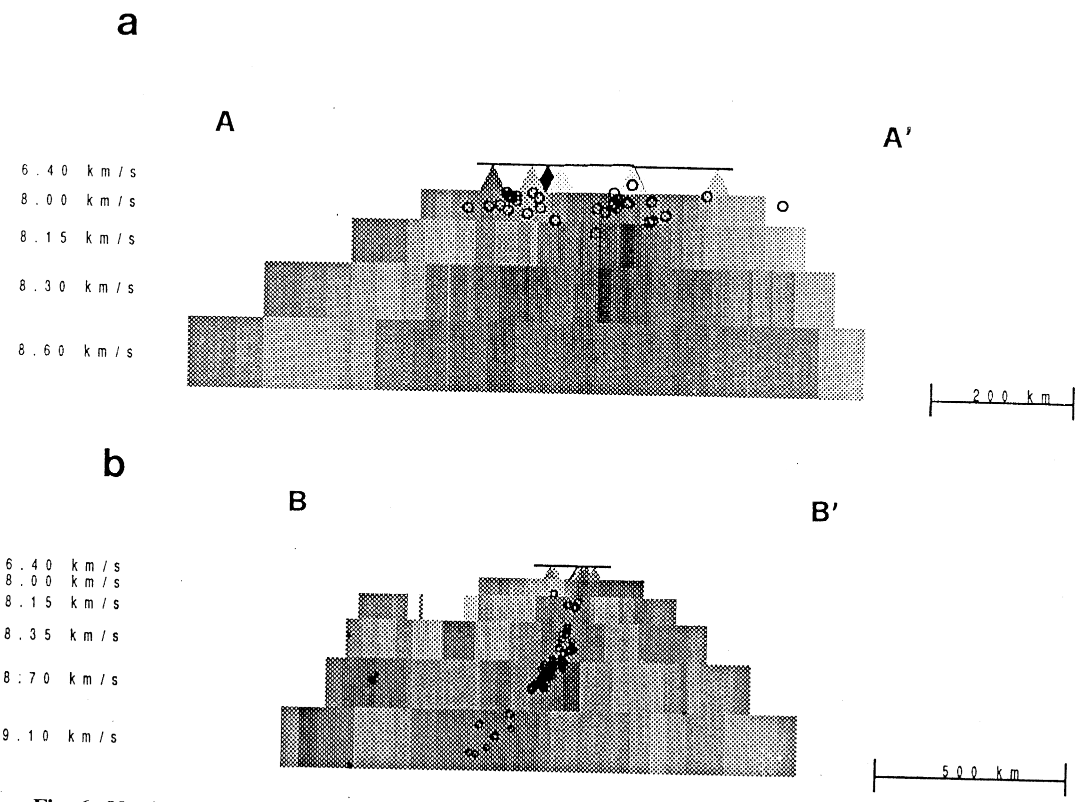

Fig. 6. Vertical sections of the velocity model in fig.5. The traces of the sections and the scale are shown in fig.5.

pocenters is observed in the upper 130 km (Giardini and Velonà, 1991).

Since one of the commonly accepted indications of active or recent subduction is the occurrence of intermediate and deep seismicity, we carefully reanalysed and relocated the seismicity recorded in Italy by Centralized Seismic National Network and by other local networks in the last nine years. The results show that a few earthquakes also occur in the upper mantle beneath the northern Apennines (see also Selvaggi and Amato, 1992).

Besides the crustal seismicity, that delineates the NW-trending plate boundary between the Adriatic microplate and the European plate (fig. 7a)), 40 anomalously deep ($\geq$30 km) earthquakes beneath the northern Apennines (fig. 7b)) have been located with horizontal and vertical errors lower than 4 km. The sub-crustal earthquakes of the northern Apennines (fig. 7b)) are mainly located beneath the axis of the chain, following the bend of the northern Apenninic arc and apparently deepening to the southwest. They approximately delineate a (35÷45)° dipping wedge from the Adriatic to the Tyrrhenian Sea. The deepest earthquake is located at a depth of 93 km beneath the northern Apennines (fig. 8). However, the earthquake distribution at depth cannot be clearly related to a well-defined Wadati-Benioff zone. The sub-crustal earthquakes seem to cluster in two roughly parallel southwest dipping zones. As a speculation, we may invoke two mechanisms to explain this observation: the first hypothesis is that two wedges of Adriatic lithosphere have been sub-ducting beneath the Tuscany-Corsica block in different times. The second explanation is that the sub-crustal seismicity occurs both at the boundary between the

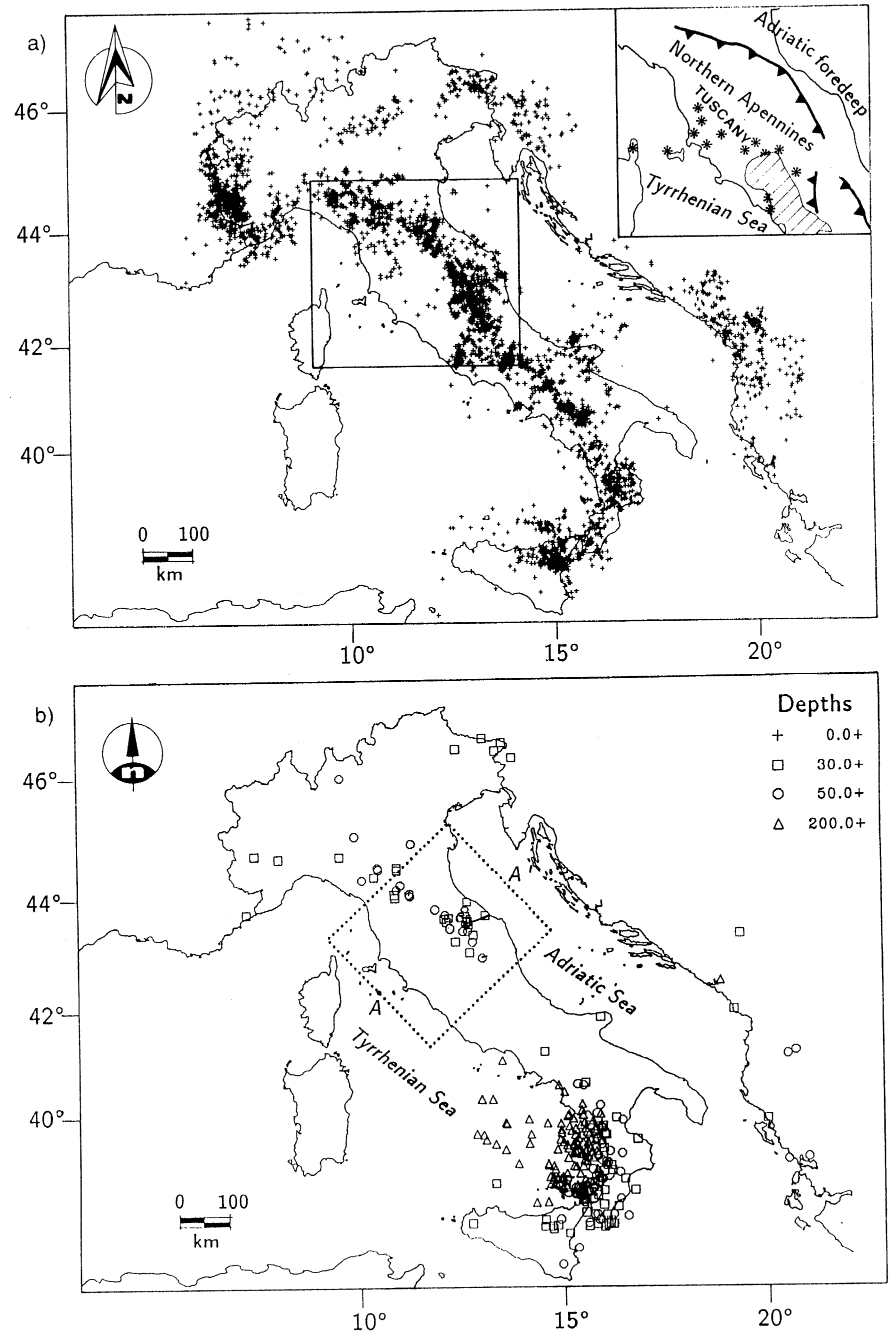

Fig. 7. a) Epicentral map of 4700 selected crustal earthquakes (ERH-ERZ less than 8 km) occurred between 1983 and 1991. b) Epicenters of the anomalously deep ($h \geq 30$ km) earthquakes. Also shown is the zone of projection of the vertical section A - A′ (fig. 8) (modified from Selvaggi and Amato, 1992).

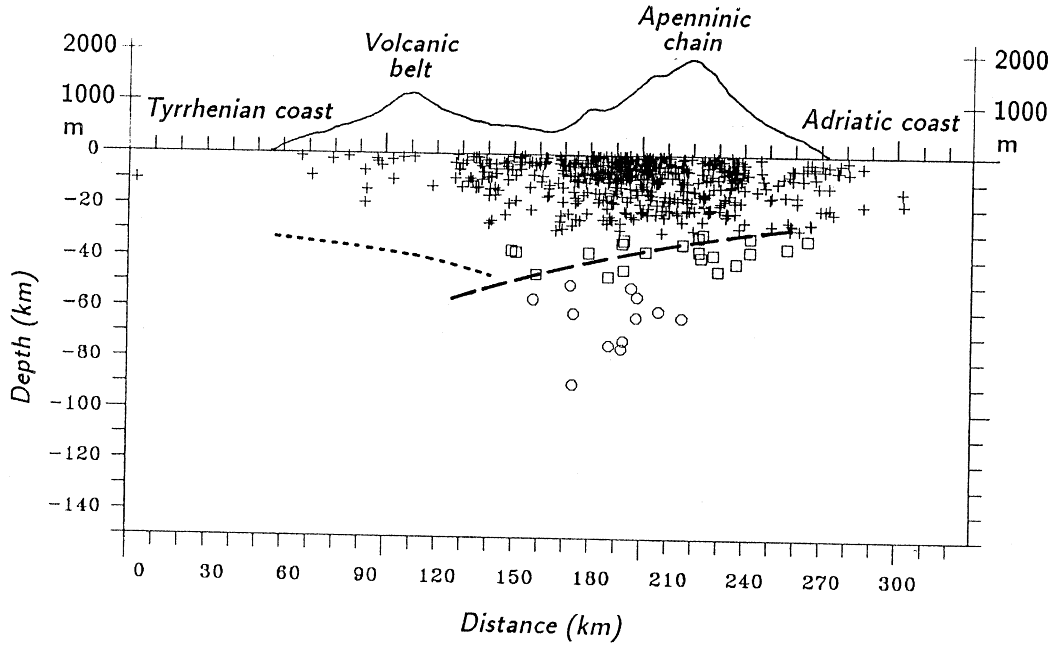

Fig. 8. Seismicity distribution at depth in the northern Apennines. Stars indicate the subcrustal earthquakes. The dashed and the dotted lines are the «Adriatic» and the «European» Moho trends, respectively (after Roeder, 1990). A schematic topographic profile crossing the Italian peninsula is also reported (modified from Selvaggi and Amato, 1992).

two converging plates (the Adriatic microplate and the overthrusting Tuscany plate), and within the Adriatic plate itself. The two seismic zones are roughly parallel to each other and (20 ÷ 30) km apart (fig. 8).

5. Discussion

Our interpretation of the velocity anomalies detected by the three-dimensional inversion is mainly based on the hypothesis that a complex subduction system has developed diachronously in the Italian region since the Cretaceous and through most of the Cainozoic and the Quaternary. The «engine» of this process is the relative approximately north-south compression between the European and the African main plates, but the present structure appears to be complicated by the existence of many secondary features, as for instance the Adriatic microplate. The high-velocity anomalies observed at different depths and with different extension almost everywhere beneath the Alps and the Apennines are mostly interpreted as relics of the ancient oceanic «Tethyan Lithosphere». The southern Tyrrhenian anomaly is related to a portion of the Ionian lithosphere presently subducting from the Calabrian arc northwestward.

The correspondence between high-velocity anomalies and subducted oceanic lithosphere is not unically demonstrated. Other factors may be responsible for the existence of regions of apparently higher velocity in the upper mantle, especially anisotropy. Moreover, in regions of continental collision, when the subduction zone reaches the continental lithosphere, the latter may be pulled down to a certain extent by the sinking oceanic lithosphere. The existence of «lithospheric roots» in the upper mantle would cause high-velocity anomalies, as the «roots» (either oceanic or continental) are supposed to have higher velocities compared to the surrounding asthenosphere, at least until it is thermally reassimilated.

This is probably what happened in the Alps, when the European and the Adriatic plates collided. The wide high-velocity anomaly that we observe beneath the Alps probably represents what is left formerly by subduction of oceanic Tethyan lithosphere, and afterwards by continental collision. Although the distribution of velocity anomalies does not allow one to define a clear geometry of the lithosphere-asthenosphere structure in this region, it seems that the high-velocity anomaly in the western Alps dips to the southeast (fig. 5 and 6), as suggested also by the strong azimuthal dependence of *P* residuals (fig. 4) and by other tomographic studies (Spakman, 1990). This would imply that the European plate underthrusted the Adriatic plate.

In the eastern Alps, the high-velocity anomaly is deeper than in the western Alps, and apparently dips to the north (fig. 5), although our limited station distribution in this region prevents a detailed mapping of the anomalies to the north (fig. 2).

In the Apennines, our tomographic images reveal the presence of a high-velocity anomaly at different depths beneath the axis of the chain. The most interesting result is found in northern Apennines, where the high-velocity anomaly is stronger ($\sim(5 \div 6)\%$) than anywhere else in Italy (fig. 5). We believe that this anomaly depicts a slab of oceanic (or partly continental) lithosphere that is presently sinking under Tuscany. Although a subduction model had been already proposed for northern Apennines mainly based on geological and volcanological evidence (Reutter, 1981; Malinverno and Ryan, 1986; Royden *et al.*, 1987; Laubscher, 1988; Philip, 1988; Beccaluva *et al.*, 1989; Civetta *et al.*, 1989; Patacca and Scandone, 1989; Doglioni, 1991), few geophysical data were carried in the past to substatiate this hypothesis (Panza, 1984; Babuška and Plomerová, 1990). Despite these data and models, there is still a strong debate on the origin of the Apenninic chain (see Malinverno and Ryan, 1986, and Lavecchia, 1988, and references therein).

The deep (up to $\sim(200 \div 300)$ km) high-velocity anomaly (fig. 6a)) may represent a remnant of the Tethyan oceanic lithosphere which escaped the former subduction beneath the Alps, as already proposed by Reutter (1981). The combination of this anomaly with the sub-crustal earthquakes represents a strong constraint to the presence of a subducting slab of Adriatic lithosphere beneath the Tuscany-Corsica-Sardinia block. The discrepancy between the depth of the high- velocity anomaly (up to $\sim$ 300 km) and the seismicity (up to $\sim$ 90 km) may be due to the thermal assimilation of the deepest part of the slab, that is now aseismic. However, it must be remembered that the vertical resolution of the tomographic images is poor in this area. Thus the shape of high-velocity anomaly is poorly constrained. It is worth noting that the ISC data for the years 1964-1982 show that four earthquakes did occur in this region in the depth range $(120 \div 160)$ km, within the region of the largest velocity anomaly.

The high-velocity anomaly along the Apennines is deeper going to the southeast (fig. 5). The depth of the maximum anomaly is approximately proportional to the amount of shortening occurred across the Apennines (ranging between $\sim$ 1 cm/y to the north, up to $\sim$ 5 cm/y in the southern Apennines) which in turn is proportional to the opening of the Tyrrhenian basin (Malinverno and Ryan, 1986; Patacca and Scandone, 1989).

If a subsubduction mechanism can be applied to the formation of the whole Apenninic chain, we may explain the different depths of the high-velocity anomaly, assuming a variable velocity of convergence for the past $\sim$15 My, due for instance to an oblique direction of convergence between the Tuscany-Sardinia-Corsica block and the Adriatic microplate. An oblique convergence may be explained by a migrating arc, whose curvature has been increasing with time from the upper Miocene to the present, as proposed for instance by Malinverno and Ryan (1986) and Doglioni (1991).

Alternatively, as there is evidence from geological data of a clear boundary between the northern and the southern Apennines (fig. 1), that underwent different geodynamic evolution, we can also hypothesize that the subduction has not been continuous beneath the whole Apenninic arc, with the development of a «slab window» in Central Italy, between the northern Apennines and the eastern wing of the Calabrian subduction. A slab window may derive either by an irregular geometry of the two colliding plates, as proposed for instance by Benz and Zandt (1993) for California, or by a faster thermo-assimilation in the central part of the slab at depth. The latter hypothesis is substantiated by the high heat-flow observed in the central Apenninic Tyrrhenian margin (Mongelli *et al.*, 1989). A higher heat-flow would also explain the absence of sub-crustal earthquakes observed beneath the central Apennines (Selvaggi an Amato, 1992).

As already discussed, the existence of a NW-dipping Benioff zone in the southern Tyrrhenian sea (see, *e.g.*, Anderson and Jackson, 1987), and an associated island arc (Barberi *et al.*, 1973), allows one to define a subduction of the Ionian (oceanic?) lithosphere to a depth of at least 500 km. The coincidence of the seismicity with the high-velocity anomaly detected by our analysis (fig. 5, 6), as well as by previous tomographic studies using different data and techniques (Spakman, 1988 and 1990), confirms that such a process is still active, although we cannot determine the precise geometry of the slab.

Our model shows a rather continuous high-velocity anomaly up to at least ~ 400 km, with the strongest anomaly between 220 and 400 km (fig. 6). Anyway, the absence of seismic stations on the Tyrrhenian side limits the resolution in this part of the model, as most of the seimic rays travel in the same direction along the high-velocity region. Therefore, we do not feel confident to assess whether the slab is detached, as proposed by other authors, or continuous. At depth greater than 400 km, the velocity and the seismicity distributions appear to be more complicated. Anyway, the deepest earthquakes occur close to the Campanian coastline, in coincidence with the Apenninic high-velocity anomaly. This confirms that a continuity exists at depth between the Calabrian arc and the southern Apennine subuction.

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