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Tomographic studies of the deep structure of the Tyrrhenian-Apennine system
Studi tomografici della struttura profonda del sistema Tirreno-Appennino

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ABSTRACT - Since the beginning of the 1980s seismic tomography studies have helped to unravel the deep structure and to constrain the kinematic models of tectonic evolution of Italy. In this chapter I describe the main features of the upper mantle structure beneath the Tyrrhenian – Apennine system obtained by jointly analysing the tomographic results with the distribution of subcrustal earthquakes. A new three-dimensional P-wave velocity model is also presented to give the most recent advancement in this research field. The model is computed by applying a non linear inversion algorithm on an improved data set of high-quality teleseismic arrival times recorded at the National Seismic Network and by the stations of a temporary passive array deployed in southern Italy. The resulting picture indicates a remarkable along-strike complexity of the subduction system below the Tyrrhenian – Apennine region, with at least three basic types of lithospheric sinking. The recognized slabs are characterized by significant differences in the geometry, continuity at depth, velocity contrasts with respect to the surrounding mantle, and reology. In the uppermost mantle the seismic structure is furtherly complicated by the presence of prominent low – velocity regions interpreted as asthenospheric upwelling in front of the downgoing lithosphere.

KEY WORDS:seismic tomography, upper mantle, subduction, Tyrrhenian-Appennines

RIASSUNTO - Sin dall'inizio degli anni 80 gli studi di tomografia sismica hanno aiutato a dipanare la struttura profonda e a vincolare i modelli cinematici dell'evoluzione tettonica dell'Italia. In questo capitolo si descrivono le principali caratteristiche della struttura del mantello superiore al disotto del sistema Tirreno – Appennino, ottenute analizzando congiuntamente i risultati di studi tomografici con la distribuzione dei terremoti subcrostali. Si presenta, inoltre, un nuovo modello tridimensionale delle velocità delle onde P per fornire gli avanzamenti più recenti in questo campo di ricerche. Il modello è calcolato applicando un algoritmo di inversione non lineare su un dataset selezionato di tempi di arrivo di fasi telesismiche registrate dalla rete sismica nazionale e dalle stazioni di un array temporaneo installato nell'Italia meridionale. I risultati di questo studio mostrano una rimarchevole complessità del sistema di subduzione sotto la regione Tirreno – Appennino, con almeno tre tipi base di sprofondamento litosferico. Gli slabs ricostruiti sono caratterizzati da differenze consistenti nella geometria, continuità con la profondità, contrasti di velocità rispetto al mantello circostante e reologia della litosfera subdotta. Nella parte più superiore del mantello della regione la struttura sismica è ulteriormente complicata dalla presenza di estese zone di bassa velocità interpretate come risalita di materiale astenosferico di fronte alla litosfera in subduzione.

PAROLE CHIAVE: tomografia sisimica, mantello, subduzione, Tirreno-Appennini

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1. - INTRODUCTION

In the last two decades, many tomographic reconstructions of the seismic velocity field in the crust and upper mantle beneath the Tyrrhenian – Apennine system have been carried out in order to provide constraints on the geodynamic evolution of this part of the Mediterranean region (BABUSKA & PLOMEROVÁ, 1990; SPAKMAN, 1990; SCARPA, 1982; AMATO *et alii*, 1993a; AMATO *et alii*, 1993b; SPAKMAN *et alii,* 1993; CIMINI & AMATO, 1993; CIMINI & DE GORI, 1997; PIROMALLO & MORELLI, 1997; CIACCIO *et alii*, 1998; LUCENTE *et alii*, 1999; CIMINI, 1999; DI STEFANO *et alii*, 1999; CIMINI & DE GORI, 2001). From these investigations, characterized by the use of different datasets of seismic phase arrival times, inversion techniques, and Earth's parameterizations of the target volume, a common, although somewhat controversial result has emerged: the existence below the region of a complex, nearly continuous subduction system. This evidence, still matter of debate among Earth scientists for the implications it provides on the past tectonic processes, comes from the interpretation in terms of mantle structural features of the strong, broad high-velocity bodies imaged in the lithosphere – asthenosphere system of the Apennines and surrounding seas.

In regions of plate boundaries, deep tectonic processes, such as lithospheric subduction, continental collision, and magmatism generate strong thermal heterogeneities, the primary cause of anomalies in the propagation of seismic waves. Following the wide literature on seismic tomography, the existence of high velocity anomalies (HVA) in the upper mantle is generally interpreted as due to cold (dense) oceanic lithosphere which penetrates or sinks into a warm (soft) asthenosphere, characterized by lower velocity (HIRAHARA & HASEMI, 1993; LAY,1994; GRAND *et alii*, 1997).

In our region, however, despite the efforts undertaken to provide more and more reliable images of the deep structure, uncertanties still exist on the geometry, lateral extension and continuity with depth of the subducted lithosphere. Besides the intrinsic difficulty in reconstructing adequately the deep structure in complicated plate boundary zones, discrepancies between models arise also from the approximate experimental condition with which the tomographic inversions are usually performed, i.e. insufficient station coverage, poor data quality, and inhomogeneous and/or inadequate sampling of the target volume. Particularly the incomplete ray sampling may have severe consequences on the reliability of tomographic reconstructions, resulting in low resolution images of large regions of the study target. Lack of resolution can, for instance, lead to spurious mapping of the existing velocity anomalies with smearing in the predominant direction of illumination (EVANS & ACHAUER, 1993).

Another critical point in interpreting tomographic images is the type of lithosphere which has been involved in the subduction process. Below the Tyrrhenian – Apennine region, the presence of subducted lithosphere of both oceanic and continental-type have been hypothesized. 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 slabs in the upper mantle (either oceanic or continental) are supposed to cause higher velocities with respect to the surrounding asthenosphere, thus suitable to be recovered by seismic tomography methods provided a thermal contrast is mantained.

In this chapter, after briefly reviewing the basic ideas concerning the structural setting and evolution of the Tyrrhenian – Apennine system, I summarize the most recent results obtained with seismic tomography and deep seismicity studies. Then, a new three-dimensional P-wave velocity model for the upper mantle of the region is described, enhancing the main robust features displayed by the tomograms. Finally, I discuss the geodynamic implications of the tomographic reconstructions, in terms of active and past subduction processes.

2. - TECTONIC SETTING

The present-day tectonic setting of the Tyrrhenian-Apennine system is the result of a complex collision process between the African and Eurasian plates, active since at least 65 Ma (DERCOURT *et alii*, 1986; DEWEY *et alii*, 1989; PATACCA *et alii*, 1990). According to one of the most accreditated geodynamic models, the evolution of this system after the Alpine orogenesis was driven by the eastward migration of the Adriatic-Ionian lithosphere through a complex subduction system (MALINVERNO & RYAN, 1986; FACCENNA *et alii*, 1996). In the late Oligocene-early Miocene (~26 Ma), the estward retreat of subduction of Adriatic lithosphere produced rifting processes in the Hercinic crust of the European foreland and led to the opening of the Liguro-Provençal basin with a 25°- 30° counter-clockwise drifting of the Sardinia-Corsica block (MALINVERNO & RYAN, 1986; BECCALUVA *et alii*, 1989). During this tectonic phase calc-alkaline volcanism was widespread on Sardinia (BECCALUVA *et alii*, 1989) and the Apenninic accretionary wedge underwent shortening. In the Tortonian (10 Ma), the back arc related extensional phase migrated to the Tyrrhenian area while compression continued to affect the Apenninic accretionary prism. The opening of the newly formed Tyrrhenian basin produced wide crustal thinning along the western side of the Apenninic belt with normal faulting and graben tectonics. During Quaternary age, intensive magmatic activity developed along the Tyrrhenian rim of the Apennines, from Tuscany to Campania. The volcanoes show complex evolutionary histories, with high alkali-potassic content and a wide spectrum of silica percentages (WILSON & BIANCHINI, 1999). To the east of the volcanic area, three distinct sectors can be distinguished: the orogenic belt, the Bradanic foredeep and the Apulian foreland (fig. 1).

The orogenic belt, characterized by an extensional

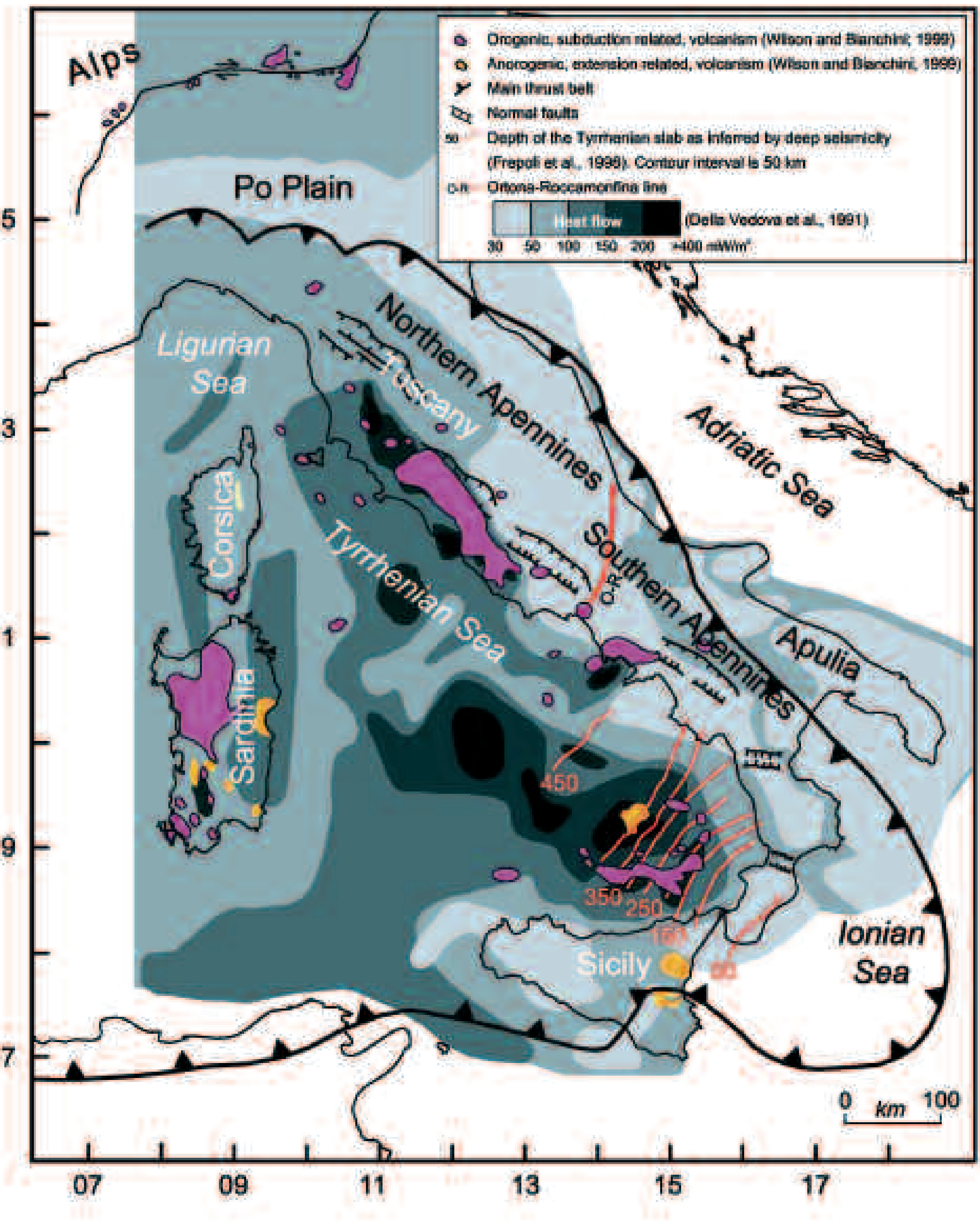

Fig. 1 - *Main tectonic features of the Italian peninsula (after* JOLIVET *et alii, 1998).*

stress regime with the strongest normal faulting Apenninic earthquakes (AMATO & MONTONE, 1997), consists of several Adriatic vergent nappes, emplaced during the Miocene. The Bradanic foredeep, that extends from the Po plain to Sicily, is filled by 6-8 km of Plio- Quaternary sediments, and, according to ROYDEN *et alii* (1987), PATACCA & SCANDONE (1989), KRUSE & ROYDEN (1994), its considerable depth extension is related to the roll-back of the subducting slab beneath the belt rather than the lithostatic load of the orogen. The foreland, part of the Adria microplate, consists for the upper crust, of thick Meso-Cenozoic carbonate platform sequences, mostly undeformed during the compressive phases of the Alpine-Apenninic orogenesis (DOGLIONI *et alii*, 1994).

The present configuration of the Apennines consists of two major orogenic arcs, the Northern Apennine (NA) arc and the Southern Apennine (SA) arc, separated in the central Apennines by a ~ N-S trending fault zone (the Ortona-Roccamonfina line; O-R in fig. 1) that according to some authors is related to a deep lithospheric discontinuity (LOCARDI, 1982; PATACCA & SCANDONE, 1989). The SA arc is composed of two wings, the Southern Apennines wing to the north and the Calabrian arc to the south. As suggested by MALINVERNO & RYAN (1986), PATACCA & SCANDONE (1989), the different curvature of the two main arcs is an expression of a non-uniform retreat of the subducting slab beneath the belt, probably due to a strong lateral heterogeneity of the downgoing lithosphere. The more pronounced slab retreat beneath the northern Apennines and the Calabrian arc with respect to the southern Apennines produced, in this part of the belt, a tearing of the crust through a system of anti-Apenninic transfer faults that accommodates the differential movements between different sectors (PATACCA & SCANDONE, 1989).

3. - PREVIOUS TOMOGRAPHIC AND DEEP EARTHQUAKE STUDIES

The tomographic images together with the hypocentral distribution of crustal and subcrustal earthquakes, pose some of the tightest constraints to reconstruct the geodynamic evolution of our region. The study of the upper mantle structure using arrival times seismic tomography started only in the early 1980s, after the first reliable inversion technique was devoloped (AKI *et alii*, 1977). In this context it is worth recalling the first teleseismic tomography of Italy performed by SCARPA (1982), by using P and PKP data taken from seismic bulletins. He computed a velocity model of the upper mantle down to 360 km depth. The inversion revealed marked velocity contrasts especially in the deep structure of the southern Tyrrhenian Sea, although with a not satisfactory resolution. Further attempts with teleseisms were those of BABUSKA & PLOMEROVÁ (1990), that evidenced high velocities beneath the Alps and the northern Apennines, but still suffered from the use of poor quality data. The tomographic study by SPAKMAN *et alii*, (1993) is the first that investigates the 3-D P-wave velocity structure below the entire Mediterranean region, encompassing the mantle to a depth of 1400 km, by inverting a huge dataset of arrival times ($\sim 10^6$) of both regional and teleseismic events. This study, based on P delay time data collected by the International Seismological Centre (ISC) from 18 years of observation, represents a considerable extension of earlier tomographic experiments.

Differently from SPAKMAN *et alii*, (1993), AMATO *et alii* (1993a), CIMINI & AMATO (1993) carried out their tomographic studies of the upper mantle below Italy by using a smaller teleseismic dataset ($\sim 10^3$), but characterized by high precision in the estimate of the arrival times and a more homogeneous azimuthal coverage of the ray sampling. Compared to the use of noisy bulletin data, the use of accurately picked arrival times significantly improves the fit of the data, and the spatial resolution of the tomographic images (CIMINI & AMATO, 1993). Both these approaches, with some significative differences in the reconstruction of the velocity contrasts and in the geometry of lateral heterogeneities, found consistent high-velocity anomalies below peninsular Italy which were interpreted as related to remnants of subducted lithospheric slabs underlying the region.

More recent investigation of the deep structure of Italy are those by CIMINI & DE GORI (1997), PIROMALLO & MORELLI (1997), LUCENTE *et alii* (1999), DI STEFANO *et alii* (1999). In the study by CIMINI & DE GORI (1997), both direct (P and PKPdf) and secondary (pP, sP, PcP) P-wave arrival times were used to improve the sampling of the target volume and to reduce smearing effects. The tomographic model obtained by LUCENTE *et alii* (1999) extends the definition of the deep structures beneath both the Alps and the Apennines down to 800 km depth. The main finding is a nearly continuous pattern of high-velocity anomalies located between 250 and 670 km depth below the Apennines, shifting toward the Tyrrhenian basin with increasing depth. Finally, the paper by DI STEFANO *et alii* (1999) focuses on the P-wave velocity structure in the crust and uppermost mantle of Italy. They used a large dataset of arrival times of crustal earthquakes to retrieve the lateral heterogeneities at three depth levels located in the upper crust, lower crust, and beneath the Moho. The tomographic image for the lower crust (layer 2, 22 km depth) shows a pronounced low-velocity belt beneath the entire Apennines. This feature was interpreted by the authors as the effect of high temperatures caused by upwelling of asthenospheric material in front of the Adriatic slab.

In addition to seismic tomography, another important contribution to the delineation of the deep structure in regions of plate boundary comes from the distribution of intermediate and deep earthquakes foci. In peninsular Italy, subcrustal earthquakes are observed beneath the southern Tyrrhenian Sea and the northern Apennines. Below the southern Tyrrhenian Sea, the occurrence of intermediate and deep hypocentres defines a continuous, well documented Wadati – Benioff zone from the surface down to at least 500 km depth (CAPUTO *et alii*, 1970; MCKENZIE, 1972; ANDERSON & JACKSON, 1987; GIARDINI & VELONÀ, 1991; among many others). The deep seismicity extends laterally for about 250 km and is mostly concentrated in depth range 50÷350 km (intermediate foci; fig. 2).

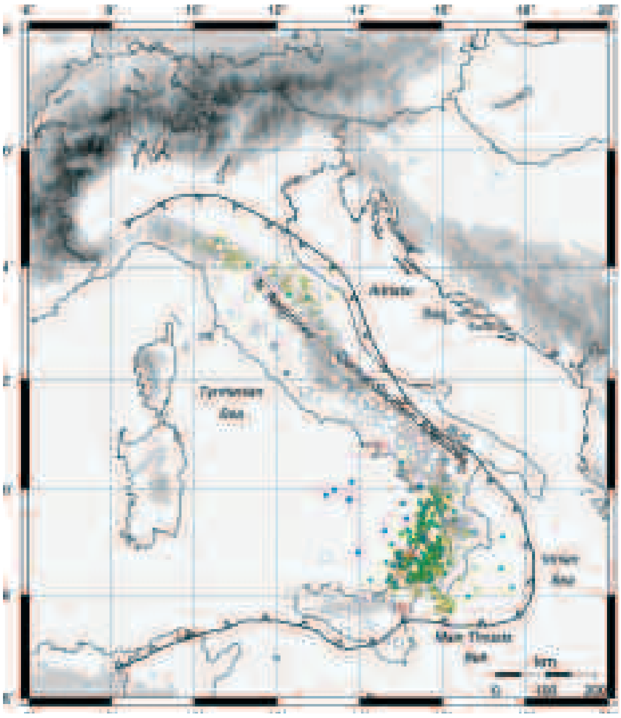

Fig. 2 - *Locations of the permanent and temporary seismic stations used for the tomographic analysis. White squares are the permanent short-period stations of the Istituto Nazionale di Geofisica e Vulcanologia (INGV) seismic network. Grey stars are the temporary three-component stations deployed for the SAPTEX passive array in southern Italy during the period 2001 – 2003. Circles indicate subcrustal seismicity selected from the INGV dataset in the period 1985 -2002: yellow circles are shallow foci (30 < h < 50 km); green circles are intermediate foci (50 < h < 350 km); blue circles are deep foci (h > 350 km). Note the absence of subcrustal seismicity below the central-southern Apennines and the northwestward migration of the deep seismicity (h > 350 km) of the southern Tyrrhenian subduction zone.*

The subcrustal earthquakes located beneath the Ionian Sea and the Calabrian Arc depict a subhorizontal seismic zone probably associated to the upper portion of the subduction zone delineated by seismic tomography (SELVAGGI & CHIARABBA, 1995; FREPOLI *et alii*, 1996; CIMINI, 1999). Below ~350 km depth the distribution appears to be shifted northwestward in the Tyrrhenian basin (blue circles in fig. 2), accordingly with the lateral deflection of the subducted lithosphere within the transition zone observed by CIMINI (1999).

In the northern Apennines, subcrustal earthquakes are observed down to 100 km (AMATO *et alii*, 1993b; SELVAGGI & AMATO, 1992). They are mainly located beneath the axis of the chain, following the bend of the northern Apenninic arc and apparently concentrated in two adjacent NW-SE trending zones (fig. 2). The distribution at depth delineates a ~45 dipping wedge from the Adriatic to the Tyrrhenian Sea, approximately coincident with the high-velocity anomaly detected by tomographic studies (AMATO *et alii*, 1993b; CIACCIO *et alii*, 1998).

Unlike the southern Tyrrhenian Sea and the northern Apennines, no subcrustal seismicity is currently observed beneath the central – southern Apennines (fig. 2). This evidence, along with the lack of clear high-velocity anomalies inferred from tomography in the uppermost mantle of the region, led various authors to suggest that the subduction has not been continuous beneath the whole Apenninic arc. This could be due either to the development of a slab window, as hypothesized by AMATO *et alii* (1993b) or to the presence of a detached slab as proposed by SPAKMAN *et alii* (1993), BIJWAARD & SPAKMAN (2000) A slab window may derive either by an irregular geometry of the two colliding plates or by a faster thermo-assimilation of the subducting lithosphere beneath the central part of the belt. The latter hypothesis is substantiated by the high heat-flow observed in the central Apenninic – Tyrrhenian margin (DELLA VEDOVA *et alii*, 1991; fig. 1). Moreover, a recent tomographic study by CIMINI & DE GORI (2001) shows a pronounced low-velocity zone ($\Delta Vp \cong$ -3 ÷-5%) extending from the surface down to ~200 km in the upper mantle of the region. This feature is probably related to the presence of hot, high-attenuation asthenospheric material at uppermost mantle depths (MELE *et alii*, 1998), and has been proposed to affect the seismic structure of the downgoing Adriatic continental lithosphere, weakening its velocity signature.

4. - UPPER MANTLE STRUCTURE BELOW THE TYRRHENIAN - APENNINE REGION

In this section we show results from a new three-dimensional P-wave velocity model of the study region, computed with a modern teleseismic tomography procedure developed and previously applied by the author to the deep structure of southern Italy (CIMINI, 1999; CIMINI & DE GORI, 2001). This model differs from previous tomographic reconstructions (AMATO *et alii*, 1993a,b; CIMINI & AMATO, 1993; SPAKMAN *et alii*, 1993; CIMINI & DE GORI, 1997; LUCENTE *et alii*, 1999) by the use of an iterative inversion algorithm that incorporates a robust 3-D raytracer to compute more accurate ray paths in strongly heteregeneous media. By iterating, the velocity field is reconstructed gradually and larger data misfit reductions are usually achieved with respect to single step inversion (CIMINI & DE GORI, 2001). Furthermore, to better constrain the geometry of the velocity anomalies, we used an improved dataset of high-quality teleseismic waveforms recorded by the seismic network of the Istituto Nazionale di Geofisica e Vulcanologia in the past 10 years, and by the stations of the SAPTEX array (CIMINI *et alii*, 2003) in southern Italy (fig. 2). The SAPTEX (Southern APpenines Tomography EXperiment) array is an ongoing deployment of temporary three-components digital stations, planned as a two-years passive experiment for high-resolution seismological studies of the southern Apennines.

For this nonlinear inversion we selected 140 teleseisms of magnitude $m_b \geq 5.5$ recorded by at least 30 stations. From the collected seismograms, the arrival times of 4765 P, and 1206 PKPdf phases were handpicked, giving a total of 5971 travel times. Figure 3 is a map of the great circle teleseismic ray paths showing the back azimuthal coverage of the region Since this kind of tomography inverts relative arrival times to estimate velocity perturbations, we used the 1-D velocity model ak135 (KENNETT *et alii*, 1995) to compute the predicted P-wave arrival times and, hence, the travel time residuals.

The tomography was performed by parameterizing the Earth structure beneath the Tyrrhenian –Apennines system with a three dimensional grid of nodes whith parameters are listed in table 1. The centre of the grid (x=0, y=0) corresponds to the geographic coordinates 40.5N, 14.0E, and, for ray paths computation, the bottom layer (600 km depth) is not inverted.

In figure 4 (a to c), six slices of the three-dimensional model are shown, from the uppermost mantle lithospheric layer (layer1, 50 km depth) down to 300 km (layer 6). The deepest part of the model, down to 500 km depth, is displayed subsequently in figure 5 by the three vertical sections across the Tyrrhenian – Apennine region.

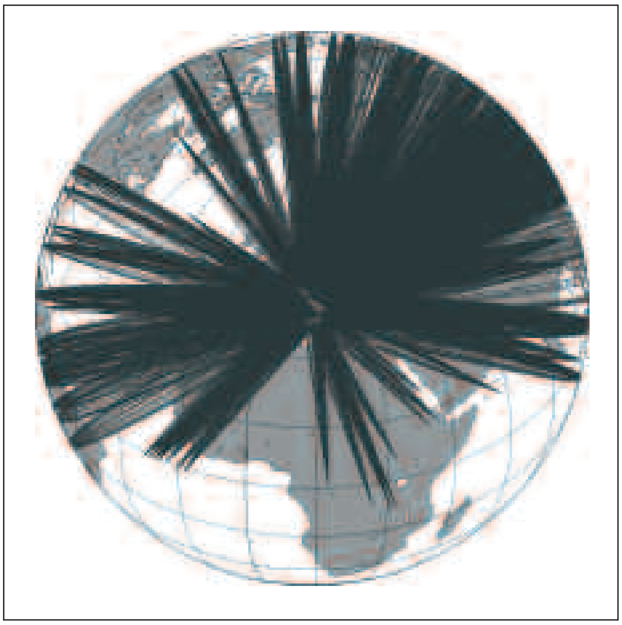

Fig. 3 - *Orthographic map showing the teleseismic ray sampling (great circle paths) of the deep structure beneath the study region. White circles represent the seismic stations of figure 2. The back azimuthal coverage is rather good, except from the south. The numerous ray crossing in the region significantly improve the resolution of the present tomographic model.*

The first two layers of the model (fig. 4a) show three main regions of high-velocity anomalies, located in the northern Apennines, Apulia region, and southern Tyrrhenian sea. The northern Apennines

TAB. 1 - *Grid model and reference P-wave velocities adopted for the iterative inversion.*

Layer	Depth km	Nodes in x	Nodes in y	Delta x km	Delta y Km	Vp km/s
0	0	Station layer - 110 recording sites				5.80
1	50	19	21	50	50	8.04
2	100	19	21	55	55	8.05
3	150	19	21	60	60	8.13
4	200	19	21	65	65	8.27
5	250	19	21	70	70	8.45
6	300	19	21	75	75	8.63
7	350	19	21	80	80	8.81
8	425	19	21	85	85	9.41
9	500	19	21	90	90	9.66
10	600	19	21	100	100	10.00

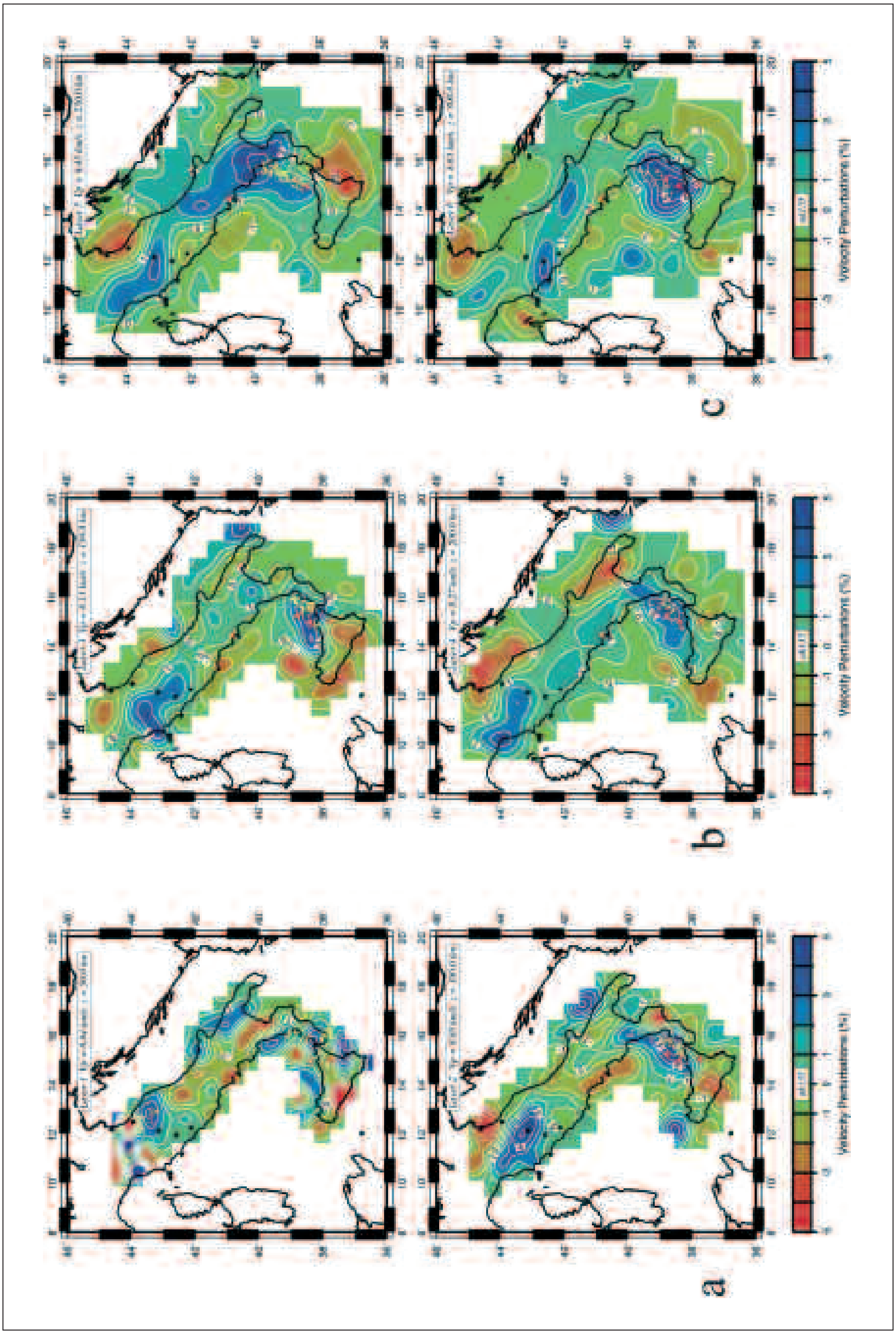

Fig. 4 - *Horizontal maps showing the 3-D P-wave velocity model for the upper mantle structure beneath the Tyrrhenian – Apennine system obtained by the nonlinear tomographic inversion after three iterations. a) layer1 (50 km), and layer2 (100 km); b) layer3 (150 km), and layer4 (200 km); c) layer5 (250 km), and layer6 (300 km). Note how the high-velocity regions, concentrated beneath the northern Apennines and the southern Tyrrhenian Sea at uppermost mantle depths (layer1 and layer 2), delineate a more continuous pattern at greater depths (particularly in layer 5, 250 km depth).*

HVA is very clear in the uppermost mantle at a depth of 100 km (fig. 4a, layer 2), where the velocity perturbations, as large as +4%, delineates a linear NW-SE anomalous body beneath the internal part of the chain. At shallower depths, the shape of the high velocity feature is strongly arcuate, suggesting that the slab curvature was acquired in the late stage of subduction (CIACCIO *et alii*, 1998). The subcrustal seismicity, which epicentral distribution closely follows the curvature of the northern Apenninic arc (fig. 2), appears mostly concentrated within the fast structures or at the border with the low-velocity zone reconstructed below the external front of the belt. Low-velocity anomalies are also found beneath the central-southern Apennines, the Campanian Tyrrhenian margin, and Sicily.

Figure 4b shows the P-wave velocity model for layers 3 and 4, set at 150 and 200 km depth, respectively. The main feature displayed by these tomograms is the nearly continuous pattern of high-velocity anomalies beneath the entire Apenninic chain and the southern Tyrrhenian sea. The largest positive perturbations are imaged in the southern Tyrrhenian area ($\Delta Vp \approx +3 \div +5\%$), consistently with the presence of a cold, dense oceanic-type subducted lithosphere (HIRAHARA & HASEMI, 1993). The resulting geometry delineates a SW-NE striking slab with thickness of about 100 km, lateral extent increasing with depth from ~200 km (layer 2) to ~400 km (layer 4), and that includes all the deep hypocenters. In central-southern Italy, between approximately 40N and 42N, the fast structures become weaker ($\Delta Vp \sim +1 \div +2\%$), thus confirming the along-strike difference in the HVA signature of the upper mantle below the Apennines pointed out by previous tomographic studies (AMATO *et alii*, 1993b; LUCENTE *et alii*, 1999; AMATO & CIMINI, 2001). Possible explanations are a heterogenous composition of the subducted lithosphere or a differential thermal assimilation of the slab at depth, or both. The prominent low-velocity anomaly recognized beneath the pery-Tyrrhenian area from the uppermost mantle (fig. 4a) below at least 150 km depth (fig. 4b, layer 3), suggests the presence of high temperature, probably partially melted, asthenospheric material in front of the Adriatic slab. This asthenospheric upwelling, as hypothesized by CIMINI & DE GORI (2001), may have promoted a more pronounced heating process and a faster termal assimilation of the downgoing slab.

The lateral heterogeneities in the P-wave velocity structure of the study region at greater upper mantle depths are displayed in figure 4c. The tomogram at 250 km depth (layer 5) shows a laterally continuous distribution of high-velocity anomalies from the northern Apennines to northeastern Sicily. The pattern is characterized by two main HVA regions ($\Delta Vp \geq +2\%$), separated in central Italy, around 42N, by an area of weaker perturbations marking the transition between the northern and the central-southern Apennines Two broad low-velocity anomalies are also reconstructed beneath the northern Adriatic sea-Po plain region and eastern Sicily. These slow features are visible from the uppermost mantle depths (figs. 4a,b), the latter probably related to the Mt. Etna volcanism. The horizontal map at 300 km depth (layer 6) depicts a more complex aspherical P-wave structure with respect to the previous one. The most prominent feature is still represented by the southern Tyrrhenian HVA that at this depth exibits the largest magnitude ($\Delta Vp \geq +5\%$) and the progressive shift toward the center of the Tyrrhenian basin, jointly with the NW migration of the deep seismicity (see also figs. 1, 2).

Figure 5 shows three vertical slices through the 3-D velocity model to better depict the different deep tectonic settings along peninsular Italy and surrounding seas.

Section AA' (upper panel) crosses the study region from Corsica, through the northern Apennines, to the Dinarides. Below the belt, the teleseismic image reveals a continuous HVA that extends from the uppermost mantle to at least 300 km depth. The slab is steeply dipping toward the back-arc region (Tuscany) and has a thickness of about 100 km. The maximum positive perturbations ($\Delta Vp = +4\%$) are reconstructed around 100 km depth, correspondently with the end of the subcrustal seismicity so far observed (SELVAGGI & AMATO, 1992). Section BB' (middle panel) is from the Tyrrhenian Sea, through the central Apennines, to the Dinarides. Here the velocity pattern shows a southwestward dipping HVA from about 200 km depth to the bottom of the present model. At uppermost mantle depths, the seismic structure is marked by a low-velocity region; this feature further enhances the difference in the deep structure between the Northern and Southern Apennines. Section CC' (lower panel) shows the upper mantle structure beneath the southern Tyrrhenian Sea and Calabria along a NW-SE profile. The high-velocity body depicting the subducting slab, steeply dipping from the Calabrian Arc to the northwest, is observed from the uppermost mantle down to 350 km. It includes all the intermediate and deep seismicity, which, in the present study, represents independent evidence for the geometry of the subduction zone. Below ~400 km, the tomogram displays a subhorizontal HVA, possibly detached from the highly seismic upper portion. This deep HVA may represent the oldest portion of the subducted lithosphere which is presently stagnant in the transition zone (CIMINI, 1999; LUCENTE *et alii*, 1999).

5. – DISCUSSION

Seismic tomography methods involve analysis of seismic waves that travel through the Earth to provide insights into the deep structure and tectonic evolution. High-velocity anomalies, where seismic waves speed-up, are comparatively common and correspond to regions where cold pieces of lithosphere have sunk into the mantle at the convergent margins of tectonic plates (subduction zones). Low-velocity anomalies are mainly explained as due to the effect of hot, low-Q

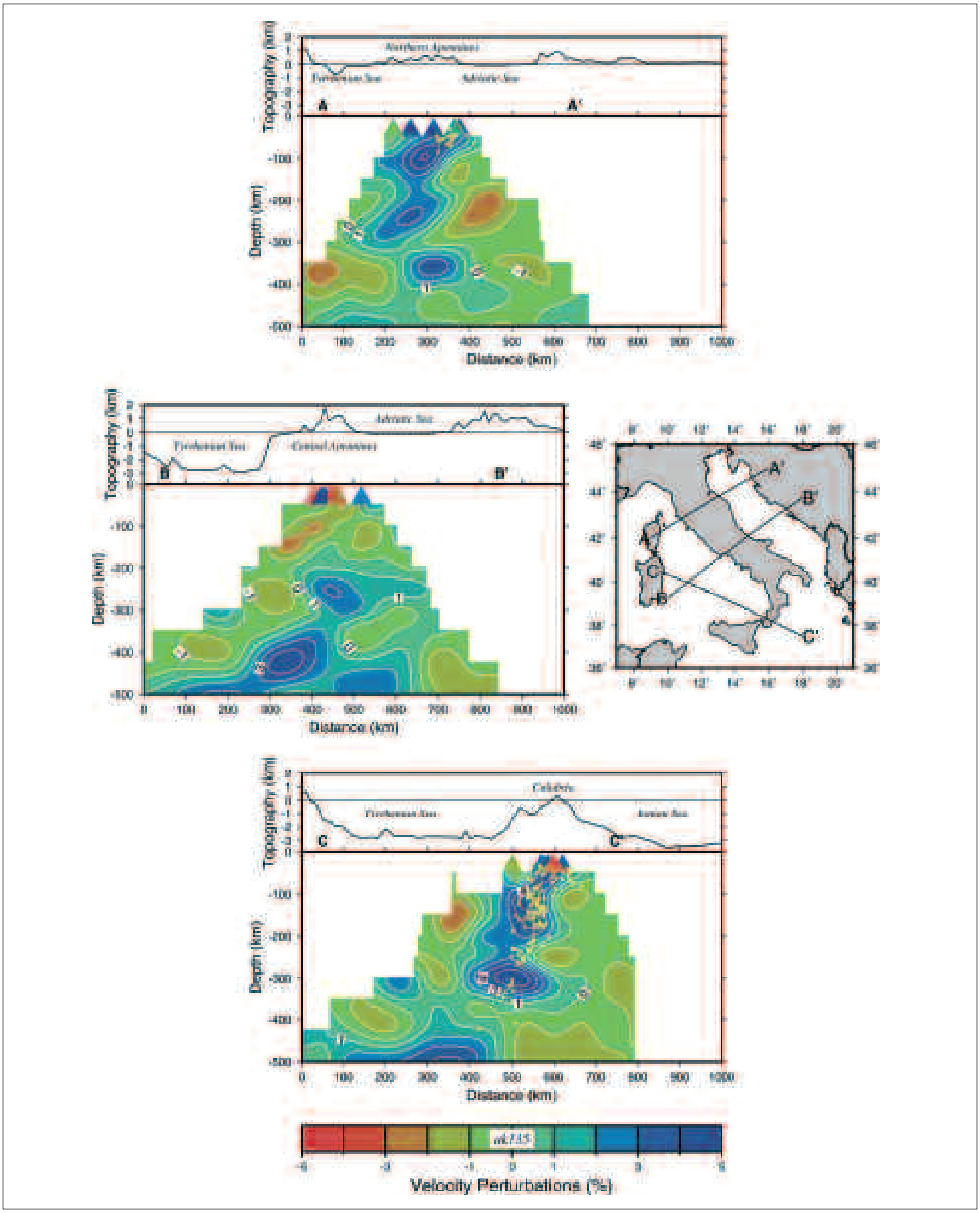

Fig. 5 - *Cross sections through the Tyrrhenian – Apennine region (see the panel for locations) showing the geometry of the subducted lithosphere and its relationship with the surrounding mantle. Yellow stars depict earthquake hypocenters located within 50 km of the vertical plane. A Beneath the northern Apennines a continuous high-velocity body characterized by positive perturbations as large as +4% is imaged between 50 and 300 km depth; B Beneath the central Apennines the downgoing slab is recognized from 200 km down to the bottom of the model. The fast structure, detached from the subcrustal high-velocity anomaly displayed in layer 1 (fig. 4a) at 50 km depth, is overlain by a pronounced low-velocity region extending from the uppermost mantle down to about 300 km below the central Tyrrhenian basin; C Deep velocity structure of the southern Tyrrhenian subduction zone along a NW-SE profile. The image delineates a main high-velocity seismic body from the uppermost mantle down to 350 km depth. Below this depth, a clear deflection of the subducted lithosphere to a nearly horizontal posture is observed.*

regions of upwelling asthenospheric material (hot spots, mid-ocean ridges, continental rift zones, etc.), or even, as in collision zone settings, associated to the subduction of continental crust (ROEKER, 1993). Within the spatial resolution limits previously pointed out (see section Introduction), seismic tomography tools can be used to visualize these mantle features because they produce strong temperature anomalies.

For the deep structure of the Italian region, the tomographic investigations carried out in the past twenty years enhance the presence of remnants of past subduction beneath the entire Apenninic belt.

The published models, although displaying significant differences both in the geometry and magnitude of the velocity contrasts between the subducted slabs and the surrounding mantle, all indicate a remarkable along-strike complexity of the subduction system below the Tyrrhenian – Apennine region. In particular, as also this study makes clear, the deep structures inferred from tomography depict three basic types of the Apenninic subduction, dividing the range into three segments. The main elements characterizing these different deep tectonic setting along the Apennines are summarized in figure 6, where the most reliable features reconstructed by the present nonlinear tomographic inversion are compared with surface tectonics, local seismicity, and regional Pn-wave studies.

The upper panel depicts the northern Apennines structure, in which the continuous slab determines the present subsidence of the foredeep, a still active compressional front and widespread extension in the back-arc region (FREPOLI & AMATO, 1997). No evidence for slab detachment are found in the depth range 150÷200 km, like the one reported by SPAKMAN *et alii* (1993) beneath the entire Apenninic belt. The arcuate shape of the high-velocity anomaly at uppermost mantle depths (fig. 4a, layer 1) reflects the arc curvature seen at the surface, repeating at smaller scale the arc migration model proposed for the earlier stages of the evolution of the Tyrrhenian – Apennine system (MALINVERNO & RYAN, 1986; DOGLIONI, 1991). This idea fits well with the post Miocene differential rotations observed along the outer thrust front from paleomagnetic data (SPERANZA *et alii*, 1997). At present, the subduction process in this area is probably close to the end because of the exhaustion of the oceanic lithosphere available in front of the trench and of the amount of continental lithosphere already subducted into the mantle. The geometry of the high-velocity anomalies depicted by the tomographic images (fig. 5, upper panel), suggest that the present-day configuration was reached through progressive slab roll-back, possibly determined by the older, deeper, oceanic lithosphere drawing from below. An alternative explanation of the steep dipping of the slab is the proposed E-W mantle flow that could increase the plunge of the subducting lithosphere in west-dipping subduction zones, like the Apennines (DOGLIONI, 1991).

The complex morphology of the subducted lithosphere beneath central-southern Apennines is outlined in the middle panel of figure 6. Below the Moho, MELE *et alii* (1996), MELE *et alii* (1998) found evidence for a broad low-Q, low-velocity zone of Pn phases. The high-attenuation feature was related to the presence of asthenospheric material at uppermost mantle depths. The prominent low-velocity anomaly imaged beneath the chain and the pery-Tyrrhenian area down to ~200 km depth (fig. 5, middle panel) strengthens this interpretation, featuring asthenospheric upwelling in front of the subducting lithosphere. Beneath the central Apennines, the slow structures join in a high-temperature mantle wedge that, as proposed by CIMINI & DE GORI (2001), may have been affecting the thermal and reological properties of the shallower, continental part of the Apenninic slab. A pronounced heating process of the downgoing lithosphere is consistent with the most recent (2-3 Ma) evolution of the Thyrrenian basin – Apenninic belt system, since the thick (~110 km) Apulian lithosphere reached the subduction hinge, slowing down (or even stopping) the eastward rollback and its penetration into the asthenosphere (MALINVERNO & RYAN, 1986; DOGLIONI *et alii*, 1994; AMATO & CIMINI, 2001). The lack of significant HVA observed in the ~50÷~200 km depth range (Fig. 4, layer 1 to layer 4) may then reflect a subducting lithosphere the seismic structure of which has been strongly modified by the long exposure to the uprising hot asthenosphere. A warmer, or less dense slab, could also explain the absence of active compression at the outer front suggested by present-day stress indicators (AMATO & MONTONE, 1997) and the diffuse uplift of the entire southern peninsula (WESTAWAY, 1993). Beneath ~200 km, the upper mantle structure is characterized by a clear SW-ward dipping high-velocity body, probably related to the past oceanic subduction. This portion could represent the lithosphere subducted before the collision of continental lithosphere in the central – southern Apennines, which most likely took place during the Messinian (6.5 Ma) as we can infer from paleomagnetic results (SPERANZA *et alii*, 1997).

The lower panel in figure 6 schematizes the southern Tyrrhenian subduction zone, enhancing the northwestward sinking of the Ionian oceanic lithosphere beneath Calabria. The oceanic nature of the slab was proposed by DE VOOGD *et alii* (1992), based on crustal thickness (~17 km in the Ionian area) and velocity profiles, as already hypothesized by BARBERI *et alii* (1973) based on volcanological data. The new teleseismic image (fig. 5, lower panel) shows two main fast structures depicting a ~650 km long slab. The broad low-velocity region reconstructed in front of the upper, steeply dipping HVA, may be due to a pronounced thermal anomaly induced by slab retreat and the subsequent rising of the asthenosphere in the Tyrrhenian basin. It is interesting to note that this feature appears to be the continuation at depth (not visible in cross-section CC', fig. 5) of the low-velocity zone imaged at 50 km depth below the Stromboli volcano (fig. 4a, layer 1). The deeper, almost

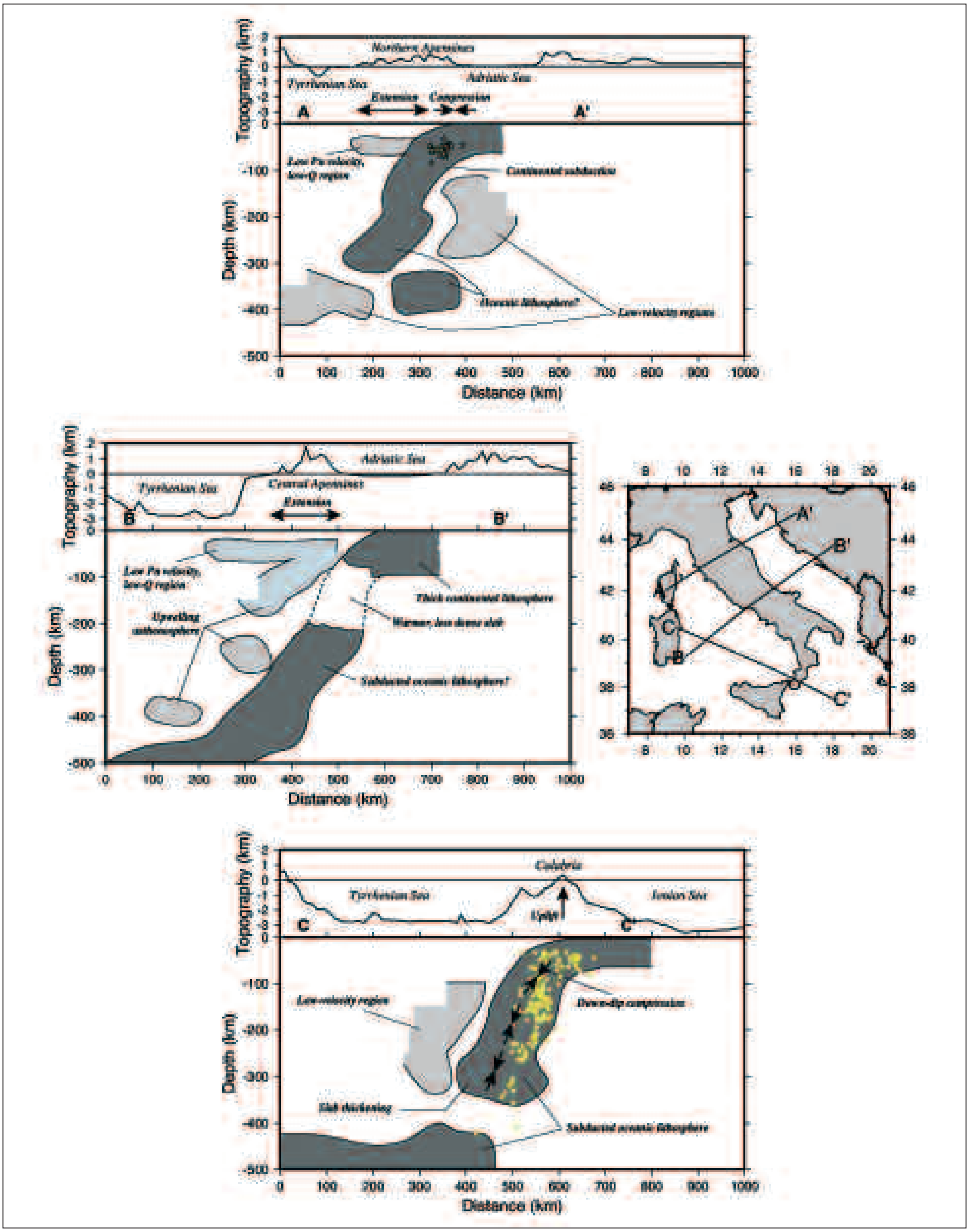

Fig. 6 - *Schematic diagrams along the same vertical planes of figure 5 summarizing the results of the present tomographic study of the Tyrrhenian – Apennine system. The main findings from some recent crustal and upper mantle studies of the region are also included in the maps for greater details and completeness. The Pn attenuation and low-velocity zones result from the study by* MELE *et alii,* 1998. *Deformation patterns are from earthquake fault plane solutions* (FREPOLI et alii, 1996; FREPOLI & AMATO, 1997) *and from borehole breakouts* (AMATO & MONTONE, 1997).

aseismic, portion of the slab lies subhorizontally in the transition zone, suggesting a difficult penetration into a high-strength lower mantle (CIMINI, 1999; LUCENTE *et alii*, 1999). The lateral deflection seen in the tomographic reconstructions is corroborated by the fault-plane geometries of intermediate and deep seismicity. This analysis enhances the shallowing of P-axes from dips of ~70°, found between 165 and 370 km depth, to subhorizontal dip observed for the deepest events located toward the central Tyrrhenian basin (FREPOLI *et alii*, 1996). Furthermore, it shows a diffuse down-dip compression within the upper portion of the subducted lithosphere (fig. 6), with the orientation of P-axes strikingly coinciding with the ~75° dipping seismogenic slab.

Another structural element characterizing the uppermost mantle geometry of the southern Tyrrhenian suduction zone is the increasing of lateral extent with depth. This observation, primarily reported by CIMINI (1999), can be related to the tectonic evolution undergone by the migrating Calabrian Arc in the last 2-3 Ma. During this period, the southeastward roll-back of the Apenninic subduction experienced, in the southern Tyrrhenian area, the highest rate of trench retreat (5-7 cm/yr), as witnessed by the rapid opening of the Marsili basin, forming the present-day shape of the arc (MALINVERNO & RYAN, 1986; FACCENNA *et alii*, 1996). The narrow lateral extent of the HVA depicting the shallower part of the slab, may reflect the narrow strip of oceanic lithosphere remaining after the continental collision took place at its eastern (southern Apennines) and western (Sicily) borders.

6. - CONCLUSIONS

Lateral heterogeneities, different thicknesses and a strongly irregular shape of the Ionian – Adriatic lithosphere have produced a complex subduction system beneath the Tyrrhenian – Apennine area. In this study, I summarized the contribution of seismic tomography to unravel the upper mantle structure of the region. The resulting picture, improved by the new tomographic images obtained with a modern nonlinear inversion of high-quality teleseismic data, shows different pieces of subducted slabs in a general geodynamic context of oceanic – continental subduction. This model is further complicated by along-strike variations that can be represented by at least three basic types of lithospheric sinking below peninsular Italy. Although no inferences can be made from the present results on the precise nature of the subducted lithosphere, we may consider the widespread evidence in collision zones of subducted thick crustal material to mantle depths (~50÷~150 km) to draw the following conclusive remarks. Beneath the northern Apennines the continental Adriatic lithosphere is attached to a deeper (>~150 km), probably oceanic, portion, forming a continuous, at least 300 km long, subducting slab. In the uppermost mantle of central – southern Apennines and central pery-Tyrrhenian area, low-velocity zones, laterally extending for about 300 km, interrupt the continuous HVA reconstructed below ~200 km depth. The slow structures, in good agreement with the observed high heat-flow, the thinning of the crust, and the presence of Quaternary volcanoes along the Tyrrhenian margin, form at depth a low-Q, high-temperature, mantle wedge lying above a heated, less dense slab. Beneath Calabria and the southern Tyrrhenian Sea, a long, seismically active, oceanic slab is subducting northwestward. The further and faster retreat experienced by this segment of the Apenninic subduction in the last few million years could have produced the apparent detachment of the deeper portion of the slab, which is presently stagnant in the upper mantle transition zone.

More investigations are still needed to better define the structure of the lithosphere-asthenosphere system beneath the Tyrrhenian - Apennine region. The most important seismological approaches to this goal include reconstruction of the Moho geometry from receiver function analysis, seismic anisotropy and attenuation studies, and both P- and S-wave tomographic models. Temporary passive deployments of three-components seismic arrays, like the ongoing SAPTEX array in southern Italy, have proved to be an essential tool for high-resolution studies, allowing to collect new data in areas characterized by paucity of permanent recording sites.

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