United Nations Educational Scientific and Cultural Organization
and
International Atomic Energy Agency

THE ABDUS SALAM INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

THE LITHOSPHERE-ASTHENOSPHERE: ITALY AND SURROUNDINGS

G.F. Panza
Department of Earth Sciences, University of Trieste,
Via Weiss 4, 34127, Trieste, Italy
and
The Abdus Salam International Centre for Theoretical Physics, SAND Group,
Trieste, Italy,

A. Pontevivo, G. Chimera, R. Raykova
Department of Earth Sciences, University of Trieste,
Via Weiss 4, 34127, Trieste, Italy

and

A. Aoudia
Department of Earth Sciences, University of Trieste,
Via Weiss 4, 34127, Trieste, Italy

and
The Abdus Salam International Centre for Theoretical Physics, SAND Group,
Trieste, Italy.

MIRAMARE – TRIESTE
February 2003

1 panza@dst.units.it
Abstract

The velocity-depth distribution of the lithosphere-asthenosphere in the Italian region and surroundings is imaged, with a lateral resolution of about 100 km, by surface wave velocity tomography and non-linear inversion. Maps of the Moho depth, of the thickness of the lithosphere and of the shear-wave velocities, down to depths of 200 km and more, are constructed. A mantle wedge, identified in the uppermost mantle along the Apennines and the Calabrian Arc, underlies the principal recent volcanoes, and partial melting can be relevant in this part of the uppermost mantle. In Calabria a lithospheric doubling is seen, in connection with the subduction of the Ionian lithosphere. The asthenosphere is shallow in the Southern Tyrhenian Sea. High velocity bodies, cutting the asthenosphere, outline the Adria-Ionian subduction in the Tyrrenhenian Sea and the deep-reaching lithospheric root in the Western Alps. Less deep lithospheric roots are seen in the Central Apennines. The lithosphere-asthenosphere properties delineate a differentiation between the northern and the southern sectors of the Adriatic Sea, likely attesting the fragmentation of Adria.
**Introduction**

The first definition of the gross features of the lithosphere-asthenosphere system in Italy and surroundings dates back to Panza et al. (1980) and it is chiefly based on the analysis of Rayleigh wave dispersion. More recent models are based both on surface waves (e.g. Marquering and Snieder, 1996; Martinez et al., 1997, 2000, 2001; Ritzwoller and Levshin, 1998; Yanovskaya et al., 1998, 2000; Pasyanos et al., 2001; Karagianni et al., 2002; Pontevivo and Panza, 2002) and body waves tomography (e.g. Gobarenko, 1990; Spakman, 1990; Babuska and Plomerova, 1990; Alessandrini et al., 1995, 1997; Papazachos et al., 1995; Papazachos and Kiratzi, 1996; Cimini and De Gori, 1997; Parolai et al., 1997; Piromallo and Morelli, 1997; Bijwaard et al., 1998; Lucente et al., 1999). Based on the existing information derived both from refraction and reflection experiments, and body-wave and surface-wave tomography, a compilation of the compressional ($V_p$), shear ($V_s$), and density ($\rho$) distribution in space is due to Du et al. (1998).

We show here features of the lithosphere-asthenosphere system that characterize Italy and surroundings, with a multiscale lateral resolution, as obtained from the simultaneous inversion of regionalized surface wave tomography (e.g. Pontevivo and Panza, 2002; Panza and Pontevivo, 2002; Chimera et al. 2002) and refraction and reflection seismology data (e.g. Aljinovic and Blaskovic, 1987; Bally et al., 1986; Blundell et al., 1992; Catalano et al., 1996, 2001; Cernobori et al., 1996; Cristofolini et al., 1985; De Voggd et al., 1992; Doglioni et al., 2001; Ferrucci et al., 1991; Finetti et al., 2001; Gentile et al., 2000; Improta et al., 2000; Kissling and Spakman, 1996; Morelli, 1998; Mostaanpour, 1984; Pepe et al., 2000; Pialli et al., 1995, 1998; Scarascia and Cassinis, 1997).

**Data and Method**

The data and methods used to obtain the tomographic maps are described by Pontevivo and Panza (2002), Panza et al. (2003a), Chimera et al. (2002), Levshin et al.
(1972, 1992), Ditmar and Yanovskaya (1987) and Yanovskaya and Ditmar (1990). The tomographic maps can be discretized with a proper grid and for each cell of the grid the cellular average group or phase velocity curve is computed. The cellular dispersion curves can be grouped accordingly to their shape and average value (e.g. Panza et al., 2003b) to define regional properties. The lateral resolving power common to most of the available surface-wave tomography (Pontevivo and Panza, 2002) is of about 200 km, but if some parameters of the uppermost part of the crust are fixed on the base of a priori independent geological and geophysical information, the lateral resolving power of the cellular mean dispersion curves can be improved and this justifies the choice to perform the inversion for cells of $1^\circ \times 1^\circ$ (Panza and Pontevivo, 2002; Panza et al., 2003a). If dispersion relations are available for periods as low as 1 sec, local studies can be performed at the scale of a few tens of km.

Due to the complexity of the area we prefer non-linear inversion, since it is independent from the initial model. Through the non-linear inversion, known as the hedgehog method (Valyus et al., 1969; Valyus, 1972; Knopoff, 1972), of the group and phase velocity curves at regional, cellular and local scale, average multiscale lithospheric models that reach a depth of about 250 km are obtained. As a priori information, we use the exiting literature. In the inversion, the unknown Earth model is replaced by a set of parameters and the definition of the structure is reduced to the determination of the numerical values of these parameters. In the elastic approximation, the structure is modelled as a stack of $N$ homogeneous isotropic layers, each one defined by four parameters: $V_p$, $V_s$, $\rho$ and thickness. Each parameter can be fixed (during the inversion the parameter is held constant accordingly to independent geophysical evidences – the a priori information), independent (the variable parameters that can be well resolved by the data) or dependent (the parameter has a fixed relationship with an independent parameter). For each cell, a set of solutions, which are consistent with the observations and with the resolving power of the data (Knopoff and Panza, 1977; Panza 1981), is obtained.
Retrieval of multiscale structural models

In Fig. 1 three examples of average models of the crust and of the upper mantle are presented. In each frame, the inverted dispersion data, the set of solutions (thin lines) $V_s$ versus depth, the explored part of the parameters space (grey area), the chosen solution (bold line), are shown. It could be attractive to consider as solution a median of all solutions, but this is formally not correct. At the base of our choice of the representative solution there is a tenet of modern science known as Occam’s razor: it is vain to do with more what can be done with fewer (Russel, 1946). To reduce the effects of the projection of possible systematic errors into the inverted model, the root mean square (r.m.s.) of the chosen solution is as close as possible to the average r.m.s. computed from all the solutions.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Average models ($V_s$) of crust and upper mantle for: (a) Western Alps, (b) 1°x1° cell containing Vavilov Seamount, (c) part of UMD; as marked by dots. In each frame, measured (with error bars) and computed dispersion relations are given; thin lines: set of solutions, grey area: explored part of the parameters space, bold line: chosen solution.}
\end{figure}

The set of solutions in Fig.1a corresponds to the Western Alps region defined by Panza et al. (2003b). Due to the complexity of the Alpine domain, at crustal level, the model is formally correct but has no straightforward geological significance. On the
other side at mantle level, the slight increase of $V_s$ from about 4.35 km/sec, just below the Moho, to about 4.7 km/sec, at depths larger than 200 km, is consistent with the presence of lithospheric roots, as first indicated by Panza and Mueller (1979).

In Fig. 1b the solutions corresponds to the $1^\circ \times 1^\circ$ cell in the central area of the Southern Tyrrhenian Sea, which contains the Vavilov Seamount (Panza and Pontevivo, 2002). The Moho is very shallow (about 7 km deep) and the lid thickness is less than 10 km, with $V_s$ about 4.1 km/sec. Below this lid, there is a very well developed low velocity layer, centred at a depth of about 20 km, with $V_s$ about 3.0 km/sec and thickness of about 8 km. This value of $V_s$ is consistent, accordingly with Bottinga and Steinmetz (1979), with about 10% of partial melting. The $V_s$ just below this very low velocity layer, about 4.1 km/sec, defines the uppermost asthenosphere. In the asthenosphere $V_s$ increases with increasing depth to about 4.3 km/sec.

In Fig. 1c the chosen structure corresponding to the Umbria-Marche geological Domain (UMD) is characterized by a layered crust, about 32 km thick, with a relatively high velocity upper and lower crust ($V_s$ about 3.20 – 3.65 km/sec) separated by a low-velocity transition zone ($V_s$ about 2.75 km/sec) about 10 km thick. The Moho is followed by a relatively low velocity layer ($V_s$ of about 4.0 km/sec), about 20 km thick. Below this layer, a lithospheric root, with $V_s$ about 4.75 km/sec, reaches the depth of about 130 km, which is the top of the asthenosphere, with $V_s$ about 4.2 km/sec and about 70 km thick. The outlined $V_s$ sequence versus depth in the uppermost mantle is consistent with the concept of mantle wedge, decoupling the crust from the underlying lithosphere. Therefore, we define mantle wedge the low velocity zone ($V_s$ less than about 4.2 km/sec) in the uppermost mantle that overlies the high velocity lid ($V_s$ greater than about 4.5 km/sec).

**Selected cross sections**

Examples of sections, crossing key areas, are given in Fig. 2 (Panza and Pontevivo, 2002; Panza et al., 2003a; Chimera et al., 2002). In Fig. 2b two vertical sections, trending NE-SW, from the Tyrrhenian Sea across the Southern Apennines to the Dinarides are plotted. In the same sections the shallow and intermediate-depth
seismicity, with the depth error bars as given by ISC and falling in a stripe about 100 km wide and centred on the profiles, is shown.

Figure 2: (a) Position of sections and of all recent volcanoes (triangles) (Amiata-Vulsini, Cimino-Vico-Sabatini, Albani, Roccamonfina, Phlegraean Fields-Vesuvio, Vulture, Ischia, Stromboli, Vulcano-Lipari, Etna, Ustica, Marsili, Magnaghi, Vavilov); (b) Tyrrhenian Sea - Southern Apennines – Dinarides: the almost continuous high velocity body seen along BB’ is not visible along AA’; (c) Tyrrhenian – Ionian Sea: outlined Ionian slab; shallow, intermediate-depth and deep earthquakes that fall into a band, about 100 km wide, along the sections in (b) and (c), with the depth error bars are shown; (d) lithosphere-asthenosphere system from the Tyrrhenian (a) to the Adriatic coast (f) and related intermediate-depth seismicity; the mantle wedge supports the lithospheric delamination beneath Central Italy.
The northernmost section AA' crosses Vavilov seamount in the Tyrrhenian Sea, Apennines, middle Adriatic Sea and Dinarides. Starting from A’, the most evident feature is the presence of a high velocity lid, with $V_s$ about 4.8 km/sec. This lid reaches the maximum depth of about 155 km in the zone that goes from the western side of the Apennines to the Tyrrhenian coast. More to the southwest, this thick high velocity lid is missing. The section BB’, less than about 100 km southeast of AA’, crosses the Tyrrhenian Sea, the Vesuvio and Phlegraean Fields zone, the Gargano region, the Adriatic Sea and the Dinarides. Along BB’, the high velocity body with $4.6 \leq V_s \leq 4.8$ km/sec reaches depths of about 110 km under the Dinarides, about 170 km under the Adriatic Sea and about 150 km under the western side of the Apennines. More to the southwest, below Vesuvio and Phlegraean Fields, the high velocity body extends to depths not less than 250 km.

In Fig. 2c, a balanced cross section from the Tyrrhenian to the Ionian Seas, along CC’, is plotted down to 500 km. Our data do not resolve deeper than about 250 km, therefore, below this depth, the subducting Ionian lithosphere is outlined on the base of the hypocenters distribution of the intermediate-depth and deep seismicity. In correspondence of the shallow-mantle magma sources of the volcanic bodies Magnaghi-Vavilov and Marsili, low $V_s$ layers (very shallow asthenosphere) below the thin lid are detected. A very low velocity layer (mantle wedge) below a thin uppermost lid in the Stromboli area and a lithospheric doubling beneath Calabria are seen. In the southernmost part of CC’, the crustal thickness is about 30 km and the lithospheric upper mantle is characterized by a layering where a relatively low velocity body ($V_s$ about 4.3 km/sec) lies between two fast ones. At depths greater than about 150 km, a very well developed low velocity ($V_s$ about 4.0 km/sec) asthenospheric layer is present. Crossing Calabria, the low velocity asthenospheric layer is absent and the relatively low velocity body ($V_s$ about 4.25 km/sec) in the lithospheric mantle becomes deeper and thicker going towards west.

Fig. 2d shows the lithosphere-asthenosphere system along a stripe from the Tyrrhenian to the Adriatic coasts (Chimera et al., 2002), particularly detailed in UMD (see zone e in Fig. 2d). Beneath Central Italy high velocity bodies reach at least a depth of 130 km with a width of about 120 km. The crust exhibits clear $V_s$ layering and lateral
variation in thickness: less than 30 km below the Tuscan Metamorphic Complex (TMC) and about 35 km below UMD. The lid is thin (about 30 km) below the TMC, while it is about 70 km thick below UMD. Along the profile, particularly in the western part where it gets shallower, a developed mantle wedge separates the crust from the high velocity lid.

**Maps of the lithosphere-asthenosphere**

The horizontal resolution of our maps is about 100 km and the vertical penetration reaches a depth of about 250 km. All the features shown at depth larger than 250 km are schematically based on the intermediate-depth and deep seismicity, as given by ISC, schematised by dashed segments in Figs. 3b and 4b,c.

![Maps of the lithosphere-asthenosphere](image)

**Figure 3:** (a) Moho depth with contouring of the deeper Moho where lithospheric doubling is unambiguously detected; (b) thickness of the lithosphere. Here and in Figure 4, the dashed lines schematise the subduction of the Ionian-Adria lithosphere, traced accordingly with ISC hypocenters distribution, and red triangles mark the recent volcanoes.

In Fig. 3a,b the Moho depth and the thickness of the lithosphere are shown, together with the recent volcanoes (red triangles). In Fig. 3a the contouring of the deeper Moho indicates where lithospheric doubling is unambiguously detected by our data. In the northernmost area of the map in Fig. 3b the lithospheric thickness is about 200 km, while in the Western Alps it is at least 250 km. The lithospheric thickness varies in the
range of about 100-150 km along the Northern Apennines, around the Padan plain and in the Dinarides area, except in its westernmost part, where the lithosphere is only about 80 km thick. The Northern Adriatic Sea has a lithosphere thinner than the Central-Southern Adriatic Sea. In the southernmost Adriatic Sea and in the Otranto channel area the lithosphere is less than about 100 km thick. In the Calabrian and Campanian areas the lithospheric thickness exceeds 250 km.

Figure 4: (a) $V_s$ just below the Moho (different dashed patterns outline where mantle wedge and a very shallow asthenosphere are detected); (b) maximum $V_s$ in the uppermost 200 km; (c) minimum $V_s$ in the asthenosphere, in the depth range from about 80 km to about 220 km. In (c) the dark blue areas indicate the fast velocity bodies cutting the asthenosphere.

The two different dashing patterns in Fig. 4a, where the $V_s$ just below the Moho is shown, indicate the presence of the mantle wedge and of a very shallow asthenosphere, respectively. Large lateral variations (Fig. 4b) characterize the maximum $V_s$ in the uppermost 200 km. Peak values are found in the western Alps, central Po valley, Dinarides, Central Adria, Southern-Central Apennines, Northern Tyrrenhian and Ionian Seas. In correspondence of all the volcanoes, except the Tyrrenhian Seamounts, the maximum lithospheric $V_s$ exceeds about 4.6 km/sec. Magnaghi - Vavilov and Marsili are separated by a region with relatively high $V_s$, but in correspondence of these volcanoes $V_s$ is very low. The high velocity bodies of the Ionian-Adria subducting slabs extend below the volcanoes of the Aeolian Arc and of the Campanian province. The
minimum $V_s$ in the asthenosphere, in the depth range from about 80 km to about 220 km, is shown in Fig. 4c. The dark blue area in the northern part of the map corresponds to the fast velocity bodies present in the western Alps. East of this lithospheric body, the $V_s$ in the asthenosphere is as low as in the Northern Adriatic. The properties of the asthenosphere in the Northern Adriatic Sea ($V_s$ between 4.0-4.1 km/sec), are different from those of the Southern Adriatic Sea and around the Otranto channel ($V_s$ larger than about 4.3 km/sec). Low asthenospheric $V_s$ is seen in Sicily and in the Tyrrhenian and Ionian Sea. The dark blue areas around the Tyrrhenian Sea indicate the fast velocity Ionian-Adria slabs that cut the asthenosphere, and that can be traced at depth larger than 250 km from the distribution of subcrustal seismicity.

**Discussion**

In BB’ (Fig. 2b) the high velocity body extending to depths not less than 250 km can be related to the westward subduction of the Adriatic lithosphere towards the Tyrrhenian Basin. This feature is in agreement with the results of De Gori et al. (2001). Along a section very close to AA’ (Fig. 2b) they find a weak velocity perturbation in the mantle beneath the mountain belt with a small high velocity anomaly dipping south-westward. This feature can be correlated with the layer with $V_s$ about 4.6 km/sec, whose top is at about 190 km, in AA’. The rising of the bottom of the asthenosphere could be caused by remnants of high velocity bodies probably detached (Wortel and Spakman, 2002 and references therein) from the lithospheric roots, through thermo-mechanical processes. The remarkable difference between the two sections of Fig 2b, confirmed by completely independent data, indicates that the subducted lithosphere has a very complex morphology.

In CC’ (Fig. 2c), the body with $V_s$ about 4.4 km/sec near the center, above the slab, is probably due to thermal effects induced by the mechanical interaction between the Ionian lithosphere and the hot Tyrrhenian upper mantle. In the center of the section, the layer with $V_s$ around 4.0 km/sec, extending from about 140 km to 220 km depth, can be explained by dehydration processes and melting along the down going slab (e.g. Goes et al., 2000 and references therein). The layering along the easternmost half of
CC’, in the Ionian area, seems to be consistent with the subduction of serpentinized and attenuated continental lithosphere, formed in response to the Jurassic extensional phase. During the tensional phase, the relatively low velocity ($V_s$ in the range 4.25-4.30 km/sec) layer could be formed as a result of the serpentinization of peridotites. Such process produces $V_s$ retardations of a few percent (Christensen, 1966). The presence of a low velocity layer of chemical and not of thermal origin is consistent with the low heat flow in the Ionian Sea (Della Vedova et al., 1991). This layer, when subducted, gets thicker, consistently with the dehydration of serpentine, which is responsible of the weakening of the neighboring material. The seismicity is distributed along the slab and it seems to decrease, but it is not absent, in correspondence of the serpentinized layer. In the studied part of the Ionian Sea, the lithosphere is attenuated continental, thermally relaxed after the Jurassic extensional phase, while in the Southern Tyrrhenian Sea it is very young oceanic.

Beneath Central Italy (see Fig. 2d) there is clear evidence of lithospheric roots surmounted by a well-developed mantle wedge. Young magmatism at the surface and high heat flow in the TMC region suggest that, in agreement with petrological and geochemical data (Peccerillo, 2001), this layer may represent a partially molten mantle. In Tuscany the mantle wedge is underlined by a thin lithosphere and an up-risen asthenosphere roof, in agreement with the heat flow data (Della Vedova et al., 2001). Along the same vertical section, the rising of the bottom of the asthenosphere may have the same origin discussed for section AA’ (Fig. 2b) The sub-crustal earthquakes (ISC) cluster in the shallower part of the thick Adriatic lid and in the eastern part of the lithospheric root, consistently with a slab-like geometry, while the part of the lithospheric root and thin lid to the west seems to be almost free of seismic activity. The absence of deep seismicity and the non in-depth continuity of the fast velocity body below Central Apennines (Fig. 2d) and Southern Apennines (section AA’ in Fig 2b) clearly highlight a major difference when compared to the structure and related deep seismicity of the Calabrian arc, where there is a sound evidence of a continuous slab.

The complex crustal structure, where shearing and thrusting involve the whole crust and the upper mantle, causing the occurrence of more than one Moho, described by Nicolich and Dal Piaz (1990) is confirmed by our data and the map in Fig. 3a.
reproduces several other features identified by the same authors. Near the Otranto channel the Moho is in the range 25-30 km, i.e. shallower with respect to Nicolich and Dal Piaz (1990) results, but well in agreement with the Moho depth proposed by Herak and Herak (1995).

In Fig. 3b, the Western Alps lithosphere at least 250 km thick is consistent with the presence of the lithospheric root (Panza and Mueller, 1979). The Northern Adriatic Sea has a lithosphere thinner than the Central-Southern Adriatic Sea, where a band with moderate seismicity can be identified. The lithosphere is very thin, less than about 25 km, in correspondence of the Magnaghi, Vavilov and Marsili. The lithospheric thickness exceeding 250 km in the Campanian and Calabrian areas is associated to the subduction of the Ionian-Adria lithosphere, schematically represented, for depths larger than 250 km, by the isolines in Fig. 3b.

The mantle wedge area shown in Fig. 4a is in agreement with what proposed by Meletti et al. (2000) in their structural and kinematic model of Italy. In some cases the lowest velocity material is not just below the Moho but below a thin mantle lid, possibly formed by thermal underplating. All the volcanic areas (see the caption of Fig. 2), except those with the inactive volcanoes of Vulture and Ustica, are characterized by the presence of a low velocity layer just below the Moho or below a very thin lid.

The dark blue area in the northern part of Fig. 4c, due to the plate collision process between Eurasian and African plate, contains the so far proposed locations of the rotation pole of Adria versus Europe (Meletti et al., 2000 and references therein).

Acknowledgements

Research funded by Italian MIUR Cofin-2001 (2001045878_007), CNR (CNRC007AF8) and INGV-2001. We thank F. Wezel for critically reading the manuscript.
References


Parolai, S., Spallarossa, D., and Eva C., 1997, Bootstrap inversion for Pn wave velocity in North-Western Italy, Annali di Geofis., v. XL, no 1, pp 133-150.


Spakman, W., 1990, Tomographic images of the upper mantle below central Europe and the Mediterranean, Terra Nova, v. 2, pp 542-553.


Giuliano F. Panza, Professor of seismology in the Department of Earth Sciences - University of Trieste, and head of SAND Group ICTP-Trieste. Laurea in physics from the University of Bologna in 1967; PostDoc at UCLA. He is fellow of Academia Nazionale dei Lincei, of Academia Europea, and Third World Academy of Sciences. He is winner of the EGS Beno Gutenberg medal in 2000 and he received Laurea Honoris Causa in Physics in 2002 from the University of Bucharest. He is leader of several projects funded by EC related to seismic hazard assessment.

Antonella Pontevivo, PhD from the Department of Earth Sciences - University of Trieste in 2003. Laurea in physics from the University of Trieste in 1999. At present PostDoc in the Geological Institute - University of Copenhagen. Her PhD thesis is on surface-wave tomography, non-linear inversion and geophysical implications in the Italian area and surroundings.

Giordano Chimera is PhD student in the Department of Earth Sciences - University of Trieste. He received his Laurea in physics from the University of Trieste in 1998. His interests are: tomography and non-linear inversion in the Apenninic and Alpine areas.

Reneta Raykova, Laurea in physics from the University of Sofia in 1994. As PhD student in the Department of Seismology at the Geophysical Institute of Sofia, she received in 2003 from the Department of Earth Sciences - University of Trieste, a one year EU - Marie Curie fellowship. Her interests are surface wave tomography and structure of the crust and upper mantle.

Abdelkrim Aoudia, research scientist at the Abdus Salam International Centre for Theoretical Physics at Trieste. He received his PhD in geophysics from the University of Trieste in 1998. His research interests revolve around using geophysical, geodetic and tectonic data to understand the mechanical behavior of earthquake faults and to constrain better conceptual and quantitative models for lithospheric deformation.