MODELLO STRUTTURALE:
NOTE ILLUSTRATIVE DEL MODELLO DELLA LITOSFERA IN ITALIA E REGIONI CIRCOSTANTI

THE STRUCTURAL MODEL:
GENERAL REMARKS ON THE LITHOSPHERE-ASTHENOSPHERE SYSTEM IN ITALY AND SURROUNDING REGIONS

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It has been widely acknowledged (e.g. Panza et al., 1980 a,b; Hovland et al., 1981; Aki, 1982; Spakman, 1986) that lateral heterogeneities in the elastic properties of the European area are to be found not only in the crust but are also present in the upper mantle. In recent years the attention of many researchers has been focused on the investigation of lateral variations in the lithosphere-asthenosphere system. In fact the regional character of these heterogeneities may reflect, better than the local crustal variations, the large geodynamic processes that led to the present day structural setting.

One of the most suitable tools for a detailed study of the elastic properties of the lithosphere-asthenosphere system is still represented by the measurements of the regional dispersion of surface waves. In the last two decades intensive efforts have been made to study details of the crust and upper mantle in the Mediterranean area. To this purpose a considerable amount of measurements have been carried out within the framework of a large international project (Panza et al., 1980a).

The main aim of the study of surface wave dispersion is to infer the characteristics of the crust and upper mantle, the thickness of the layers and their shear-wave velocity. This last quantity is rather sensitive to thermal conditions and hence is a good indicator of the temperature in the upper mantle. However, most of the dispersion measurements are carried out over paths sampling different tectonic regimes (especially true for the very complex European-Mediterranean area). Therefore Panza et al. (1978, 1980a) have developed a trial and error method to extract regional dispersion relations, whose inversion allows to obtain models for fairly well-defined tectonic regions.

THE CRUST

Short period surface-wave phase and group velocities dispersion data have made it possible to get some kind of regionalization of the uppermost part of the lithosphere, the crust, in Italy and its surrounding regions (Calcagnile et al., 1982; Calcagnile and Scarpa, 1985; Panza, 1986).

On the basis of the shear-wave velocity it is possible to distinguish several types of crust with average S-wave velocities in the range of 2.8-3.8 km/s and thicknesses varying from a minimum of about 10-16 km - in correspondence of the Tyrrhenian and Balearic Basins - to a maximum of about 50 km (including a possible transitional layer) beneath the Ionian Sea, which has a crust of continental or continental margin type. A general feature of the results of the inversion is the possibility of finding a rather smooth crust-mantle transition for all the studied regions: there are models with a layer characterized by S-wave velocities of about 4.0-4.3 km/s at the crust-mantle boundary, yielding a transition zone between the crust and the uppermost mantle. However, the transitional layer is a necessary condition in order to satisfy the experimental data only for the Southern and Northern Adriatic Sea and for the area of the Sicily channel, while for the other areas a sharp crust-mantle discontinuity is also consistent with the data.

LOWER LITHOSPHERE OR LID

On the basis of the available data it has been possible to draw the gross features of the elastic properties of the sub-Moho material in the Mediterranean area (Panza et al., 1980a).

A "normal lid" - by lid we denote the high-velocity subcrustal layer - with thickness not exceeding about 75 km and shear-wave velocities equal to or greater than 4.50 km/s corresponds to platforms and massifs, and in general to stable continental areas (Knopoff,1972), and must be considered to represent the "undisturbed" sub-Moho structure in large parts of Europe. The northern Adriatic Sea, the eastern part of the Italian peninsula as well as the Corsica-Sardinia block fall into this category.

A considerable thinning of the lid (thickness not exceeding 15 km) is observed as the Central European Rift system is approached. This graben system extends from the North Sea to the Rhinegraben and through the Bresse graben merges with the Rhone depression. This major structure is one of the dominant mantle features in Europe. A similar thinning of the lid is observed under the Western Mediterranean associated with an average shear-wave velocity of about 4.35 km/s. The lid is extremely thin or even absent in the Tyrrhenian Sea where the average sub-Moho S-wave velocity is about 4.20 km/s. This anomaly extends under the North-Central Apennines, where the S-wave velocity in the sub- Moho material may be as low as about 4.05 km/s.

Regions with a "thick" lid (maximum thickness of about 105 km) are mainly associated with tectonically active areas, such as the Greece-Aegean Sea area, the Central-Eastern and the Southern Alps, while in the North-Eastern Alps (shear-wave velocity as low as 4.35 km/s) the lid thins through a rather rapid transition to about 50 km. Recent tomographic studies (Babuska et al., 1985; Spakman, 1986) indicate for the lid a possible maximum thickness of about 120 km in the Alpine area. An interesting feature is to be observed in the Adriatic Sea, where the southern part seems to have a thicker lid than the northern part.

The average properties of the crust and of the high-velocity lithospheric part of the mantle (the lid) indicate that it is possible to identify at depth a continuous structure which extends from northern Africa through the Ionian Sea to the Adriatic Sea. This region is characterized by the presence of a transitional layer marking the crust-mantle boundary. Below this transitional layer a lid with high velocity is present. This continuous structure can be taken as the witness of the merging of two continental margins. In other words the hypothesis that the Adriatic plate has originated as part of the African continent (e.g. Channell and Horvath, 1976) may explain the considerable similarity of the dispersive properties of the Adriatic Sea and the north African region.

LITHOSPHERE-ASTHENOSPHERE SYSTEM

Combining the elastic properties described in the two preceding paragraphs with the information deducible from surface wave dispersion analysis on the deeper portion of the mantle, it is possible to construct a map of the lithosphere-asthenosphere system in Italy and surrounding regions (Fig. 1). When interpreting this map, it must be realized that it represents only an approximate solution of the inverse problem and that it is subject to inherent uncertainties (e.g. 15 to 20 km in the lithospheric thickness).

The first row of each set of numerals refers to the possible range of the average S-wave velocity from the Moho to the depth indicated by isolines (lower lithosphere or lid), while the second row describes the possible range of the average S-wave velocity below the depth indicated by the isolines (upper asthenosphere or low-velocity zone). In some areas only one S-wave velocity value is given, and this means that its range of variability is less than the incremental step (0.15 km/s for the upper layer and 0.10 km/s for the other layer) of the S-wave velocities used in the inversion. Only in the areas where a marked contrast (clear decrease of velocity with increasing depth) exists between the values in the two rows, can the isolines be considered as representative of the lithospheric thickness. It can be moreover observed that a thick (thin) crust does not always correspond to a thick (thin) lithosphere.

From the figure the presence of strong lateral variations is evident both in thickness (from 30-50 km to about 130 km) and in S-wave velocity (from 4.1-4.2 km/s up to 4.8 km/s). In the foreland stable areas, characterized by a mature continental crust, the lithosphere is about 100 km thick and the rigidity reaches values typical of a continental plate. An example is given by the rather continuous structure extending from the north African coasts to the Adriatic Sea. The north African coastal ranges, between Rabat and Tunis, have a lithosphere with a thickness of about 90 km, which is increasing southwards, with a clear lid - to-low- velocity layer contrast. Further to the east in correspondence of the Ionian and Adriatic Seas, the lithosphere has still a thickness of about 90 km and more. The property of the lithosphere under the Ionian Sea leaves little doubt that the present situation is mainly due to the foundering of a lithosphere of continental or continental-margin type (Cloetingh et al., 1979; Farrugia and Panza, 1981; Calcagnile et al., 1982). The continuity in elastic properties under the Adriatic and Ionian Seas, together with the similarities in their heat flow and free-air gravity anomalies (Suhadolc and Panza, 1987), support the concept of an African promontory (Channell et al., 1979; Mueller, 1982) - but at the same time constitute a major challenge to relate these facts to the present bathymetry and the subsidence history of the Ionian Sea.

A particularly striking structure delineated in the map is the lithospheric thinning in correspondence of the Central European Rift System. Along this rift system the lithosphere has an average thickness of about 50 km and markedly lowered S-wave velocities.

Somehow similar characteristics can be found on the western side of the northern Tyrrhenian Sea and the Tuscan-Latial Apennines, a chain zone associated with an extremely thinned crust and lid, where the lithosphere does not exceed a thickness of about 70 km.

The lower Tyrrhenian and Algerian-Provencal basins are characterized by an even thinner lithosphere (less than 30 km in the bathyal plains) of a young oceanic type. The high heat flow and the low rigidity values in the Tyrrhenian Sea (shear-wave velocities of about 4.2-4.3 km/s) agree very well with the abyssal plain age (more than 7 Ma and probably around 10 Ma) of this basin, which is younger than the basin of the Western Mediterranean (20-25 Ma). In fact, an attempt to estimate the ages of such basins, taking as a reference the model of the evolution of the lithosphere in the Pacific Ocean, indicates that the Western Mediterranean basin dates back to early Miocene or late Oligocene, while the Tyrrhenian basin was formed largerly prior to the Messinian salinity crisis, in good agreement with the results of the Deep Sea Drilling Project (Panza and Calcagnile, 1979). "Brittle" material embedded in the low-velocity asthenospheric layer is present in correspondence of the Tyrrhenian Sea (Caputo et al., 1970; 1972; Ritsema, 1979;

Gasparini et al., 1982; Malinverno and Ryan, 1986). Under the Calabrian arc there are strong lateral gradients in the lithospheric thickness, which is increasing in passing to the Ionian Sea region.

In the Central-Eastern and Southern Alps the lithosphere is about 130 km thick and the lid is well recognizable with shear-wave velocities as high as 4.65 km/s. The crustal roots are well pronounced along the axis of the entire Alpine chain.

The presence of deep-seated lithospheric roots in correspondence of the Western Alps and Central Apennines (Panza et al., 1980 b), can be reasonably inferred from the high values of S-wave velocities (up to 4.6 km/s) at depths larger than about 70 km. These lithospheric roots, which seem to be almost vertical, interrupt the low-velocity layer - a common feature to stable Europe and north Africa - and do not seem to give rise to any seismic activity, with the exception of southern Spain (Chung and Kanamori, 1976).

The structural difference between the Central and Western Alps on one side and the Eastern Alps on the other may reflect different modes in the building process of the Alps, and may be related to the different orientation of the two parts of the chain with respect to the direction of the main component of the compressional forces originating by the relative motion of the two colliding plates. On the other hand, the minimum compressional stresses observed normal to the longitudinal axis of the Central Apennines are quite well in agreement with neogenic and quaternary magmatism, indicating that in this area tensional processes have played a relevant role after the collision.

The areas with a thinned lithosphere are associated in general with anomalously low velocities just below the Moho, as in the Central European Rift System. However, low sub-Moho shear-wave velocities also overly the lithospheric roots under the Alps and the Apennines. It is not surprising to note that the strongest lateral heterogeneities in the lithosphere occur in tectonically active areas. The complexity of the lithospheric structure in these areas indicates therefore that the whole lithosphere-asthenosphere system has been strongly modified by the interaction between the European and African plates and more particularly by the Alpine tectonics.

Summarizing the main features illustrated in the map, it is possible to sketch the lithosphere-asthenosphere system in Italy and its surrounding regions as follows (Calcagnile and Panza, 1981).

Going from the Central Alps to the southern Adriatic Sea almost longitudinally along the Adriatic Sea, the lithosphere-asthenosphere system presents elastic properties rather typical for continental areas, while relevant thickness variations are encountered. The lithosphere is around 130 km thick in the Alpine part, is thinned to about 80 km in the North-Central Adriatic and reaches about 110 km in the Southern Adriatic Sea. The bottom of the channel is not well resolved, but it seems to be at a depth of about 300 km. In the channel the S-wave velocities are in the range of 4.2-4.4 km/s.

If we move from the Tuscan Archipelago to the Southern Adriatic Sea, there is a low-velocity layer lying beneath a possible veneer of high-velocity material (not thicker than about 15 km), but above high-velocity material extending to great depths from about 70-80 km downwards. As one moves southeastward, a "typical" continental lithosphere-asthenosphere system is again reached in the Southern Adriatic Sea. In this area the S-wave velocities in the channel are in the range of 4.3-4.5 km/s.

Following a north-south profile, from the Central Alps to the Southern Tyrrhenian Sea, a large amount of lateral variations is encountered down to the bottom of the low-velocity channel, which rises from about 300 km underneath the Central Alps to about 200 km in the bathyal plain. In the central part of this profile, the Central Apennines zone, the presence of an anomalous zone with shear-wave velocities in the range of 4.4-4.6 km/s must be noted below a depth of about 70-80 km (a "lithospheric root" similar to the one detected in the Western Alps and probably associated with the continent-continent collision which started in the Eocene). This root underlies sub-Moho low-velocity material having shear-wave velocities of around 4.05-4.20 km/s (interpretable as the result of rifting processes subsequent to the collision).

Moving from the Southern Tyrrhenian Sea to the Southern Adriatic Sea, there is a rapid transition from an oceanic-type upper mantle structure to a "typical" continental lithosphere. The difference extends to the bottom of the channel, which is at a depth of about 200 km on the Tyrrhenian side and at about 300 km depth on the Adriatic side.

For comparison the significant heat flow anomalies (Cermak and Hurtig, 1979) have also been included in the map of the lithosphere-asthenosphere system. Only contours for heat flow values larger than 80 mW/m^2 and less than 40 mW/m^2 are plotted to avoid overcrowding. No clear correlation seems to exist between large crustal thickness and high heat-flow values or vice versa, if we exclude the two basins of oceanic type. If, however, the thickness and shear-wave velocity distribution in the lithosphere-asthenosphere system are compared with heat flow values (Calcagnile, 1983) a rather good correlation is seen.

CONCLUSIONS

The geodynamic history of the Mediterranean area can be traced from the Triassic, when Africa, Europe, South and North America were grouped together in a single land mass "Pangea", and the subsequent continental break-up and rotational processes, which led to the continent-continent collision, occurred in the Eocene, responsible for squeezing out the central Tethys (e.g. Dewey et al., 1973; Illies, 1975 a,b; Panza et al., 1980 b). At this stage the subduction did not stop as required by the original formulatin of the Plate Tectonics Theory, but continued subducting the African continental lithosphere beneath the European one (e.g. Panza et al., 1980 b), giving rise to complex lithosphere-asthenosphere interactions. This interaction has been further complicated by the opening, during the orogenic phase, of small oceanic-type basins (Hsu, 1977; Hsu and Bernoulli, 1978; Panza and Calcagnile, 1979). The huge deformations occurring at the continental margins as a consequence of such a complicated tectonic pattern, must have affected the whole lithosphere-asthenosphere system around the contact zone, perturbing the elastic properties down to the asthenospheric low-velocity zone. In fact, large structural differences have been detected between the Central and Western Alps on one side, which, according to a hypothesis originally based on geological arguments (Illies, 1975 a,b), evolved more or less simultaneously with the Central European Rift System, and the Eastern Alps on the other (IESG and ETH, 1981). This difference may be interpreted as due to the result, under the eastern part of the Alpine system, of the interaction between two different stress fields. The first is the principal compressional stress field (with its present-day NNW-SSE direction), arising from the relative motion of the colliding African and Eurasian macroplates, the second is the tensional stress field, directed roughly E-W, associated with the western part of Pannonian basin. Furthermore, the recent opening of the Tyrrhenian basin is rather clearly reflected by the lithospheric thinning which characterizes the western part of the Italian peninsula and the eastern side of the Corsica-Sardinia block. The tensional geological features observed in Central Italy turn out to be also rather well correlated with the lithospheric thinning and the "very soft" lid characteristics found in that area. The continental character of the Adriatic Sea is inferred from the evidences which for this region show elastic properties rather typical for continental areas.

The lithosphere and the asthenosphere are well differentiated due to the presence of a low-velocity zone in stable continental areas, in agreement with the usual plate tectonics schemes. In the rift areas the differentiation is not clear-cut on account of a loss of lid strength, probably due to the tensional stress field characteristics of these areas and to an uprising of isotherms. Finally, in the collision areas there is a complex lithosphere-asthenosphere interaction which may lead to a disappearance of the low-velocity zone beneath the orogenic areas, e.g. the Western Alps. In these areas large deformations extend to depths much greater than the crustal thickness and may reach the lower boundary of the low-velocity zone. This is a strong hint that the subduction of continental lithosphere has taken place as a consequence of the continent-continent collision.

The presence of "lithospheric roots", which interrupt the continuity of the asthenospheric low-velocity zone, seems to characterize most of the collision belt (Suhadolc and Panza, 1987). These roots are detectable from the seismic wave velocity anomalies, while, with the exception of southern Spain, there is no intermediate or deep seismic activity as normally found along the classical Benioff zones.

Some kind of correlation seems to exist between the characteristics of the lithosphere and the seismicity and stress pattern inferred from the available fault-plane solutions (Ritsema, 1979; Panza, 1983; Gasparini et al., 1985). The main seismic activity indicates that the largest shocks tend to occur along belts, where lid rigidity values which are very close to those of stable areas are associated with very rapid changes in the lithospheric thickness, especially of its lower part (Panza, 1983). This is the case for northern and southern Italy and the Calabrian arc. On the contrary, the considered seismicity seems to be totally absent in areas, namely the Central Apennines, where a significant reduction of lid rigidity is observed. In the same area there is a rather large scatter of stress axes (Calcagnile and Scarpa, 1985). Along the Dinarides a drastic change of stresses from compressive to tensile is observed. The margins of the Corsica-Sardinia massif, which has behaved as a passive block at least since Late Miocene-Early Pliocene (Scandone, 1979), are of Atlantic passive margin type bordering the Tyrrhenian and Balearic basins. This fact might account for the lack of strong shocks in the Corsica-Sardinia area.

The structure of the upper mantle in the studied area gives a possible physical framework for understanding the occurrence in space of the main shocks. In other words, the active belts can be defined not only on the basis of historical seismic records, but also on the basis of structural properties. Following these observations, any area within these belts may be affected by a rather strong earthquake (with magnitude greater than 6.5). Conversely, according to this model, in the areas with a "soft" lid the occurrence of a shock with magnitude larger than 6.5 seems to be highly unlikely if not impossible.

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