INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
34100 TRIESTE (ITALY) - P.O.B. 586 - MIRAMARE - STRADA COSTIERA 11 - TELEPHONE: 2240-1
CABLE: CENTRATOM - TELEX 460392 - 1

H4.SMR/303 - 30

WORKSHOP
GLOBAL GEOPHYSICAL INFORMATICS WITH APPLICATIONS TO RESEARCH IN EARTHQUAKE PREDICTIONS AND REDUCTION OF SEISMIC RISK

(15 November - 16 December 1988)

LITHOSPHERIC PROPERTIES IN SEISMICITY STUDIES

Part I

G.F. PANZA[1,2] & P. SUHADOLC[1]

1. Istituto di Geodesia e Geofisica
University of Trieste, Italy

2. International School for Advanced Studies, Trieste, Italy

Con preghiera d'immediato rinvio

VISTO: SI STAMPI
(Firma Autore)......

P. SUHADOLC[a] and G.F. PANZA[a-b]

PHYSICAL PROPERTIES OF THE LITHOSPHERE-ASTHENOSPHERE SYSTEM IN EUROPE FROM GEOPHYSICAL DATA

RIASSUNTO. - Nell'area europea è possibile mettere chiaramente in evidenza variazioni laterali nello spessore del lid. Le eterogeneità laterali della velocità delle onde S nell'ambito del sistema litosfera-astenosfera sono molto pronunciate. I dati gravimetrici implicano un contrasto di densità positivo nel mantello superiore di circa 0.05 g/cm³ in corrispondenza delle radici litosferiche, che sembrano caratterizzare molte catene orogeniche. L'analisi di un profilo lungo l'asse delle Alpi sembra indicare la presenza di rilevanti variazioni laterali in densità anche nella parte litosferica del mantello. Tutti i dati geofisici mettono inoltre in evidenza una chiara differenza strutturale tra il mar Adriatico ed il bacino Ionico da una parte ed il mar Tirreno ed il Mediterraneo occidentale dall'altra. I primi hanno caratteristiche di tipo continentale, mentre i secondi hanno proprietà chiaramente associabili a bacini oceanici giovani.

ABSTRACT. - Lateral variations in the thickness of the high-velocity subcrustal layer, the "lid", are clearly evidenced in the European area. The lateral changes in the shear-wave velocities of the litosphere-astenosphere system are quite pronounced. The gravity data imply a positive density contrast in the upper mantle of the order of 0.05 g/cm³ related to almost aseismic high-velocity lithospheric roots, which seem to characterize many orogenic belts. The strong upper-mantle lateral variations are evidenced by considering profiles. The analysis of a profile along the axis of the Alps seems to indicate that relevant lateral variations in density are also present in the lithospheric part of the mantle. All the geophysical fields considered evidence a clear structural difference between the Adriatic Sea-Ionian Sea basin on one side and the Tyrrhenian Sea-Western Mediterranean basin on the other. The former displays continental-type characteristics, while the latter shows features definitely related to young ocean basins.

KEY WORDS - Crust, lithosphere, asthenosphere, heat flow, free-air anomalies, Europe.

The present structural setting beneath the Neo-European area may be considered as the result of a sequence of geodynamic events taking place in a time span ranging from the Triassic (about 200 Ma ago) to the present: from the continental rifting and break-up of Pangea, through the plate divergence and ocean-floor spreading in the Tethyan realm, the subsequent plate convergence and continent-continent collision, to the progressive consumption, still in progress today, of the original European and African continental margins.

This Africa-Europe interaction may be described, according to plate tectonics theory, as a kinematic system dominated by the Atlantic Ocean spreading (Smith, 1971). Presently, the African plate undergoes gradual counterclockwise rotation due to the higher spreading rate of the ocean floor in the South Atlantic (~40 mm per year) as compared with the Central Atlantic (~30 mm per year). This rotation results in a roughly northward directed push, which is met by a northwest-southeastward oriented spreading in the North Atlantic (~20 mm per year). This leads to a large compression, causing a lithospheric shortening in the Mediterranean - Alpine belt of about 5 to 10 mm per year.

The effects of this collision are not confined to the crustal layers, but seem to involve also the upper mantle. Examples are found in the presence of lithospheric roots in the Alps (Panza and Mueller, 1979; Babuška *et al.*, 1985), the thinning of the lithosphere in the Rhine Graben area (Panza *et al.*, 1980a) and the thickening of the lithosphere in the Alpine area and south of it, including almost all of the Po Valley (Calcagnile and Panza, 1981).

THE CRUST-MANTLE BOUNDARY

It is well-known that the crust is thickened under stable shields and orogenic belts and thinned under ocean and extensional basins. These characteristics are pretty well reproduced in Fig.1. Under the Scandinavian shield and NE Europe the crust is thick and it is even thicker under the youngest orogenic belts: Alps, Dinarides, Hellenides and part of Pyrenees. A thin belt of thickened crust is found also under the Calabrian arc and to the north of it. On the other hand the crust is of oceanic type in the Western Mediterranean and the Tyrrhenian Sea, which can be classified among young basins also because of the average elastic properties of their lithosphere (Panza and Calcagnile, 1979). The crust is found to be thin along the Rhine Graben and this thinning seems to continue along the Central and Viking Grabens in the North Sea. A thin crust is also found in central France, in the North-Central Apennines, in the Pannonian basin, in the Aegean back-arc basin associated with the Hellenic subduction and under Iceland. The crustal thickness of this island, located at the intersection of two major structures, i.e. the Mid-Atlantic Ridge (the diverging plate boundary between the European and American plates) and the Greenland-Faeroes Ridge (thought to be the trail of the Iceland hot spot, presently located below east-central Iceland) is not well-known. Seismic studies indicate that it resembles the oceanic crust, but is twice as thick (Pálmason, 1971; Angenheister *et al.*, 1980; Gebrande *et al.*, 1980). The crust is underlain by a diapirically updoming asthenosphere. At this direct contact between the crust and the asthenosphere, at a depth not exceeding 30 km, there is a partially molten basaltic layer a few kilometers thick (Björnsson, 1985).

The information about the crustal thickness (Fig. 1) is in general derived from the interpretation of the arrival times of P-wave phases in Deep Seismic Sounding (DSS) experiments. For a better understanding of the geodynamic processes involved in the formation of the present-day crustal structure the use of the information contained in P-wave amplitudes (Deichman *et al.*, 1986) is gaining increasing relevance,

(a) Institute of Geodesy and Geophysics - University of Trieste - 34100 TRIESTE (Italy).
(b) International School for Advanced Studies, Miramar - 34100 TRIESTE (Italy).

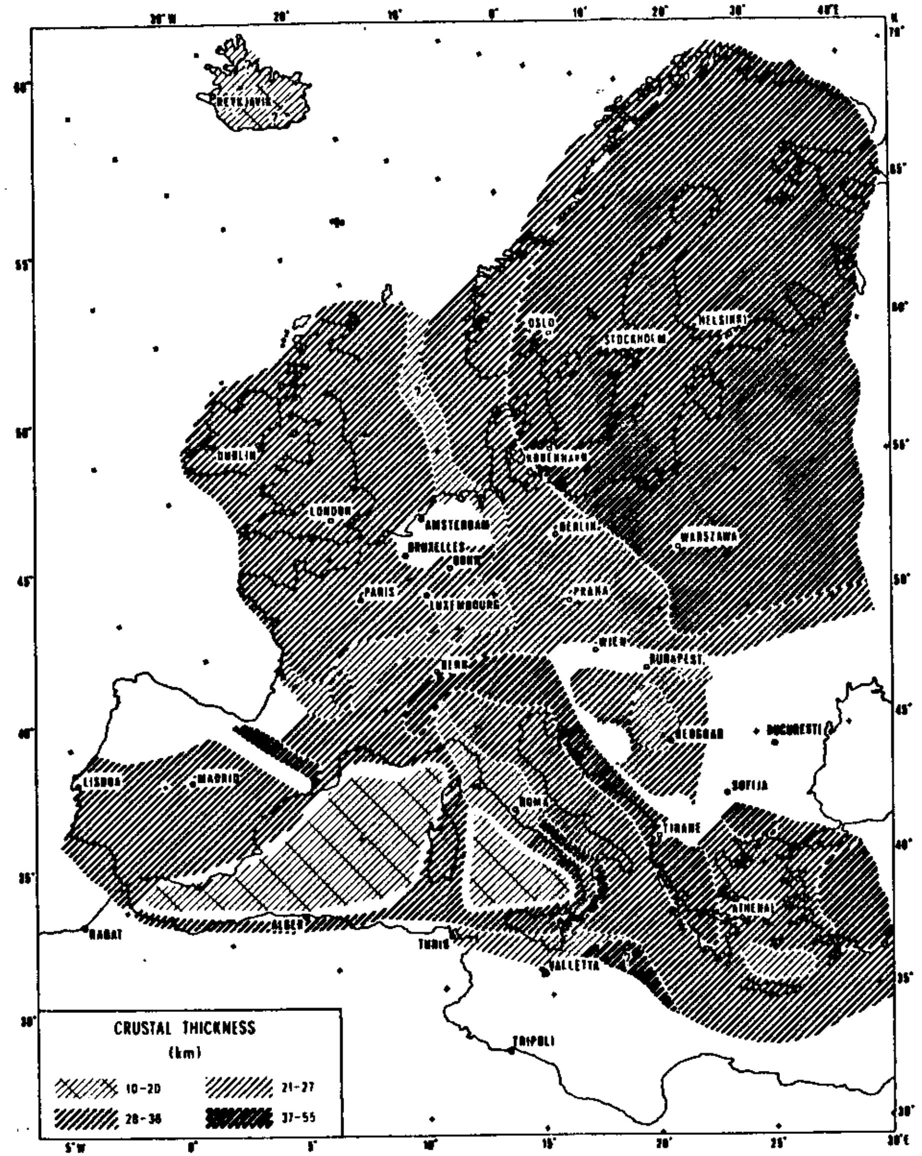

Fig. 1. - Map of the crustal thickness in the European area. For most of the area the depth of the Mohorovičić discontinuity has been compiled on the basis of the interpretation of DSS experiments (Makris, 1978; Mostaanpour, 1984; Ribarič, 1986); in some parts (North Sea and Ionian Sea) it is the result of the analysis of Lg-waves propagation and surface-wave dispersion measurements (Kennett *et al.*, 1986; Panza *et al.*, 1980b; Calcagnile *et al.*, 1982).

mainly because it permits a more accurate definition of the size and entity of crustal low-velocity layers, which seem to play a determinant role in geodynamic processes (Mueller, 1977; Panza *et al.*, 1980b). In this frame, the definition of the distribution versus depth of S-wave velocity has even greater relevance, therefore it is worth mentioning a very promising new methodology (Marson *et al.*, 1987), which uses complete synthetic DSS profiles (see Fig. 2) to determine the possible kinematic and dynamic effects of crustal low-velocity channels for S-waves in standard DSS sections. From a systematic application of this approach we expect a drastic reduction of the ambiguity which at present characterizes the definition of crustal low-velocity layers both for P- and S-waves.

THE LITHOSPHERE-ASTHENOSPHERE SYSTEM

It has been widely acknowledged (e.g. Panza *et al.*, 1980a; Hovland *et al.*, 1981; Aki, 1982) that lateral heterogeneities 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 local crustal variations, the large geodynamic processes that led to the present-day structural setting.

The most powerful geophysical tool for determining the elastic properties of the lithosphere-asthenosphere system is still represented by the measurement of the dispersion of surface waves (e.g. Panza, 1976). In the last twenty years, a considerable amount of measurements has been carried out within the framework of a large international project. The combination of the dispersion measurements with the results of DSS experiments has permitted, through a systematic inversion of the data, to infer the main features of the lithosphere-asthenosphere system (e.g. Panza *et al.*, 1980a).

A map of the elastic properties of the lithosphere-asthenosphere system in Europe, drawn on the basis of a huge number of inversions of surface-wave phase and group velocities, is shown in Fig. 3. For more details about the meaning and limitations of such a representation see Panza (1984). Here we simply recall that the lithosphere is formed by the crust and by the high-velocity subcrustal layer called "lid", while the asthenosphere is the layer just below it.

From a comparison between Fig.1 and Fig.3 one can see that a thick (thin) crust does not always correspond to a thick (thin) lithosphere.

A "normal" lid, with thickness not exceeding about 75 km and shear velocities equal to or greater than 4.50 km/s, corresponds to platforms and massifs and must be considered to represent the "undisturbed" upper mantle structure in large parts of Europe and in general in stable continental areas (Knopoff, 1972). Practically the entire Iberian peninsula, western and northern France, Britain and Ireland, Belgium, Denmark, southern Sweden, northern and central Germany, Czechoslovakia,

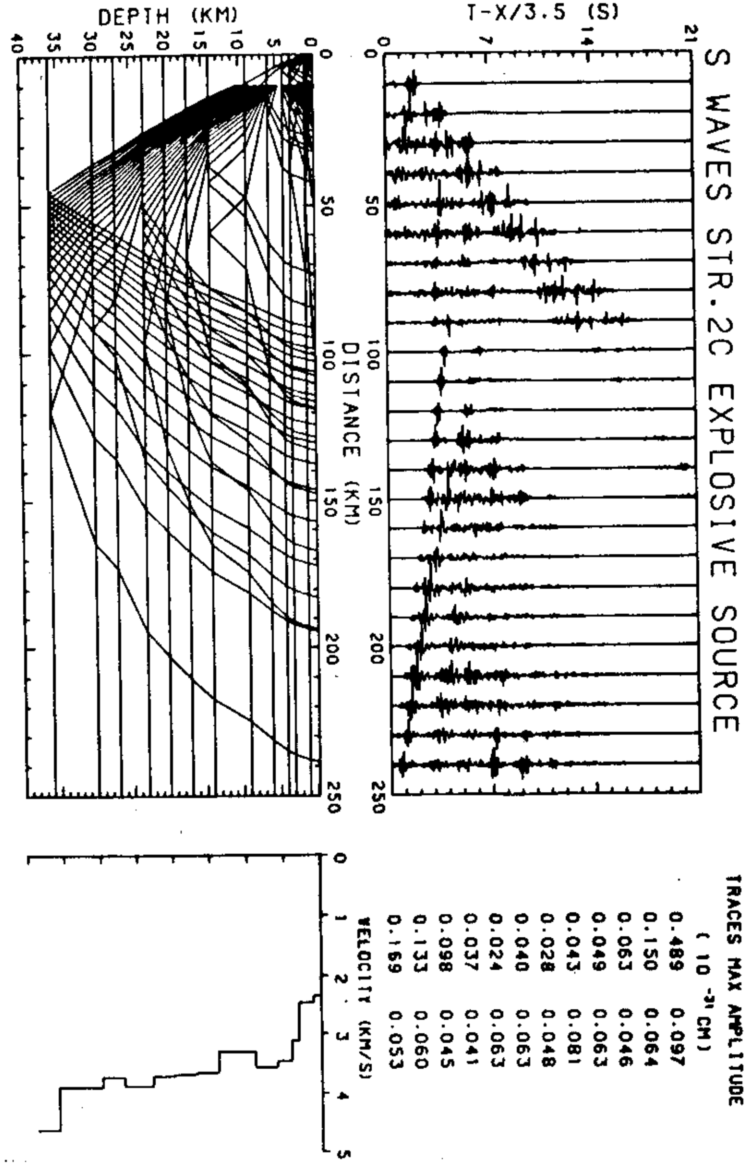

Fig. 2. – Synthetic seismic section obtained with the multimode approach (Panza, 1985; Marson *et al.*, 1987) and the ray-tracing diagram for the crustal model shown in the lower right-hand corner. The numbers in the upper right-hand corner are the maximum amplitudes of the traces in the section, which are arbitrarily normalized for drawing purposes.

Poland, the northern Adriatic Sea, the eastern part of the Italian peninsula as well as the Corsica-Sardinia block fall within this category.

A considerable thinning of the lid (thickness not exceeding 15 km) is observed as one approaches the Central European Rift system, which extends from the North Sea through the Netherlands into the Lower Rhine Embayment. It then cuts through the eastern part of the Rhenish massif, follows the Upper Rhine Graben, passes under the Franco-Swiss Jura mountains into the Molasse basin of western Switzerland, traverses the French Prealps and finally merges with the Rhône depression further south. 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 4.2 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 active areas, such as the French Massif Central, the Greece-Aegean Sea area and the Central-Eastern Alps. Recent tomographic studies (Babuška *et al.*, 1985) indicate for the lid a possible maximum thickness of about 120 km in the Alpine area (see Fig. 4). An interesting feature is to be observed in the Adriatic Sea,

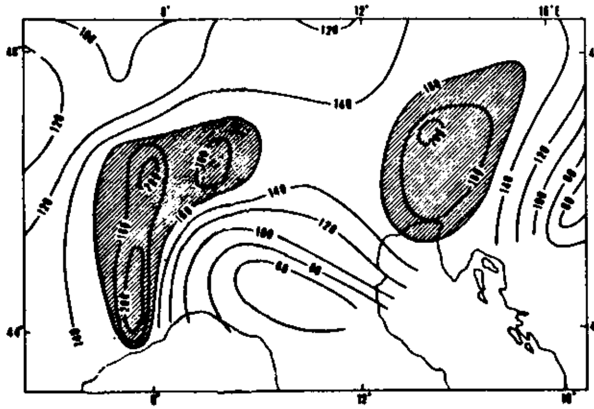

Fig. 4. – Lithospheric roots (shaded areas) as evidenced by P-wave tomography (after Babuška *et al.*, 1985). The continuous lines indicate the lithospheric thickness in km.

where the southern part seems to have a thicker lithosphere than the northern part. An even thicker "lid", up to around 135 km, is found under Fennoscandia (Calcagnile, 1982), with almost no shear-wave velocity contrast with the underlying layer, implying the absence of a clear asthenospheric low-velocity layer. The entity comprising these high-velocity materials, reaching depths down to 400 km under stable cratons, and the overlying lithosphere, has been called "tectosphere" by Jordan

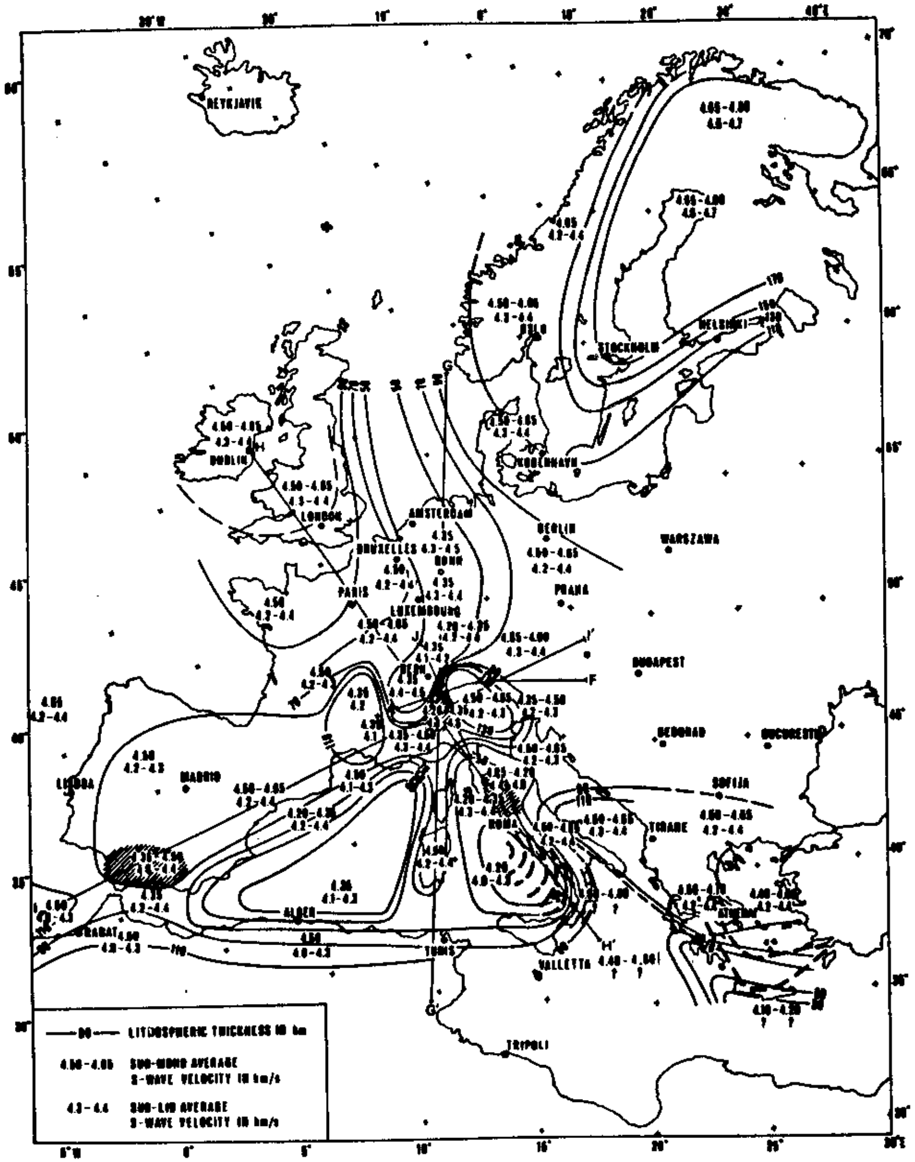

Fig. 3. – Map of the lithospheric thickness (in km) in the European region, deduced from the regional dispersion of seismic surface waves (after Mueller and Panza, 1984). Representative shear-wave velocities are given for the lower lithosphere or lid (row of upper numbers) and for the upper asthenosphere (row of lower numbers). The three shaded areas indicate the presence of "lithospheric roots" to depths of about 200 km, while the thick dashed lines define the space distribution of intermediate and deep-focus earthquakes in the Tyrrhenian Sea and the Aegean Sea. Five segments are indicated in the figure, along which the cross sections of Figs. 7, 8, 9, and 10 are computed.

(1975). The tectosphere is defined on the basis of its kinematical behavior, since the lithospheric and sublithospheric portion of the continental plates move around as a single entity. On the other hand the lithosphere and asthenosphere are defined on the basis of their dynamical behavior, that is how they react to applied forces. Under the oceans the tectosphere and lithosphere can be considered as coincident, while under the continents, as is the case of Fennoscandia, the tectosphere may reach depths well below the lithospheric ones.

In correspondence to the three shaded areas in Fig. 3, the value of the velocities below about 70 km of depth can be as high as 4.6 km/s. These high velocities at such depths denote the presence of deep-seated lithospheric roots, which seem to be almost vertical and to interrupt the asthenospheric low-velocity layer regions corresponding to the Cordillera Betica, the Western Alps and the Central Apennines. These roots do not seem to give rise to any seismic activity, with the exception of the two deep events, which occurred in southern Spain (Chung and Kanamori, 1976). Brittle material embedded in the low-velocity asthenospheric layer is present beneath of the Tyrrhenian and Aegean Seas. In these areas the thick dashed lines indicate schematically the space distribution of intermediate and deep focus earthquakes (Caputo *et al.*, 1970, 1972; Papazachos and Comninakis, 1977; Ritsema, 1979; Gasparini *et al.*, 1982; Malinverno and Ryan, 1986). The asthenospheric low-velocity layer is otherwise a common feature to stable Europe and North Africa, with the exception, as we have seen, of the Baltic shield, characterized by velocities so high to exclude the presence a of significant amount of partial melting in the whole upper mantle.

The areas with a thinned lithosphere are, in general, associated with anomalously low velocities just below the Moho, as in the Central European Rift system. However, low sub-Moho velocities also overlie the lithospheric roots under the Alps and Apennines. This might imply that the Central and Western Alps have evolved more or less simultaneously with the Central Europe rift system in accord with a hypothesis originally based on geological arguments (Illies, 1975; 1975b).

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.

The heat flow

A simplified schematic map of the heat flow in Europe, drawn from the map by Čermak and Hurtig (1979), is shown in Fig. 5.

Most of Central and Western Europe is subject to normal or high heat flow, the regions with higher values being Central and Eastern France, northern Switzerland, the Pannonian Basin, the Aegean Sea, and the Tyrrhenian and Western Mediterranean Seas with the Cordillera Betica range.

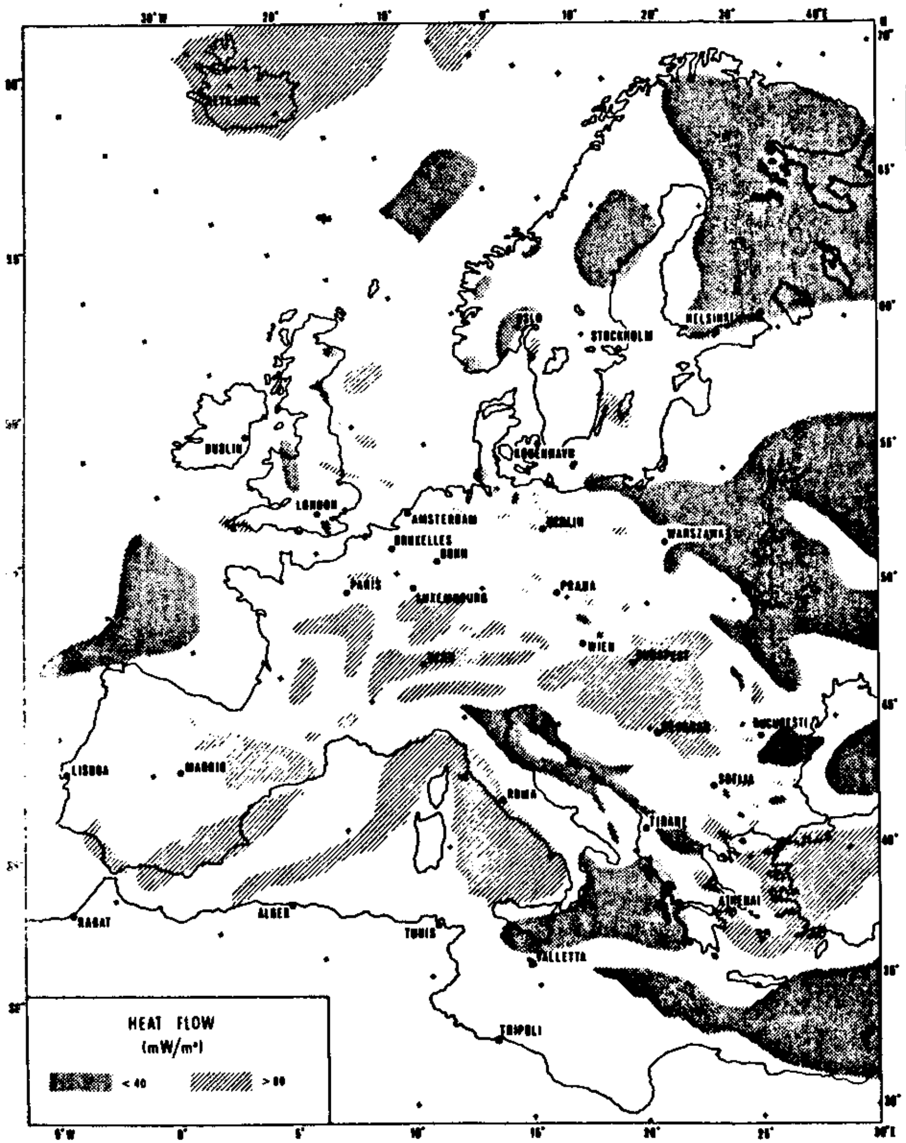

Fig. 5. - Schematic map of the heat flow in Europe (after Čermak and Hurtig, 1979). Only the areas with a heat flow exceeding 80 mW/m² and less than 40 mW/m² are shown.

Low heat flow regions occur, on the other hand, mainly in the Baltic shield, NE Europe and in the Ionian, Adriatic and Eastern Mediterranean Seas. A region of low heat flow is also found in the Atlantic Ocean, to the W of France, in correspondence of the old Cretaceus oceanic lithosphere. The most interesting feature, however, is the cold Adriatic promontory, which seems to be linked with the cold, stable African plate through the Ionian Sea.

It can be noted that at large the heat flow pattern is much more in accord with the elastic properties of the "lid" (Fig. 3) than with those of the crust (Fig. 1). High heat flow, in fact, occurs in those regions, where the product of the S-wave velocity in the "lid" and the "lid" thickness is small: where this product has large values, like in NE Europe, the heat flow is low. Small-wavelength heat flow variations on the other hand have probably a more local, crustal origin.

Free-air anomalies

Gravity field variations as reflected in the free-air and Bouguer anomalies and in the variations in the geoid level contain valuable information on lithospheric and deeper structures and related dynamic processes. The free-air anomalies mainly delineate the significant differences in the structural properties of the different basins forming the Mediterranean Sea.

Fig.6 shows the free-air anomalies schematically drawn for what concerns the sea part, according to the data published by Bowin *et al.* (1981). The main feature on this map is the big negative anomaly found along the Hellenic arc, which correlates nicely with a rather narrow but deep minimum of the geoid (Nasa, 1977). To the north of Crete there is, on the other hand, a wide zone of highly positive anomalies, which could be associated with an upswelling of the mantle in the back-arc Aegean basin as indicated by the rising of the Moho (Fig. 1).

The big negative anomaly along the Hellenic arc, which could be associated with the thick sedimentary cover forming the Mediterranean Ridge, is interrupted, south of Crete, where surface-wave dispersion data indicate a rapid rise of asthenospheric material.

Another striking interruption of a negative anomaly area is seen in the Central Adriatic Sea in correspondence, this time, of the maximum lithospheric gradient (see Fig. 3).

Highly negative anomalies, even though of rather small extent, are also encountered in the Gibraltar area and in the Atlantic Ocean to the west of France in correspondence to the Biscay trough, which we have seen is also a region of low heat flow.

The main feature of Fig. 6 is anyway the clear contrast between the Eastern Mediterranean, the Ionian and Adriatic Sea regions on one part, and the Tyrrhenian Sea and Western Mediterranean region on the other. In the former, mainly negative anomalies are present, while in the latter positive anomalies prevail. These features

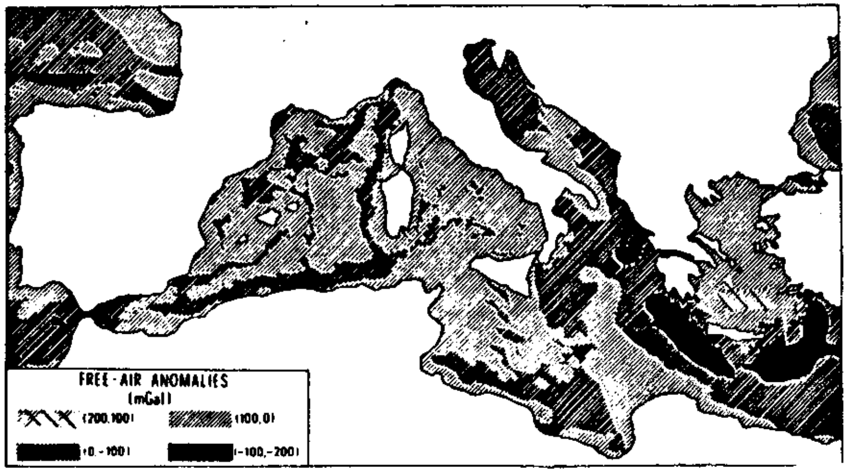

Fig. 6. - Schematic map of the free-air anomalies in the Mediterranean area (after Bowin *et al.*, 1981). The data are grouped into four ranges, as shown in the inset.

can be reconduced to the fact that the eastern area has a continental or continental margin character with an older environment, a thicker lithosphere and sedimentary cover, while the western area is an oceanic zone, where the environment is younger, with a thinner lithosphere and lower sedimentation. This pattern is a further element in favour of our previous conclusions, based on heat flow and lithospheric thicknesses, about the differences between the Eastern and Western Mediterranean.

Regional features

Some of the features outlined in the previous chapters are worth to be discussed together and in more detail, taking into consideration also recent results of tomographic studies (Babuška *et al.*, 1985; Spakman, 1986a).

The Adriatic and Ionian Seas

In ~~correspondence of~~ these basins the lithosphere is quite thick, about 90 km or more and the average crustal thickness largely exceeds oceanic values (Calcagnile *et al.*, 1982). The concept of Adria as an African promontory has, in fact, gained further recognition in the last years (Channell *et al.*, 1979), although there still exist a wide spectrum of ideas as to its original shape and the period during which it was connected to the African plate. The link between the Adriatic microplate and Africa passes through the Ionian Sea, where the lithosphere is of continental or continental-margin type (Cloetingh *et al.*, 1979; Farrugia and Panza, 1981; Calcagnile *et al.*, 1982). The continuity in the average elastic properties in the lid under the Adriatic and Ionian Seas supports the concept above, but at the same time constitutes a major challenge to relate it to the present bathymetry and the history of Ionian Sea subsidence. The northernmost extension of the Adriatic promontory is still doubtful, but a significant thinning of the lithosphere can be observed in correspondence of the North-Central Adriatic Sea, north of the line Ortona-Roccamonfina, which seems to be the main line of displacement between the Northern and Southern Apennines (Locardi, 1984). This thinning of the lithosphere can be very reasonably associated with the tensional deformations of Adria after the continental collision (e.g. D'Argenio and Horvath, 1984).

The heat flow in this region is almost everywhere low to normal and the free-air anomalies are mainly negative, as should be expected if the idea of the cold Adriatic promontory being related to the African platform is accepted.

The Aegean Sea and Greece

In these two areas, most of the lithosphere is found to be thick with high sub-Moho velocities on land. In ~~correspondence of~~ the Aegean Sea the sub-Moho velocities are, on the other hand, significantly smaller and this is in accord with the higher heat flow in the region. A strong gradient in the lithospheric thickness is present in the area between the Central Aegean and Crete Island. From north to south the lithosphere gets very thin, characterized by very low velocities. The thick dashed lines in fig. 3 represent the space distribution of intermediate focus earthquakes witnessing the ongoing subduction process (e.g. Papazachos and Comninakis, 1977). Spakman (1986a) proposes, from a tomographic inversion of teleseismic P-wave delays, that the subduction slab beneath Greece, the Aegean Sea and Turkey reaches depths of at least 600 km, and that its deeper part seems to be detached from the upper one at depths between 150 and 250 km.

The high heat flow values and the positive free-air anomalies, with a pronounced peak north of Crete, strongly support the idea of a back-arc basin and of an upwelling asthenosphere.

The French Massif Central

A relative maximum lithospheric thickness, associated with quite low upper-mantle velocities, is observed in this area. Such a feature cannot be easily explained within the known tectonic setting, however its presence might be due to the interaction between the Central European Rift system formation and the Alpine tectonics. The area also has a relatively high heat flow, especielly along its boundaries. This lithospheric thickening could be related to the deformations due to the early Alpine orogenetic processes in the Western Mediterranean.

The North-Central Apennines

This zone is characterized by a high heat flow, thin lithosphere and sub-Moho material with extremely low velocities overlying deeper mantle material with much higher velocities, greater than about 4.40 km/s. This situation may be considered as due to a post-collisional mantle diapir with an associated upwelling of the asthenospheric layer (Locardi, 1986), in which cold lithospheric roots are present (Panza *et al.*, 1980b) *probably remnants of the Alpine collision process. The minimum compressional stresses observed normal to the longitudinal axis of the Central Apennines, well in agreement with Neogenic and Quaternary magmatism, indicate that tensional processes in this area have at intervals layed a relevant role, in the internal areas, after the collision. Peculiarities in the upper mantle of this region extending to even greater depths, which caused a rise, of about 100 km, in the 400 km discontinuity, were detected by Scalera et al.* (1981). This rise of the "400 km" discontinuity seems, however, to be a feature common to most of the European area. A normal location of the "400 km" discontinuity can be found in ~~correspondence of~~ the Baltic shield (Calcagnile and Panza, 1978) and in ~~correspondence of~~ the Mediterranean basins (Mayer-Rosa and Mueller, 1973) and south of them (Mseddi, 1976).

The Tyrrhenian Sea

The Tyrrhenian Sea and the Western Mediterranean are believed to be small post-collisional oceanic basins. They are characterized by thin and young oceanic lithosphere (Hsü, 1977; Panza and Calcagnile, 1979; Sartori, this vol.). The heat flow in this area is among the highest measured in Europe and the free-air anomalies are generally very high. This is in accord with the hypothesis of an ocean opening and thinning of the lithosphere.

In the Tyrrhenian the presence of a cold and "brittle" body is evidenced by the occurrence of intermediate and deep focus earthquakes (e.g. Calcagnile *et al.*, 1981). This situation cannot anyway be reconciled with that of a classical Benioff zone, since no great shallow earthquakes are present at the surface projection of the Benioff zone. This deep-reaching body is also strongly deformed, having a concave shape (Caputo *et al.*, 1972; Gasparini *et al.*, 1982). Anderson (1985) has recently proposed that the intermediate and deep-focus earthquakes are related to the large-scale disruption of a slab probably a remnant of the early-Alpine convergent plate margin, which is no more in active subduction.

The Alps

The lithospheric root in the Western Alps and the thickened lithosphere in the Central Alps have been recognized by many authors (Panza and Mueller, 1979; Baer, 1980). Lately, Babuška *et al.* (1985), on the basis of teleseismic P-wave delays, confirmed the root under the Western Alps and proposed that a similar body also exists under the Eastern Alps (Fig. 4). Moreover Babuška *et al.* (1984) had also detected a lithospheric root in the East Carpathians, probably being the remnant of a paleosubduction. A detailed discussion of these features will be made in connection with the description of some lithospheric profiles; for further references see Mueller and Panza (1986).

A high-velocity root under the Western Alps, up to a depth of about 170 km, is detected also by Spakman (1986b) who carried out a tomographic inversion of teleseismic P-wave delays. According to him, however, the deeper structure of the Alps shows the collision of two high-velocity slabs, the northern one of which slightly underthrusts its southern couterpart. Spakman (1986c) detects at depths below 250 to 300 km a zone of high P-wave velocities with the same outline as the Alpine orogenic belt at the surface. This zone, he proposes, represents parts of the subducted Mesozoic Tethys.

The high-to-normal values of the heat flow in this area seem to originate mainly from crustal sources, the mantle contribution being very small due to the presence of a thick lithosphere and the cold lithospheric roots.

Lithospheric profiles

From all the geophysical fields considered so far, strong lateral variations have been evidenced in the European area. In order to have a closer look at these inhomogeneities, they have been investigated along several profiles.

Let us consider Fig. 7 and Fig. 8, where the three vertical cross sections along the profiles GG', HH' and II', indicated in Fig. 3 are represented. The vertical hatchings in Fig. 7 represent the uncertainties in the determination of the maximum lithospheric thickness (about 30 km) and of the upper-to-lower asthenosphere boundary (about 70 km) as derived from surface-wave analysis.

The first profile GG' runs in a north-south direction. From point G, located on the rim of the Baltic shield, the thick lithosphere (Fig. 7) is gradually thinning southward toward the Rhine Graben, where the thickness is reduced to about 50 km. The sub-Moho S-wave velocities slow down to the 4.20-4.35 km/s range. The asthenospheric shear-wave velocities, on the other hand, do not show significant changes until the southern part of the Rhine Graben is reached, where they drop significantly denoting the presence higher heat (A maximum heat flow of about 110 mW/m^2 is found in the area. The asthenosphere is interrupted beneath the Alpine foreland and the Alps by a zone of high velocities, possibly characterizing a cold body, which has been interpreted as lithospheric roots (Panza and Muller, 1979). Above these roots the sub-Moho S-wave velocities continue to be in the 4.20-4.35 km/s range, as in the Central European Rift system. Towards the south, the asthenospheric velocities, the lithospheric thicknesses, and the sub-Moho S-wave velocities regain typical values for continental areas (Panza, 1980). Under Northern Tunisia, the lithosphere begins to thicken and the upper-to-lower asthenosphere boundary seems to rise. The corresponding heat flow in Fig. 8 shows normal values until the southern part of the Rhine Graben is reached, where a peak in the heat flow curve is observed. In ~~correspondence of~~ the Alps the heat flow decreases but the minimum values are still above 60 mW/m^2. It becomes low in ~~correspondence of~~ the Western Alpine lithospheric root and the sedimentary Po Plain, but it rises

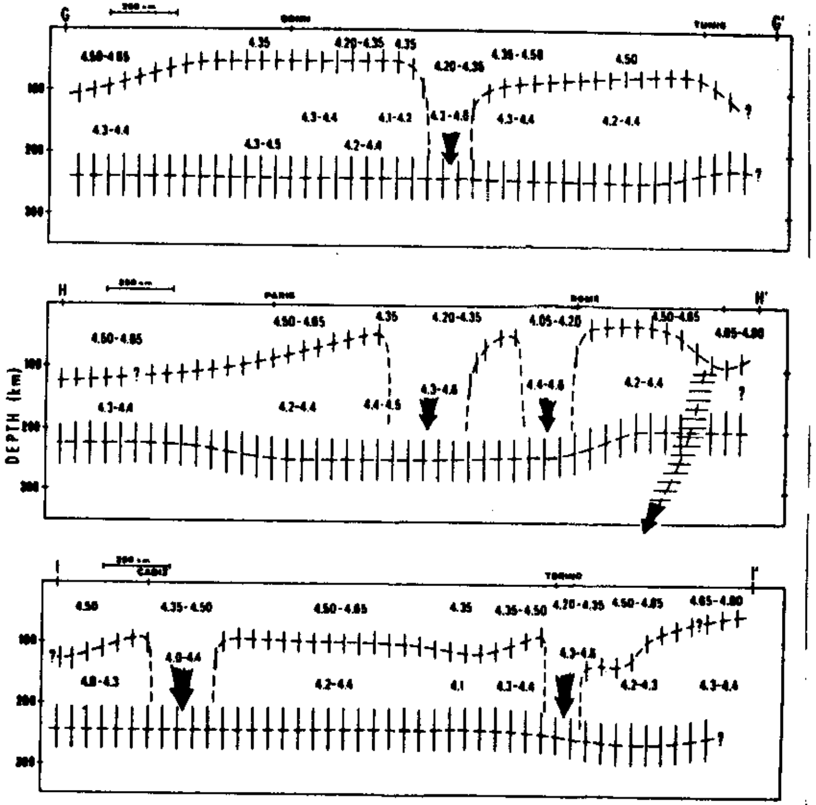

Fig. 7. - Cross sections through the lithosphere-asthenosphere system along the three profiles GG' HH' and II' of Fig. 3. The hatchings denote the uncertainties connected with the determination of the lithosphere to upper asthenosphere and the upper to lower asthenosphere boundaries. The arrows indicate the lithospheric roots and (in conjunction with a horizontal hatching) the presence of intermediate and deep-focus earthquakes in the Tyrrhenian Sea. The numbers are the permissible values for the shear-wave velocity in the corresponding area.

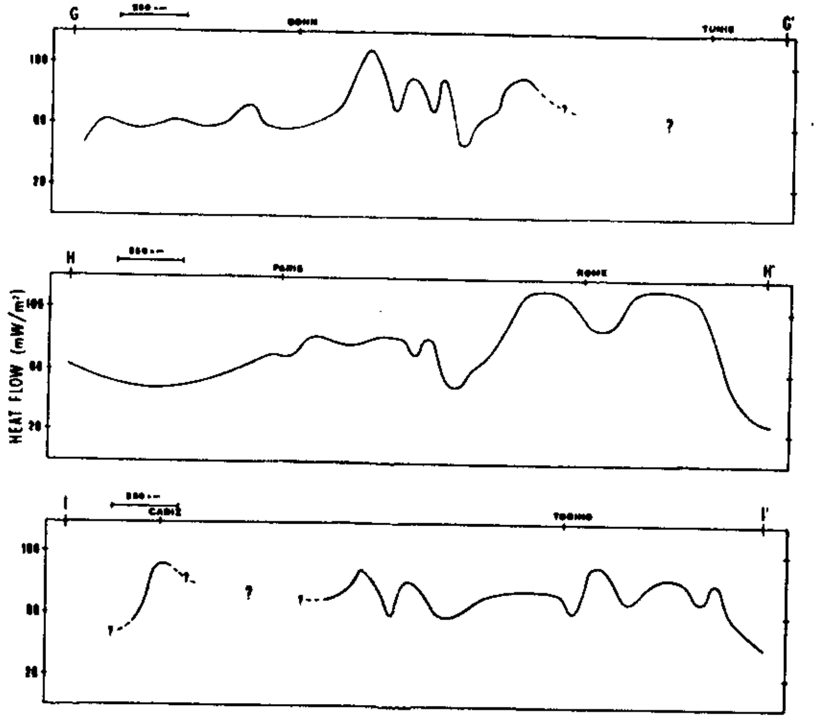

Fig. 8. - Heat flow in correspondence of the three profiles GG' HH' and II' of Fig. 3. [related to]

again in the area of the Ligurian Sea. The heat flow data available for the southern portion of the profile (Lucazeau *et al.*, 1985; Lucazeau and Mailhe, 1986) do not allow to draw a continuous curve. The heat flow Sardinia oscillates from 50 to over 100 mW/m² and high values (between 100 amd 110 mW/m²) are observed between in Sardinia and Tunisia (Della Vedova, personal communication). No heat flow data are available in Tunisia, but estimates based on thermal gradient data (Ben Dhia, 1986) indicate a decrease from 100 mW/m² in the north to about 60 mW/m² in the south of Tunisia.

The second section HH' begins in Ireland and reaches the Calabrian Arc. The lithosphere gradually thins in passing from on old stable cratonized Mesoeurope, the British Isles, through France, where it is "normal" for continental areas, till it reaches its minimum thickness under the Southern Rhine Graben. After this minimum the lithosphere plunges into the root system under the Alps. Here the transient region to the lithospheric root seems to be more gradual than in the section GG'. This broad root is followed, after a small thinned lithospheric tract in the Northern Apennines, by another lithospheric root under the North-Central Apennines. The astonishing contrast between the "hot", extremely low sub-Moho velocities and the "cold", very high velocities in the roots region is to be noted. More to the south, near of the Tyrrhenian Sea, the lithospheric thickness reaches a maximum of about 30 km. Under the Calabrian Arc, the lithosphere gets thicker in connection with the orogenic mountain belt and the sub-Moho velocities are quite high. The presence of a cold and seismogenetic body in the upper mantle under the Tyrrhenian Sea is schematically indicated by horizontal hatching. Note also that, in the area ~~corresponding~~ to the two lithospheric roots, the upper-to-lower asthenosphere boundary seems to be significantly deeper. The heat flow (Fig. 8), low to normal under Great Britain, starts to increase in passing through France and approaching the Central European Rift system. It has a local minimum in correspondence of the Western Alpine lithospheric root, but becomes very high in the Ligurian Sea area. It stays then high, except for a local low found when the profile passes through the lithospheric root to the north of Rome, up to the Calabrian Arc and the Ionian Sea where it dips to very low values. In this profile it is possible to distinguish (1) a long-wavelength component with its maximum located near Rome originating in the deep mantle, (2) local minima, that can be correlated with the presence of lithospheric roots, and (3) a local maximum, that can be correlated with the Tyrrhenian volcanic environment.

The last profile, II, running from SW to NE, shows (Fig. 7) the lithospheric root connected to the Cordillera Betica Range. The contrast with the surrounding S-wave asthenospheric velocities is, however, smaller than in the previous cases, the same being true for the sub-Moho shear-wave velocities. This migh perhaps indicate a different stage of evolution of these roots in comparison with those under the Alps and in the North-Central Apennines. Moving northeastward a "normal" lithosphere-asthenosphere system is visible, interrupted only by the "anomalous" French Massif Central region, until the Alpine lithospheric root is reached. In the Central Massif

region the shear-wave velocities below the Moho as well as in the upper asthenosphere are lower than in the surrounding areas, implying perhaps a warm upper mantle environment. In the east-west direction, the Alpine root is very asymmetrical, with a big bulge to the east. This Alpine section is very interesting and will now be discussed in more detail also taking gravity data and P-wave tomography into consideration. The heat flow along the profile II (Fig. 8) has a very broad long-wavelength component characterized by higher than average values. Superimposed on it, there are local oscillations which can be correlated with the Pyrenees and the Alpine chain.

Lithospheric roots in the Alpine area

A summary of the seismic and gravimetric information available on the Central Alps provides a unique data set, which permits a rather detailed modelling of the lithospheric structure from Konstanz to Carrara (Schwendener, 1984; Schwendener and Mueller, 1985; Mueller and Panza, 1986), along the profile JJ in Fig. 3.

The Bouguer anomalies along this profile are shown in Fig. 9a. In a first step, these anomalies were reduced with three-dimensional models for all known near-surface density anomalies, such as the sediments of the northern Molasse Basin, the Quaterny sediments of the Alpine valleys and the sediments of the Po Plain. A three-dimensional model of a simplified three-layer crust and the underlying upper mantle was then constructed, on the basis of seismic reflection and refraction data, borehole logs and geoelectric soundings (Fig. 9d). The data suggest the existence of bodies with negative density contrast in the middle crust, beneath the northern margin of the Alps and near the surface in the Northern Apennines. In order to find a realistic density distribution a least-squares inversion technique was applied to this crust-mantle model and the reduced Bouguer anomalies.

As a result of this "stripping" procedure (Schwendener, 1984; Schwendener and Mueller, 1985), a smooth positive residual gravity anomaly of about 500 km in width has been obtained with a maximum amplitude close to +100 mGal situated in the region of the Southern Alps (Fig. 9b). Since high-quality seismic data do not support the presence of anomalously low intracrustal densities as a source for this anomaly, the source has to be sought in the upper mantle. As we have seen, the upper-mantle origin of this anomaly agrees with seismic surface-wave studies (Panza *et al.*, 1980a) and travel time investigations (Baer, 1980; Babuška *et al.*, 1985). The shape of the anomalous body was chosen according to temperature anomalies (maximum decrease of -400 to -500 °C compared to the ambient temperature) calculated with models of the Alpine orogeny (Kissling *et al.*, 1983; Werner and Kissling, 1985). A least-squares inversion to determine the density of this anomolous body results in a positive density contrast of about 0.05 g/cm³. A nearly perfect fit is obtained for the Bouguer anomalies and the anomalies calculated from the crust-mantle model (see Fig. 9c). The density contrast found is too large to be explained solely by ther-

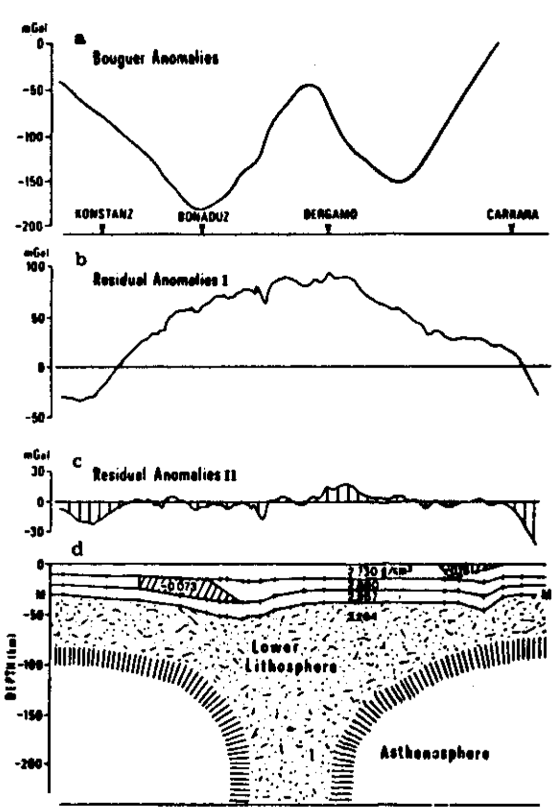

Fig. 9. – Interpretation of a gravimetric crust-mantle profile (JJ in Fig. 3) from the northern foreland of the Alps to the Ligurian Sea (after Schwendener, 1984; Schwendener and Mueller, 1985): (a) Bouguer anomalies along the profile. (b) Pronounced positive residual gravity anomalies obtained after the mass effect of a three-dimensional crustal model (see cross section in part d) has been subtracted from the Bouger anomalies. (c) Residual gravity anomalies after subtraction of the mass effect caused by the crust and the "lithospheric root" in the upper mantle. (d) Simplified model of the three-layered crust and the anomalous "block" in the upper mantle with the densities obtained by inversion. Local anomalous masses in the middle crust under the northern margin of the Alps and in the upper crust of the Northern Apennines with their respective negative density contrasts are indicated by shading.

mal contraction due to the negative thermal anomaly (Mueller and Panza, 1986). The presence of high-density (and associated high-velocity) material must, therefore, be ascribed to a lithospheric root which has penetrated into the asthenosphere beneath the southern Alps (Fig. 9d), as suggested by Panza and Mueller (1979).

From this model it is possible to infer that the lithospheric root has a rigidity which is more than 10% larger than that of the surrounding asthenosphere and about 10% smaller than that of the standard continental lithosphere. Analogous variations can be deduced also for Poisson's ratio and Young's modulus. These variations in the mechanical properties of rocks passing from the unperturbed asthenosphere to the lithosphere root region may be responsible (Ebblin *et al.*, 1982) of an uplift in correspondence of the root of the order of 500 m, assuming a confining horizontal tectonic stress of about 1 kbar. In this respect surfaced we consider worthwhile to mention the work by Arca and Beretta (1985) summarizing the vertical ground movements in Northern Italy. Their results suggest a tilting of the whole Po Valley with an uplift of the western part and a subsidence of the eastern part. The presence of the lithospheric root may contribute to this phenomenon.

Let us now consider the east-west Alpine profile (ALP 75) from Aix-les-Bains in France to the Pannonian Basin in Hungary (profile AF in Fig. 3) The Mohorovičić discontinuity, indicated with M in Fig. 10c, reaches a depth of about 50 km below the Central Alps and rises, towards the Rhône Graben in the west, and towards the Pannonian Basin in the east. Long-range seismic refraction measurements in the northern Alpine foreland and along the strike of the Alps (Miller *et al.*, 1982) revealed the existence of a layer with a P-wave velocity of up to 8.6 km/s in the uppermost mantle extending to depths of approximately 100 km. No such structure is detected in the eastern and western margins, where a distinct layering has been found in the upper mantle (the P-wave velocities being in brackets in Fig. 10c). The dimensions of this anomalous body of high-velocity material are estimated to be about 500 km in length (E-W) and 100 to 150 km in width (N-S) extending to a depth of at least 100 km (Mueller, 1982). The dashed lines in Fig. 10c indicate the boundaries between the lithosphere and upper asthenosphere and between the upper and lower asthenosphere as determined from surface-wave dispersion studies (Panza *et al.*, 1980a) and P-wave travel time residuals (Babuška *et al.*, 1985), while solid lines are from DSS interpretation. The vertical hatching on the dashed lines denotes the range of uncertainty connected with their determination from surface-wave analysis. The lithospheric root under the Western Alps and the lithospheric bulge to the east are clearly evidenced; the portion of lithosphere marked with a question-mark under the Eastern Alps is evidenced only by P-wave tomography, since proper coverage of surface-wave profiles in that area is lacking.

The Bouguer anomalies along the profile are reported in Fig. 10a. By means of a stripping procedure, analogous to the one made for the north-south profile JJ, the residual anomalies in Fig. 10b are obtained. The purpose of the stripping procedure is to remove in the best possible way the effects of the Ivrea body, of a three-layer crust, like the one of Fig. 9, and of the sediments in the Pannonian Basin. Even if

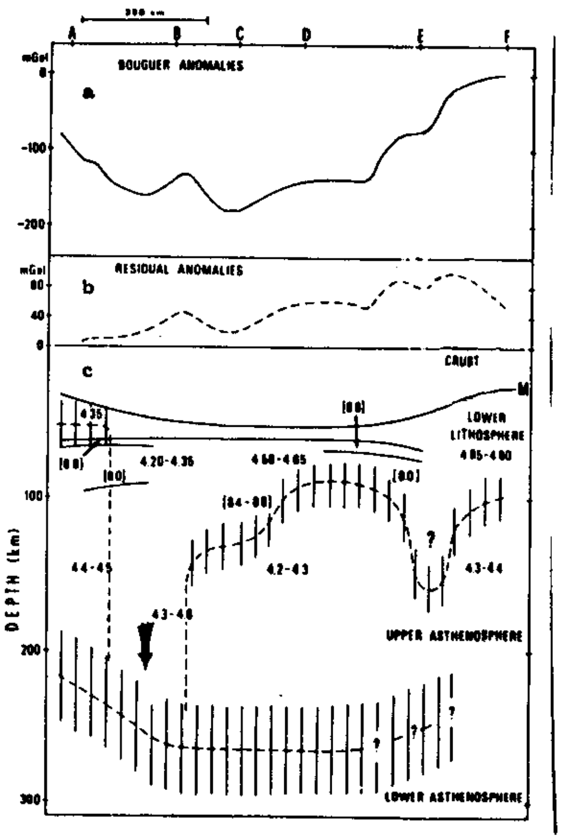

Fig. 10. - Interpretation of a gravimetric crust-mantle profile (AF in Fig. 3) along the longitudinal axis of the Alps from Aix-les-Bains (A) in France to the Pannonian Basin (F) in Hungary. The schematic structural section through the crust and upper mantle is drawn after Miller *et al.*, 1982, Panza *et al.*, 1980b and Babuška *et al.*, 1985.The crust-mantle boundary is marked M. The numbers are shear-wave and, in brackets, P-wave velocities. The vertical hatching indicates the uncertainty in the boundary determination. The "lithospheric root" under the Western Alps is indicated by an arrow. (a) Bouguer anomalies along the profile. (b) Positive residual gravity anomalies obtained after the mass effect of a homogeneous crust (see cross section in part c), an estimated effect of the Ivrea body and the Pannonian Basin sediments have been subtracted from the Bouguer anomalies. (c) Schematic model of the crust and upper mantle structure.

we cannot exclude some crustal origin, most of the long-wavelength residual anomalies are probably due to lateral heterogeneities in the upper mantle, even if the correlation existing between the trend of the anomalies and the topography of the lower lithosphere-upper asthenosphere boundary outlined in Fig. 10c is only partial. This may be taken as an indicator of relevant density variations which are also present in the "lid". However, before introducing a further degree of freedom to fit the data, a very detailed and systematic analysis is necessary of crust and upper mantle geophysical properties, which may allow to define, with the necessary accuracy, a 3-D model for the lithospheric root.

Conclusions

Lateral variations in the "lid" thickness and lateral changes of the shear-wave velocities in the lithosphere-asthenosphere system have been clearly shown by surface-wave dispersion measurements and P-wave tomography. In some areas it is possible to detect heterogeneities even at depths as large as 400 km.

The strong upper mantle lateral variations are especially apparent when considering profiles. In particular, along the profile HH, the heat flow pattern combined with the elastic properties of the lithosphere-asthenosphere system permits to identify, superimposed on a long-wavelength variation probably with origin in the deeper mantle, small wavelength perturbations that might be correlated with the presence of lithospheric roots and volcanic enviroments.

All the geophysical fields considered evidence a clear structural difference between the Adriatic Sea-Ionian Sea basin on one side and the Tyrrhenian Sea-Western Mediterranean basin on the other. The first region indicative has continental-type characteristics, while the latter has features definitely of young oceanic basins.

The gravity data imply a positive density contrast in the upper mantle of the order of 0.05 g/cm^3 corresponding to lithospheric roots, which seem to characterize many orogenic belts and which do not seem to give rise to any seismic activity with the exception to a sporadic activity in Southern Spain. The analysis of a profile along the axis of the Alps seems to indicate that relevant lateral variations in density are present also in the lithospheric part of the mantle. The present stage of investigation, however, does not allow to introduce a further degree of freedom to explain the data, but rather clearly indicates a target for further investigations.

In this respect we may anticipate that a relevant contribution may arise from the study of seismic energy attenuation. These studies are very important for our understanding of the Earth's structure, since anelasticity is likely to be more sensitive to changes in crustal structure produced by temperature and phase changes, or to the effects of crystal defects or interstitial fluids, than elasticity is. The intrinsic anelasticity of the Earth is most commonly represented by values of Q (quality factor) or Q^{-1} (internal friction) as a function of depth. Owing to the difficulties encountered in measuring the intrinsic anelasticity in a physically meaningful way (see

e. g. Panza *et al.*, 1986), such data are utterly scanty. A tentative regionalization of Q values for the Adriatic promontory and surrounding regions, on the basis of multimode surface-wave analysis is presently in progress (Craglietto *et al.*, 1987).

The study of Q, using currently available data, requires waveform modelling. The availability of satisfactory algorithms for this purpose (Panza, 1985; Panza *et al.*, 1986) makes waveform modelling very promising not only for the refinement of the existing structural models, but also for a better definition of the source properties. In this way we predict it will be possible to refine the evolutionary model for the European area with the aim of constituting an essential base for a deterministic earthquake prediction. A first step in this direction can be the definition of the stress pattern in the lithosphere – asthenosphere system as it arises, due to lateral variations in elastic properties, from the tectonic interaction between Eurasia and Africa.

Acknowledgements

We are very grateful to prof. St. Mueller and prof. C. Ebblin for the extremely careful and critical reading of the manuscript and for their very valuable suggestions. Thanks are due to Mr. G. Cavicchi for the accurate drawing of the figures.

This paper has been financially supported by MPI 40% and 60% funds and CNR grants n. 85.00933.05 and 86.00666.05.

References

Aki K. (1982) – *Three – Dimensional Seismic Inhomogeneities in the Lithosphere and Asthenosphere: Evidence for Decoupling in the Lithosphere and Flow in the Asthenosphere.* «Rev. Geophys. Sp. Phys.», *20*, 161-170.

Anderson H.J. (1985) – *Seismotectonics of the western Mediterranean.* «University of Cambridge, Ph. D. Thesis».

Angenheister G., Gebrande H., Miller H., Goldflam P., Weigel W., Jacoby W.R., Pálmason G., Björnsson S., Einarsson P., Pavlenkova N.I., Zverev S.M., Litvinenko I.V., Loncarevic B. and Solomon S.C. (1980) – *Reykjanes Ridge Iceland Seismic Experiment (RRISP 77).* «J. Geophys.», *47*, 228-238.

Arca S. and Beretta G.P. (1985) – *Prima sintesi geodetico-geologica sui movimenti verticali del suolo nell'Italia settentrionale* (1897-1957), «Boll. Geod. Sci. Aff.», *46*, 125-156.

Babuška V., Plomerova J. and Šileny J. (1984) – *Large-scale oriented structures in the subcrustal lithosphere of Central Europe.* «Ann. Geophys.», *2*, 649-662.

Babuška V., Plomerova J., Šileny J. and Baer M. (1985) – *Deep structure of the lithosphere and seismicity of the Alps.* Proc. 3rd Inter. Symp. on the "Analysis of the Seismicity and Seismic Risk", Geophys. Inst. Czechoslovakia, Prague, pp. 265-270.

Baer M. (1980) – *Relative travel time residuals for teleseismic events at the new Swiss seismic station network.* «Ann. Geophys.», *36*, 119-126.

Ben Dhia M. (1986) – *The geothermal gradient map of Central Tunisia: comparison with structural, gravimetric and petroleum data.* «Submitted to Tectonophysics».

Björnsson A. (1985) – *Dynamics of crustal rifting in NE Iceland.* «J. Geophys. Res.», *90*, 10151-10162.

Bowin C., Warsi W. and Milligan J. (1981) – *Free-Air Gravity Anomaly Map of the World.* «Geol. Soc. Am., Map and Chart Ser. MC-45, 1-13.

Calcagnile G. (1982) – *The lithosphere-asthenosphere system in Fennoscandia.* «Tectonophysics», *90*, 19-35.

Calcagnile G. and Panza G.F. (1978) – *Crust and upper mantle structure under the Baltic shield and Barent's sea from the dispersion of Rayleigh waves.* «Tectonophysics», *47*, 59-71.

Calcagnile G. and Panza G.F. (1981) – *The main characteristics of the lithosphere-asthenosphere system in Italy and surrounding regions.* «Pure Appl. Geophys.», *119*, 865-879.

Calcagnile G., Fabbri A., Farsi F., Gallignani P., Gasparini C., Iannaccone G., Mantovani E., Panza G.F., Sartori R., Scandone P. and Scarpa R. (1981) – *Structure and evolution of the Tyrrhenian basin.* «Rapp. Comm. Int. Mér Médit.», *27*, 8, 197-208.

Calcagnile G., D'Ingeo F., Farrugia P. and Panza G.F. (1982) – *The lithosphere in the Central Eastern Mediterranean area.* «Pure Appl. Geophys.», *120*, 389 – 406.

Caputo M., Panza G.F. and Postpischl D. (1970) – *Deep structure of the Mediterranean basin.* «J. Geophys. Res.», *75*, 4919-4923.

Caputo M., Panza G.F. and Postpischl D. (1972) – *New evidences about deep structure of the Lipari arc.* «Tectonophysics», *15*, 219-231.

Čermak V. and Hurtig E. (1979) – *Heat flow map of Europe: Enclosure for "Terestrial Heat Flow in Europe"*, «ed. Čermak V. and Rybach L., Berlin.»

Channell J. E. T., D'Argenio B. and Horvath F. (1979) – *Adria, the African promontory.* «Earth Sci. Rev.», *15*, 213-292.

Chung W.-Y. and Kanamori H. (1976) – *Source process and tectonic implications of the Spanish deep-focus earthquake of March 29, 1954.* «Phys. Earth Planet. Int.», *13*, 85-96.

Cloetingh S., Nolet G. and Wortel R. (1979) – *On the use of Rayleigh wave group velocities for the analysis of continental margins.* «Tectonophysics», *59*, 335-346.

Craglietto A., Panza G.F., Mitchell B. and Costa G. (1987) – *Anelastic Properties of the Crust the Mediterranean area.* Submitted to AGU for the 19th IUGG U7 Symposium volume on the Lower Crust: Properties and Processes.

D'Argenio B. and Horvath F. (1984) - *Some remarks on the deformation history of Adria, from the Mesozoic to the Tertiary.* «Ann. Geophys.», *2*, 143-146.

Deichmann N., Ansorge J. and Mueller St. (1986) - *Crustal structure of the southern Alps beneath the intersection with the European Geotraverse.* «Tectonophysics», *126*, 57-83.

Farrugia P. and Panza G.F. (1981) - *Continental character of the lithosphere beneath the Ionian sea.* In: The solution of the inverse problem in geophysical interpretation, «ed.Cassinis R., Plenum, New York», *327* - 334.

Emlin C., Salahoris M. and Zadro M. (1982) - *Variations of mechanical properties of rocks as a source of vertical ground displacements.* «Tectonophysics», *88*, T17-T23.

Gasparini C., Scarpa R. and Vezzani L. (1982) - *Seismotectonics of the Calabrian arc.* «Tectonophysics», *84*, 267-286.

Gebrande H., Miller H. and Einarsson P. (1980) - *Seismic structure of Iceland along RRISP - profile I.* «J. Geophys.», *47*, 239-249.

Hovland J., Gubbins D. and Husebye E.S. (1981) - *Upper mantle heterogeneities beneath Central Europe.* «Geophys. J. R. astr. Soc.», *66*, 261-284.

Hsü K.J. (1977) - *Tectonic evolution of the Mediterranean basin.* In: The oceanic basins and margins, ed. «Nairn A.E.M., Kanes W.H. and Stehli F.G., Plenum press, London.»

Illies J.H. (1975a) - *Recent and paleo-interplate tectonics in stable Europe and the Rhinegraben rift system.* «Tectonophysics», *29*, 251-264.

Illies J.H. (1975b) - *Interplate tectonics in stable Europe as related to plate tectonics in the Alpine system.* «Geol. Rund.», *64*, 677-699.

Jordan T.H. (1975) - *The continental tectosphere.* «Rev. Geophys. and Space Phys.», *13*, 1-12.

Kennett B.L.N., Gregersen S., Mykkeltveit S., Newmark S. (1986) - *Mapping of crustal heterogeneity in the North Sea basin via the propagation of Lg-waves.* «Geophys. J. R. Astr. Soc.», *83*, 299-306.

Kissling E., Mueller St. and Werner D. (1983) - *Gravity anomalies, seismic structure and geothermal history of the Central Alps.* «Ann. Geophys.», *1*, 37-46.

Knopoff L. (1972) - *Observation and inversion of surface wave dispersion.* «Tectonophysics», *13*, 497-519.

Locardi E. (1984) - *Individuazione di strutture sismogenetiche dall'esame della evoluzione vulcano - tettonica dell'Appennino e del Tirreno.* «Mem. Soc. Geol. It.». 24, 569-596.

Locardi E. (1986) - *Tyrrhenian volcanic arcs: volcanotectonics, petrogenesis and economic aspects.* «Terra Cognita», *6*, 578.

Lucazeau F., Vasseur G., Foucher J.P. and Mongelli F. (1985) - *Heat flow along the southern segment of EGT.* In: Proceedings of the second workshop on the European Geotraverse Project (EGT): the southern segment, ed. «Galson D.A. and Mueller St., European Science Foundation, Strasbourg», 59-63.

Lucazeau F. and Mailhe D. (1986) - *Heat flow, heat production and fission track data from the Hercynian basement around the Provencal basin (Western Mediterranean).* «Tectonophysics», *128*, 335-356.

Makris J. (1978) - *The crust and upper mantle of the Aegean region from deep seismic soundings.* «Tectonophysics», *46*, 269-284.

Malinverno A. and Ryan W.B.F. (1986) - *Extension in the Tyrrhenian Sea and shortening in the Apennines as a result of arc migration driven by sinking of the lithosphere.* «Tectonics», *5*, 227-245.

Marson I., Panza G.F., Suhadolc P. and Calocchio D. (1987) - *Sismogrammi sintetici applicati alla definizione della distribuzione in profondità della velocità delle onde S ed esperimenti DSS.* In: Atti 4. Convegno GNGTS, CNR, Roma, 581-587.

Mayer-Rosa D. and Mueller St. (1973) - *The gross velocity-depth distribution of P- and S-waves in the upper mantle of Europe from earthquake observations.* «Zeits. fuer Geophysik», *39*, 395-410.

Miller H., Mueller S. and Perrier G. (1982) - *Structure and dynamics of the Alps - a geophysical inventory.* In: Alpine-Mediterranean Geodynamics, ed. «Berckhemer H. and Hsü K., AGU, Washington», 175-203.

Mostaanpour M.M. (1984) - *Einheitliche Auswertung Krustenseismischer Daten in Westeuropa: Darstellung von Krustenparametern und Laufzeitanomalien.* «Berliner Geowiss. Abh., B10, Berlin.»

Mseddi R. (1976) - *Détermination sismique de la structure du manteau superier sous la Méditerranée.* «Ph. D. thesis, Université P. et M. Curie, Paris VI».

Mueller St. (1977) - *A new model of the continental crust.* In: The Earth's Crust, ed. «Heacock J.G., AGU, Washington», 289-317.

Mueller St. (1982) - *Deep structure and recent dynamics in the Alps.* In: Mountain building processes, ed. «Hsü K.J., Academic press, London», 181-199.

Mueller St. and Panza G.F. (1984) - *The lithosphere - asthenosphere system in Europe.* In: First EGT workshop: The northern segment, ed. «Galson D.A. and Mueller St., European Science Foundation, Strasbourg», 23-26.

Mueller St. and Panza G.F. (1986) - *Evidence of a deep-reaching lithospheric root under the Alpine arc.* In: The Origin of Arcs, ed. «Wezel F.C., Elsevier, Amsterdam», 93-112.

Nasa (1977) - *Global detailed gravimetric geoid based upon a combination of the GSFC GEM - 10 Earth model and 1°×1° surface gravity data.* «NASA - Goddard Space Flight Center, Greenbelt, MD 20771, USA».

Pálmason G. (1971) - *Crustal structure of Iceland from explosion seismology.* «Visindafelag Isl. Rit.», 40, 187 pp.

Panza G.F. (1976) - *Phase velocity determination of fundamental Love and Rayleigh waves.* «Pure Appl. Geophys.», *114*, 753-763.

Panza G.F. (1980) - *Evolution of the Earth's lithosphere.* In: Mechanism of Continental Drift and Plate Tectonics, ed. «Davies P.A. and Runcorn S.K., Academic press, London», 75 - 87.

Panza G.F. (1984) - *The deep structure of the Mediterranean - alpine region and large shallow earthquakes.* «Mem. Soc. Geol. It.», 29, 3-11.

Panza G.F. (1985) - *Synthetic seismograms: the Rayleigh waves modal summation.* «J. Geophys.», *58*, 125-145.

Panza G.F. and Calcagnile G. (1979) - *The upper mantle structure in Balearic and Tyrrhenian bathyal plains and the Messinian salinity crisis.* «Paleogeogr. Paleoclimatol. Paleocol.», *29*, 3 - 14.

Panza G.F. and Mueller St. (1979) - *The plate boundary between Eurasia and Africa in the Alpine area.* «Mem. Sci. Geol.», *33*, 43-50.

Panza G.F., Mueller St. and Calcagnile G. (1980a) - *The gross features of the lithosphere - asthenosphere system in Europe from seimic surface waves and body waves.* «Pure Appl. Geophys.», 118, 1209-1213.

Panza G.F., Calcagnile G., Scandone P. and Mueller St. (1980b) - *La struttura profonda dell'area mediterranea.* «Le scienze», *141*, 60-69.

Panza G.F., Suhadolc P. and Chiaruttini C. (1986) - *Exploitation of broadband networks through broadband synthetic seismograms.* «Ann. Geophys.», 4B, 315 - 328.

Papazachos B.C. and Comninakis P.E. (1977) - *Modes of lithospheric interaction in the Aegean sea.* In: Structural History of the Mediterranean Basin, ed. «Biju-Duval B. and Montadert L., Technip», Paris, 319-331.

Ribarič V. (1986) - *Prilozi proučavanja seizmičnosti i seizmičnog zoniranja Slovenije.* «Ph. D. thesis, University of Zagreb».

Ritsema A.R. (1979) - *Active or passive subduction at the Calabrian Arc.* «Geol. Mijn.», *58*, 127-134.

Scalera G., Calcagnile G. and Panza G.F. (1981) - *Lateral variation of the "400 - kilometers" discontinuity in the Mediterranean area.* «Boll. Geof. Teor. Appl.», *23*, 11-16.

Schwendener H. (1984) - *Ein gravimetrisches Krusten-Mantel-Modell fuer ein Profil vom noerdlichen Alpenvorland bis an die Ligurische Kueste.* Geodaetisch-Geophysikalische Arbeiten in der Schweiz (Schweizer. Geodaet. Komm.), Bern, Band *36*, 160 pp.

Schwendener H. and Mueller St. (1985) - *New evidence for a density anomaly in the upper mantle below the Southern Alps.* In: Second EGT Workshop: The southern segment, ed.

«Galson D.A. and Mueller St.» European Science Foundation, Strasbourg, 115-120.
SMITH A.G. (1971) - *Alpine deformation and oceanic areas of the Tethys, Mediterranean and Atlantic.* «Geol. Soc. Am. Bull.», *82*, 2039-2072.
SPAKMAN W. (1986a) - *The upper mantle benath Europe, the Mediterranean and the Middle East: results from large scale body wave tomography.* «Terra Cognita», 6, 440.
SPAKMAN W. (1986b) - *Subduction beneath the Alpine collision belt.* «Terra Cognita», 6, 585-586.
SPAKMAN W. (1986c) - *Subduction benath Eurasia in connection with the Mesozoic Tethys.* «Geol. Mijnbouw.», *65*, 145—153.
WERNER D. and KISSLING E. (1985) - *Gravity anomalies and dynamics of the Swiss Alps.* «Tectonophysics», *117*, 97-108.