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The Mediterranean Area: A Challenge for Plate Tectonics

[1], [2] G. F. Panza, [1] P. Suhadolc

[1] Istituto di Geodesia e Geofisica
Università di Trieste,
Trieste, Italy

[2] International School for Advanced Studies
Miramare, Trieste, Italy

CRITICAL ASPECTS OF THE PLATE TECTONICS THEORY

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THE MEDITERRANEAN AREA: A CHALLENGE FOR PLATE TECTONICS

G.F. PANZA
Istituto di Geodesia e Geofisica
Università di Trieste
Trieste, Italy

International School for Advanced Studies
Miramar, Trieste, Italy

P. SUHADOLC
Istituto di Geodesia e Geofisica
Università di Trieste
Trieste, Italy

ABSTRACT

According to the classical Plate Tectonics theory, the interaction between the "rigid" plates is exhausted at the lithospheric level and does not involve, apart from the subduction zones, relevant heterogeneities in the upper mantle. In the Mediterranean area, lateral variations of the "lid" thickness–from about 0 to 100 km–and lateral changes as large as about 15% of the shear-wave velocities in the lithosphere-asthenosphere system have been clearly evidenced on the basis of surface-wave dispersion measurements and P-wave tomography. The strongest lateral heterogeneities in the lithosphere occur in the proximity of tectonically active areas. In particular, subduction of continental lithosphere–not allowed by Plate Tectonics–has been clearly detected in relation to many orogenic belts. In relation to these almost aseismic "lithospheric roots" gravity data imply a positive density contrast in the upper mantle of the order of 0.05 g/cm^3. Another challenge to classical Plate Tectonics in continent-continent collision zones are the plate boundaries, which are not linear features, but rather wide "belts". Large shocks seem to occur in well-defined zones where a relevant gradient in the lid thickness has been detected.

1. INTRODUCTION

About thirty years ago a new theory, named Plate Tectonics, evolved and very quickly

acquired such importance that its impact was felt in each branch of Earth sciences. It has been supported by a spectacularly increasing amount of evidence which has ensured its growing popularity. The theory explains the tectonic evolution of the outer layers of the Earth by the relative movements, at the surface of the globe, of a limited number of "rigid" plates. These boundaries are delimited by earthquake belts of variable width. At the accreting boundaries hot new material is brought up to the surface and expands laterally whereas, at consuming boundaries, the cooled old material sinks down, being thrusted under an adjoining plate. Continents, because they are lighter, override oceanic plates and are never consumed. The rigid plates, which together make up the lithosphere, are believed to be partially decoupled from the underlying material through a zone of reduced strength, the asthenosphere. Deformations of the plates can only occur near the plate boundaries; one expects to find there large tectonic features such as orogens, subduction, rift zones, and volcanoes.

In the case of an oceanic lithosphere located between two continental plates being completely consumed, a continent-continent collision follows, possibly leading to an Alpine-Himalayan type of belt. In such a way continental masses join together leading to an accretion of the single continents. Thus, from the Precambrian to the Carboniferous, several elements have been accreted, through a series of orogenesis, to the European continent. The circum-mediterranean belts could represent, in the future, the seam joining Europe with Africa. According to the classical schemes of Plate Tectonics, when the continent-continent collision begins the subduction process terminates and only a "crustal shortening" ensues due to the push acting on the two lithospheric masses. This stems from the fact that an old oceanic lithosphere can sink and be subducted in the underlying asthenosphere due to the high density values acquired during its cooling and ageing process (Vlaar and Wortel, 1976). A continental lithosphere, on the other hand, could not undergo such a process due to the low density values of the crust.

The interaction of Africa and Europe may be described, according to the theory of Plate Tectonics, as a kinematic system dominated by the spreading in the Atlantic Ocean (e.g., Smith, 1971). The boundary which separates the African from the Eurasian plate runs from the Azores Islands at the Mid-Atlantic Ridge to the Strait of Gibraltar along a well defined fracture zone in the ocean and continues on to NW Africa, Sicily, Italy and SE Europe along a rather wide deformation belt. As a result of this gigantic collision major orogens were formed such as the Atlas mountain range, the Apennines, the Alps, the Carpathians, the Dinarides and the Taurides. The effects of the plate collision, which at present implies a lithospheric shortening in the Mediterranean-Alpine belt of about 5 to 10 mm/yr (Mueller, 1984), are not confined to the crustal layers, but seem to involve also the upper mantle. Examples are found in the presence of slices of oceanic and subcontinental mantle peridotites within the collisional suture (Dal Piaz et al., 1972), in the existence of lithospheric roots in the Betic Cordillera (Panza et al., 1980a, b; Marillier and Mueller, 1985), in the Alps (Panza and Mueller, 1979; Babuška et al., 1985; Spakman, 1986a) and in the Central Apennines (Calcagnile and Panza, 1981), in the thickening of the lithosphere in the Alpine area and to the south of it, including almost all of the Po Valley (Calcagnile and Panza, 1981), and in the possibly related (Illies, 1975a, b) thinning of the lithosphere in the Rhine Graben area (Panza et al., 1980a, b). Therefore the basic concepts of Plate Tectonics, which give an elegant explanation of the "orogenic cycles" cannot be applied to the Alpine tectonics in the Mediterranean area. The existence of large lateral variations in the physico-chemical properties of the upper mantle near the circum-mediterranean mountain belts is also required by recent palinspastic reconstructions (Scandone and Patacca, 1984). The total volume of continental crust that has been involved in the deformational process is by far (at least twice) greater than that present today in the mountain belts, even taking into account erosional effects. If this computation is extended to the whole lithosphere the amount of "missing" masses is even greater. The shortening cannot therefore justify the disappearance of enormous quantities of continental crust which, for the circum-mediterranean case, are of the order of several tens of millions of cubic kilometers. One has to allow, therefore, an open system for the continent-continent collision processes and consider that large portions of continental crust have been involved in the subduction process. With the term subduction we intend a sinking of the lithosphere into the asthenosphere without implying that the geometry of the system has to be similar to the classical Benioff planes which have been identified along the Pacific plate margins.

The most powerful geophysical tool for regional studies of the lithosphere-asthenosphere system is at present represented by the combined use of surface-wave dispersion measurements and body-wave travel times (tomography and deep seismic sounding experiments). The interpretation of deep seismic sounding experiments has clearly evidenced a layering in old continental crusts such as those present in the stable parts of Africa and Europe. Detailed models of the crust in the European area (Mueller, 1977) indicate the presence of a low-velocity sedimentary layer lying over a crystalline basement, in which the velocity of body waves increases with depth (upper crust). At a depth of about 10 km a soft layer is encountered characterized by a decrease of P-wave velocity (middle crust). Below it there is a layer (lower crust), with much higher velocities, composed of metamorphic rocks (amphibolites and granulites) arising from the transformation of various rock types residing originally in shallower parts of the crust. This material has been transported by collisional processes to depths where it is not in equilibrium and, therefore, the different rocks undergo a series of metamorphic processes which change their physico-chemical character. Among such processes, the progressive expulsion and migration towards the surface of volatile elements is particularly relevant. The concentration of these volatiles and incipient processes of partial melting are probably responsible for the reduction in strength of the middle crust and the ensuing low-velocity channel. In some areas, a low-velocity channel has been identified also in the lower crust.

It is very likely that in the belts arising from the collision of continental plates, the various nappes have their origin in the slivers of crust sheared off along these weakness

zones, defined by the low-velocity layers. It is therefore reasonable to assume a model in which the upper crust is responsible for the formation of parts of the nappes and of the crustal roots. Almost all of the lower crust, on the other hand, along with the lithospheric part of the mantle (the lid) is undergoing subduction. Due to the high values of the density of the lower crust there are no more isostatic effects preventing the subduction of the continental lithosphere deprived of its low-density upper crustal "skin". In some cases, as in the Ivrea zone, slices of the lower crust can also be peeled off and contribute to the Alpine nappe edifice. Recent results of the seismological investigation based on the analysis of body-wave travel time data (Dziewonski, 1984; Spakman, 1986a, b) and surface-wave dispersion (Panza et al., 1980a, b; Woodhouse and Dziewonski, 1984) indicate the presence of large lateral variations not only in the lithosphere but also in the deeper mantle up to depths of several hundred kilometers. In the case of the Precambrian shields, the asthenospheric low-velocity layer is practically absent (Calcagnile and Panza, 1978; Poupinet, 1979; Panza, 1980; Calcagnile, 1982). The entity comprising these high-velocity materials, reaching depths of the order of 400 km under stable cratons, and the overlying lithosphere, has been called "tectosphere" by Jordan (1975). The tectosphere is defined on the basis of its kinematical behavior, since the lithospheric and sublithospheric portions 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 (e.g., Fennoscandia) the tectosphere may reach depths well below the lithospheric ones. The discovery of these tectospheric roots is therefore a further challenge for the classical Plate Tectonics theory, which postulates that the plates are formed everywhere by the lithosphere and that the upper mantle does not present lateral heterogeneities from a chemical point of view.

The Mediterranean area is the result of a complex lithosphere-asthenosphere interaction in relation to the collision of continental masses. In this region, both the European and African blocks are subject to systems of great fractures that generated continental rift structures and tectonic troughs such as the Rhine and Rhone Grabens and the Pantelleria trough in the Channel of Sicily. In the deformation belt situated between these two more stable masses, several orogenic systems can be distinguished: the Pyrenees-Provençal system in the interaction zone between the European plate and the Iberian microplate and the series of systems arising from the collision between Europe and Africa. Among these last are the Betic-Balearic system, the Alpine-Carpathian-Balkan system with its nappes overlying the European foreland, and the Maghrebian-Apenninic-Southalpine-Dinaric-Hellenic system with its nappes overlying the African foreland (Panza et al., 1980b). The geographic distribution and the direction of formation of these systems are already irregular due to the form of the continental margins that have collided. Moreover, their irregularity has been enhanced by the subsequent tectonics, like the overriding of one orogenic belt over the other (e.g., the Alpine belt is in part overriden in Tuscany-Liguria and in Calabria by the Apenninic belt) and by the rotation of microplates leading to the opening of oceanic-type basins (Algero-Provençal and Tyrrhenian basins) with the contemporaneous deformation of whole orogenic belts (Calabrian Arc) (Amodio Morelli et al., 1976; Scandone, 1979; Calcagnile et al., 1981).

2. THE MAIN FEATURES OF THE LITHOSPHERE-ASTHENOSPHERE SYSTEM IN THE MEDITERRANEAN AREA

In the Mediterranean area, it is possible to distinguish several types of crusts (for a recent review see Meissner et al., 1987). Stable continental areas, such as Central Europe, the Iberian plate and the High and Middle Atlas are characterized by crusts having an evident and regular seismic layering with a mean thickness of about 30-35 km. Rift areas (e.g., the Rhine Graben) have a thinned crust, while young orogenic zones (e.g., the Alps) have a thickened crust. Young oceanic basins (e.g., the Tyrrhenian and Western Mediterranean ones) have an intermediate or oceanic type of crust, while some recent orogenic belts (e.g., the Apennines) have, in general, a crustal thickness of only about 35 km, which is less than one would expect. At crustal level there seems to be, therefore, a very weak signature of these orogenic belts. Laubscher (1988) proposes a pulled-back Adriatic subduction zone beneath the Northern Apennines, which is decoupled from the overriding plate. The smoothly transitional Moho in the area may only be apparent, due to the difficulty of identifying, with the presently available data, the merging features of two different types of Moho, the Tyrrhenian and the Adriatic one.

Also, the lithospheric part of the mantle, "the lid" presents strong lateral variations both in thickness and elastic properties (Panza et al., 1980a; Suhadolc and Panza, 1988). 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, the whole Alpine domain of North Africa, western and northern France, Britain and Ireland, Belgium, Denmark, southern Sweden, northern and central Germany, Czechoslovakia, Poland, 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, 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 Bresse and the Franco-Swiss Jura mountains into the Molasse basin of western Switzerland, traverses the French Prealps and finally merges with the Rhone 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 in regard to the Balearic Promontory and the Valencia Trough (Marillier and Mueller, 1985) associated with an

average shear-wave velocity of about 4.35 km/s. Quite low lid velocities (about 4.3 km/s) are found also in the deeper Algerian and Provençal basins. 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.

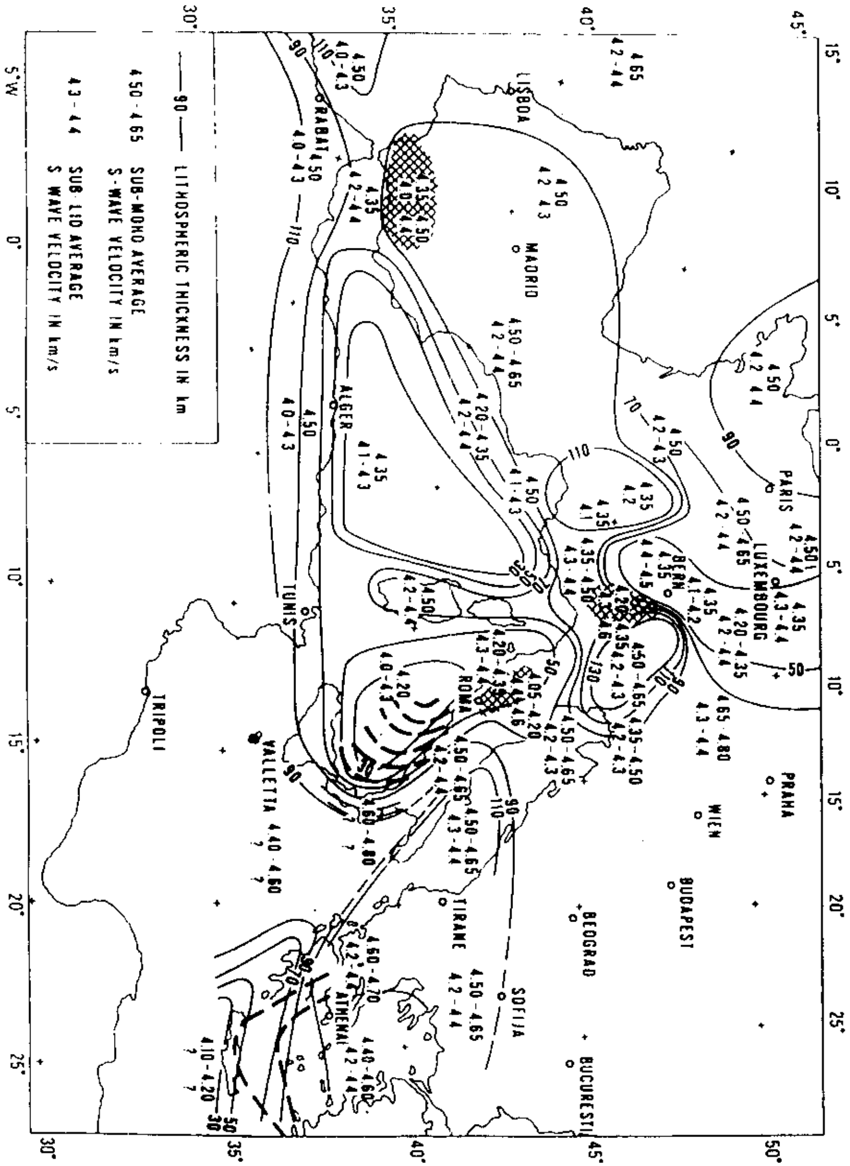
Regions with a thick lid (maximum thickness of about 105 km) are mainly associated with tectonically active areas, such as the French Massif Central, the Greece - Aegean Sea area and the Central-Eastern Alps. Recent tomographic studies (Babuška et al., 1985) indicate for the lid a possible maximum thickness of about 120 km in the Alpine area. In the Adriatic Sea the southern part seems to have a thicker lid than the northern part (Panza, 1985).

The asthenospheric low-velocity layer is a common feature to stable Europe and North Africa, with the exception of the Baltic shield, characterized by velocities so high as to exclude the presence of a significant amount of partial melting in the whole upper mantle.

A map of the elastic properties of the lithosphere-asthenosphere system in the Mediterranean area, drawn on the basis of a huge number of inversions of surface wave phase and group velocities, is shown in Figure 1. The isolines represent the gross features of the lithospheric thickness in the case of a clear contrast existing between the shear-wave velocities in the lid and in the asthenosphere. 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, when present, by the high-velocity subcrustal layer termed lid, while the asthenosphere is the layer just below it.

In the *Aegean Sea* and *Greece* areas most of the lithosphere is found to be thick with high sub-Moho velocities on land. In regard to 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 and is characterized by very low velocities. The thick dashed lines represent the space distribution of intermediate-focus earthquakes witnessing the ongoing subduction process (e.g., Papazachos and Comninakis, 1977). Spakman (1986b) proposes, from a tomographic inversion of teleseismic P-wave delays, that the subduc-

Fig. 1: 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). In the absence of a contrast between the values of the row of upper numbers and those of the lower numbers, the isoline defining the lithospheric thickness, of course, loses its meaning. 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.



tion 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. Laubscher (1988) has recently proposed for back-arc spreading areas a "pull-arc" model in which the slab is falling due to gravity and the subduction zone recedes from the plate in front leaving in its wake a roughly equidimensional extensional basin (back-arc basin). 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.

Below the *Adriatic Sea* and *Ionian Sea* 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), even if there is still a wide spectrum of ideas about its original shape and on the time period during which it was in connection with 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 Ionian Sea subsidence history. The northernmost extension of the Adriatic promontory is still doubtful, but a significant thinning of the lithosphere can be observed in the North-Central Adriatic Sea, north of the Ortona-Roccamonfina line, which seems to be the main line of dislocation between the Northern and Southern Apennines (Locardi, 1983; 1988). This thinning of the lithosphere can be very reasonably associated with the 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 *North-Central Apennines* zone is characterized by 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 mantle diapir with an associated upwelling of the asthenospheric layer (Locardi, 1986, 1988; Della Vedova et al., 1988), in which cold lithospheric roots, probably remnants of the Alpine collision process are present. 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 played a relevant role after the collision. Peculiarities in the upper mantle of this region extending to even greater depths have been detected by Scalera et al. (1981), who determined a rise, of about 100 km, of the "400 km" discontinuity. 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 the Baltic shield (Calcagnile and Panza, 1978) and in the Mediterranean basins (Mayer-Rosa and Mueller, 1973) and south of them (Mseddi, 1976).

The *Tyrrhenian Sea* as well as the *Western Mediterranean Sea* are believed to be post-collisional small oceanic basins. They are characterized by thin and young oceanic lithosphere (Hsü, 1977; Panza and Calcagnile, 1979) with thickness less than about 50 km. Both sub-Moho and sub-lid average S-wave velocities are quite low (in the ranges 4.20 - 4.35 km/s and 4.0 - 4.3 km/s, respectively). A layered lithosphere below the crust has to be introduced to interpret the surface-wave data from the Balearic Promontory and the Valencia Trough (Marillier and Mueller, 1985). The anomalous structure of these two regions is similar to what is found in regard to continental rifts (Mueller and Bonjer, 1973; Nolet and Mueller, 1981). The main characteristics of the upper-mantle are comparable to those found near spreading axes of opening oceans, but also resemble models proposed for back-arc basins (Evans et al., 1978), even if, for the latter, a much higher lid velocity (about 4.6 km/s) and a not-so-low asthenospheric velocity (about 4.35 km/s or more) are found.

The heat flow is among the highest measured in Europe and the free-air anomalies are positive. This is in accord with the hypothesis of an ocean opening and thinning of the lithosphere.

Seismogenetic material embedded in the low-velocity asthenospheric layer is present in the Tyrrhenian and Aegean Seas. In these areas, the thick dashed lines in Figure 1 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). In the Tyrrhenian Sea the presence at depth of a cold and brittle (seismogenetic) body cannot be however reconciled with the situation 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). Many controversial hypotheses exist concerning the dynamical evolution of the Tyrrhenian Sea (for more details, see Calcagnile et al., 1981). Anderson and Jackson (1987) have recently proposed that the intermediate and deep-focus earthquakes are related to the large-scale disruption of a slab, which is no longer in active subduction.

The *Sardinia-Corsica* block has continental characteristics and its margins to the Tyrrhenian Sea and the Sardo-Balearic basin are passive or of Atlantic-type (Scandone, 1979) with no seismicity. In the area the lithospheric thickness is around 70 km, a value indicating a gentle thinning of a continental lithospheric block. It is generally agreed that Corsica-Sardinia has rotated by about 30° counterclockwise leaving in its wake the Ligurian basin. The manoeuvering space for this Lower Burdigalian rotation (Montigny et al., 1981; Rehault et al., 1985) might have been provided by the rapid sinking of a detached subduction zone under the Northern Apenninic arc (Laubscher, 1988). Rapid rotations of small blocks along the strike-slip boundaries of the resulting back-arc basins would thus be possible.

The *Moroccan Meseta* and the *High and Middle Atlas* have quite similar upper-mantle structures (Marillier and Mueller, 1985), which can be compared to the European Platform, and appear to be quite different from the undeformed interior of Africa (e.g., Gumper and Pomeroy, 1970). Although some earthquakes about 150 km deep have been reported under the High Atlas, the surface-wave results indicate no major thickening of the lithosphere below the Atlas mountain range (Marillier and Mueller, 1985). This may be a consequence of the relatively small horizontal (compared to the Alpine chain) shortening of the continental platform during the Atlas mountain building.

The situation under the *Betic Cordillera* is much more similar to that in the Alps since the lithosphere may reach to depths of about 170 km. Earthquakes well below the crust, up to 110 km depth (Vidal et al., 1988), indicate that a large part of the lithosphere is involved in the active tectonics of that area. The clearcut velocity contrast usually present at the lithosphere-asthenosphere transition disappears (Marillier and Mueller, 1985), low lid velocities are encountered in this area and therefore only a weak velocity contrast exists against the underlying asthenosphere. A similar feature found in the Alps has been interpreted by Panza and Mueller (1979) in terms of a "Verschluckungszone" (Ampferer, 1906). Since strong lateral heterogeneities in these areas are present, the existing surface wave investigations might be giving only the average models illustrated here.

The main features of the lithosphere-asthenosphere system in the Mediterranean area can be summarized as follows. In stable foreland areas, which have a well layered crust, the lid presents a normal thickness ranging from 50 to 70 km and overlies a well-defined low-velocity channel. In these areas, the whole lithospheric thickness is of the order of 90 - 100 km or slightly less. The rigidity values are typical of continental areas and present a sharp decrease at the base of the lithosphere. In continental rift areas, characterized by a thinned crust, the lithospheric part of the mantle is also thin and the whole lithosphere does not exceed 50 km. Below the Moho, a mantle with soft elastic properties is quite often present.

Low to very low velocities in the lithospheric lid are found in the same regions where the heat flow is high. Since high heat flow is usually encountered in areas where the tectonic activity is recent, the same conclusion can be drawn about the low lithospheric velocities. On this basis it can be suggested that the whole lithosphere of the Western Mediterranean basins is involved in the tectonic processes. This is not only the case of the deep oceanic or pseudo-oceanic basins where extension very likely occurred on a large scale, but also for the shallow basins.

It is therefore evident that the strongest lateral heterogeneities in the lithosphere occur in tectonically active areas. The complexity of the lithospheric structure in these areas indicates that the whole lithosphere-asthenosphere system has been strongly modified by the interaction between the European and African plates, and more particularly, by Alpine tectonics.

3. LITHOSPHERIC ROOTS

In the case of the Western Alps, the Northern Apennines and the Cordillera Betica (shaded areas in Fig. 1), the value of the velocities below about 70 km 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.

These roots do not seem to give rise to any seismic activity, with the exception of some deep activity in southern Spain (Chung and Kanamori, 1976; Hatzfeld and Frogneux, 1980; Vidal et al., 1988). 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 its cold roots.

The subduction of continental lithosphere is dogmatically excluded by the orthodox global tectonicians, while it is commonly admitted by many Alpine geologists who have to justify either the high-pressure low-temperature metamorphism in coherent units formed by continental crust (Dal Piaz et al., 1972), or the deficit in the volumes of continental lithosphere resulting from the comparison of the present structures of the Mediterranean region with the original dimensions of the continental margins before the continent-continent collision (Laubscher, 1970).

The effects of the possible subduction of continental lithosphere ought to be detectable in the form of perturbations of the elastic properties of the asthenospheric low-velocity layer, usually detected under the continents (Knopoff, 1972; Panza, 1980). On the contrary, an unperturbed asthenosphere would imply that continent-continent collision exhausts its effects at lithospheric level.

The lithospheric roots in the Western Alps and the thickened lithosphere in the Central Alps have been recognized by many authors (Panza and Mueller, 1979; Baer, 1980; Mueller et al., 1980; Schwendener, 1984; Scarpa et al., 1988). Babuška et al., (1985), on the basis of teleseismic P-wave delays, confirm the root under the Western Alps and propose that a similar body exists under the Eastern Alps. A lithospheric root in the East Carpathians, probably being the remnant of a paleosubduction, is detected by Babuška et al. (1984).

A high-velocity root under the Western Alps, extending to a depth of about 170 km, is detected by Spakman (1986a) who carried out a tomographic inversion of teleseismic P-wave delays. In his interpretation, the deeper structure of the Alps shows the collision of two high-velocity slabs, the northern one slightly underthrusting its southern counterpart. Spakman (1986b) detects at depths below 250 to 300 km a zone of high P-wave velocities with the same outline as the whole Alpine orogenic belt in the Mediterranean. This zone could represent parts of the subducted Mesozoic Tethys.

An anomalous mantle zone under the Alps has been proposed more than 50 years ago by Kraus (1931), who postulated a "double orogen" model that was envisaged with

lithospheric material "flowing down into the mantle from both sides". In the foreland, extensional structures associated with rifting and volcanism may thus be created.

As a consequence of the described deep-reaching lithospheric subduction, slivers of upper crustal material were peeled off ("flakes") and piled up (Laubscher, 1974) thus

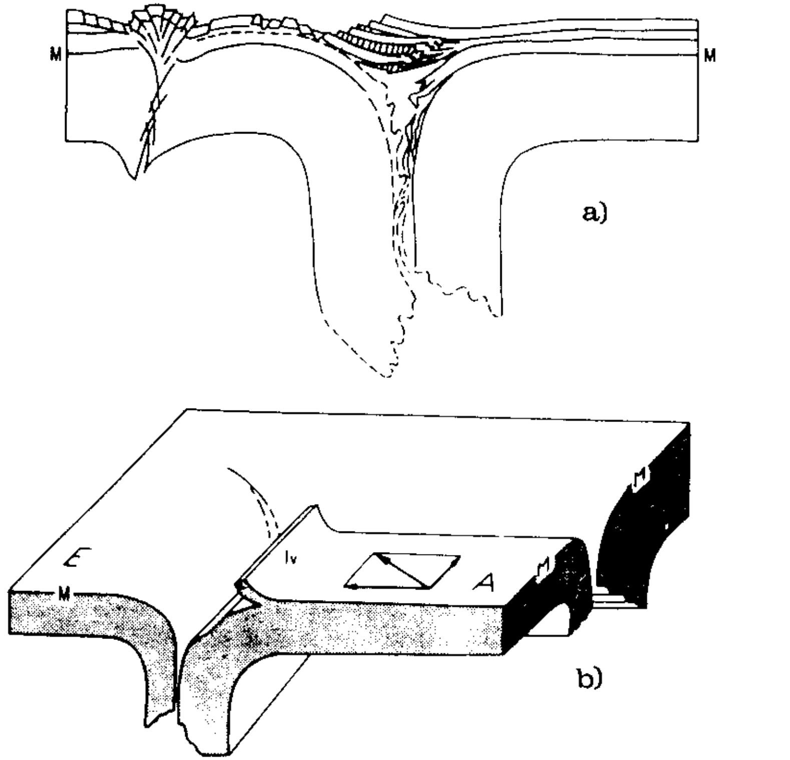


Fig. 2: a) Schematic cross-section through the crust-mantle system of the Alps (after Laubscher, 1974). Caused by the plate collision process, the subducting northern and southern lithospheres form a nearly vertical zone of "subfluence" in the Alpine region ("lithospheric root") which penetrates deeply into the asthenosphere.
b) Schematic block diagram of the lower lithosphere (uppermost mantle) in the arc of the Western Alps (after Laubscher, 1985). Since both the African (A) and the Eurasian (E) upper crusts make up the Alpine nappe edifice, both lower lithospheres must be involved and somehow subducted at depth. Usually only the upper part of the crust is involved in the Alpine nappe tectonics, except for the Ivrea zone (Iv) where a whole lower crustal "flake" seems to have been obducted. A "bivergent" (double) subduction zone is the simplest and most reasonable model to explain this deep-reaching collision structure.

creating the complex nappe edifice of the Alpine mountains (Fig. 2a). Deeper parts of the crust were shoved into each other (Mueller et al., 1980) and in this manner formed the less dense crustal root above the much wider and deeper-reaching "lithospheric root" beneath the Alps (Fig. 2a). A crust-mantle model of this type most easily explains where the excess lithospheric material must have gone during this plate collision process.

The tectonics of the Alps are usually displayed in the form of two-dimensional cross sections. As the arc of the Western Alps has a radius of only about 100 km which is of the same order as the thickness of the lithosphere, it is necessary to view the actual situation in all three dimensions (Laubscher, 1985). The pile of nappes which has been mapped on the surface consists of rocks derived from sediments of the uppermost more or less 5 km of crystalline basement. It is apparent that the surficial masses were delaminated (or "decoupled" in a low-velocity zone) from the main body of the crust and lower lithosphere which must have been subducted (Mueller et al., 1980). Since upper crusts of both the African and Eurasian plates are involved in the Alpine nappe edifice, both African and Eurasian lithospheres must have been subducted. The simplest solution would be a double or "bivergent" subduction as illustrated in Figure 2b (Laubscher, 1985).

Between the shallow and deep lithospheric masses there exists a depth range of profound disharmony which makes it virtually impossible to combine the surface geology with the deep structures deduced by geophysical methods. Smoothing out the surficial nappes in the Western Alps proves shortening both in a N-S and in an E-W direction. Consequently, keeping the Eurasian plate (E) in a fixed position, the Adriatic promontory of the African plate (A) must have moved relatively northwestwards. The motion of the plate boundary must, therefore, have had a compressive and a strike-slip component which at depth looks quite different from what can be mapped at the surface.

Field evidence supports the concept of "flake tectonics" which requires zones of weakness within the lithosphere which are identical with depth ranges of lowered seismic velocities (Mueller, 1977). Three depth levels have been identified where slivers of crustal material can be sheared off more easily: (1) at the top of the crystalline basement beneath the sedimentary cover ("Jura" type), (2) near the lower boundary of the upper crustal (or "sialic") low-velocity zone ("Massif Central" type), and (3) immediately above the M discontinuity ("Ivrea" type). The Ivrea body (Iv in Fig. 2b) is a prime example where the obducted "flake" consists of lower crustal material and even thin slices of upper mantle rocks.

A synthesis of the available seismic and gravimetric information in the region of the Central Alps provides a unique data set, which permits a rather detailed modeling of the lithospheric structure (Schwendener, 1984; Schwendener and Mueller, 1985; Mueller and Panza, 1986). As a result of a gravity "stripping" procedure along a profile running from Konstanz to Carrara (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. 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. A least-squares inversion to determine the density of this anomalous body results in a positive density contrast of about 0.05 g/cm^3. A nearly perfect fit is obtained for the observed Bouguer anomalies and the anomalies calculated from the crust-mantle model. The density contrast found in the upper mantle is too large to be explained solely by thermal 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 lithospheric roots which have penetrated into the asthenosphere beneath the Southern Alps, as suggested by Panza and Mueller (1979).

A gravity stripping procedure analogous to that followed by Schwendener (1984) and Schwendener and Mueller (1985) has been applied to the Bouguer anomalies on a profile running along the E-W axis of the Alps (Suhadolc and Panza, 1988). Even if some crustal origin cannot be excluded, most of the long-wavelength residual anomalies can be associated with lateral heterogeneities in the upper mantle, possibly related to the postulated lithospheric roots. 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 of crust and upper mantle geophysical properties is necessary, which may allow us to define, with the necessary accuracy, a 3-D model for the area.

The lithospheric root detected in the *North-Central Apennines* by surface wave dispersion measurements (Panza et al., 1980a; Calcagnile and Panza, 1981) and analysis of travel time residuals (Scarpa et al., 1988) is overlain by hot low-velocity material which might have been emplaced by lateral gravity sliding connected with the Tyrrhenian Sea opening process (Locardi, 1988). This root is probably detached from the lithospheric layer above and fits quite well the "pull-arc" model proposed by Laubscher (1988). The long-wavelength component of Bouguer anomalies along a profile from Corsica to Istria can be interpreted as due to the presence of a high-density lithospheric root (Della Vedova et al., 1988).

The root detected by surface-wave dispersion measurements in the *Cordillera Betica* area is less clearcut, since the S-wave velocity contrast with respect to the surrounding material is rather small (Marillier and Mueller, 1985). This could mean a different evolutionary stage of this root with respect to those in the Alps and in the Apennines. Its origin might be traced back to the Early Tertiary Alpine orogenesis or could be related to the formation of the Arc of Gibraltar as a consequence of the Oligocene-Miocene WSW motion of the Alboran block (Bouillin et al., 1986).

In relation to the North African coasts and the Western Mediterranean basin P-wave tomographic studies (Spakman, 1986a) detect a portion of the upper mantle with high-velocities–up to 1% greater than the surrounding material–which extends continuously to depths of the order of 600 km. The interpretation of such observations in terms of a descending slab is extremely fascinating, but it requires a relevant increase (at least about 4%) of the seismic velocity in the slab as it penetrates in the mantle to depths greater than about 300 km. A possible way to obtain such an increase in velocity is to invoke phase transitions, which in turn could be responsible for the few deep events recorded in the area (Chung and Kanamori, 1976; Hatzfeld and Frogneux, 1980; Vidal et al., 1988). Taking into account the pressure and temperature conditions, the origin of deep events as due to phase transitions seems to supply a physically more acceptable explanation than that offered by the idea of dislocations induced by stress accumulation during the plate descent. An alternative to phase transitions as being responsible for deep events, and equally free from the necessity of stress accumulation in the descending slab, is to explain deep events as the result of the collision of different lithospheric blocks detached from the surface and gravitationally sinking in the asthenosphere (Ringwood and Green, 1966; Freund et al., 1980). The origin of deep earthquakes is still an open question and only the collection of more high-quality data may help in shedding some light on this very complex problem.

The subduction model proposed by Freund et al. (1980) seems to be particularly well suited to explain the tectonic evolution of the Italian region and in particular of the Tyrrhenian Sea. The opening of the Tyrrhenian Sea and its intermediate and deep earthquakes can be explained by the dynamical subduction occurring on a moving plate. The gravitationally descending block is overrun by the moving plate and this motion can pull down and detach another block. The repetition of this process creates a subduction zone in the direction of the movement. The gap in front of the subduction zone is filled up by hot mantle material, forming an inter-arc marginal basin, whose spreading velocity is equal to the velocity of the moving plate. The relative shear motion between the descending blocks might be responsible for the intermediate and deep earthquakes observed. Anderson and Jackson (1987) have shown from fault-plane solutions of Tyrrhenian events in the range 230 - 300 km that all solutions except one have one plane that dips within 20° of the horizontal and that shear occurs in a direction out of the plane of the slab. This implies that the slab must be breaking up or, at least, that topography is generated on its surface. These observations are, thus, very well explained by the Freund et al. (1980) subduction model.

The root detected under the Apennines may be, on the other hand, the result of two steps of the subduction process. The first may be related to the early Alpine collision, the second to the gradual opening of the Tyrrhenian Sea, as recently proposed by Laubscher (1988) in his push-arc and pull-arc models.

4. PLATE BOUNDARIES

The spatial distribution of shallow earthquakes is generally taken as the marker of active plate boundaries. This is generally true along the narrow oceanic plate boundaries, the study of which has led to some of the basic concepts of Plate Tectonics. In continent-

continent collision areas, on the other hand, the plate interaction is more complicated and the scatter of earthquake epicenters is very large. In the Mediterranean area the location of the boundary between Europe and Africa has been proposed by Lort (1971) on the base of shallow seismicity recorded in the time interval 1962-1967. According to her the plate boundary runs from the Azores Islands triple-junction eastward to the North African coasts and Sicily, then encircles the Adriatic Sea and follows the Aegean trench. Similar conclusions could be reached on the basis of other seismicity maps covering different time intervals (Waniek et al., 1982; Udias, 1985; CSEM, 1986; Goter, 1988). In these maps, however, the recognition of a narrow seismic belt defining the Africa-Europe boundary is not so immediate. Diffuse seismicity is recorded also in Central France, Pyrenees, Southeastern Spain (Udias et al., 1986). Clusters of seismicity occur west of Norway, in Central Europe, to the north of the Alps, in Hungary and Rumania. This diffuse seismicity is not associated with the uncertainties in the epicentral location (usually less than 30 km) but rather suggests that the Africa-Europe interaction is sustained by a whole system of "boundaries", which might have been more or less active in different time periods and which sometimes border small plates of different size. The general increase in seismicity encountered moving eastward from the Azores triple junction through the Western Mediterranean to Italy and Greece could be well explained by the different Africa-Europe converging rates (McKenzie, 1972), about 1 cm/yr to the west of Spain and about 2 - 3 cm/yr in the Western and Eastern Mediterranean, resulting in a counterclockwise rotation of Africa relative to Europe. The diffuse seismicity far from the boundaries proposed by Lort (1971) could be associated, as already proposed by McKenzie (1972), to zones of weakness which have been strongly active in different geological time intervals and which might be at present releasing stress either diffusing from the major presently-active fault zones or connected with the non-rigid intraplate deformations.

The Azore-Gibraltar Ridge appears to be a relatively sharp boundary across which the upper-mantle structure changes abruptly, over deep oceanic basins as well as over the continental margins, while this is not the case in the Western Mediterranean. Seismicity has been tentatively used to locate the plate boundary as precisely as possible in this region. but in fact we have shown that the whole Western Mediterranean area, and the upper mantle below it, are involved in the interaction between the two large plates. As a consequence the concept of a sharp plate boundary, as defined by the theory of Plate Tectonics, should be replaced, in the case of continent-continent collision, by a relatively wide "boundary zone" across which the transition occurs between the neighbouring plates.

If an attempt is made to correlate the distribution of epicentres (Fig. 3) with the lithospheric model of Figure 1, no significant conclusions can be reached. If, however, a high-pass filter in magnitude or intensity is applied to the available data, it is easy to see that the largest shocks distribute quite well along the active plate boundaries outlined by lateral variations in lithospheric thickness. An example, limited to the Central-

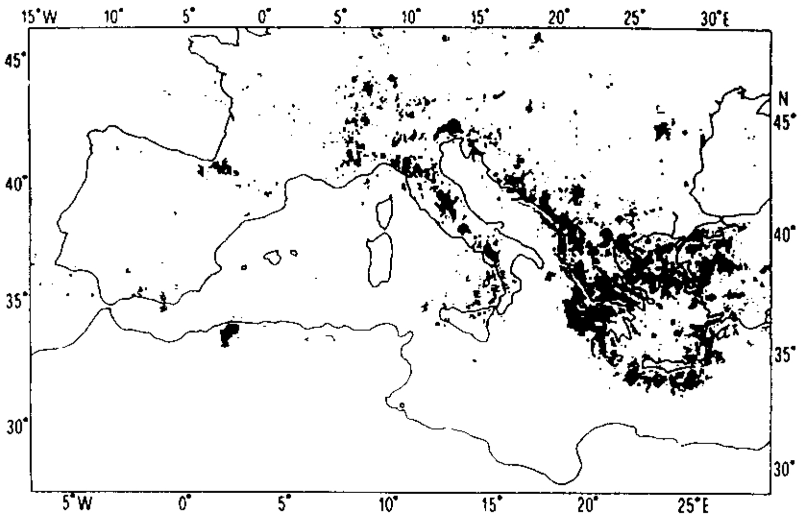
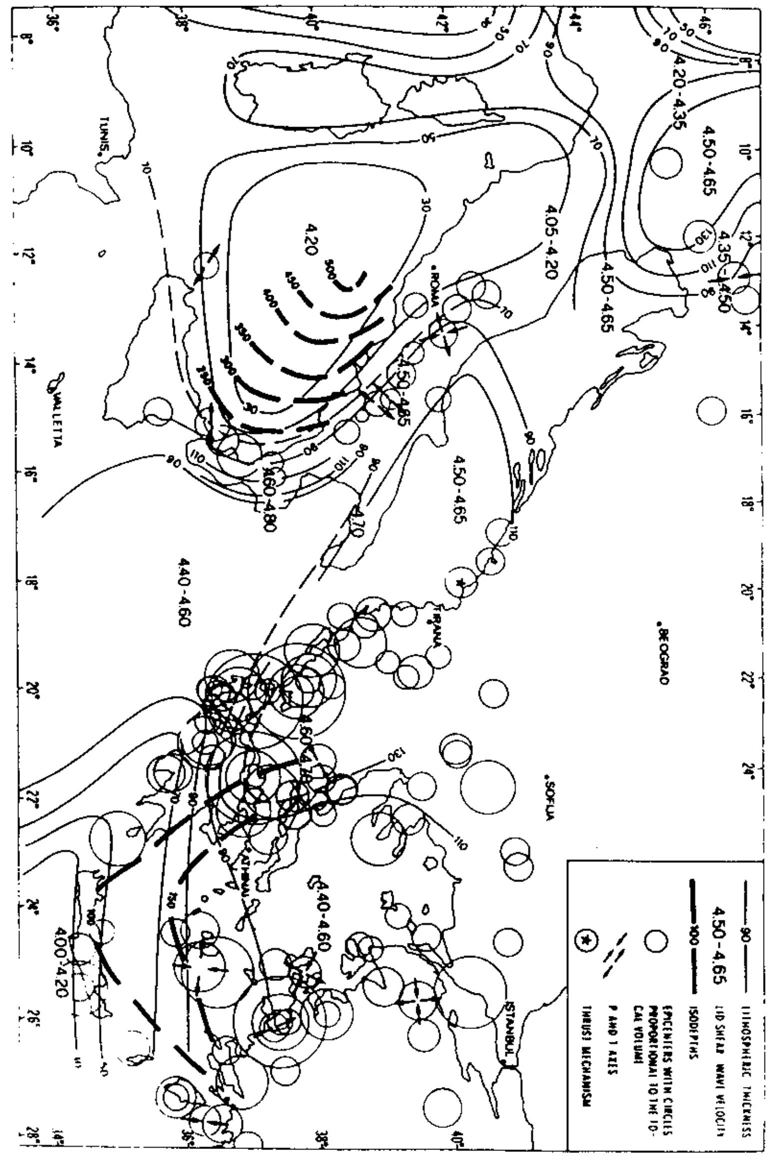


Fig. 3: Map of epicentres reported by CSEM from 1976 to 1985 including shallow, intermediate and deep-focus earthquakes.

Eastern Mediterranean, is given in Figure 4 (Panza, 1983, 1984). Strong events seem to be correlated with the gradient of the lid thickness rather than with that of the whole lithosphere.

It seems therefore reasonable to formulate the hypothesis that the major stress concentration, responsible for the genesis of large shocks, takes place in the lid and not in the crust. Because of the increase of pressure and temperature with depth, aseismic slip might be occurring in the lower part of the lid, at the plate boundary. This may cause enough stress to accumulate in the most brittle upper part of the lithosphere (the upper crust) as to produce fracturing and thus generating the strongest shocks (e.g., Sibson, 1982; Bonafede et al., 1987; Main, 1988). The smaller shocks, located outside the belts defined by the occurrence of strong shocks, would then represent secondary adjustments to the stress field in portions of the lithosphere not directly driven by the aseismic slip at depth. As a consequence it is possible to draw the conclusion that the knowledge of the gross structure of the upper mantle in the European area allows a physical understanding of the occurrence in space of large shocks. The active belts can be defined not only on the basis of historical seismic records, but also on the basis of structural properties. In the Mediterranean area the trace of the plate boundaries can be, at present, defined by narrow bands rather than by linear features, as implied by the classical scheme of plate tectonics.



5. CONCLUSIONS

According to the classical Plate Tectonics theory, the interaction between the "rigid" plates is exhausted at the lithospheric level and does not involve, apart from the subduction zones, variations in the upper mantle. However, lateral variations of the lid thickness and lateral changes of the shear-wave velocities in the lithosphere-asthenosphere system in the Mediterranean area have been clearly evidenced on the basis of surface-wave dispersion measurements and P-wave tomography. In some areas it is possible to detect heterogeneities even at depths as great as 400 km.

The strongest lateral heterogeneities in the lithosphere occur in the proximity of tectonically active areas. The complexity of the lithospheric structure in these areas indicates that the whole lithosphere-asthenosphere system has been strongly modified by the interaction between European and African plates and more particularly by Alpine tectonics.

Moreover, Plate Tectonics does not allow for the subduction of continental lithosphere. Thi type of subduction, at first invoked by Alpine geologists, has been later detected by means of surface-wave dispersion measurements and body-wave tomography mainly as relevant lateral variations in the elastic properties of the asthenosphere. The gravity data imply a positive density contrast in the upper mantle of the order of 0.05 g/cm^3 in relation 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 of southern Spain.

According to Plate Tectonics, the boundaries between the various plates are defined by linear features marked by seismic activity. This is true for ocean-ocean or ocean-continent interaction, but it seems not to be true for continent-continent collisions. In this last case the interaction between colliding plates is sustained by relatively wide "boundary belts". The interaction might even cause stress release along zones of weakness marking boundary zones strongly active in different geological times. In the Mediterranean area large shocks seem to occur in well-defined zones where a relevant gradient in the lid thickness has been detected, while smaller shocks are quite scattered in space.

In conclusion, the theory of Plate Tectonics preserves its general validity, but the large amount of geophysical and geological data gathered in the Mediterranean area shows that it has to be subjected to a major revision for what concerns the collision of continental masses.

Fig. 4: Synoptic representation of lithospheric properties in the central-eastern Mediterranean region and distribution in space of shallow seismic events with $M \geqslant 6.5$ or $I \geqslant X$. The size of the circles, representing epicentres, is proportional to focal volume. The space distribution of intermediate and deep-focus earthquakes in the Tyrrhenian Sea and the Aegean Sea is schematized by thick dashed lines. The few available fault-plane solutions are schematized by means of arrows.

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