Geologie en Mijnbouw 65: 145–153 (1986)

Subduction beneath Eurasia in connection with the Mesozoic Tethys

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Received 5 February 1986; accepted in revised form 2 May 1986

Abstract

In this paper we present new results concerning the existence and subduction of Meso-Tethyan oceanic lithosphere in the upper mantle beneath Europe, the Mediterranean and the Middle-East. The results arise from a large scale body wave tomographic analysis of the upper mantle in this region. It is shown that much more subduction has taken place beneath the Aegean and Tyrrhenean region than was previously estimated. The Eastern Mediterranean basins are linked to the old Meso-Tethyan passive margin and may in some parts be underlain by oceanic lithosphere. We demonstrate the existence of an old northward dipping subducted slab beneath Spain and the Western Mediterranean. A large zone of subducted oceanic lithosphere is found beneath the entire Alpine orogenic belt from Spain to Iran at depths between 250–600 km. This zone represents major parts of the Meso-Tethys.

Introduction

Despite the huge amount of geophysical and geological data there is still no satisfactory solution for the large scale geodynamical evolution of the Alpine – Mediterranean region, in particular with respect to the existence, size and geometry of the so-called Meso-Tethys, the ocean that separated Eurasia and Africa during Cretaceous and Tertiary time (e.g. Berckhemer & Hsu 1982, Dixon & Robertson 1984, Stanley & Wezel 1985). This evolution is governed by the complex relative motions between Eurasia and Africa from Jurassic to early Cretaceous onward. Simply stated these motions gave rise to the opening and destruction of the Meso-Tethys, the Alpine orogeny and the present-day Mediterranean deep sea and backarc basins (e.g. Biju-Duval et al. 1977, Smith & Woodcock 1982).

Obviously we have to look into the upper mantle for the disappeared Meso-Tethys. Calgagnile & Scarpa (1985) gave a summary of results concerning the upper mantle structure beneath Europe and the Mediterranean derived from surface-wave dispersion data, P-wave travel time observations and P-wave tomography. Those results cover the major part of the European upper mantle but they are characterised by a poor spatial resolution (implicitly hidden in the applied methods and data sets) which makes it very difficult to relate the inferred lateral heterogeneities to the subducted Meso-Tethys. At present seismic tomography is the only tool for imaging large parts of the earth's interior in three dimensions. Major advances in body wave tomography enable us now to apply more detailed inversion models to the earth using a huge amount of data (e.g. Nolet 1985).

In this paper I will present results of a body wave tomographic study applied to the upper mantle beneath Europe, the Mediterranean and the Middle-East (fig. 1a) with a spatial resolution high enough to permit a significant interpretation with respect to the subducted Meso-Tethys. After an introduction to the method I will discuss some results in the form of upper mantle cross sections through European subduction zones and then show their connection to large scale upper mantle heterogeneities that outline major parts of the Meso-Tethys beneath Europe. In this paper I am only concerned with some aspects of subduction in connection with the Meso-Tethys. An extensive report on the tomographic method, its results and their implications will be published elsewhere (Spakman & Nolet, in prep., Spakman in prep.).

Body wave tomography

Body wave tomography is an inversion method that estimates the seismic wave velocity inside the earth from the travel times of body waves which are observed at the earth's surface. In the linearised approach the method inverts for the deviation of the velocity field from a radially symmetric reference earth using the difference between the observed and calculated travel time (the so-called delay time or travel time residual). The method was introduced in seismology by Aki et al. in 1977. They divided a part of the earth's interior in a number of cells (blocks) that are illuminated by seismic rays from teleseismic earthquakes. In every cell Aki et al. estimated the mean seismic velocity anomaly by linear inversion of the delay times that are observed at the earth's surface. Up to a few years ago both computer memory size and the availability of matrix-inversion algorithms limited the practice of tomography to relatively small size inversions. Typically a few hundred unknowns and several thousands delay limes could be treated. These problems have been largely solved and now we are able to invert for several ten thousands of unknowns using hundred thousands of data (e.g. Nolet 1985). After the inversion we may relate the velocity anomalies to structural and/or thermal properties of the upper mantle. An example that is relevant for this paper concerns oceanic lithosphere. Before thermal assimilation older subducted oceanic lithosphere exhibits lower temperatures than the surrounding mantle. Seismically this property is expressed in somewhat higher velocities for the propagation of waves than the surrounding material. Hence such subducted slabs will be imaged as high velocity zones in tomography. Of course every conclusion drawn from the tomographic results should be warranted within some reliability bounds by an error and spatial resolution analysis. Although there is a method for estimating the spatial resolution (Nolet 1985) its application is not feasible in the case of very large inversions, using a huge number of unknowns, because it is computationaly too expensive. An alternative is provided by estimating how well synthetic velocity models are solved by tomography using the same ray paths as in the actual inversion but with delay times calculated from the synthetic model.

This brief introduction to body wave tomography provides the framework from which the method applied in this paper raises. Figure 1a shows the geographical region beneath which the upper mantle is tomographically scanned using regional earthquakes and station observations up to 90 degrees of epicentral distance. The upper mantle (0–670 km) is divided into 9 layers of increasing thickness (33–130 km). Every layer is subdivided into 1040 approximately one by one degree cells. In every cell we try to estimate the mean P-wave velocity anomaly. More than 550.000 P-wave residuals were used in this study, i.e. more than 550.000 seismic rays illuminate the upper mantle. All tomographic results presented here are supported by sufficient spatial resolution inferred from the inversion of synthetic velocity models (Spakman & Nolet, in prep.).

Subduction beneath the Aegean, the Tyrrhenean and Western Mediterranean basins

Aegean subduction

Beneath the Aegean basin subduction of oceanic lithosphere up to a maximum depth of 150 km has

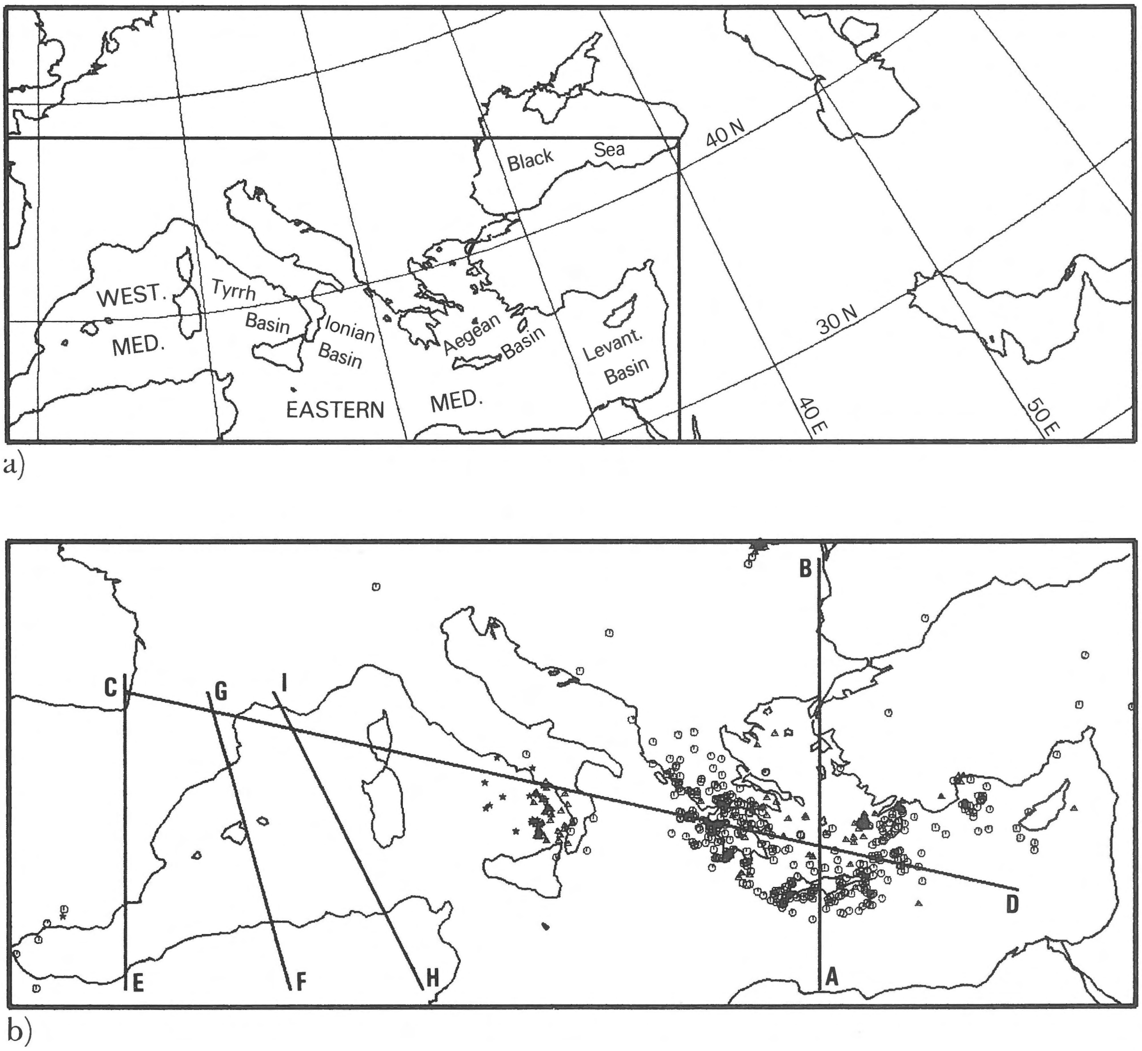

Fig. 1a. The geographical region beneath which the upper mantle is tomographically investigated. The straight lines show the outline of figure 1b. *1b.* The Mediterranean. Straight lines mark the location of the upper mantle profiles shown in Figs 3–4. Symbols denote earthquake epicentres with focal depths deeper than 50 km that occured between 1960–1980: circles, 50–100 km; triangles, 100–300 km; and stars, deeper than 300 km.

been estimated from the depth distribution of the seismicity (e.g. Papazachos & Comninakis 1971, 1977, the deeper seismicity is shown in Figure 1b). Gregersen (1977) calculated a comparable amount of subduction from a study of P-wave residuals using local earthquakes and observations in Europe and Greenland. Agarwal et al. (1976) using teleseismic residuals observed in local stations confirmed the existence of a high velocity slab beneath the Aegean but their data do not allow a conclusion about depth penetration. The existence and geometry of the subduction zone is of great importance for many studies that are concerned with the Aegean basin formation. For example in their kinematic reconstruction of the Aegean area Le Pichon & Angelier (1979, 1981) relied heavily on the geometry of the slab which they took as being imaged by the seismicity pattern. Horvath et al. (1981) on the other hand argued that the seismicity pattern is discontinuous and too poorly defined to represent a well developed subduction zone and they explained the Aegean basin formation in ab-

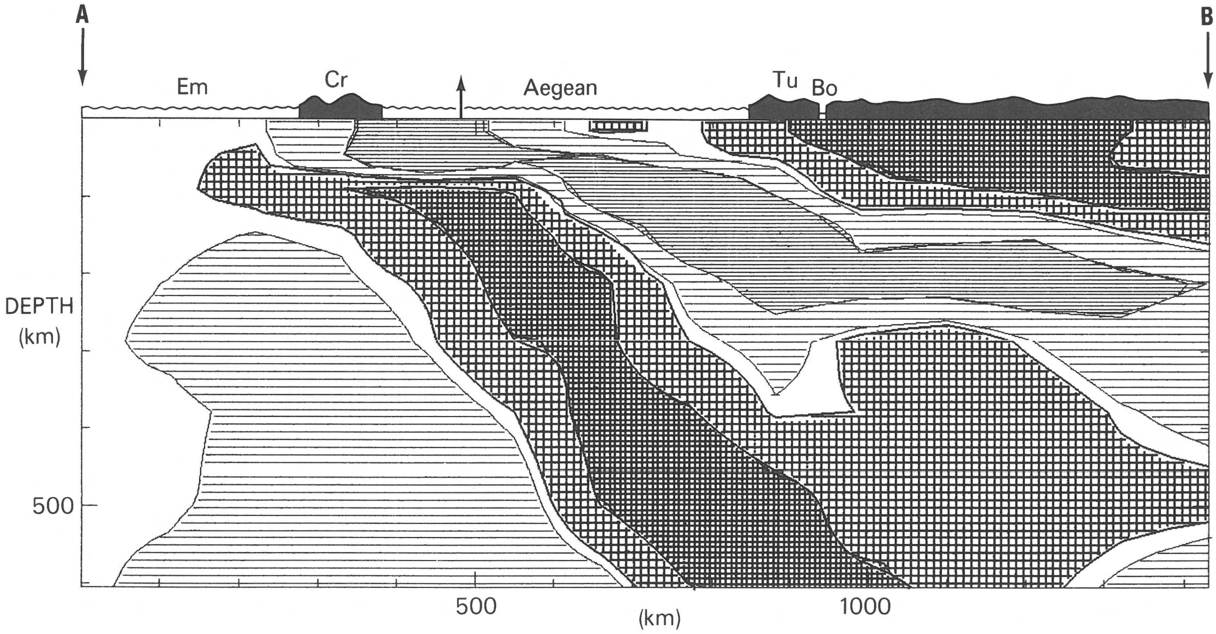

Fig. 2. S–N upper mantle cross section A–B (Fig. 1b) through the Aegean area. The shading indicates P-wave velocity anomalies relative to the mean Jeffreys-Bullen velocity at depth. Widely hatched: −0.1 to −1.0 %, closely hatched: less than −1,0 %, widely cross-hatched: +0.1 to +1.0 %, closely cross-hatched: greater than +1.0 %. Intersected geographical areas are indicated at the top of the figure: Em = Eastern Mediterranean; Cr = Crete; Tu = Turkey; Bo = Bosporus. The arrow denotes the location of cross section CD. For explanation see section on Aegean subduction.

sence of simultaneous subduction.

I will now discuss an Aegean upper mantle cross section as determined by seismic tomography. Figure 2 displays a south (A) to north (B) cross section through the upper mantle below the Eastern Mediterranean and Aegean region. The shaded areas indicate regions where the P-wave velocity is anomalous with respect to the Jeffreys-Bullen reference earth (Jeffreys & Bullen 1940). The large north-dipping zone of higher velocities is interpreted as the (blurred) tomographic image of the subducted oceanic lithosphere beneath the Aegean. The width of the anomaly across the slab is about 250 km. This number exceeds the thickness of very old oceanic lithosphere by 100 to 130 km. This width results from a combination of the subdivision of the upper mantle into cells, lack of spatial resolution and cooling of the surrounding mantle by the cold slab. It is not clear wether the slab extends below the bottom of the upper mantle cell-model but certainly the amount of subduction exceeds present estimates by far. Deeper than approximately 150 km below the centre of the Aegean basin the slab is aseismic.

The assumption that the deepest foci roughly coincide with the deepest part of the slab thus proves to be quite incorrect. Wortel (1980) has shown that age-dependent thermal assimilation of subducted oceanic lithosphere in the upper mantle provides constraints for the occurence of seismicity. For example subduction of 100 Ma old oceanic lithosphere may result in at most 12 ± 3 Ma of seismic activity in that part of the slab. After this time span the slab will behave aseismically due to reheating. Temperature differences with the surrounding mantle of several hundreds of degrees still exist at this stage, hence we are able to image the slab tomographically. Another possible reason for the aseismicity deeper than 150 km may be found in the absence of strongly deforming stresses due to gravitational sinking that is governed by reheating of a slab in an inactive (non-converging) subduction proces.

Tyrrhenean and Western Mediterranean subduction

In the Tyrrhenean region the modest deep seismicity (200–500 km, Fig. 1b) has also been interpreted as being related to a subducted oceanic lithosphere (Ritsema 1972). An interesting aspect is the absence of intermediate depth seismicity between 100 to 200 km. The deeper seismicity is explained as being caused by a relatively small and detached subducted slab. Figure 3 shows the roughly west to east running cross section C–D through the upper mantle from Spain crossing the Western Mediterranean, Tyrrhenean, Ionian, and Aegean basins into the Levantine basin in the Eastern Mediterranean. The layer of higher velocities extending from beneath the Ionian basin into the Levantine basin is best interpreted to represent old oceanic lithosphere, because of its connection to the Aegean subduction zone. Independent evidence from the inversion of Rayleigh wave dispersion data (Cloetingh et al. 1980) indicates a passive continental margin structure or parts of the Eastern Mediterranean basins. However, their method and results do not rule out the presence of oceanic parts in the inner zones of the Ionian and Levantine basins. In any case these results explain the Eastern Mediterranean as a remnant of an old ocean bordering on a passive margin roughly to the south and subduction of oceanic lithosphere roughly to the north and are not indicative for an origin as sub-sided continental areas (e.g. Smith & Woodcock 1982). To the west (left), at the same depth intervals, the high velocity anomalies illustrate the oceanic nature of the Western Mediterranean lithosphere (e.g. Rehault et al. 1985). The high velocity region in the middle of the figure beneath the Tyrrhenean basin is also interpreted as subducted oceanic lithosphere in accordance with the occurring seismicity. Its connection with the lithosphere in the Ionian basin seems to be detached beneath the Calabrian Arc (It, Fig. 3). The depth of detachment coincides with the gap in seismicity mentioned above. Apparently also in this region much more subduction has taken place than previously estimated and a large portion of the slab behaves aseismic.

The deeper seismicity in the Spanish and Western Mediterranean regions is characterised by only a few events shallower than 100 km and two very deep events (640 km) with about the same hypocentre (Fig. 1b). These two events are the only indication for deep subduction beneath southern Spain and perhaps the Western Mediterranean (e.g. Vlaar & Wortel 1976, Udias 1985). Figure 4 shows three cross sections through the upper mantle which run roughly south to north (E–C, F–G, H–J). This part of the upper mantle is not well resolved which is caused by the poor illumination of the upper mantle by seismic waves due to lack of observing stations. The rather irregularly shaped

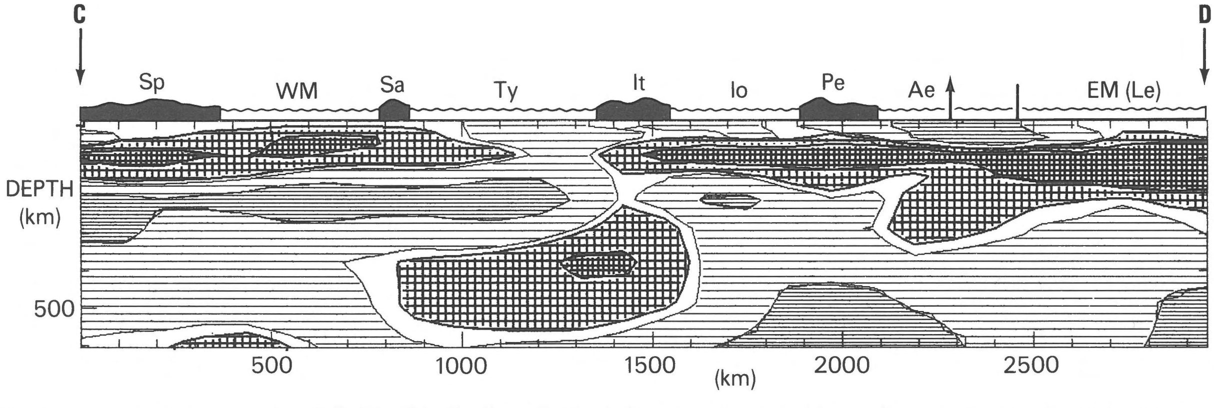

Fig. 3. Upper mantle cross section C–D (Fig. 1b). Shading as in Fig. 2. Intersected geographical regions are; Sp = Spain; WM = Western Mediterranean; Sa = Sardine; Ty = Tyrrhenean basin; It = Italy; Io = Ionian basin; Pe = Peloponesos; Ae = Aegean and EM (Le) = Eastern Mediterranean (Levantine basin). The arrow denotes the intersection with cross section AB. For explanation see section on Tyrrhenean subduction.

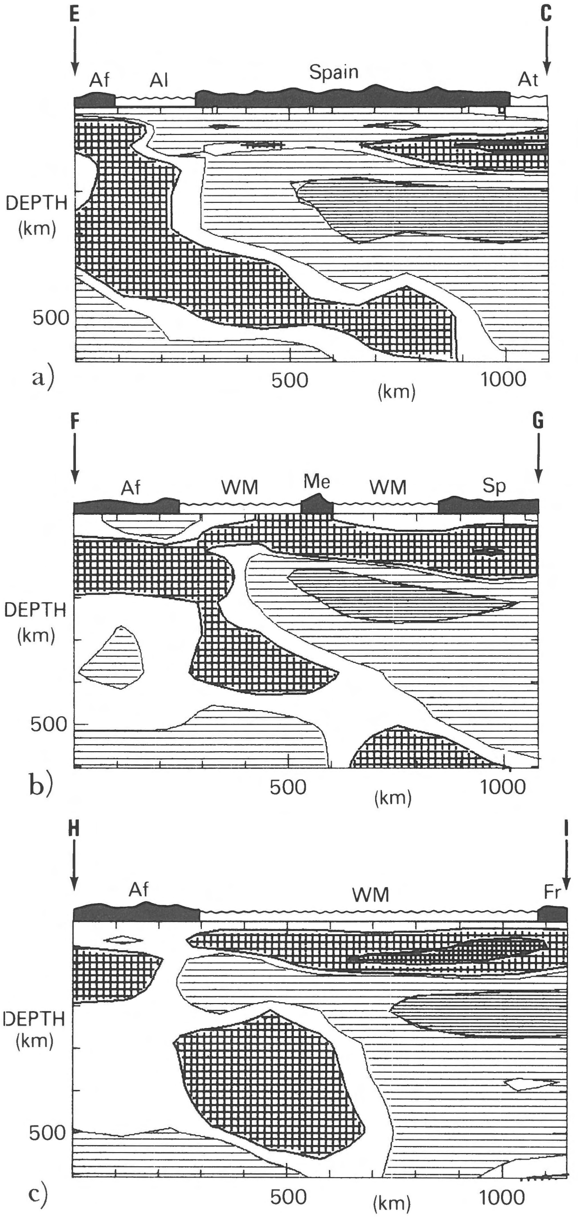

Fig. 4. Upper mantle crossections: a) E–C, b) F–G, c) H–I (see Fig. 1b) through Spain and the Western Mediterranean. Shading as in Fig. 2. Geographical regions are: Af = Africa; Al = Alboran sea; At = Atlantic; Me = Menorca; WM = Western Mediterranean; Fr = France. For explanation see section on Western Mediterranean subduction.

north-dipping zones of higher velocity in Fig. 4a–c are interpreted as the expression of an old subduction zone. Profile E–C unfortunately represents the western edge of the investigated upper mantle. But if we extrapolate the apparent strike and increasing dip of the slab westward we may locate the two deep foci below southern Spain at the slab. To the upper right in fig 4b–4c we can again recognise the Western Mediterranean oceanic lithosphere.

Figures 3 and 4 evidence that beneath the Western Mediterranean and the Tyrrhanean regions a large amount of oceanic lithosphere has been subducted in a (at present) north to north-westerly direction. This amount of subduction constrains a lower limit of the convergence between Africa and Europe.

The Meso-Tethys

In Figures 2–4 I have shown cross sections through the upper mantle revealing the approximate depth-geometry of three subduction zones in the Mediterranean region. The next step is to fit the profiles into a general pattern of higher velocities beneath the Mediterranean and Europe. This is displayed in Figure 5 where I plotted the P-wave velocity anomalies in the 3 lower radial layers of the cell-model. We can easily conclude from Figures 5a and 5b that the lower parts of the slabs fit in the zone of higher velocities which extends from beneath Spain, Italy, the Alps, the Balcan, the Aegean, Turkey into the upper mantle beneath Iran. This zone, although less continuous, is also present at depths between 240 to 320 km (not shown here). To the east and north of Iran spatial resolution becomes poor which is illustrated by the rather discontinuous and irregular shapes of the anomalies. Figure 5c shows that most of the higher velocities have disappeared below a depth of 540 km except beneath Western Europe (compare with Fig. 3, 4), north of the Aegean (compare with Fig. 2), and north of Iran. From the interpretations of the results presented in Figures 2–4 we can conclude that this zone of higher velocity anomalies represents subducted oceanic lithosphere which is related to major parts of the Meso-Tethys. At this stage it is not clear whether this subducted lithosphere stems from one large part of the ancient ocean or that it must be related to several parts, i.e southern or northern units, of the Meso-Tethys which were separated by continental fragments and/or an oceanic ridge and

5 A - LAYER 7 : 320 - 420 km

5 B - LAYER 8 : 420 - 530 km

5 C - LAYER 9 : 540 - 670 km

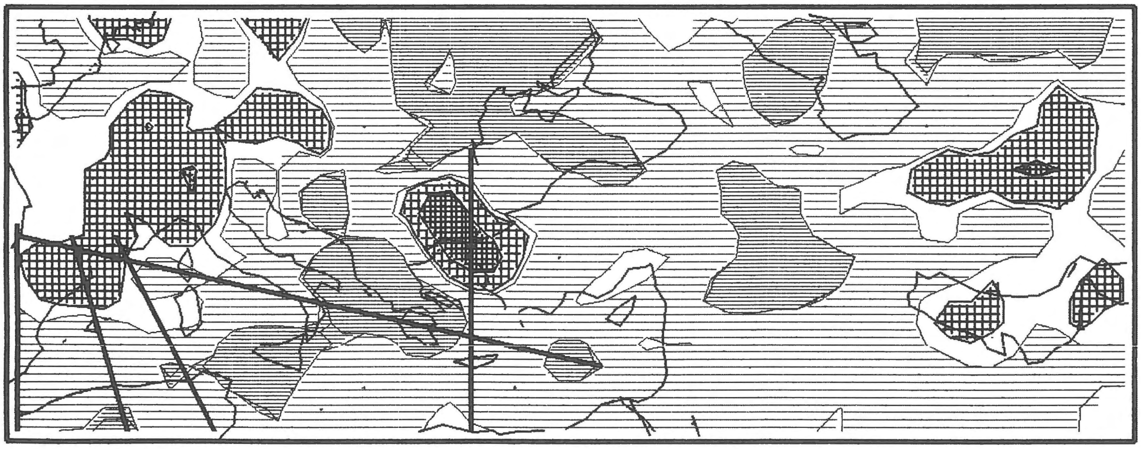

Fig. 5 a–c. The P-wave velocity anomalies in the lower three radial layers of the used upper mantle cell model. Layer depths are indicated above each figure. Note that the shading is superimposed on the geographical map of this region (Fig. 1a) for orientation. Shading as in Fig. 2. For explanation see section on the Meso-Tethys.

transform fault system. What is clear is that the ocean lithosphere must be relatively old (cold) because otherwise it would not sink into the upper mantle. The oceanic ridge system that has disappeared cannot be found at these depths because it is to buoyant to sink (Vlaar & Wortel 1976). See also Vlaar & Cloetingh (1984) for a discussion on this matter with reference to the Alps.

Except for the deep Eastern Mediterranean basins the Meso-Tethys is completely destroyed. Its subducted remnants show a strong positive correlation with the surface outlines of the entire Alpine orogenic belt from Spain to Iran giving credit for an intimate causative relation.

Conclusions

The tomographic results presented here provide new evidence for the existence and subduction of Meso-Tethyan oceanic lithosphere in the European-Mediterranean upper mantle. In particular I have demonstrated that the the Eastern Mediterranean basins are linked to the Meso-Tethyan ocean. They can partly be underlain by old oceanic lithosphere and partly by the old Meso-Tethyan passive margin and do not represent subsided continental areas. The tomographic images of the Aegean and Tyrrhenean subduction zones clearly evidence that much more oceanic lithosphere is subducted than was previously estimated on the basis of seismicity patterns. Beneath Spain and the Western Mediterranean I demonstrated the existence of another subducted slab that once, together with the Tyrrhenean slab occupied the present Western Mediterranean region. The two very deep earthquakes beneath southern Spain can be located in this slab. Finally I have shown how all these subducted slabs fit into a large zone of higher P-wave velocities in the lower upper mantle. This zone follows the outline of the entire Alphine orogenic belt in the investigated region and, because of its connection with the existing subduction zones, can be interpreted as subducted Meso-Tethyan lithosphere.

Acknowledgements

I am grateful to G. Nolet whose knowledge of seismic tomography was fundamental to this research. I thank especially R. Wortel and N.J. Vlaar for many inspiring and instructive discussions and S. Cloetingh for reading and improving the manuscript. This research has been financed by the Netherlands Organisation for Advancement of Pure Research (ZWO).

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