Proc. Kon. Ned. Akad. v. Wetensch. 95 (3), 325-347 September 21, 1992

Structure and dynamics of subducted lithosphere in the Mediterranean region

by M.J.R. Wortel and W. Spakman

Department of Geophysics, Institute of Earth Sciences, University of Utrecht, P.O. Box 80021, 3508 TA Utrecht, the Netherlands

Communicated by Prof. J.E. van Hinte and Prof. J.L.R. Touret at the meeting of March 30, 1992

ABSTRACT

The geodynamical evolution of the Mediterranean region is generally considered in the context of the interaction (convergence) of the Eurasian plate and the African plate. In analyses of this interaction the distribution of earthquake hypocentres and the focal mechanisms of earthquakes – in particular those occurring in subduction zones – have been an important source of data. Recently, new information concerning the nature of this interaction has been obtained by the application of seismic tomography techniques. The resulting three-dimensional seismic velocity structure provides insight into the history of plate convergence in the region on a time scale much beyond that contained in the distribution of present-day seismic activity. From the seismic velocity structure of the subducted lithosphere we infer that deeper parts of subducted slabs have become detached from lithosphere near the surface. This detachment process has interesting geodynamical implications on a regional scale. Using this process as a key element we propose a hypothesis for the first-order geodynamic evolution which includes a dynamic basis for the observed kinematic patterns involving rotation of continental blocks, migration of island arcs and opening of back-arc basins.

INTRODUCTION

Over the years the abundant data available on the structure and tectonics of the Mediterranean region have been compiled into regional paleogeographic and tectonic reconstructions. Among these are those by Dewey et al. (1973), Biju-Duval et al. (1977), Dercourt et al. (1986) and Le Pichon et al. (1988), for the entire Mediterranean region, and those by Channell et al. (1979), Dewey et al. (1989), and Mantovani et al. (1990) for the western and central parts (see also Smith and Woodcock 1982). Probably the most fundamental observation made for the Mediterranean is the non-uniformity in age of the deep basins. A variety of data sets (paleomagnetic data, see VandenBerg and Zijderveld, 1982; heatflow data, Erickson et al. 1977; Dercourt et al. 1986 for a compiled data set, and Kastens et al. 1988 for recent ODP results for the Tyrrhenian Sea) have led to the conclusion that the basins in the western Mediterranean (Balearic Basin) and also the Tyrrhenian Basin are at least partially of oceanic nature and of Cenozoic age, mostly Miocene or younger. The age of the Eastern Mediterranean Basin (oceanic with a thick sedimentary cover) is considerably older, probably Mesozoic (Savostin et al. 1986). The lithosphere of Aegean Sea area – of continental origin – is subject to extensional tectonics which probably started in the Late Miocene (Angelier et al. 1982, see also Kissel and Laj 1988). Although considerable thinning of the crust is apparent – in particular in the Sea of Crete – the extension has not yet led to the creation of oceanic type of lithosphere (Makris 1978).

The general framework of the current hypotheses is that of the interaction between European continent, or the Eurasian plate, and the African plate. In this context subduction is envisaged to play an important role in accommodating the shortening. In the final stages the interaction is often described to be of a collisional nature.

The reconstructions mentioned are essentially kinematic descriptions strongly based on geological and marine geophysical data and often on results of paleomagnetic studies. A dynamical element was introduced into Mediterranean tectonics by Le Pichon & Angelier (1981, see also Le Pichon 1982). Starting from the locked-in situation which the oceanic lithosphere of Mesozoic age of the present-day eastern Mediterranean arrived at upon the approach of the Eurasian and African continent – referred to as "landlocked basin setting" – they drew attention to possible relevance of the roll-back process (Elsasser 1971). The latter involves a (oceanward) migration of a convergent plate boundary induced by the gravitational instability of subducting old oceanic lithosphere (Vlaar and Wortel 1976). This roll-back process was considered to be the cause of the back-arc extension in the Aegean Sea (Le Pichon and Angelier 1981). A similar explanation was put forward by Malinverno and Ryan (1986) to account for the extension in the Tyrrhenian Sea.

Until recently the most direct information on the extent and duration of subduction process and the convergence involved was inferred from the distribution of earthquake hypocentres, in particular those at depths greater than approximately 100 km, occurring in subduction zones. In the Mediterranean region (see fig. 1) earthquakes of such depths are confined to three areas: 1) The Aegean region, with events down to depths of about 200 km (Papazachos 1988), 2) the Tyrrhenian region, with a maximum hypocentral depth of approximately 485 km (Caputo et al. 1970, Ritsema, 1972, Anderson and Jackson 1987, Giardini and Velona 1991), and 3) Southern Spain, where so far only three earthquakes deeper than about 130 km have been observed, the hypocentres of which are located very near each other at a depth of about 640 km (Buforn et al. 1988). The seismicity in the Aegean region has been used to derive estimates for the length of the subducted slab, on the basis of the assumption that the deepest events are near the leading edge of the slab. Along these lines Le Pichon and Angelier

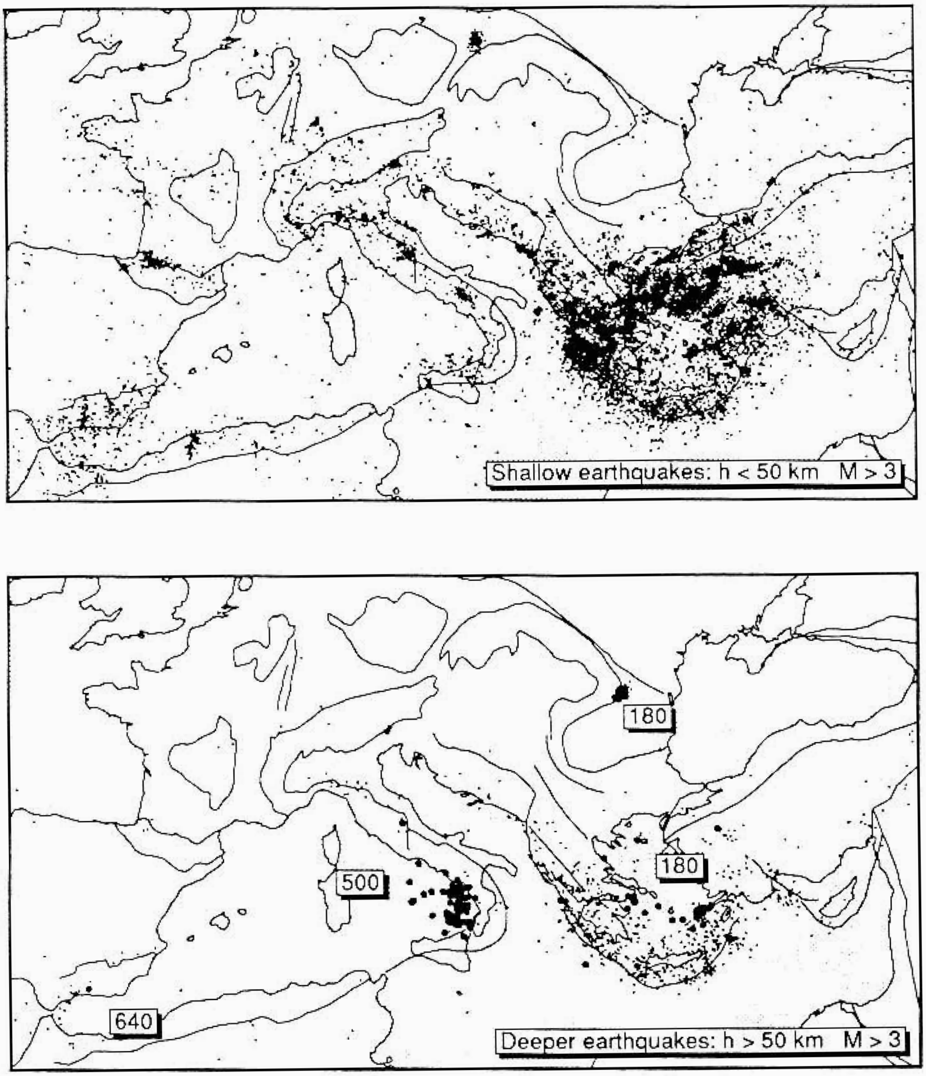


Fig. 1. Shallow seismicity (top) and intermediate and deep seismicity (bottom) for years 1964–1982, M > 3. Large dots in the bottom panel indicate earthquakes with depths greater than 150 km. Labels indicate maximum depths (in km) of seismicity in southern Spanish, Tyrrhenian, Aegean and Vrancea (Rumanian) zones.

(1979) arrived at the conclusion that subduction in the present-day (Aegean) Hellenic Trench was initiated about 13 Ma ago (other estimates (e.g. Mercier 1981; McKenzie 1978) are in the range 5 to 13 Ma). Since this is also the time (Late Serravallian-Early Tortonian) in which significant changes in the tectonic regime (and vertical motion) were established (Meulenkamp 1979), these changes – and hence part of the geological evolution of the area – were considered to be causally related to initiation of subduction.

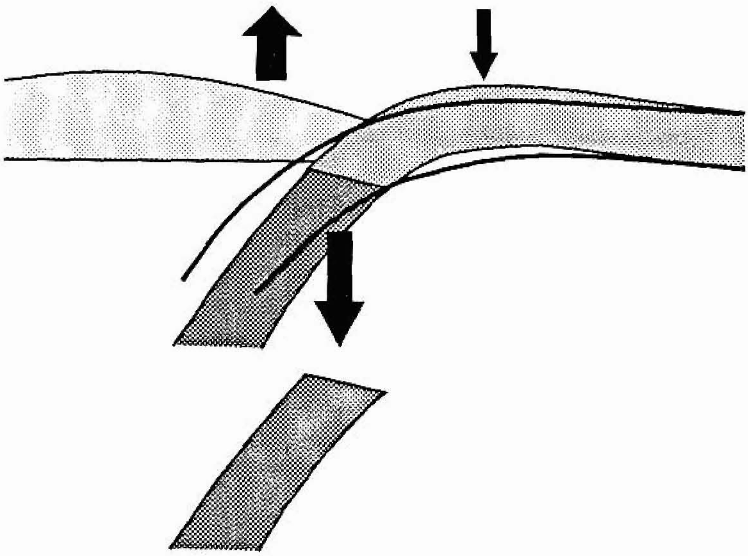


Fig. 2. Vertical section through a subduction zone: slab detachment and qualitative indication of associated vertical motion (see arrows). Shaded areas indicate configuration before detachment; solid lines schematically indicate slab geometry after detachment.

New information on the structure of the lithosphere and upper mantle was obtained by Spakman (1988, see also Spakman et al. 1988, and Spakman 1990) from seismic tomography studies. The derived three-dimensional seismic velocity structure sheds new light on the evolution of the Mediterranean, by providing information on subducted lithosphere in the upper mantle the presence of which was not evident from distribution of hypocentres. Subducting lithosphere, especially if it is old lithosphere, is cold relative to the surrounding mantle and it will remain so for several tens of million years because of the low rate of reheating (low thermal conductivity). The temperature plays also a dominant controlling role in generation of earthquakes in subducting lithosphere. It appears, however, that the thermal anomaly in a subducting slab remains "visible" for tomography long after generation of earthquakes has ceased. From a comparison of thermal modelling results and observational data Wortel (1982, see also Wortel and Vlaar 1988) derived that – for a seismically active part of the subducted slab – the minimum temperature difference between subducted lithosphere and surrounding upper mantle is about 500°C. Considerably smaller temperature differences are detectable by seismic tomography, via the temperature dependence of seismic velocities. A temperature difference of only 100°C results in a velocity anomaly of about 50 m/s, which – for the upper mantle – amounts to about 0.5 percent. Such an anomaly is easily detected in a seismic tomography study provided that the anomalous volume is not too small.

In this paper we will present an analysis of tomographic results for the Mediterranean region, with special emphasis on the dynamic processes which have created the observed velocity structure. We present a hypothesis for the large scale geodynamical evolution of the Mediterranean region since approximately the Early Tertiary. An important role in this hypothesis is played by the process of slab detachment, by which we mean to indicate that deeper parts of subducted lithosphere become – or have become – separated (detached) from shallower parts of a downgoing slab as illustrated schematically in figure 2.

THE STRUCTURE OF THE MEDITERRANEAN MANTLE

For the Mediterranean region the inversion of surface wave dispersion data (see Suhadolc and Panza (1988) for a review) and of surface wave scattering (Snieder 1988) have revealed the S-wave structure of the lithosphere and asthenosphere in relatively great deal. Distinct differences in structure between the Western and Eastern Mediterranean basins are reflected in these results. The limited depth to which these results apply, however, hampers interpretations in terms of possible slab subduction related to the convergence and collision of the African and European plates. With the method of travel time tomography results for the mantle P-wave velocity structure below Europe and the entire Mediterranean could be obtained to a depth of 670 km (Spakman 1988). The location of positive P-velocity anomalies found in the upper mantle correlate excellently with the plate boundary between the European and African plates. These anomalies have been largely interpreted as images of subducted lithosphere (Spakman 1986, 1990, Spakman et al. 1988). The bulk of the subducted material is not seismically active.

Here, we present a brief review of the tomographic results necessary to provide the basis for our hypothesis for the large scale evolution of the Mediterranean region. To introduce the interpretation of slab subduction we first consider the few areas in the Mediterranean for which we know from the occurrence of intermediate and/or deep seismicity that subducted lithosphere exists: southern Spain, the Tyrrhenian basin, and the Aegean basin. Figure 3 displays a roughly S to N cross section through the Aegean mantle. Positive velocity anomalies correspond to high velocity regions. The scale of the anomaly contouring is in percentages of the ambient (reference) mantle velocity given by the laterally homogeneous Jeffreys-Bullen model for P-waves. Dots in the cross section and map represent earthquakes. The northward dipping positive anomaly can be interpreted as the image of the subducting Eastern Mediterranean (African plate). The high velocities in the upper right are a mapping of the European plate. Between these anomalies we find a low velocity wedge which extends into the lithosphere of the southern Aegean. The image must be regarded as a blurred mapping of actual velocity structures below the Aegean. This particular section has been subject to a detailed resolution analysis (Spakman and Nolet 1988) with the result that the slab image is most likely a mapping of an existing structure and is not an erroneous mapping due to resolution artifacts. Notice that the intermediate seismicity occurs to a depth of at most 200 km. Below this depth the slab is aseismic. Wortel et al. (1990) have investigated why no deep earthquakes occur in the Aegean subduction zone at depths greater than about 200 km. Using a thermo-mechanical modelling approach, they found that the non-stationary input of the subduction zone – both in convergence rate and in thermal structure of the downgoing lithosphere – adequately accounts for both the presence of a velocity anomaly associated with a slab and the absence of deep seismicity. Spakman et al. (1988) used the imaged slab length to estimate that the minimum duration time of the ongoing subduction process lies between 26 Ma and 40 Ma which is much longer than the 5–13 Ma duration of subduction used in earlier studies of the evolution of the Aegean area. The latter estimates are, however, partly based on the assumption that the toe of the subducted slab did not reach further than the depth of the deepest events, i.e. 200 km.

In figure 4 a cross section through the Tyrrhenian mantle is presented. The deep seismicity correlates well with a positive anomaly which is interpreted as the (blurred) image of African plate subduction. Also here the slab seems to have an aseismic extension. The slab image is not continuous; this supports earlier interpretations or suggestions derived from slab seismicity that the Tyrrhenian slab is detached (e.g. Ritsema 1972).

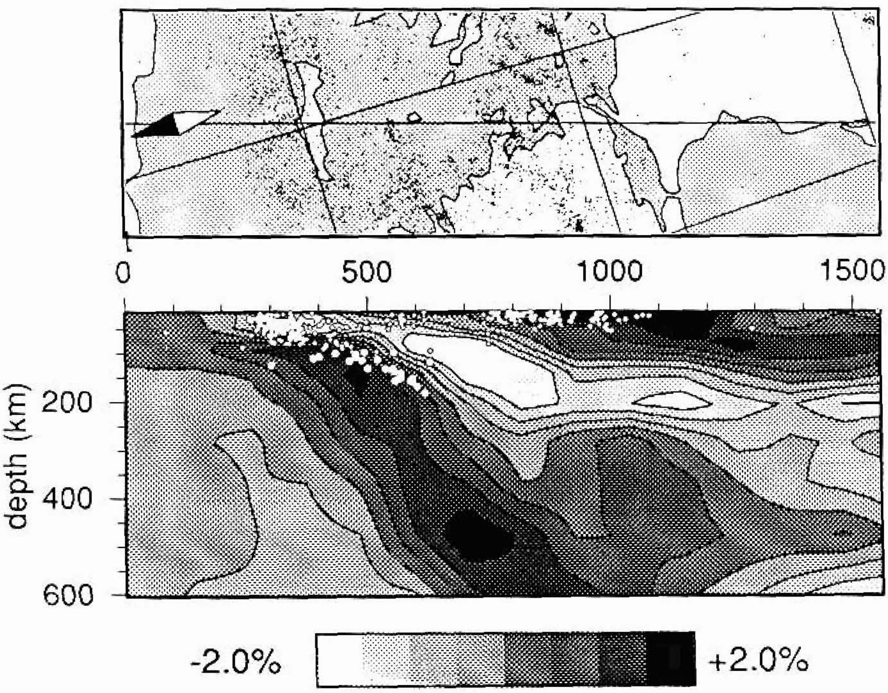


Fig. 3. Cross section through the Aegean upper mantle along the straight profile indicated in the map (top panel). White arrow point indicates North. The contouring scale is in percentages of the ambient mantle velocity given by the laterally homogeneous P-wave velocity model of Jeffreys and Bullen (1940). Dots in the map and cross section represent earthquake locations for events with M > 3. The hypocenters in the cross section belong to events located within 100 km of distance from the plane of cross section.

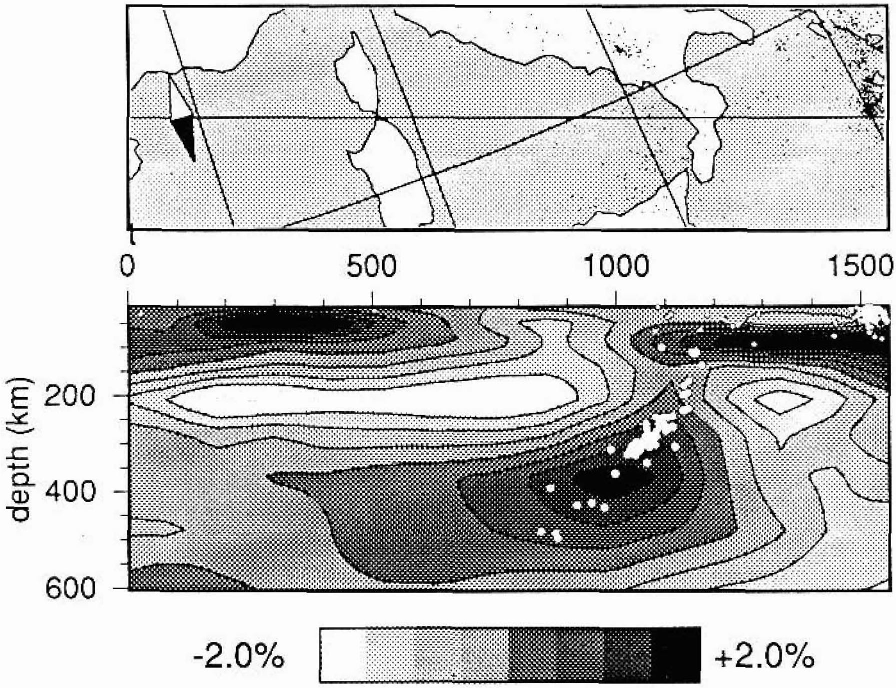


Fig. 4. Cross section through the Tyrrhenian upper mantle. See also caption of figure 3.

The last region with deep seismicity is southern Spain. A cross section through the mantle in this area suggests the presence of a slab but the image is very poorly resolved (see Spakman 1986, 1990). Recently, Blanco and Spakman (1992) performed a detailed tomographic study of the mantle below the Iberian Peninsula down to a depth 1400 km. They found a presumably detached slab below the Betic-Alboran region between 200–670 km of depth. The slab is of limited extent, situated only below the Betic-Alboran region and with apparent SW-NE strike direction. No dip direction could be inferred. A cross section through their model is displayed in figure 5. Notice the deep event in this cross section at a depth of 640 km.

In all three areas with localized deep or intermediate seismicity the results from seismic tomography support the presence of subducted lithosphere to large depth. Moreover, below southern Spain and the Tyrrhenian the slab seems detached from the lithosphere at surface. It is now interesting to relate these interpretations to the three-dimensional anomaly patterns found in the Mediterranean mantle. In figure 6 the patterns at 7 different depths are displayed from 66 to 670 km. Between 66–110 km positive anomalies are found almost in the entire Mediterranean reflecting high velocity lithosphere of the African plate (Eastern Mediterranean, including the Adriatic region) and of the Western Mediterranean oceanic lithosphere. In the next depth level (110–170 km) we enter the asthenosphere but positive velocities are still found at the northeastern

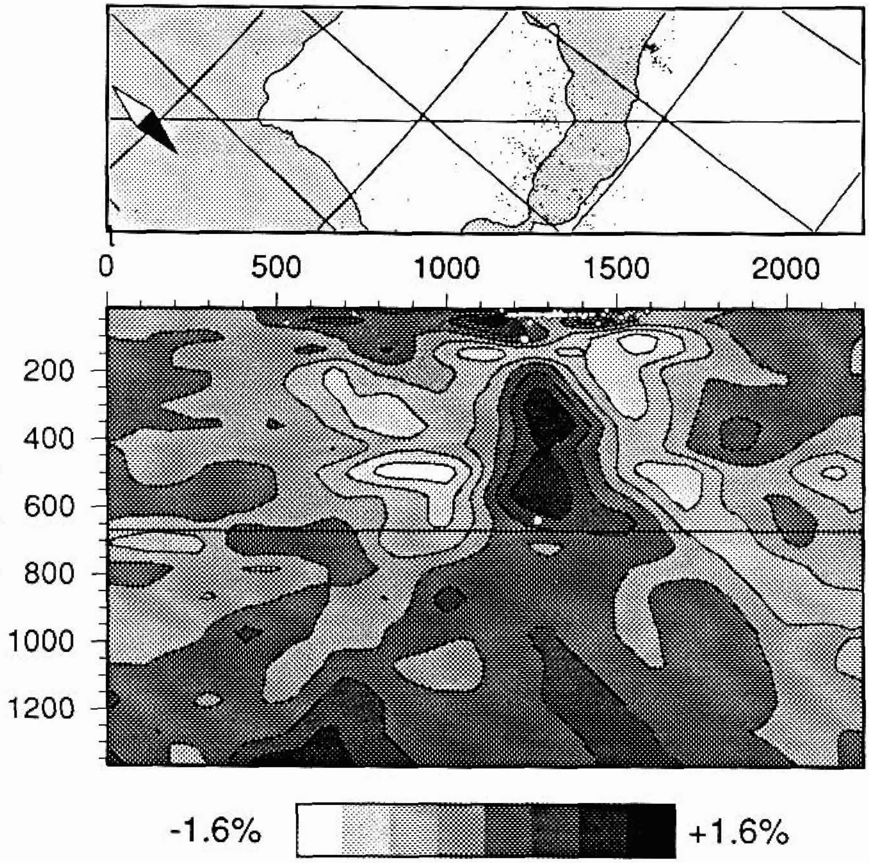


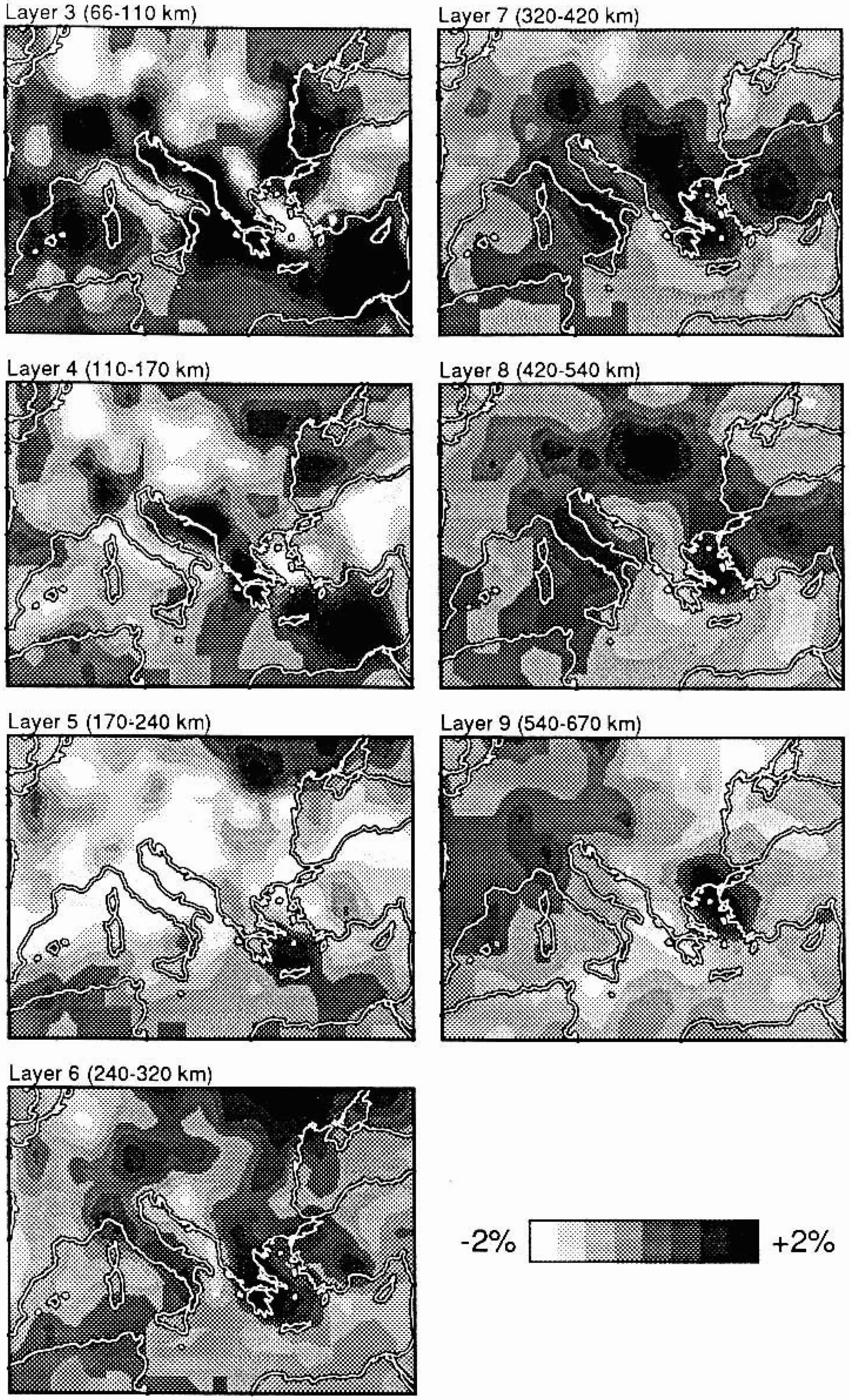
Fig. 5. Cross section through the mantle below the Iberian Peninsula to a depth of 1400 km after Blanco and Spakman (1991). See also caption of figure 3 (note the different limits of the contouring scale in the present figure).

boundary of the African plate and the Adriatic region. Notice that the location of this boundary has shifted towards the northeast relative to the previous depth level. In layer 5 (170–240 km) low velocities are found everywhere in the Mediterranean except for a few anomalies in the Aegean, the North African margin, and in Calabria. Below the asthenosphere a pattern of positive anomalies appears which develops at greater depths to a much larger zone correlating with the surface expression of the entire Alpine collison Belt from Spain to Turkey. The seismically active subducted slabs below southern Spain, the Tyrrhenian and

---

→

Fig. 6. Map view images of the velocity heterogeneity of the European-Mediterranean upper mantle at different depth levels (as indicated). Thick white lines indicate the coastline map. Contouring similar as described in the caption of figure 3.


Layer 3 (66-110 km)
Layer 7 (320-420 km)
Layer 4 (110-170 km)
Layer 8 (420-540 km)
Layer 5 (170-240 km)
Layer 9 (540-670 km)
Layer 6 (240-320 km)
-2%
+2%

southern Aegean regions make part of this high velocity belt which leads us to conclude that this zone is a mapping of subducted lithosphere. This conclusion is strongly supported by forward modelling results concerning the thermal structure of the Mediterranean upper mantle (DeJonge and Wortel 1990).

If all subducted material in the mantle below Europe and the Mediterranean would still have the geometry of slabs continuous from the surface to large depth the tomographic images would have been quite different since the estimated spatial resolution is high enough to detect continuous slabs (Spakman 1991). Instead, low velocities at depths between 170–240 km separate most of the lithosphere structure from that of the deeper upper mantle. Below the Dinarides and western Greece a low velocity zone is located between the high velocities of the underthrusting Adriatic lithosphere and subducted material at larger depth. This suggests that along this entire margin (except for the south Aegean) a once continuous slab has been detached. Under western Italy low velocities are imaged in the lithosphere. Then, at depths greater than 200 km subducted lithosphere appears which makes part of the large belt of subducted material. Below southern Italy it incorporates the seismically active Tyrrhenian slab. Also under western Italy we interpret the subducted material as detached. Spakman (1990) presents a sequence of roughly parallel sections taken perpendicular to the peri-Adriatic plate boundaries to support the interpretation of slab detachment. One

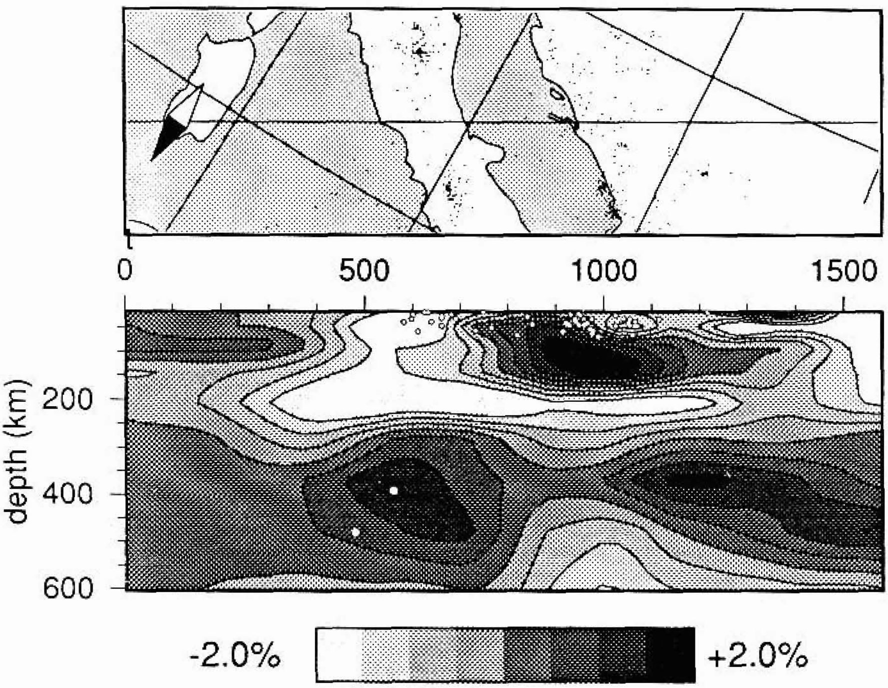


Fig. 7. Cross section through southern Italy and the Dinarides-Hellenides zone. See also caption of figure 3.

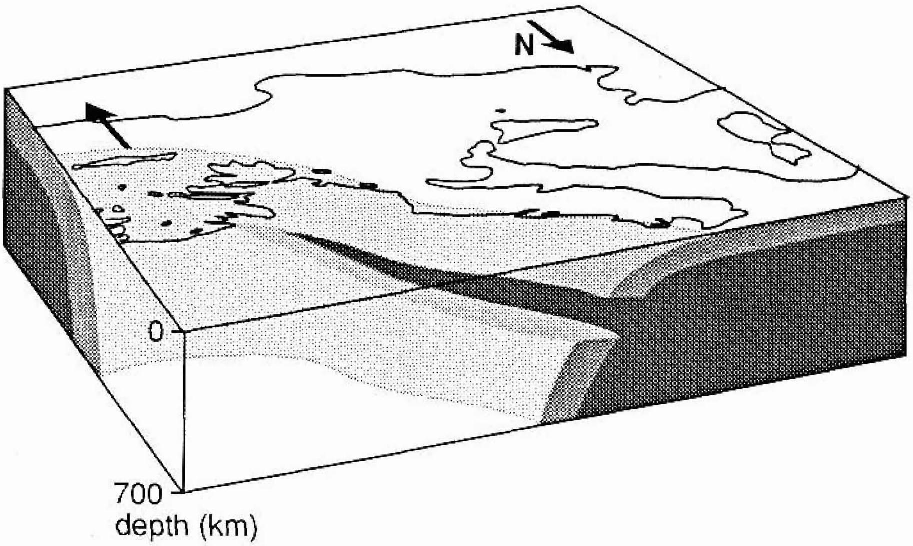


Fig. 8. Eastern Mediterranean. Schematic slab geometry for the Hellenic/Aegean subduction zone (interpretation of tomography results), as viewed from the Northeast (note North direction). The deep parts of the descending slab are detached, except in the region near Crete (left side of the figure). Arrow near Crete indicates direction of roll-back of the trench system.

of these is presented in figure 7. The section crosses the large zone of subducted lithosphere twice; once below Italy and once below the Dinarides. The apparent connection between both anomalies is a resolution artefact (also visible in layer 7 of figure 6). The Adriatic region plays a key role in our interpretation because we infer subduction along both its western and eastern borders, underneath the (present day) Italian Peninsula and in opposite direction underneath the Dinarides and Hellenides, respectively.

To summarize, we have interpreted the mapped velocity heterogeneity in terms of large scale subduction below the entire Alpine-Mediterranean belt from Spain to the Aegean. The subducted slabs are detached except for the subduction zone below the southern Aegean and perhaps for the Tyrrhenian subduction zone. We emphasize that many problems exists with the method of seismic tomography, the delay-time data, and the reliability of the tomographic results which prompt us to be cautious (see Spakman 1991 for a discussion). The interpretation we give here is the one we prefer and will be used in the next sections as the basis for a hypothesis for the large scale evolution of the entire Mediterranean region.

DETACHMENT OF SUBDUCTED SLABS

The tomographic results show evidence for a gap in the subducted lithospheric slab, both underneath the Dinarides-Hellenides (Hellenic/Aegean subduction zone and its extension in NW direction) and the Apennines-Tyrrhenian region.

Most noteworthy is the lateral extent of the gap. In the Hellenic subduction zone the detachment (gap) extends from the NW along strike to approximately the southeastern part of the Peloponnisos or the western tip of Crete. Figure 8 gives a schematic representation of our interpretation of the tomographic results for the Hellenic subduction zone. On the basis of the present-day structure we envisage the structure to be the result of a detachment process which started in the NW part of the zone and migrated in SW direction. For the Appennines/Tyrrhenian region our schematic interpretation is shown in figure 9, which constitutes a kind of mirror-type image relative to that in figure 8. In this subduction zone we consider slab detachment to have started in the northernmost end of the zone (near present-day northern Italy) followed by lateral migration along the strike of the zone towards present-day Calabria-Sicily. In figure 9 the slab is shown to have maintained its downdip continuity underneath Calabria-Sicily; as noted before, however, the slab may just have become detached in that segment as well.

The detachment process is essentially self-perpetuating, once detachment is triggered in a small segment of the convergent plate boundary. The weight of the initially small detached part (small in lateral extent) is partially transferred to the adjacent, still continuous segment(s). This will lead to a continuation of the tearing process in the direction along strike, which process we refer to as "lateral migration of slab detachment". Effectively this leads to as concentration of slab pull forces into a continuously decreasing part of the plate boundary. We hypothesize this to cause an increased tendency for roll-back and associated

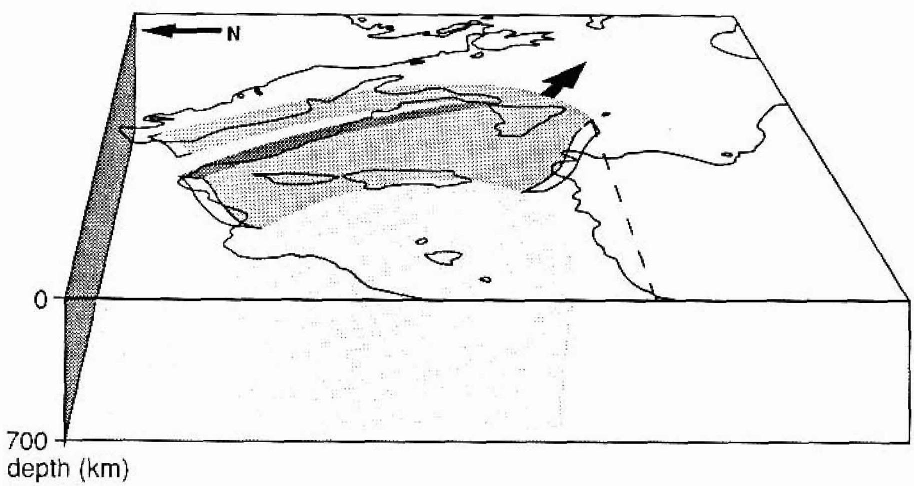


Fig. 9. Western-Central Mediterranean. Schematic slab geometry for the Apenennines/Tyrrhenian subduction zone (interpretation of tomography results), as viewed from west-northwestern direction. The slab is detached underneath the Italian peninsula. A continuous slab is shown underneath Sicily, although it is possible (not certain) that the slab is detached there, as well. Arrow near Sicily indicates direction of roll-back of trench system.

oceanward migration of the trench system. Extension of the continental margin (in general, overriding plate) and eventually the inception of back-arc spreading would be expected to accompany this process.

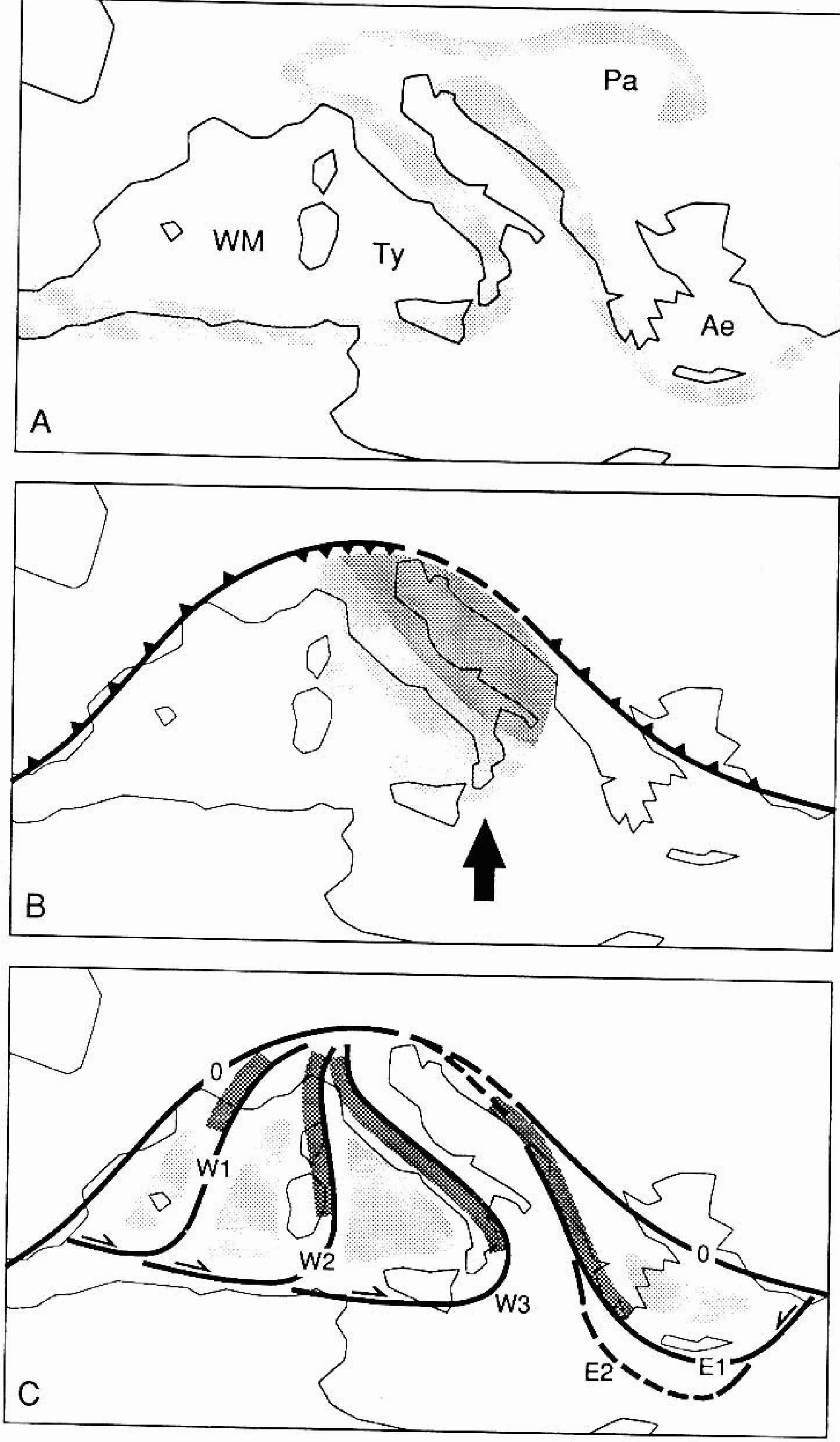
HYPOTHESIS FOR THE GEODYNAMICAL EVOLUTION OF THE MEDITERRANEAN REGION

The seismic structure of the Mediterranean upper mantle, the inferred slab detachment process, and its consequences outlined above (in combination with data concerning structure and age of the basins) lead us to formulate the following hypothesis for the geodynamical evolution of the Mediterranean region (see figure 10):

Mediterranean tectonics: from kinematics to dynamics

We start from two assumptions: (i) a situation in which subduction of oceanic lithosphere takes place in northward direction along the southern edge of the European (Eurasian) continent (see figure 10b), and (ii) by some mechanism slab detachment (as in figure 2) occurs in a segment of the plate boundary. This segment corresponds with the contact zone between the European continent and the Adria region (see Figure 10b), in other words the present location of the Alps. For this segment the underthrusting has been taken to be in southern direction (see figure 10b) in agreement with tomographic results (Spakman 1990). From the reconstruction by Dercourt et al. (1986) we infer that the initial stage of detachment occurred in the Eocene, or possibly already in the Paleocene.

If these two conditions are fulfilled, the self-perpetuating nature of the detachment process will lead to the lateral migration of slab detachment (along strike) in both western and eastern direction. The initial trench system (subduction zone) – see figure 10b – develops into two separate systems, one in the western/central part of the Mediterranean region and one is the eastern part (figure 10c). In each of these systems the concentration of slab pull forces into a smaller part of the plate boundary induces tensional stresses in the edge of the overriding plate (Europe) and oceanward migration of the trench system. The two trench systems shown in figure 10c represent the Apennines/Tyrrhenian system and the Dinarides/Hellenides or Aegean system, respectively, in consecutive stages of development. Following the changing geometry of the plate boundary and the subducted lithosphere the direction of the outward directed roll-back force gradually changes direction (see figure 10c). Continued lateral migration of slab detachment leads to a continued tendency for outward movement of the arc and development of larger regions of extensional tectonics and eventually back-arc spreading. In the Mediterranean region this process progresses from two sides and contributes strongly to the disappearance of the lithosphere originally located between the European and African continents. The difference in structural evolution between the western Mediterranean basins and the Aegean Sea basin implies that the outward migration of the western (Apennines/Tyrrhenian)



Pa
WM
Ty
Ae
A
B
0
W1
W2
W3
0
E2
E1
C

trench system is in a more advanced stage than the eastern branch (Hellenic/ Aegean). Continuation of the eastern system will lead to the further disappearance of the Mesozoic lithosphere presently underlying the eastern Mediterranean basin.

The various stages in the geodynamical evolution of the Mediterranean region are schematically displayed in figure 10c. For the western-central region this is done in three consecutive stages (starting from the original configuration "0", via W1 and W2 to W3). The convergent plate boundary migrates around the present-day Adria region, in response to the lateral migration of slab detachment. Stage W3 approximately corresponds with the present-day situation. In the eastern Mediterranean region the evolution started more recently (Late Miocene). The evolution is displayed in one step from the original plate boundary configuration (labelled "0") towards the present-day configuration (E1). The dashed line (E2) is the expected future configuration.

In the Hellenic arc the slab is still continuous underneath Crete and, hence, the process outlined above is taken to be still in operation. For the western subduction system we regard it to be possible that in the Calabria/Sicily segment of the plate boundary – towards which the detachment process has been migrating laterally – slab detachment has occurred, as well, thereby completing the process of lateral migration of slab detachment. Speculations on detachment in the Tyrrhenian zone have been made at least since 1972 on the basis of the discontinuous nature of the seismic Wadati-Benioff zone (e.g. Ritsema, 1972). In support of this possible detachment we mention the very recent uplift in Calabria

←

Fig. 10. Dynamic evolution of convergent plate boundaries in Mediterranean region.

a. (top): Map view of the present-day Mediterranean region (to be used for orientation in middle and bottom part of this figure 10). Shaded regions indicate approximate locations of plate boundaries. WM = Western Mediterranean Basin, Ty = Tyrrhenian Sea, Pa = Pannonian Basin, Ae = Aegean Sea.

b. (middle): Map view of initial position corresponding with situation postulated for interaction between the European continent and northern part of the African plate in Early Tertiary (Paleocene-Eocene). The arrow schematically indicates the northward relative motion of Africa with respect to Europe. Triangles indicate direction of underthrusting in subduction zone. Shaded area represents Adriatic region (Adria), which is considered to be part of the African plate. The darkest part approximately corresponds with the present-day Adriatic region.

c. (bottom): Evolution from initial situation (labelled "0") as in figure 10b, towards the present-day configuration. For the western-central Mediterranean region the evolution is displayed in three consecutive stages "W1" to "W3". The convergent plate boundary (solid lines labelled "0" "W1" to "W3") migrates around the present-day Adria region, in response to lateral migration of slab detachment. Stage "W3" approximately corresponds with the present-day situation (extension in Tyrrhenian Sea). In the eastern Mediterranean region the evolution started more recently (Late Miocene). It is displayed in one step from the original plate boundary configuration (labelled "0") towards the present-day configuration ("E1"). The dashed line ("E2") is the expected future configuration. The segments of the plate boundary (both in the western-central and the eastern region) where detachment has occurred are indicated by dark grey bands. Within the deforming edges of the European margin extension occurs (indicated by a medium grey). In this simplified representation the relatively minor convergence between Alps and Adria has been ignored.

(see also the section Implications below) and the nature of the gravity field and geoid in this region which differs strongly from that in the Aegean region (e.g. Remkes 1990).

Of special interest is the development of the western Mediterranean. The subduction zone along the southern and southeastern boundary of Iberia became divided in two main segments: one (the southernmost part) underneath the present Betic Cordilleras, and its extension towards the northeast as the other. The transition between the two is located near present-day Alicante. The role of these two segments in the evolution of the western Mediterranean differs significantly. In the northern (northeastern) segment the roll-back process came into operation and led to the development of a passive margin structure along the eastern edge of Iberia. As a result of the confining conditions imposed by its surroundings the Betic segment did not participate in the roll-back pattern and remained more or less stationary. The deeper part of the subducted slab probably became detached (Blanco and Spakman 1992) which event is likely to have affected the regional tectonics quite strongly. As such we propose this event as an alternative for the detachment of a thickened continental lithosphere as hypothesized by Platt and Vissers (1989). This alternative merely concerns the underlying mechanism; the consequences (extensional deformation in response to rapid unlift, see section below on Implications) would be similar to those proposed by Platt and Vissers (1989).

As a result of the large scale roll-back process in roughly eastern direction in the western Mediterranean, the North African margin has – in addition to some convergence – experienced a significant component of dextral motion, especially in the advanced stages of opening of the western Mediterranean basin. Such a motion is very much comparable with the strike-slip component in the eastern (Pliny-Strabo) part of the Hellenic Trench as described by Le Pichon et al. (1979).

We note that the rotation of Italy (VandenBerg 1979), which has been located (and to a large extent created) at or near the convergent plate contact since the Early Tertiary, and the recent concentration of back-arc spreading activity in the Tyrrhenian Sea naturally follow from the continuously changing geometry and dynamics of the system.

Several situations or processes may have provided the postulated trigger required to start the lateral migration of slab detachment: for example, interaction of spreading centres or transform faults with a trench system, or a significant change in the type of lithospheric structure (e.g. from oceanic to continental) arriving at the trench system. In this stage we merely assume (as stated above) that such a trigger occurred and do not wish to speculate on the details of such a process. Similarly, the closely related evolution of the Alps is beyond the scope of the present paper.

In figure 10b Adria has been indicated for identification purposes; we refer to Channell et al. (1979) and Mantovani et al. (1990) for a discussion of Adria as a promontory of the African plate. The interaction of this region with the southern edge of the Eurasian continent may have played a role in triggering the detachment process. So far we consider Adria to be a non-subducted remnant of the once much larger northern part of the African plate.

The pattern of deformation and motion (kinematic evolution) which we derive from the slab detachment process is not new. Furthermore, the hypothesis contains a natural sequence of events and changes; it does not contain details on the exact temporal history of the geodynamical evolution. By a comparison of model predictions (see below) and geological observations we can test the hypothesis and constrain the time constants involved. The most important of such constants is the rate of lateral migration of slab detachment. In our opinion, the merits of our hypothesis are that it provides a dynamic basis for the observed kinematic patterns (as incorporated for example in the reconstruction by Dercourt et al. 1986) involving rotation of continental blocks, migration of island arcs and opening of back-arc basins.

IMPLICATIONS

In this paper we primarily draw attention to the role of lateral migration of slab detachment in the formation and subsequent migration of island arc structures (like the Hellenic and Appennines/Tyrrhenian arcs) and associated regions of back-arc extension (Balearic Basin, Tyrrhenian and Aegean Seas). In addition, we consider a number of interesting implications.

Vertical motions, state of stress, sedimentation

Apart from the roll-back type of process discussed above, a detached slab structure as inferred (see figures 2, 8 and 9) has several very interesting geodynamical implications and consequences. These stem from the intrinsically transient nature of the process leading to the present structure. For a section of the plate margin underneath which detachment occurs the dynamic situation changes significantly and rapidly. In such a section the deeper part of the descending slab becomes detached from the lithosphere at the surface (trench). Hence, the gravitational force (slab pull) associated with the relatively dense sinking part no longer affects the dynamics of the plate contact region. This has two consequences: 1) the state of stress at the plate boundary suddenly changes, and 2) the plate boundary undergoes a rebound type of process, schematically illustrated in figure 2. Upon lateral migration of slab detachment these changes migrate along strike as well. The resulting structures are superimposed on existing structures and may add considerably to the complexity of the margin's structure.

Given the important role of both changes in state of stress and of vertical motions in a variety of geological (in particular tectonic) processes we envisage lateral migration of slab detachment to have implications for, among others: (1) fault patterns (2) basin formation and evolution, (3) tectonic transport of nappes, and (4) sedimentation patterns (on a regional scale; depocentre shifts). To this we add (5) volcanic activity (see below); the latter aspect differs from the other four in the sense that it does not result from changes in state of stress or

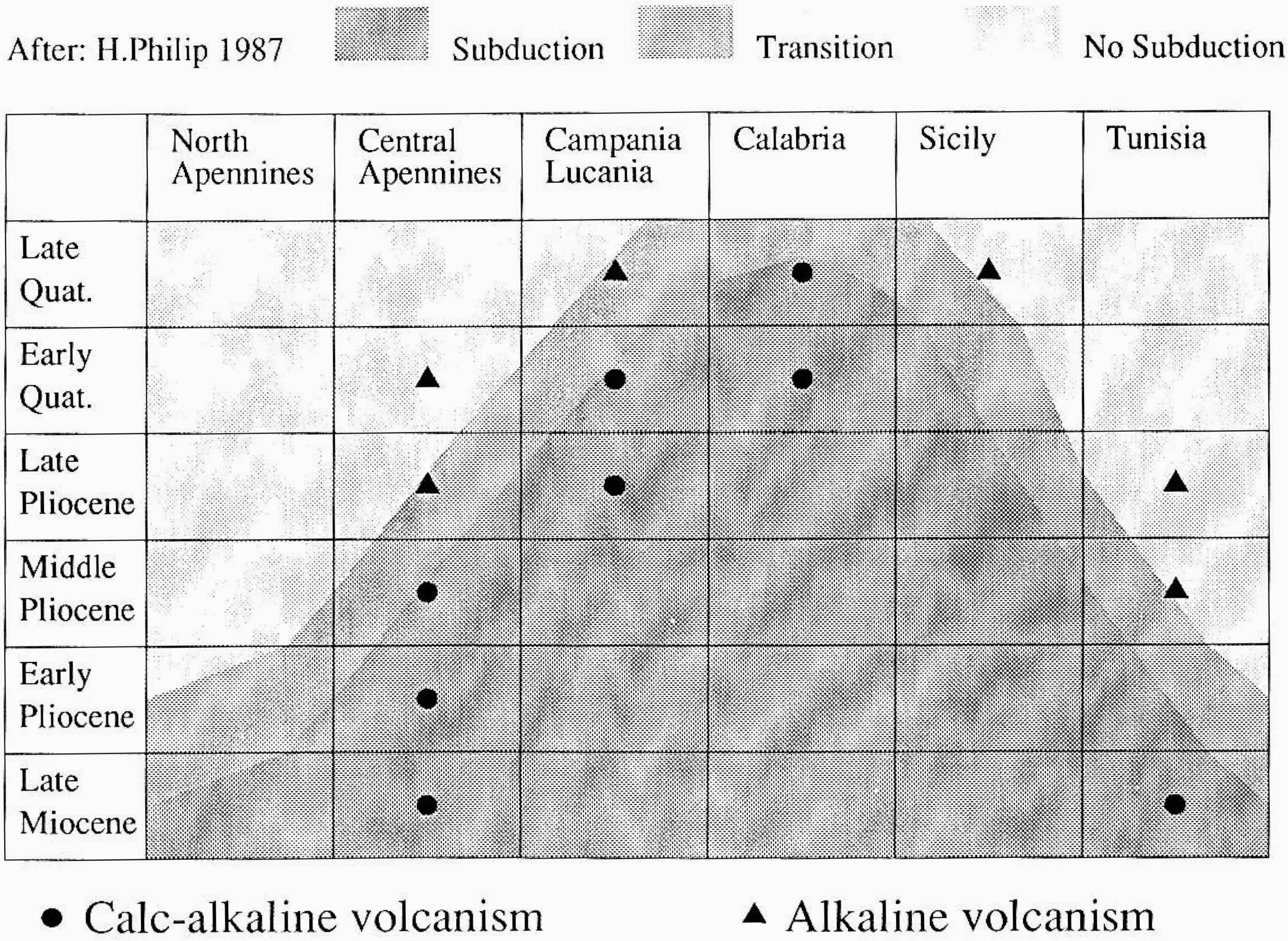


Fig. 11. Transition from calc-alkaline volcanism towards alkaline volcanism in Italy, Sicily and Tunesia as a function of time and space. From Philip (1987).

vertical motions, but from the changes in slab configuration in the upper mantle which may affect the distribution of source regions for magma formation (see e.g. Beccaluva et al. 1991).

Paleomagnetism

In general paleomagnetic data have greatly contributed to our understanding of the kinematic aspects of the evolution of the Mediterranean region (VandenBerg 1979, VandenBerg and Zijderveld 1982). For the Italian Peninsula, however, paleomagnetic studies by various groups have not led to an unambiguous result (see also Lowrie 1986). The interpretation of the data has been complicated by the fundamental problem concerning the tectonic significance of the data, the central issue being the allochtonous or autochtonous nature of the formations studied. Our hypothesis implies that the origin of the various parts of present-day Italian crust may vary significantly. In this hypothesis present-day Italy is the region of which the structure is the result of accretion and other tectonic processes along a convergent plate boundary over a period of at least several tens of million years involving strong horizontal migrations. It is envisaged that during this evolution material has been accumulated from basically two different types of sources: (1) the material may be (or may have been) part of the original African plate, either in its original position within this plate or having been scraped of that plate during convergence, or (2) the source region of the material may be the southern edges of the Iberian-European lithosphere; it may have been deposited or accreted at or near the trench region either in the present trench position or in an older configuration with subsequent transport along with the migrating convergent plate boundary. Depending on the time of deposition it may bear evidence of the entire – or only a part of – the history of the migrating plate boundary.

Volcanism

On the basis of the assumption that the geometry of the subducted slab (in particular: a continuous slab or a slab with detached lower part) affects the distribution and nature of source regions for arc volcanism our hypothesis predicts significant changes – both spatial and temporal – in the volcanic regions of the Mediterranean. The tomographic results indicate that subducted slab in the Cretan segment of the Hellenic (Aegean) subduction zone is still continuous with depth, whereas probably elsewhere in the Mediterranean (with the possible exception of Calabria/Sicily) the slab is detached. This leads us to predict that of all active volcanic regions in the Mediterranean area the present-day southern Aegean Sea volcanic region (with Thera/Santorini) shows the greatest resemblance with active volcanic arcs associated with subduction zones around the Pacific with continuous slabs. Depending on the stage of evolution of the subduction zone involved, other volcanic regions in the Mediterranean region should be expected to differ significantly from the Pacific arcs. We speculate that further analysis of the relation between slab geometry as a function of time and volcanic activity will shed light on the peculiar characteristics of Mediterranean volcanism (see a.o. Ninkovich and Hays 1972).

Again if we assume that changes in slab configuration in the upper mantle affect magma formation, spatial and temporal variations in volcanic activity may provide evidence for lateral migration of slab detachment. Figure 11 (after Philip 1987) shows the timing of a transition from calc-alkaline volcanism towards alkaline volcanism as a function of location in Italy/Sicily and Tunesia. If slab detachment as a process could account for this type of petrological change, the along strike migration in time from nothern Italy towards the south would qualitatively agree with the type of pattern expected if lateral migration of slab detachment has occurred in the upper mantle underneath Italy. If we assume lateral migration of slab detachment has occurred and has caused the change in petrology, we can infer a horizontal migration velocity of approximately 15 cm/year (for the detachment tear) from the space time relation shown.

CONCLUSIONS

The slab detachment process and the working hypothesis presented for the geodynamical evolution of the Mediterranean are based on tomographic results concerning the upper mantle structure. The process of lateral migration of slab detachment appears to be an interesting new element in the dynamics of the lithosphere. In particular the formation and evolution of island arcs and their back-arc regions are adequately accounted for. We propose that this process may have occurred not only in the Mediterranean subduction zones. Since it requires only a localized trigger of the detachment process it may have happened in other subduction zones, as well.

With slab detachment as a key element we present a hypothesis for the Cenozoic evolution of the Mediterranean region, with emphasis on the dynamical basis for observed kinematic patterns. On the baiss of this hypothesis quantitative predictions can be derived for several areas in the Mediterranean realm which can be tested against geological and geophysical data. Of special interest in this respect are the spatial and temporal variations – implicit in the model of lateral migration of slab detachment – in state of stress, in vertical motions, and most likely also in volcanic activity along the strike of convergent plate margins.

ACKNOWLEDGEMENT

MJRW thanks Profs. J.L.R. Touret and J.E. van Hinte for the invitation to participate in the Seminar associated with the Cours du College de France by Prof. X. Le Pichon, and Dr. M.J. van Bergen for discussion on volcanism in the Mediterranean region.

REFERENCES

Anderson, H. and J. Jackson – The deep seismicity of the Tyrrhenian Sea. Geophys. J.R. Astron. Soc. **91**, 613–637 (1987).

Angelier, J., N. Lyberis, X. Le Pichon, E. Barrier, and P. Huchon – The tectonic development of the Hellenic arc and the Sea of Crete: a synthesis. Tectonophysics **86**, 159–196 (1982).

Beccaluva, L, P. Di Girolamo and G. Serri – Petrogenesis and tectonic setting of the Roman Volcanic Province, Italy, Lithos **26**, 191–211 (1991).

Biju-Duval, B., J. Dercourt and X. Le Pichon – From the Tethys Ocean to the Mediterranean Seas: A plate tectonic model of the evolution of the western Alpine system. In: Structural history of the Mediterranean basins (Eds.: Biju-Duval, B. and L. Montadert), Editions Technip, Paris, 143–164 (1977).

Blanco, M.J. and W. Spakman – The P-wave velocity structure of the mantle below the Iberian Peninsula. Tectonophysics, (in press) (1992).

Buforn, E., A. Udias and J. Mezcua – Seismicity and focal mechanisms in southern Spain. Bull. Seism. Soc. A. **78**, 2008–2024 (1988).

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

Channell, J.E.T., B.D'Argenio and F. Horvath – Adria, the African promontory, in Mesozoic Mediterranean paleogeography. Earth Science Reviews **15**, 213–292 (1979).

DeJonge, M.R. and M.J.R. Wortel – The thermal structure of the Mediterranean upper mantle: a forward modelling approach. Terra Nova **2**, 609–616 (1990).

Dercourt, J., L.P. Zonenshain, L.-E. Ricou, V.G. Kazmin, X. de Pichon, A.L. Knipper, C. Grandjacquet, I.M. Sbortshikov, J. Geyssant, C. Lepvrier, D.H. Perchersky, J. Boulin, J.-C. Sibuet, L.a. Savostin, O. Sorokthin, M. Westphal, M.L. Bazhenov, J.P. Lauer and B. Biju-Duval – Geological evolution of the Tethys belt from the Atlantic to the Pamirs since the Lias. Tectonophysics **123**, 241–315 (1986).

Dewey, J.F., W.C. Pitman, W.B.F. Ryan and J. Bonnin – Plate tectonics and evolution of the Alpine system. Bull. Geol. Soc. Amer. **84**, 3137–3180 (1973).

Dewey, J.F., M.L. Helman, E. Turco, D.H.W. Hutton and S.D. Knott – In: Alpine tectonics (Eds.: Coward, M.P., D. Dietrich and R.G. Park), Kinematics of the western Mediterranean, Geol. Soc. Special Publications No. **45**, 265–283 (1989).

Elsasser, W.M., – Seafloor spreading as thermal converction. J. geophys. Res. **76**, 1101–1112 (1971).

Erickson, A.J., G. Simmons and W.B. F. Ryan – Review of heat flow data from the Mediterranean and Aegean Seas. In: Structural history of the Mediterranean basins (Eds.: Biju-Duval, B. and L. Montadert), Editions Technip, Paris, 263–279 (1977).

Giardini, D. and M. Velona – The deep seismicity of the Tyrrhenian Sea. Terra Nova, 3, 57–64 (1991).

Jeffreys, H. and K.E. Bullen – Seismological Tables, British Association for the Advancement of Science, London (1940).

Kastens, K., J. Mascle et al. – ODP Leg 107 in the Tyrrhenian Sea: Insights into passive margin and back-arc basin evolution. Bull. Geol. Soc. Am. **100**, 1140–1156 (1988).

Kissel, C. and C. Laj – The Tertiary geodynamical evolution of the Aegean arc: a paleomagnetic reconstruction. Tectonophysics **146**, 183–201 (1988).

Le Pichon, X. – Land-locked oceanic basins and continental collision: the Eastern Mediterranean as a case example. In: Mountain Building Processes (Ed.: K. Hsu), Academic Press, London, pp. 201–211 (1982).

Le Pichon, X. and J. Angelier – The Hellenic arc and trench system: a key to the evolution of the Eastern Mediterranean area. Tectonophysics **60**, 1–42 (1979).

Le Pichon, X.J. Angelier, J. Aubouin, N. Lyberis, S. Monti, V. Renard, H. Got, K. Hsu, Y. Marty, J. Mascle, D. Matthews, D. Mitropoulos, P. Tsoflias and G. Chronis – From subduction to transform motion: a Seabeam survey of the Hellenic Trench system. Earth Planet. Sci. Lett. **44**, 441–450 (1979).

Le Pichon, X. and J. Angelier – The Aegean Sea. Phil. Trans. Royal Soc. Lod., A300, 357–372 (1981).

Le Pichon, X., F. Bergerat and M.-J. Roulet – Plate kinematics and tectonics leading to the Alpine belt formation; a new analysis. Geological Society of America, Special Paper 218, 111–131 (1988).

Lowrie, W. – Paleomagnetism and the Adriatic promontory. Tectonics **5**, 797–807 (1986).

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

Malinverno, A. and W.B.F. Ryan – 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 (1986).

Mantovani, E., D. Babucci, D. Albarello and M. Mucciarelli – Deformation pattern in the central Mediterranean and the behavior of the African/Adriatic promontory. Tectonophysics **179**, 63–79 (1990).

McKenzie, D.P. – Active tectonics of the Alpine-Himalayan belt: the Aegean Sea and surrounding regions. Geophys. J.R. Astron. Soc. **55**, 217–254 (1978).

Mercier, J.L. – Extensional-compressional tectonics associated with the Aegean arc: comparison with the Andean Cordillera of south Peru – north Bolivia. Phil. Trans. Royal Soc. Lond. **A300**, 337–355 (1981).

Meulenkamp, J.E. – Field guide to the Neogene of Crete. Publ. Dept. Geol. Paleontol., Univ. of Athens, **A32**, 1–32 (1979).

Ninkovich, D. and J.D. Hays – Mediterranean island arcs and origin of high potash volcanoes. Earth Planet Sci. Lett. **16**, 331–345 (1972).

Papazachos, B.C. – Active tectonics in the Aegean and surrounding area. In: Seismic hazard in Mediterranean regions (Eds: Bonnin, J., M. Cara, A. Cisternas and R. Fantechi), Kluwer Academic Publishers, Dordrecht, pp. 301–331 (1988).

Philip, H – Plio-Quaternary evolution of the stress field in the Mediterranean zones of subduction and collision. Annales Geophysicae **5B**, 301–320 (1987).

Platt, J.P. and R.L.M. Vissers – Extensional collapse of thickened continental lithosphere: a working hypothesis for the Alboran Sea and Gibraltar arc. Geology **17**, 540–543 (1989).

Remkes, M.J.N. – Eastern Mediterranean gravity potential and the Hellenic subduction process. Terra Nova **2**, 563–568 (1990).

Ritsema, A.R. – Deep earthquakes of the Tyyrhenian Sea. Geol. Mijnbouw **51**, 541–545 (1972).

Savostin, L.A., J.-C. Sibuet, L.P. Zonenshain, X. Le Pichon, and M.-J. Roulet – Kinematic evolution of the Tethys belt from the Atlantic Ocean to the Pamirs since the Triassic. Tectonophysics **123**, 1–35, (1986).

Smith, A.G. and N.H. Woodcock – Tectonic syntheses of the Alpine-Mediterranean region: a review. In: Alpine-Mediterranean geodynamics (Eds: Berckhemer, H. and K. Hsu), Geodynamics Series, AGU/GSA, USA, 15–38 (1982).

Snieder, R., – Large scale waveform inversions of surface waves for lateral heterogeneity – II: Application to surface waves in Europe and the Mediterranean. J. Geophys. Res. **93**, 12067–12080 (1988).

Spakman, W. – Subduction beneath Eurasia in connection with the Mesozoic Tethys. Geol. Mijnbouw **65**, 145–153, (1986).

Spakman, W. – Upper mantle delay time tomography with an application to the collision zone of the Eurasian, African and Arabian plates (Ph.D. Thesis, University of Utrecht). Geologica Ultraiectina **53**, 200 pp. (1988).

Spakman, W. – Tomographic images of the upper mantle below central Europe and the Mediterranean. Terra Nova **2**, 542–553 (1990).

Spakman, W. – Delay time tomography of the upper mantle below Europe, the Mediterranean, and Asia Minor. Geophys. J. Int. 107, 309–332 (1991).

Spakman, W. and G. Nolet – Imaging algorithms, accuracy and resolution in delay time tomography. In: Mathematical Geophysics: a survey of recent developments in seismology and geodynamics, (Eds.: Vlaar, N.J. et al.), Reidel, Dordrecht, 155–188 (1988).

Spakman, W., M.J.R. Wortel, M.J.R. and N.J. Vlaar – The Hellenic subduction zone: a tomographic image and its geodynamic implications. Geophys. Res. Lett. **15**, 60–63 (1988).

Suhadolc, P. and G.F. Panza – The European-African collison and its effects on the lithosphere-asthenosphere system. Tectonophysics **146**, 59–66 (1988).

VandenBerg, J. – Paleomagnetism and the changing configuration of the western Mediterranean area in the Mesozoic and Cenozoic eras (Ph. D. Thesis University of Utrecht). Geologica Ultraiectina, 20, pp. 179 (1979).

VandenBerg, J. and J.D.A. Zijderveld – Paleomagnetism in the Mediterranean area. In: Alpine-Mediterranean Geodynamics (Eds.: Berckhemer, H. and K. Hsu), Geodynamics Series Volume 7, AGU/GSA, 83–112 (1982).

Vlaar, N.J. and M.J.R. Wortel – Lithospheric aging, instability and subduction. Tectonophysics **32**, 331–351 (1976).

Wortel, R. – Seismicity and rheology of subducted slabs. Nature **296**, 553–556 (1982).

Wortel, M.J.R. and N.J. Vlaar – Subduction zone seismicity and the thermo-mechanical evolution of down-going lithosphere. Pageoph **128**, 625–659 (1988).

Wortel, M.J.R., S.D.B. Goes and W. Spakman – Structure and seismicity of the Aegean subduction zone. Terra Nova **2**, 554–562 (1990).