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REVIEW: GEOPHYSICS

Subduction and Slab Detachment in the Mediterranean-Carpathian Region

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Seismic tomography models of the three-dimensional upper mantle velocity structure of the Mediterranean-Carpathian region provide a better understanding of the lithospheric processes governing its geodynamical evolution. Slab detachment, in particular lateral migration of this process along the plate boundary, is a key element in the lithospheric dynamics of the region during the last 20 to 30 million years. It strongly affects arc and trench migration, and causes along-strike variations in vertical motions, stress fields, and magmatism. In a terminal-stage subduction zone, involving collision and suturing, slab detachment is the natural last stage in the gravitational settling of subducted lithosphere.

Among the geological features in the Mediterranean region that continue to capture Earth scientists' attention are the arcuate mountain belts of the Betics, the Maghrebides, the Apennines, the Alps, the Carpathians, and the Dinarides-Hellenides (Fig. 1). In particular, in view of the evidence for collision in the Alps, the geodynamical evolution of the region has generally been considered in the context of the convergence of Europe and Africa. In spite of convergence acting as the primary plate tectonic process, several regions exhibit large-scale extension, such as the Alboran Sea, the Algero-Provençal and Tyrrhenian Sea basins, the Pannonian Basin, and the Aegean region. These are located inside the arcuate belts (Fig. 1). The extension started about 30 million years ago (Ma) (*1*). The combination of convergence, with expected compression, and extension has been a long-standing enigmatic feature of the region (*2, 3*).

Understanding these complexities requires the recognition that the Mediterranean Sea region exhibits important lateral variations in crustal and upper mantle structure. Early studies of the deep structure (*4*) and heat flow (*5*) revealed distinct differences between the crust and upper mantle in the western-central Mediterranean [such as the Algero-Provençal and Tyrrhenian Sea basins (Fig. 1)] and those in the eastern Mediterranean. With the advent of plate tectonics, attempts were made to interpret the structure and to formulate the evolution of the Mediterranean region in terms of plate tectonic concepts. In agreement with the prominent role of seismicity in the early stages of plate tectonics, the occurrence of intermediate-depth and deep earthquakes provided the first clue toward interpreting the Mediterranean (*6–8*) and Carpathian (*9*) regions in the new framework, with subduction as an important element. The higher temperatures in the western Mediterranean basins (*5*) were associated with spreading activity in the wake of the moving continental blocks of Corsica, Sardinia, and (parts of) Italy (*10–12*), for the rotation of which paleomagnetic evidence was accumulating (*13, 14*). The growing geological and geophysical data sets, and newly developing ideas, were gradually integrated into tectonic reconstructions. By the mid to late 1980's, the various reconstructions had converged toward a small set of rather similar reconstructions (*15–17*). A noteworthy aspect is that they showed great similarity with the ideas formulated by Argand as early as 1922 (*18*). They describe, in a kinematic way, the Mediterranean region as a plate boundary zone, involving collision and migrating subduction zones accompanied by extension. The eastern Mediterranean basins (such as Ion, Adr, and Lev; Fig. 1) are part of the African plate and were formed in the Mesozoic. The western basins (A-P and Tyr; Fig. 1) constitute a deformed plate boundary region of the Eurasian plate and were created by back-arc extensional activity in the Late Oligocene to recent times.

The concept of a land-locked basin setting (*19*) provided a basis for a dynamical analysis of the region. The land-locked basin setting of the Mediterranean region leads, by slab roll-back (*20*), to the consumption of the oceanic lithosphere between Africa and Europe and to extension in the lithosphere above the subduction zone (*21*). In a kinematic sense, the slab roll-back process also accounts for the relative motions of about 3 cm/year in the Hellenic trench region, whereas the overall Africa-Eurasia convergence rate is only 5 to 10 mm/year (*22*). The same land-locked basin setting, albeit on a smaller scale, is assumed for the region now occupied by the Pannonian Basin and Carpathians (Fig. 1) (*23, 24*): an oceanic embayment which has disappeared due to subduction. In contrast with the Mediterranean case, however, this disappearance is complete. Studying the Mediterranean region in close combination with the Carpathian-Pannonian region is useful because the regions show similarities and differences, the study of which provides a more complete picture of the underlying processes.

Subduction plays a central role in most current models about the geodynamics of the region. Here, we summarize and discuss some recent and ongoing developments in studies of the evolution of this process in the region, and of its relation to geological processes at or near Earth's surface. We focus on the step from structure and kinematics to dynamics. In doing so, we concentrate on the Apennines-Maghrebides arc and Hellenic arc in the western and eastern Mediterranean, respectively, and the Carpathian arc (Fig. 1).

Seismic Velocity Structure

Seismic tomography models of parts, or all of the Mediterranean and surrounding region (*25–38*) have been fundamental for locating and delineating the subducted lithosphere involved in its Cenozoic evolution. Two important early observations are that (i) much more slab is imaged than is reflected by seismicity, implying that seismicity is a poor indicator for the amount of subducted lithosphere and the period of subduction involved (*25–27*) and that (ii) not all slabs in the Mediterranean region seem to be connected to the lithosphere at the surface, which has been interpreted as an indication for slab detachment (*25, 26, 29–31*). We will briefly review mantle structure using results from a recent tomography model of *P*-wave velocity heterogeneity (*39*). Subducted slabs appear as positive seismic velocity anomalies (*40*).

The depth slices at 200 and 600 km depth presented in Fig. 2, A and B, show structural features (*41*) which were also detected in many earlier tomographic models. At 200 km depth, slab structures are found below the Betic-Alboran region (*27, 29, 30, 35, 38*), the

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Calabrian arc (*27, 29, 32–34, 36, 37*), the Aegean region (*26, 29, 34, 35*), and the east Carpathians (Vrancea) (*29, 34, 42*). In the western Mediterranean, the Betic-Alboran slab is rather isolated in the mantle and is only seismically active at depths of about 640 km (*43*). The Apenninic-Calabrian slab is the dominant feature in the central Mediterranean. Below Calabria, the slab broadens with depth (Fig. 2, A through D), in particular below 200 km, where it starts to underlie the central and southern Apennines and the east Tyrrhenian basin (Fig. 2D). Near the base of the upper mantle, it broadens (Fig. 2B). Two vertical slices (Fig. 2, E and F) in dip direction (i.e., opening direction of the southern Tyrrhenian basin) reveal the slab lying flat on the upper to lower mantle boundary, also imaged, to some extent, in another study (*36*). Directly below the Calabrian arc, the slab is imaged as a continuous high-velocity anomaly (Fig. 2E) (*33, 36, 37*). In contrast, the slab below the central-southern Apennines has no high-velocity connection to crustal levels and is entirely overlain with low velocities (*27–29, 34, 36*) (Fig. 2, A, C, and F). The analysis of *S*-wave velocities (*44*) corroborates these results. This peculiar geometry has led to the interpretation of slab detachment below the Apeninnes (*27, 31*). Detachment of the Calabrian segment remained uncertain (*27, 31*). Although studies (*33, 36, 37, 44*) suggest a continuous slab (Fig. 2E) in the upper 200 km of the mantle, small detachment gaps (<25 km) cannot be excluded (*33, 44*). Below the northern Apennines, all regional models (*27–29, 32, 34, 36*) possess a slab-like anomaly across the upper mantle. In some models (*32, 34, 36*) it is imaged as a continuous anomaly (Fig. 2A), whereas in other models (*27–29*) an interruption with low velocities is imaged between 150 and 200 km. Inefficient *S*-wave propagation as observed for paths from deep Tyrrhenian events to northern Apeninnic stations (*44*) would also require low seismic velocities.

Remnants of deep subduction below the Pannonian basin have been detected earlier (*27, 29, 34*) but are not outlined as well as in the results presented here (Fig. 2, A, B, G, and H). Nowhere along the Carpathian arc is a continuous slab imaged from the surface down to the bottom of the upper mantle (Fig. 2, A, G, and H). The localized Vrancea slab, with seismicity down to about 200 km, reaches a depth of about 300 to 350 km, corroborating earlier results (*42*) regarding a deep aseismic portion of the slab. We interpret the flat-lying, high-velocity anomaly at the bottom of the upper mantle (Fig. 2, B, G, and H) as subducted lithosphere that could sink to the deeper mantle as a result of roll-back and slab detachment along-strike of the Carpathian arc. The Vrancea portion of the Carpathian slab seems continuous down to about 350 km.

Patterns of detached slab below the western Mediterranean and the Pannonian regions are similar. A different slab structure, however, is found in the mantle below the Aegean, where the slab penetrates into the lower mantle (Fig. 2, I and J) (*29, 35*). The Aegean slab appears to be the most western part of the Neo-Tethys subduction (*45*). In the upper mantle, between 100 km and 200 km of depth, some models (*26, 29*) showed signs of slab detachment below the Dinarides and western Greece whereas another did not (*34*). In all models, a continuous slab is imaged below Crete and the southern Peloponnesos (southwestern Greece). In the results presented here (*39*), a strong change in amplitude is found below the Peloponnesos (Fig. 2A). In cross section (Fig. 2J), only small amplitudes are imaged between 150 to 400 km below western Greece, in contrast to the strong amplitudes of the slab subducting below Crete (Fig. 2I).

From Structure and Kinematics to Dynamics

The seismic velocity structure is like a snapshot of a possibly still-moving object: it represents the present-day structure of a part of the dynamic Earth. In the present context, we discuss two ways of using this information in process-oriented geodynamic investigations.

Testing tectonic reconstructions. The seismic velocity structure can be used to test models for the kinematic evolution (often referred to as tectonic reconstructions) of a region. In an early example of this approach (*46, 47*), tectonic reconstructions of the Mediterranean-Carpathian region (*15–17*) were used to predict, by numerical modeling, the present-day upper mantle structure. The merits of this approach are twofold: (i) the available results of geological studies of various kinds, including information on timing, are incorporated into the analysis, and (ii) the three-dimensional upper mantle velocity structure was not used in the tectonic reconstructions and therefore constitutes indepen-

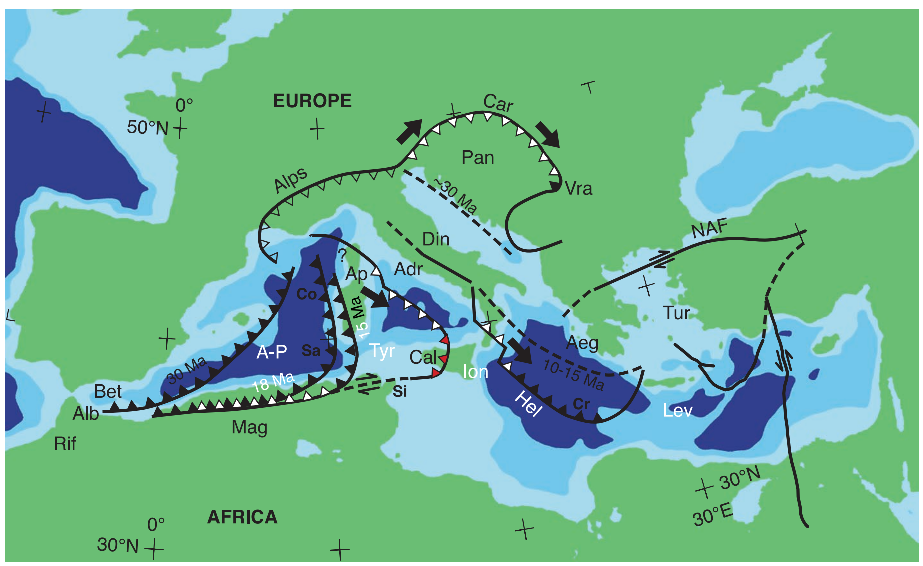


Fig. 1. Plate boundary evolution in the Mediterranean-Carpathian region. The large black arrows indicate the inferred directions of lateral migration of slab detachment along the Apennines-Calabria arc, the Hellenic arc and the Carpathian arc. The blue colors indicate bathymetry. Dark blue: deeper than 2.5 km; intermediate blue: 2.5 to 1.0 km; light blue: shallower than 1.0 km. The darkest blue color approximately corresponds with the presence of oceanic lithosphere. The Aegean Sea is underlain by (extended) continental lithosphere. The lithosphere below the Adriatic Sea is probably also continental. In all arcs, the outermost curves with the sawtooth pattern indicate the present location of the convergent boundary. The sawteeth point in the direction of subduction or underthrusting. Black sawteeth indicate where the subducting slab is considered to be continuous. White sawteeth indicate plate boundary segments where slab detachment is assumed to have occurred. Red sawteeth (Calabria) indicate that slab detachment may have taken place recently. Segments with open sawteeth (Alps) are not discussed in detail. For the western Mediterranean region, three stages in the migration of the plate boundary are displayed. Black and white sawteeth have the same meaning as above, but now refer to the situation at the indicated times in the evolution. For the Carpathian and Aegean region, the dashed lines only approximately indicate the position of the convergent boundary at the indicated times. For the Aegean, 10 to 15 Ma refers to the recent phase of extension in the southern Aegean; earlier extension started at least as early as about 25 Ma. Adr, Adriatic Sea; Aeg, Aegean Sea; Alb, Alboran Sea; Ap, Apennines; Cr, Crete; A-P, Algero-Provençal Basin; Bet, Betics; Cal, Calabria; Car, Carpathians; Co, Corsica; Cr, Crete; Din, Dinarids; Hel, Hellenic Arc/Trench; Ion, Ionian Sea; Lev, Levantine Basin; Mag, Maghrebides (from the Rif to Sicily); NAF, North Anatolian Fault; Pan, Pannonian Basin; Rif, Rif; Sa, Sardinia; Si, Sicily; Tur, Turkey; and Tyr, Tyrrhenian Sea or Basin.

dent information against which the reconstructions are tested. The principal outcome of these studies was an important one: the basic aspects of the tectonic reconstructions with east-southeastward migrating convergent plate boundaries in the western Mediterranean (Fig. 1) and subduction underneath the Hellenic arc agreed, in terms of predicted versus imaged slab length, with the upper mantle structure. Therefore, they can be used as a basis for further investigations. If we combine the tectonic reconstructions with results from studies on the effect of trench migration (*48–51*), the peculiar flat-lying slab at the base of the upper mantle is also accounted for and, in fact, supports roll-back.

From structure via hypothesis to process. As indicated above, gaps in the structure of subducted slabs suggest that slab detachment has occurred in several areas. Slab detachment, as such, is not a new feature in lithospheric dynamics; early seismicity-based studies speculated on the existence of detached slabs (*52*). However, we added a new element to the concept, the lateral migration of slab detachment (*31*). We hypothesized that a small tear in the slab initiates lateral rupture propagation (Fig. 3). The physical basis for this process stems from the notion that the distribution of the slab pull is affected by a tear in the slab. In the segment of the plate boundary where the slab is detached, the slab pull is not transferred to the lithosphere at the surface. Instead, the weight of the slab is at least partially supported by the still continuous part of the slab (Fig. 3), thereby concentrating the slab pull force. Stress concentration, with down-dip tension, near the tip of the tear causes further propagation. From the seismic tomography results, we determined three regions where the migrating slab detachment process may have occurred (or may still be occurring):

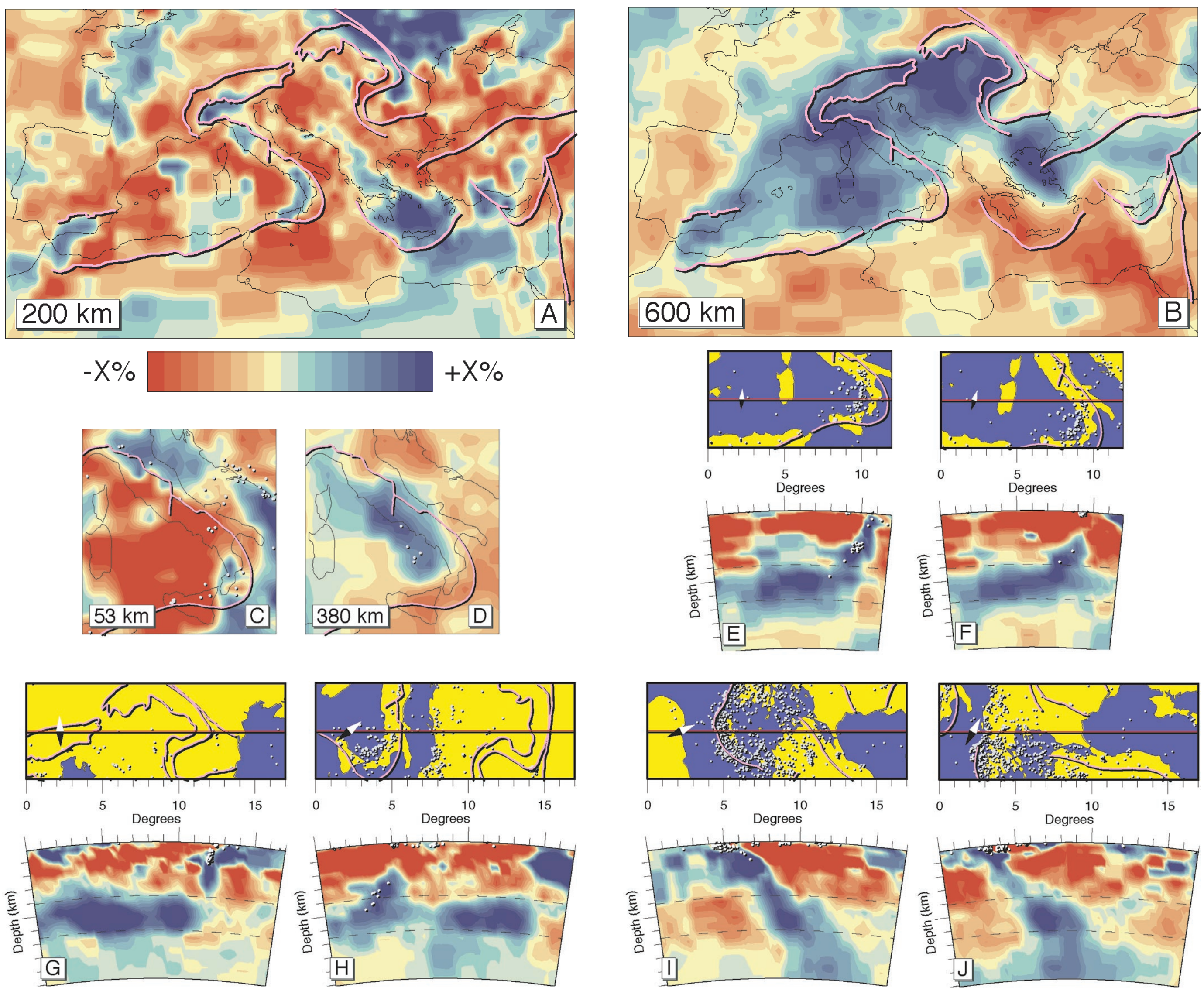


Fig. 2. Tomographic images of *P*-wave velocity anomalies (*39*) for the Mediterranean/Carpathian region. Colors indicate seismic wave speed anomalies as percentage deviations from average mantle velocities given by the one-dimensional reference model ak135 (*113*). (**A**) and (**B**) show map view images at 200 and 600 km depth, respectively. Projection and map dimensions are the same as in Fig. 1. Shadowed pink lines show the tectonic outlines similar to Fig. 1. Contouring scale ranges between –X% and +X%, where X = 2.5 in (A), (C), and (D), and X = 1.5 in (B) and (E) through (J). (**C** and **D**) Blow-up for the Apennines-Calabria region at 53 and 380 km depth. (**E** through **J**) Vertical slices computed along great-circle segments (red line in map); above each slice, the map provides geographical orientation. The white arrow of the compass needle points north. The horizontal axis is in degrees along the great-circle segment defining the slice (straight red line in map). The vertical axis shows depth with tics at 100-km intervals. White dots indicate earthquakes. The dashed lines in the tomographic section indicate the 410 and 660 km discontinuities. (E) and (F) are sections through the Calabrian arc and southern Apenines. (G) and (H) are sections through the Carpathian-Pannonian region and (I) and (J) through the Aegean region.

the Apennines-Calabria arc (and its extension into northern Africa, the Maghrebides), the Carpathian arc, and the Hellenic arc (*31, 53*). The inferred directions of migration are indicated in Fig. 1.

Lateral Migration of Slab Detachment: Testing the Hypothesis

Accepting the intrinsic limitations to spatial resolution studies, we decided to focus on (i) tests of the validity of the basic mechanical properties of the hypothesized process and (ii) tests of model predictions derived from the hypothesis against independent observables (e.g., field data). In the first category of tests, the stress distribution in a subducted slab model affected by a small tear was investigated (*54*). Under certain conditions—low or zero plate convergence velocity—the resulting stress concentration near the tip of the tear causes further propagation. The inferred conditions correspond with the situation in the Mediterranean and Carpathian regions. The postulated initiating small tear may have various causes, the most prominent of which is the arrival of continental lithosphere at the trench of a subduction zone, after a period of oceanic lithosphere subduction (*55*). From time-dependent thermo-mechanical modeling (*55*), the temperature of the subducting continental lithosphere was identified as the principal parameter controlling the depth of slab detachment. Analysis of strength and stress in the subducting lithosphere gives estimates of detachment depths, which may be as shallow as 30 km. Other causes of slab detachment may be envisaged, e.g., the arrival of a transform fault, spreading ridge segment, or any other weakness zone at the trench. In fact, it would be extremely fortuitous for slab detachment to occur simultaneously along an entire plate boundary. If it happens in a particular segment (*55*), the stress concentration mechanism would operate, and tear migration would set in.

The tests of the second category were carried out in the three regions where slab detachment may have occurred: the Apennines-Calabria arc, the Carpathian arc, and the Hellenic arc. In search of diagnostic properties of the migrating slab detachment process, we noted (*31*) that one of most pertinent aspects of the process is the redistribution and concentration of the slab pull force. We envisage arc migration through roll-back, vertical motions (Fig. 4), and stress field as plate boundary features that are directly affected.

The redistribution and concentration of the slab pull is expected to affect the roll-back type of migration of convergent plate margins in a land-locked basin setting. It should lead to an increase in arc curvature (Fig. 4). In the case where a continuous segment of the slab has a free end in the horizontal direction, the slab pull concentration will induce rotation of the slab and, therefore, of the plate boundary. The Hellenic arc, the Carpathian arc (increasing curvature), and the Apennines-Calabria arc (rotation) exhibit the predicted behavior. We note that slab detachment can also occur in a collisional setting (such as the Alps and Betics) where roll-back is inhibited (*55, 56*).

The predicted pattern of vertical motions near the plate boundary is specific: there should be extra subsidence where the slab pull force is concentrated in the still-continuous part of the slab, followed by a rebound (uplift) when the propagating tear passes underneath the plate margin segment involved. Numerical modeling results on rebound directly after slab detachment give estimates for uplift (rebound) of the order of 2 to 6 km (*56*). In a detailed study of the distribution of depocenters in the foredeeps of the Apennines-Calabria arc, Van der Meulen and co-workers (*57, 58*) found a distinct migration of depocenters from the northern Apennines toward the southeast over a period of about 8 to 9 million years (My). Evidence was found for rebound of about 500 m at a minimum, setting in rapidly after the area ceased to be a depocenter (*58–60*). Depocenter shifts similar to those obtained for the Apennines were found earlier for the Carpathian foredeeps (*61*). In this arc, the migration started in the western Carpathians around 16 Ma and migrated along the arc in an eastward direction (arrows in Fig. 1).

For the same (slab pull–based) reasons, we also predict that the stress field along the plate boundary will show the expression of the tear propagation (Fig. 1) and the associated change in dynamics. Temporal variations in the stress field in the Aegean region (*62*), such as rotations of the stress tensor, agree with tear propagation in the southeastern direction, since the Late Pliocene (*63*). Also for the Pannonian region, stress analysis (*64*) indicated the influence of temporal changes in subduction-related forces, in combination with collision-related forces acting in the Eastern Alps.

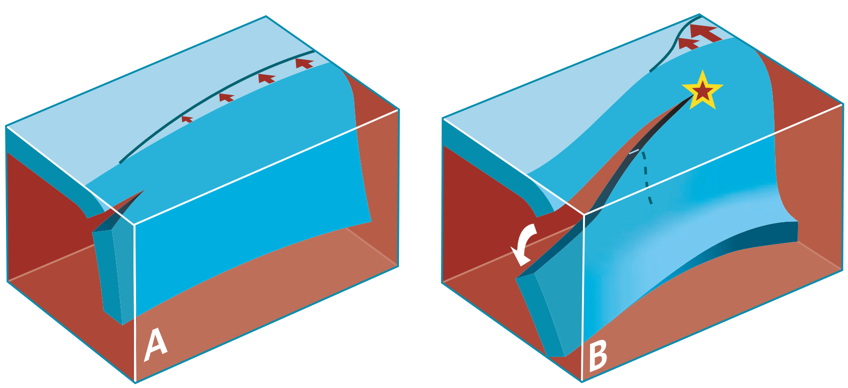


Fig. 3. Lateral migration of slab detachment: a schematic representation [after (*31*)]. An initially small tear in the slab (**A**) propagates approximately horizontally and (**B**) develops into a large tear (*54*). The tear propagation is not expected to take place at a uniform rate; slab detachment most likely occurs episodically, in segments. Eventually the entire slab may break off. The slab pull—the gravitational force associated with the cold, and hence, dense subducted lithosphere—is concentrated in the still continuous part of the slab, leading to pronounced arc curvature. The star indicates seismic activity in the stress concentration region. The initial small tear may develop at one side end of a slab (as indicated here), but also somewhere in an intermediate segment of the subduction zone. The right-hand side of the boxes may, depending on the subduction zone involved, represent the actual side end of a slab, as well as an approximate plane of symmetry. The detached part of the slab does not necessarily remain coherent. The evolving stress distribution may lead to breaking up into separate parts of the detached slab, schematically indicated by the dashed line.

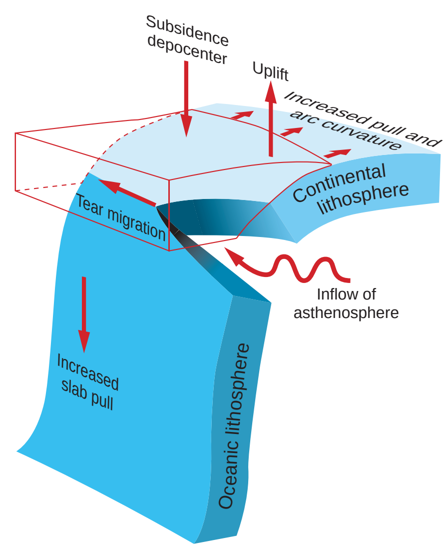


Fig. 4. Plate boundary processes predicted to accompany lateral migration of slab detachment. The concentration of slab pull forces causes a pattern of subsidence (depocenter development) and uplift migrating along strike. It also enhances arc migration (roll-back). Asthenospheric material flows into the gap resulting from slab detachment and causes a specific type of variable composition magmatism, of finite duration, and possibly mineralization.

Another class of implications of the slab detachment process concerns geodynamic processes with a strong thermal component such as magmatism, with mineralization as a closely related process, and metamorphism (*31, 65*). The basis for this is the possibility that slab detachment occurs at such a shallow depth that asthenospheric material can rise to fill the newly formed gap (Fig. 4), thereby reaching levels as shallow as 50 km or less (*55, 65*). This provides an advective-type source of heat, of a transient nature. The detachment process exposes the crust and mantle parts of the subducting lithosphere to high asthenospheric temperatures, causing melt generation, and even allows for the melting of the inflowing asthenospheric material itself. Von Blanckenburg and co-workers (*66, 67*) compiled observations on timing and composition concerning magmatism in the Alps—in particular, along the Periadriatic line—and proposed that they can be explained by the occurrence of slab detachment. Because no clearly defined upper mantle structure is available as a basis for a hypothesis, we cannot consider this situation to be a test. For the Carpathians, however, there is such a basis (Fig. 2), and the results of studies on Carpathian magmatism (*68–70*) can be taken as evidence of support of the migrating slab detachment hypothesis. For the Apennines, the temporal-spatial variations in depocenter shifts (*57–60*) and those in magmatic activity (*71, 72*) correlate to such a degree that exploring the possibility of a common origin (i.e., lateral migration of slab detachment) seems promising. Finally, observational evidence was presented for a causal relationship between the occurrence of shallow slab detachment and the distribution of mineralized zones in the European Alpine belt (*73*).

The Geodynamical Evolution of the Mediterranean-Carpathian Region

The number of different approaches to the dynamic aspects of the regional evolution is small. They can be summarized as Africa-Eurasia convergence and its consequences, delamination of the lithospheric mantle (*74*) and closely related mechanisms, and roll-back in a land-locked basin setting. The first and third approaches address arc migration in combination with (back-arc) extension, whereas the second is concerned with extension only.

Africa/Arabia-Eurasia convergence. In the pioneering attempts to relate the regional seismicity to plate tectonics (*7, 8*), the approach was primarily kinematic. The southwestern motion of the Hellenic arc, in combination with the westward motion along the North Anatolian Fault Zone (Fig. 1) of Turkey, was suggested to result from the continental collision between Arabia and Eurasia. After the land-locked basin concept was introduced, the discussion on the extension in the Aegean region focused on the role of the westward push of Turkey versus that of the slab pull–related forces acting in the Hellenic trench region (*75*). Similarly, the eastward migration of the Calabrian arc and the extension in the Tyrrhenian Sea (*76*), and the eastward motion of material in the eastern Alps and the Carpathian region (*77*) have been attributed to the Africa-Eurasia convergence and resulting collisional and extrusive processes.

For the Aegean region, its present activity and the advances in geodetic methods allow a detailed quantitative approach. Numerical modeling of stress field and deformation, combined with observations, indicated that primarily an outward-pulling effect associated with the Hellenic trench is needed (*78*). Only a secondary contribution of the push of Turkey is needed to improve the fit to the displacement and the stress field orientation data. From a recent analysis of global positioning system (GPS) measurements (*79*), this conclusion was confirmed and strengthened, in particular on the basis of the observed increase in the relative motion with respect to Eurasia, from Turkey to the Aegean. In spite of the apparent primary role of roll-back, at least for the Aegean region, plate convergence should be considered to be a significant background process, as was done in several studies (*77, 80–82*). Adopting an approach directed toward explaining the regional tectonics solely on the basis of plate–kinematically induced forces (*76, 83, 84*), and not accepting slab pull as a possible driving force, is less satisfactory. Thus, it seems that the direct role of Africa/Arabia-Eurasia convergence in arc migration and associated extension is secondary to that of roll-back in a land-locked basin setting. The stage for the latter mechanism has been set, however, by the Africa/Arabia-Eurasia convergence.

Delamination of the lithospheric mantle and gravitational collapse of an orogenic wedge. Apart from roll-back and extrusion due to convergence several other extension generating processes have been proposed as relevant in the Mediterranean region (*1, 85*): uplift and extension after delamination of thickened lithosphere (*74*), and, mechanically related but formulated in a specific setting and geometry, the collapse of a thickened wedge of crustal material at a convergent plate boundary (*80, 86*).

Delamination of the lithospheric mantle as a process responsible for the generation of the large extensional basins in the Mediterranean region is unlikely. The geometry of the high velocity anomalies in the upper mantle (Fig. 2) and their agreement with the predicted anomalies based on lithosphere subduction, in combination with the paleomagnetic evidence for rotation of continental blocks (*13, 14*), appear to rule out delamination. This does not preclude the possible validity of this mechanism on a more restricted scale, such as in the Betics (*74*), or in other regions where the difference between a subduction history ending with slab detachment and lithospheric thickening with subsequent delamination is difficult to assess and may, in fact, be small.

Collapse of an orogenic wedge of crustal material has been proposed for the Tertiary evolution of the Aegean region (*85–87*). Variations in Africa-Eurasia convergence rates are suggested to account for alternating episodes of extension and compression (*86*). This process predominantly pertains to crustal levels. The main phases of collapse are attributed to pronounced roll-back in a low convergence rate situation. The formation of an orogenic wedge requires a convergent boundary in the period involved. Evidence for a long slab subducted in the region (Fig. 2, I and J) agrees with this required condition. Thus, this approach and the previous one point to a major role of the roll-back process.

Land-locked basin setting, roll-back, and slab detachment. Slab detachment is the natural last stage of the subduction process in the

Fig. 5. Horizontal components of the motion vector solutions (velocities relative to stable Eurasia) for stations in the Mediterranean region. This is an updated version of fig. 2 in Noomen *et al.* (*102*). The solution, with code number SSC(DUT)98C02, is based on a combination of satellite laser ranging and GPS data. The error ellipses represent 3σ values. Although more detailed observations are available for separate parts of the region [e.g., (*79*)], this overall figure displays the difference between motions for the Apennines-Calabria arc and those for the Hellenic arc.

land-locked basin setting. Lateral migration of slab detachment concentrates the slab pulling forces and thereby also concentrates the arc migration inherent to the roll-back process (Figs. 3 and 4). If slab detachment is complete, roll-back stops. Here, we review the extent to which the migrating slab detachment process contributes to explain the geodynamical evolution of the Mediterranean-Carpathian region, since about 30 Ma. Although at that time the land-locked basin setting, in the strictest sense (*19, 21*), may not have been achieved yet (in particular along the eastern boundary of the region), the convergence rates were so low (*17*) that the mechanical configuration already could be described as such. Starting from convergent plate boundaries in the western Mediterranean (at ~30 Ma) and in the eastern Mediterranean (~10 to 15 Ma), slab roll-back is considered to have caused trench migration (Fig. 1). Once the trench migration results in the contact between the trench and the continental lithosphere, the downgoing slab may become detached (*55*). In the western Mediterranean this happenened (*81*) first along the north African continental margin, at about 18 Ma. By 15 to 16 Ma, the northward subducting part of the African lithosphere had become detached (without a clear migration pattern), which implied that slab pull forces were only acting along the north-south trending eastern plate boundary (Fig. 1). This is proposed to be the cause for the opening of the Tyrrhenian Basin and the rotation of the Apenninic plate boundary (*81, 82*). To allow this rotation the Apenninic-Calabrian slab had to separate along a vertical tear from the north African slab. The rotating Apenninic-Calabrian trench system again encountered continental lithosphere, this time of the Adriatic lithosphere to the east (Fig. 1). This encounter probably first occurred in the northern part of the trench system. Again, slab breakoff takes place (8 to 9 Ma) which then migrates southeastward (Fig. 1). Increasingly, the action of the slab pull forces becomes limited to, and concentrated in, the southern Apennines/Calabria segment (*57–60*). This accounts for the development of enhanced roll-back with corresponding extensional activity in the back-arc region of the southern Tyrrhenian Sea and the inception of ocean spreading activity in the Vavilov and Marsili Basins (*12*).

This model predicts that the plate boundary segment between northern Africa and Sicily cannot be a subduction zone; it should be a dextral transform boundary zone (Fig. 1). The regional tectonics support this inference (*88*), and tomographic images indicate the absence of subducted lithosphere underneath this boundary segment (*81*). North-south compressive features, however, are observed on Sicily (*89*). They may be attributed to the slow Africa-Eurasia convergence. The transform fault type of setting was used to propose an interesting explanation for the location and activity of Mount Etna (*90*).

On the basis of earlier work (*27–29*), we also proposed slab detachment for the northern Apenninic arc (*31*). As discussed above, however, the inferences made from the many models of mantle structure that appeared in the last decade, including from our own models (*28, 29, 35, 39*), are not equivocal. Slab detachment below the northern Apennines is not required to trigger detachment below the central Apennines. The trigger may have resulted from incipient subduction of the continental lithosphere (*55*) below the northern-central Apennines, after which the tear migrated southward and possibly even northward.

For the Aegean region of the eastern Mediterranean, studies (*78, 79, 85–87*) have indicated that roll-back is an important process. For this region, the role of slab detachment in this roll-back process and the relationship between the subduction zone evolution and back-arc deformation are topics of active and future research. Whereas structural evidence for slab detachment is inconclusive, several studies have indicated that slab detachment would explain observations of stress field variations (*63*), arc migration, and back-arc deformation (*91, 92*).

For the western part of the Carpathian-Pannonian region, the starting configuration of the convergent plate boundary is schematically indicated by the dashed line (Fig. 1). The indicated timing (~30 Ma) is uncertain (*24*). Eastward directed extrusion caused by collision in the eastern Alps (*77*) may have contributed to the initiation of subduction along this boundary, possibly of a dextral transform nature (dashed line in Fig. 1), and the subsequent migration. Roll-back presumably caused further east-northeastward migration of the trench, which led to collision with the continental margin, first at about 16 Ma in the north, in the area of the present-day western Carpathians (*93*). This provided the local cause for slab detachment (*55*), which from there started to migrate eastward (Fig. 1) toward the Vrancea Zone. The roll-back of the convergent plate boundary led to the subduction of the entire oceanic embayment, and came to a stop when all around the embayment the trench system reached the surrounding continental margins. The remnants of the oceanic embayment are found in the lower part of the upper mantle (Fig. 2, B, G, and H). The migrating convergent plate boundary allowed for the east-northeastward motion of the Alcapa block in the north and the east-southeast motion of the Tisza-Dacia block in the south, into the present-day Pannonian region (*24, 94*).

A close relation between the subduction processes occurring in the Alps and those in the Carpathian arc is expected (*77, 95, 96*). Also, the slab detachment process is, quite convincingly, invoked to play a major role in the Alpine evolution (*66*). In contrast with the Carpathian region, however, models of the upper mantle structure have not provided a solid basis to work on along the same lines as outlined above for the other orogenic belts. Therefore, the evolution of the subduction process and in particular the possible role of slab detachment in the Alps remains in the realm of suggested explanations for observed phenomena, without compelling structural evidence.

In summary, the migrating slab detachment process is inferred to have started at 15 to 16 Ma along the North African margin (albeit here without clear migration), at 8 to 9 Ma in the northern-central Apennines, at about 16 Ma in the Carpathians, and more recently, possibly in the Pliocene (about 4 Ma), in the Hellenic subduction zone. Parts of the three arcs, presumably being in different stages of the process, provide the opportunity to study the migrating slab detachment process in different stages. The migration of Apenninic-Calabrian plate boundary (and its early Maghrebides part) in the western Mediterranean and of the Hellenic arc in the east jointly lead to the consumption of the older "Mediterranean" lithosphere belonging to the African plate (Fig. 1). The lithosphere below the Ionian Sea, Levantine Basin, and Adriatic Sea are the present-day remnants. In the Pannonian-Carpathian region, the lithosphere of the postulated oceanic embayment has entirely disappeared by subduction.

Is slab detachment completed? Dealing with a transient process such as migrating slab detachment, one may wonder whether the process is still active in any of the arcs or whether it is completed. The plate boundary segments of the three arcs where slab continuity is possibly maintained are indicated in Fig. 1 by the filled sawteeth: the Vrancea zone in the southeastern Carpathians, and the southern segment of the Hellenic arc, near Crete (both in black), and the Calabrian part of the Apenninic-Calabrian arc (in red). These are the segments which exhibit intermediate depth or even deep seismicity (Fig. 3). Of these three, the Cretan segment shows no indication of slab detachment. For the Vrancea and Calabria segments, detachment has been the subject of debate [(*97–100, 31*); see also (*101*)]. In all tomographic models, resolution is insufficient to provide the definitive answer. The most direct way to test the continuity of the slab is to investigate possible manifestations of an active slab pull force. For the Cretan and Calabrian segments evidence can be inferred from observations of the arc migration. Geodetic observations (Fig. 5) indicate an active outward migration of the southern Hellenic arc, whereas the outward migration velocity in the Calabrian arc, where shallow seismicity is almost absent (*98, 36*), is near zero (*79, 102*). This implies a continuous slab in the Cretan segment. Because the outward migration of the Calabrian arc is not hampered by continental collision (*103*), this observation supports a detached slab in this arc segment. For the same reason, the observation that the region has exhibited strong uplift, since about 0.7 Ma (*104*), is interpreted as evidence of slab detachment (*57, 104*).

A similar test for the Vrancea segment is not possible; outward migration is blocked by the collision with the eastern European continental crust, resulting in uplift as evidenced by fission-track data (*105*). In this case, however, evidence concerning the action of a slab pull force can be found in the focal mechanisms of the intermediate depth earthquakes. They uniformly exhibit nearly vertical tensional axes (*101*), which favors a continuous slab at least down to the maximum focal depth of nearly 200 km (*101*). The pull force required to produce the tension is provided by the slab present in the tomographic images at depths between about 200 and 350 km (Fig. 2G). In the Calabrian seismic zone, however, the state of stress is characterized by downdip compression (*98, 99*), which again is indicative of the slab being detached. This detachment may have taken place at a shallower depth [about 30 to 40 km (*55*)] than previously envisaged.

Thus, the available data lead to a different conclusion for each of the three arcs (Fig. 1). In the southern segment of the Hellenic arc the downgoing slab is continuous. Apart from some uncertainties in the northern Apennines, slab detachment in the central-southern Apennines and in Calabria is completed, in the Calabrian part only very recently. The completion of slab detachment implies the termination of roll-back in the Tyrrhenian region because there is no engine to drive the roll-back. Consequently, in this region the Africa-Eurasia convergence becomes the principal lithosperic scale process. In the Carpathian arc, slab detachment is nearly completed; only in the Vrancea region is the slab still continuous. Thus, for the Carpathian arc as a whole, migrating slab detachment is in its final stage (Fig. 1) (*106*).

The key to the underlying mechanism for the geodynamical evolution of the Mediterranean region is hidden in the name, Mediterranean Sea, or in geodynamical terms: oceanic lithosphere surrounded by continental lithosphere. The potential energy stored in the oceanic lithosphere—relative to that of the surrounding continental lithosphere and, at a deeper level, the ambient upper mantle—drives subduction, roll-back, and, finally, slab detachment and its associated processes. Slab detachment is the natural last stage in the gravitational settling of subducted lithosphere in a terminal stage subduction zone. This evolution also applies to the Pannonian-Carpathian region. We expect that the understanding gained in the present study area will shed light on the evolution of other tectonically active regions, as well as ancient subduction zones and orogenic belts.

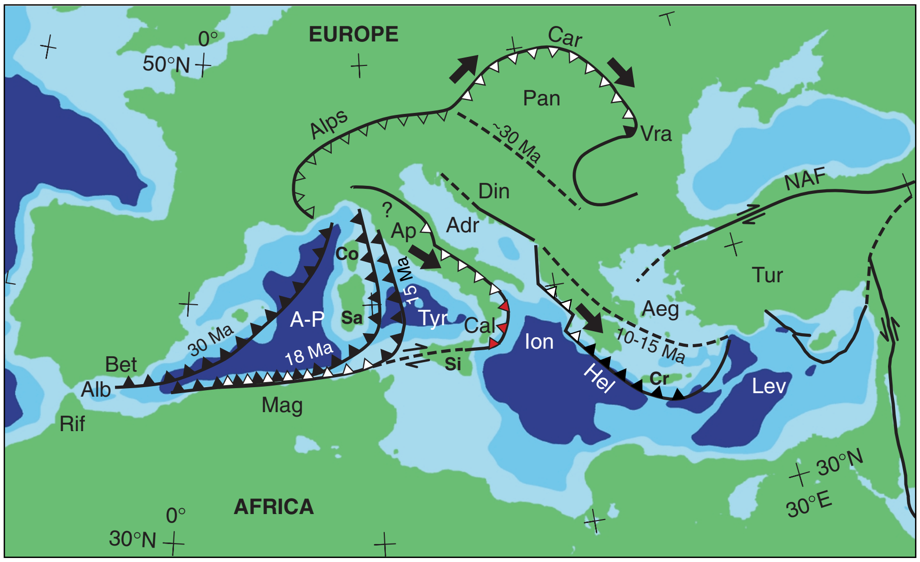
References and Notes

1. L. Jolivet, D. Frizon de la Motte, A. Mascle, M. Séranne, in *The Mediterranean Basins: Tertiary Extension Within the Alpine Orogen*, B. Durand, L. Jolivet, F. Horvath, M. Seranne, Eds., *Geol. Soc. London Spec. Publ. 156* (1999), pp. 1–14.
2. F. Horvath, H. Berckhemer, in *Alpine-Mediterranean Geodynamics*, H. Berckhemer, K. Hsu, Eds., Geodynamics Series **7** (American Geophysical Union, Washington, DC, 1982), pp. 141–174.
3. B. Durand, L. Jolivet, F. Horvath, M. Séranne, Eds., *The Mediterranean Basins: Tertiary Extension Within the Alpine Orogen*, *Geol. Soc. London Spec. Publ. 156* (1999).
4. G. Payo, *Bull. Seismol. Soc. Am.* **59**, 23 (1969). For a more recent overview of the regional structure, see (*107*).
5. E. J. Erickson, thesis, Massachusetts Institute of Technology, Cambridge, MA (1970).
6. A. R. Ritsema, *Verh. K. Ned. Geol. Mijnbouwkd. Genoot.* **26**, 105 (1969).
7. D. P. McKenzie, *Nature* **226**, 239 (1970).
8. D. McKenzie, *Geophys. J. R. Astron. Soc.* **30**, 109 (1972).
9. C. Roman, *Nature* **228**, 1176 (1970).
10. J. M. Auzende, J. Bonnin, J. L. Olivet, *J. Geol. Soc. London* **129**, 607 (1973).
11. J.-P. Rehault, G. Boillot, A. Mauffret, in *Geological Evolution of the Mediterranean Basins*, D. J. Stanley, F. C. Wezel, Eds. (Springer-Verlag, Berlin, 1985), pp. 101–129.
12. K. Kastens *et al.*, *Geol. Soc. Am. Bull.* **100**, 1140 (1988).
13. J. van den Berg, J. D. A. Zijderveld, in *Alpine-Mediterranean Geodynamics*, H. Berckhemer, K, Hsu, Eds., Geodynamics Series **7** (American Geophysical Union, Washington, DC, 1982), pp. 83–112.
14. R. van der Voo, *Paleomagnetism of the Atlantic, Tethys, and Iapetus Oceans* (Cambridge Univ. Press, New York, 1993), p. 411.
15. J. Dercourt *et al.*, *Tectonophysics* **123**, 241 (1986).
16. J. Decourt *et al.*, *Mem. Soc. Geol. Fr.* **154**, 159 (1990).
17. J. F. Dewey, M. L. Helman, E. Turco, D. H. Hutton, S. D. Knott, in *Alpine Tectonics*, M. P. Coward, D. Detrich, R. G. Park, Eds., *Geol. Soc. London Spec. Publ. 45* (1989), pp. 265–283.
18. E. Argand, *Compte-rendu du 13e Congrès Géologique International*, Brussels (1924), pp. 171–372.
19. X. Le Pichon, in *Mountain Building Processes*, K. J. Hsu, Ed. (Academic Press, London, 1982), pp. 210–211. The convergence between the Eurasian and African lithosphere with their nonfitting continental margins led to the situation in which a remnant of oceanic lithospere of Mesozoic age was locked in between the converging continents. The basin is referred to as a land-locked basin.
20. W. M. Elsasser, *J. Geophys. Res.* **76**, 1101 (1971).
21. The relevance of the land-locked basin setting (*19*) stems from the gravitational instability of old oceanic lithosphere entering a subduction zone (*20, 108*). When the plate convergence rate is zero or very nearly so, the potential energy implicit in this instability cannot be released by sinking of the lithosphere in the subduction zone's downdip (nonvertical) direction. Instead, it starts to sink vertically, thereby causing an oceanward migration—usually called roll-back—of the plate boundary (trench) location. The adjacent upper plate (the "overriding plate") responds to the pressure reduction by extension, accompanied by subsidence. Le Pichon (*19*) mainly concentrated on the Aegean region; roll-back in the Calabrian (or Tyrrhenian) subduction zone was proposed in (*109*).
22. C. DeMets, R. G. Gordon, D. F. Argus, S. Stein, *Geophys. J. Int.* **101**, 425 (1990).
23. L. Royden, F. Horvath, J. Rumpler, *Tectonics* **2**, 63 (1983).
24. L. Csontos, *Acta Vulcanol.* **7**, 1 (1995).
25. W. Spakman, *Geol. Mijnbouw* **65**, 145 (1986).
26. ———, M. J. R. Wortel, N. J. Vlaar, *Geophys. Res. Lett.* **15**, 60 (1988).
27. W. Spakman, *Terra Nova* **2**, 542, (1990).
28. ———, *Geophys. J. Int.* **107**, 309 (1991).
29. ———, S. Van der Lee, R. D. Van der Hilst, *Phys. Earth Planet. Inter.* **79**, 3 (1993).
30. M.-J. Blanco, W. Spakman, *Tectonophysics* **221**, 13 (1993).
31. M. J. R. Wortel, W. Spakman, *Proc. K. Ned. Akad. Wet.* **95**, 523 (1992).
32. A. Amato, B. Alessandrini, G. B. Cimini, in *Seismic Tomography: Theory and Practice*, H. M. Iyer, K. Hirahara, Eds. (Chapman & Hall, London, 1993), pp. 361–396.
33. G. Selvaggi, C. Chiarabba, *Geophys. J. Int.* **121**, 818 (1995).
34. C. Piromallo, A. Morelli, *Ann. Geofis.* **40**, 963 (1997).
35. H. Bijwaard, W. Spakman, E. R. Engdahl, *J. Geophys. Res.* **103**, 30055 (1998).
36. F. P. Lucente, C. Chiarabba, G. B. Cimini, D. Giardini, *J. Geophys. Res.* **104**, 20307 (1999).
37. G. B. Cimini, *Geophys. Res. Lett.* **26**, 3709 (1999).
38. A. Calvert *et al.*, *J. Geophys. Res.* **105**, 10871 (2000).
39. H. Bijwaard, W. Spakman, *Geophys. J. Int.* **141**, 71 (2000). This model is an update of model BSE of Bijwaard *et al.* (*35*). It is obtained by nonlinear inversion using model BSE as starting model. The nonlinear inversion procedure incorporates the effects of three-dimensional wave speed variations on seismic ray geometry.
40. The slightly higher than average seismic wave speeds in upper mantle slabs are mainly caused by the lower temperatures in the slab with respect to the surrounding mantle (*47*).
41. Similar to the previous tomography study (*35*), the tomographic model is supported by a large range of sensitivity tests with synthetic velocity models. So-called "spike" tests (*110*), with blocks varying in size from 0.6 to 6 degrees, and "layer-cake" tests (*35*) are used to estimate resolution on varying length scales and for different structures. Sensitivity test results indicate that for most of the region the resolvable structural details are of the order of 100 km at 200 km depth, and of the order of 250 km at 600 km depth.
42. M. C. Oncescu, *Tectonophysics* **106**, 305 (1984).
43. E. Buforn, A. Udias, R. Madariaga, *Pure Appl. Geophys.* **136**, 375 (1991).
44. G. Mele, *Geophys. Res. Lett.* **25**, 2877 (1998).
45. R. van der Voo, W. Spakman, H. Bijwaard, *Earth Planet. Sci. Lett.* **171**, 7 (1999).
46. M. R. de Jonge, M. J. R. Wortel, W. Spakman, *Tectonophysics* **223**, 53 (1993).
47. ———, *J. Geophys. Res.* **99**, 12091 (1994).
48. R. van der Hilst, R. Engdahl, W. Spakman, G. Nolet, *Nature* **353**, 37 (1991).
49. D. Olbertz, M. J. R. Wortel, U. Hansen, *Geophys. Res. Lett.* **24**, 221 (1997).
50. U. R. Christensen, *Earth Planet. Sci. Lett.* **140**, 27 (1996).
51. R. W. Griffiths, R. I. Hackney, R. D. van der Hilst, *Earth Planet. Sci. Lett.* **133**, 1 (1995).
52. B. Isacks, P. Molnar, *Rev. Geophys. Space Phys.* **9**, 103 (1971).
53. M. J. R. Wortel, W. Spakman, *Terra Nova (Abstr. Suppl.)* **5**, 97 (1993).
54. S. Yoshioka, M. J. R. Wortel, *J. Geophys. Res.* **100**, 20223 (1995).
55. S. Y. M. Wong, A. Ton, M. J. R. Wortel, *Geophys. Res. Lett.* **24**, 2095 (1997).
56. S. J. H. Buiter, thesis, Utrecht University, Utrecht, Netherlands (2000). Giunchi *et al.* (*111*) numerically investigated whether present-day surface motions show a signature of slab detachment several millions of years ago, and found no surface uplift. These authors, however, did not include the dynamical

setting prior to detachment and the process of detachment itself in their simulations.
57. M. J. van der Meulen, J. E. Meulenkamp, M. J. R. Wortel, *Earth Planet. Sci. Lett.* **154**, 203 (1998).
58. M. J. van der Meulen, thesis, Utrecht University, Utrecht, Netherlands (1999).
59. ———, T. J. Kouwenhoven, G. J. van der Zwaan, J. E. Meulenkamp, M. J. R. Wortel, *Tectonophysics* **315**, 319 (1999).
60. M. J. van der Meulen, S. J. H. Buiter, J. E. Meulenkamp, M. J. R. Wortel, *Tectonics* **19**, 300 (2000).
61. J. E. Meulenkamp, M. Kovac, I. Cicha, *Tectonophysics* **266**, 301 (1996).
62. J. L. Mercier, D. Sorel, K. Simeakis, *Ann. Tectonicae* **1**, 20 (1987).
63. P. Th. Meijer, M. J. R. Wortel, *Geophys. Res. Lett.* **23**, 439 (1996).
64. G. Bada, thesis, Vrije Universiteit, Amsterdam (1999).
65. J. H. Davies, F. von Blanckenburg, *Earth Planet. Sci. Lett.* **129**, 85 (1995).
66. F. von Blanckenburg, J. H. Davies, *Tectonics* **14**, 120 (1995).
67. F. von Blanckenburg *et al.*, *Schweiz. Mineral. Petrogr. Mitt.* **78**, 55 (1998).
68. I. Seghedi, I. Balintoni, A. Szakacs, *Lithos* **45**, 483 (1998).
69. M. Nemcok, L. Pospisil, J. Lexa, R. A. Donelick, *Tectonophysics* **295**, 307 (1998).
70. P. R. D. Mason, I. Seghedi, A. Szakacs, H. Downes, *Tectonophysics* **297**, 157 (1998).
71. G. Serri, F. Innocenti, P. Manetti, *Tectonophysics* **223**, 117 (1993).
72. M. Wilson, G. Bianchini, in *The Mediterranean Basins: Tertiary Extension Within the Alpine Orogen*, B. Durand, L. Jolivet, F. Horvath, M. Seranne, Eds., *Geol. Soc. London Spec. Publ. 156* (1999), pp. 141–168.
73. H. de Boorder, W. Spakman, S. H. White, M. J. R. Wortel, *Earth Planet. Sci. Lett.* **164**, 569 (1998). The European Science Foundation (ESF) programme on Geodynamics and Ore Deposit Evolution (GEODE) specifically addresses the tectonic setting of mineralized zones.
74. J. P. Platt, R. L. M. Vissers, *Geology* **17**, 540 (1989).
75. T. Taymaz, J. Jackson, D. McKenzie, *Geophys. J. Int.* **106**, 433 (1991).
76. E. Mantovani, D. Albarello, C. Tamburelli, B. Babbucci, *J. Geodyn.* **21**, 35 (1996).
77. L. Ratschbacher, W. Frisch, H.-G. Linzer, *Tectonics* **10**, 257 (1991).
78. P. Th. Meijer, M. J. R. Wortel, *Tectonics* **16**, 879 (1997).
79. S. McClusky *et al.*, *J. Geophys. Res.* **105**, 5695 (2000).
80. C. Faccenna *et al.*, *Geophys. J. Int.* **126**, 781 (1996).
81. E. Carminati, M. J. R. Wortel, W. Spakman, R. Sabadini, *Earth Planet. Sci. Lett.* **160**, 651 (1998).
82. E. Carminati, M. J. R. Wortel, P. Th. Meijer, R. Sabadini, *Earth Planet. Sci. Lett.* **160**, 667 (1998).
83. E. Mantovani, D. Albarello, C. Tamburelli, D. Babbucci, M. Viti, *Ann. Geofis.* **40**, 611 (1997).
84. E. Mantovani *et al.*, *J. Geodyn.* **30**, 287 (2000).
85. L. Jolivet *et al.*, *J. Geophys. Res.* **103**, 12123 (1998).
86. A. L. W. Lips, thesis, Utrecht University, Utrecht, Netherlands (1998).
87. L. Jolivet, J.-P. Brun, P. Gautier, S. Lallemant, M. Patriat, *Bull. Soc. Geol. Fr.* **165**, 195 (1994).
88. F. Ghisetti, L. Vezzani, *J. Struct. Geol.* **3**, 371 (1981).
89. D. Caccamo, G. Neri, A. Sarao, M. Wyss, *Geophys. J. Int.* **125**, 857 (1996).
90. Z. Gvirtzman, A. Nur, *Nature* **401**, 782 (1999).
91. C. E. Duermeijer, M. Nyst, P. Th. Meijer, C. G. Langereis, W. Spakman, *Earth Planet. Sci. Lett.* **176**, 509 (2000).
92. C. R. Walcott, thesis, Utrecht University, Utrecht, Netherlands (1998).
93. C. Tomek, J. Hall, *Geology* **21**, 535 (1993).
94. J.-C. Hippolyte, D. Badescu, P. Constantin, *Tectonics* **18**, 1120 (1999).
95. H. Peresson, K. Decker, *Tectonics* **16**, 38 (1997).
96. E. Willingshofer, thesis, Vrije Universiteit, Amsterdam (2000), and references therein.
97. A. R. Ritsema, *Geol. Mijnbouw* **58**, 127 (1979).
98. H. Anderson, J. Jackson, *Geophys. J. R. Astron. Soc.* **91**, 613 (1987).
99. A. Frepoli, G. Selvaggi, C. Chiarabba, A. Amato, *Geophys. J. Int.* **125**, 879 (1996).
100. R. A. Girbacea, W. Frisch, *Geology* **26**, 611 (1998).
101. M. Radulian, N. Mandrescu, G. F. Panza, E. Popescu, A. Utale, *Pure Appl. Geophys.* **157**, 57 (2000).
102. R. Noomen *et al.*, *J. Geodyn.* **21**, 73 (1996).
103. B. de Voogd *et al.*, *Geophys. J. Int.* **109**, 536 (1992).
104. R. Westaway, *J. Geophys. Res.* **98**, 741 (1993).
105. C. Sanders, P. A. M. Andriessen, S. A. P. L. Cloetingh, *J. Geophys. Res.* **104**, 29095 (1999).
106. A special tomographic study is carried out to analyze this stage (*112*).
107. St. Mueller, H.-G. Kahle, in *Crustal Dynamics*, D. E. Smith, D. L. Turcotte, Eds., *Am. Geophys. Union, Geodynamics Series* **23** (1993), pp. 249–298.
108. N. J. Vlaar, in *Progress in Geodynamics*, G. J. Borradaile, A. R. Ritsema, H. E. Rondeel, O. J. Simon, Eds. (North-Holland, Amsterdam, 1975), pp. 234–245.
109. A. Malinverno, W. B. F. Ryan, *Tectonics* **5**, 227 (1986).
110. W. Spakman, G. Nolet, in *Mathematical Geophysics: A Survey of Recent Developments in Seismology and Geodynamics*, N. J. Vlaar *et al.*, Eds. (Reidel, Dordrecht, Netherlands, 1988), pp. 155–188.
111. C. Giunchi, R. Sabadini, E. Boschi, P. Gasperini, *Geophys. J. Int.* **126**, 555 (1996).
112. F. Wenzel *et al.*, *Eos* **79**, 592 (1998).
113. B. L. N. Kennett, E. R. Engdahl, R. Buland, *Geophys. J. Int.* **122**, 108 (1995).
114. Our research underlying this contribution has been part of the PIONIER/NWO program (PGS 76-144) *Detailed Structure and Dynamics of the Upper Mantle* and is now part of the program of the Vening Meinesz Research School of Geodynamics and the Netherlands Centre for Integrated Solid Earth Science (ISES). We thank R. Noomen for permission to use Fig. 5.

ERRATUM

Post date 19 January 2001



REVIEW: "Subduction and slab detachment in the Mediterranean-Carpathian region" by M. J. R. Wortel and W. Spakman (8 Dec. 2000, p. 1910). In Figure 1, intended to illustrate the evolution of plate boundaries in the Mediterranean-Carpathian region, the text and graphics on the map did not correspond with the appropriate geographic features. The correct figure is shown here.