Subduction and the depth of convection in the Mediterranean mantle

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[1] We tie together geological data, paleotectonic reconstruction, plate motion, and tomographic analysis to unravel the history of subduction and back arc extension of the eastern and central Mediterranean. In these two regions, extensional processes started contemporaneously, around 30 Myr ago, but with marked differences. In the eastern region, the Aegean basin opened slowly ($\sim$1 cm/yr) behind a shallow dipping slab (40–45°). The corresponding high-velocity anomaly extends inside the upper mantle and can be also followed in the midmantle down to a depth of at least 1500 km. Its descent into the midmantle initiated most probably during the Late Cretaceous, and the trench moved northeastward, following the path of the Eurasian plate and under the persistent push of the African plate. Conversely, in the central Mediterranean region, subduction initiated later, and the motion of the subducting slab is confined to the upper mantle, causing punctuated and rapid episodes of back arc extension (Provençal and Tyrrhenian basins) behind a slab that dips steeply (75°). We explore the causes that control how the slab subducted and interacted with the lower, more viscous part of the mantle. *INDEX TERMS:* 8120 Tectonophysics: Dynamics of lithosphere and mantle—general; 8155 Tectonophysics: Evolution of the Earth: Plate motions—general; 8180 Tectonophysics: Evolution of the Earth: Tomography; 9335 Information Related to Geographic Region: Europe; *KEYWORDS:* subduction, Mediterranean, mantle convection, back-arc extension, plate motion, seismic tomography

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1. Introduction

[2] The increasing resolution of tomographic models provides new concepts and ideas on the way slabs of subducted lithosphere sink into the mantle. Several studies show that in some cases the 660-km mantle discontinuity can significantly distort mantle flow, trapping slabs into the upper mantle, whereas in other cases slabs appear to penetrate deeper into the lower mantle. The mechanisms that control the different behavior of the slabs are still poorly understood. However, the increasing number of geodynamic models and the comparison between regional cases, where the plate tectonic settings are defined, permit the formulation of hypotheses on the key parameters controlling the way the mantle flows over geological time [see, e.g., *Van der Hilst and Seno*, 1993; *Van der Lee and Nolet*, 1997; *Van der Voo et al.*, 1999a; *Wortel and Spakman*, 2000; *Faccenna et al.*, 2001a; *Fukao et al.*, 2001]. Here, we discuss the example from the central–eastern Mediterranean region. In this region, the boundary between the African and Eurasian plate is composed of small, narrow and arcuate trenches and suture zones, reflecting the complexity of the inherited paleogeographic scenario (Figure 1). Despite these complexities, the Mediterranean does represent a favorable candidate to investigate the style of subduction process as the plate kinematics are rather well established and the region has been investigated for decades by geologists and geophysicists.

[3] In two regions, namely the Tyrrhenian and the Aegean, deep and intermediate seismicity define Wadati–Benioff zones, described since the early ’70 [*Isacks and Molnar*, 1971]. Those two subduction zones share a common Neogene evolution, dominated by trench retreat and consequent back arc extension [*Dercourt et al.*, 1986; *Malinverno and Ryan*, 1986; *Jolivet and Faccenna*, 2000]. This caused the formation of the Liguro-Provençal and the Tyrrhenian basin, in the central Mediterranean and the Aegean basin in the eastern Mediterranean, behind their respective trenches (Figure 1). Despite the similarities in the recent tectonic evolution, those two subduction systems show contrasting evolutionary trends in terms of age, geometry, style of subduction, and depth of penetration of the slab into the mantle.

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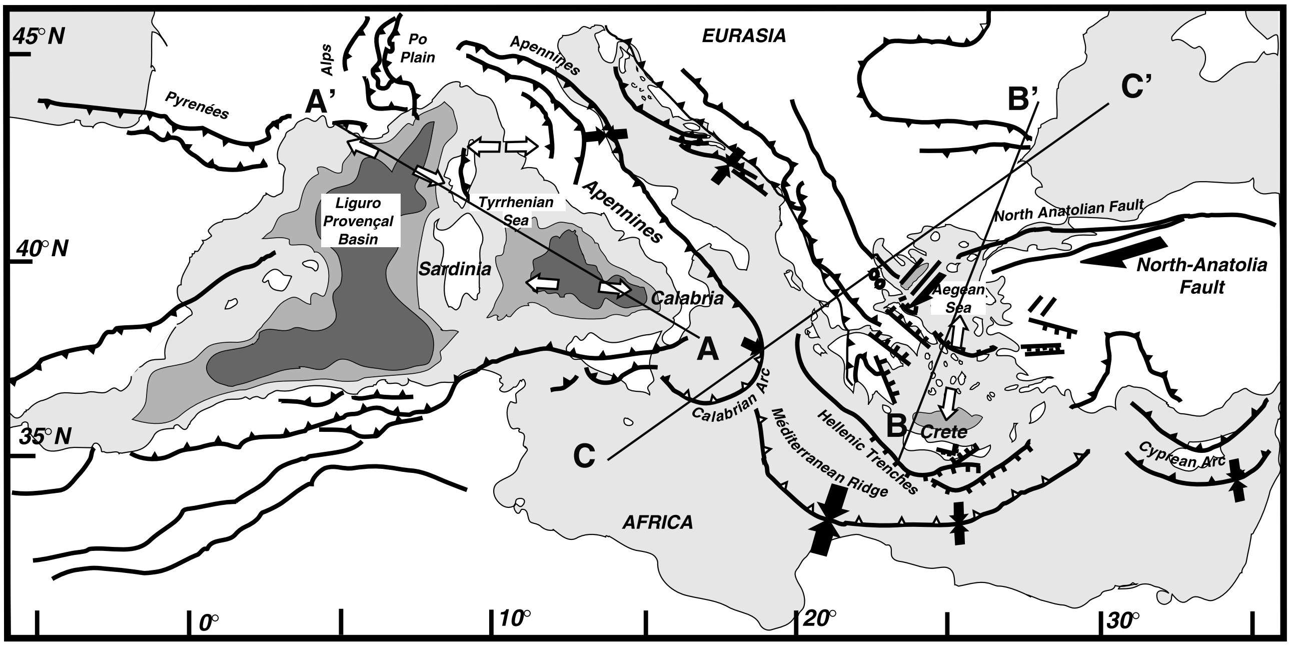

Figure 1. Tectonic map of the Mediterranean. White triangles at trenches indicate the seismically active portion of subduction zones. Lines indicate cross-sections of Figure 2 and Figure 3.

[4] Combining together geological data, plate motions, and the seismic velocity anomalies inside the mantle as detected by a recent tomographic model [*Piromallo and Morelli*, 2002], we try to unravel the history of subduction of the two systems. Our results indicate that the affinities of the two subducting systems are only apparent. The Aegean slab belongs to an older, Mesozoic, subducting system (Tethyan slab) and, under the persistent push of the African plate, its trench advanced northward together with the upper plate during much of the Tertiary, accumulating material at lower mantle depths. Conversely, the slab of the central Mediterranean is younger and initiated its retrograde motion and back arc extension during its descent into the upper mantle. Consequently, its evolution is restricted to the upper mantle. We speculate on the causes that control the depth of mantle convection and the mechanism of the slab-660 km discontinuity interaction for the two investigated regions.

2. Geological Constraints

[5] The present-day geological architecture of the Mediterranean is characterized by extensional domains surrounded by arcuate mountain belts (Figure 1). Extensional processes took place during the early Miocene disrupting and fragmenting the continuity of a preexisting, Alpine Late Cretaceous–Paleogene mountain belt. Arc volcanism and back arc extension, foredeep deposition and the widespread presence of high pressure–low temperature metamorphic assemblages indicate that the formation of back arc basins and the mountain belt is related to subduction and underthrusting of oceanic and continental lithosphere.

[6] Our discussion is limited to the central and eastern Mediterranean. Two cross-sections AA′ and BB′ (Figure 1), striking perpendicular to the two Wadati–Benioff zones (the Tyrrhenian or Calabrian and the Aegean, respectively), are chosen as indicative of the processes that characterize the whole region (Figure 2). The two sections run parallel to the stretching direction of the back arc domain and, therefore, to the direction of slab retreat. In the lower panels of Figures 2a and 2b the crustal–lithospheric profiles, along the Tyrrhenian and the Aegean cross-section respectively, are drawn on top of the corresponding mantle tomographic images, while in the upper panels syntheses of geological data pertinent to the two subduction processes are illustrated. We describe in the following the geological constraints, while the deeper structure as inferred from tomography is addressed in the next section.

2.1. Tyrrhenian Region

[7] Figure 2a shows the central Mediterranean section AA′, running from Calabria to Sardinia and to the Gulf of Lyon. This section, already presented by *Faccenna et al.* [2001a], shows the structure of the crust and of the lithosphere with the positions and the age of the two oceanic back arc basins, the Liguro-Provençal and the Tyrrhenian, separated by the Sardinia continental block [*Finetti and Del Ben*, 1986; *Suhadolc and Panza*, 1989; *Chamot-Rooke et al.*, 1999]. In the upper panel of Figure 2a, the age-distribution of the syn-rift deposits of the back arc extensional related basins and of the magmatism related to the formation of the oceanic crust and of the volcanic arc are shown. Extensional process started to the west (Liguro-Provençal basin shoulders), during the formation of calc-alkaline volcanic arc at about 30 Ma [*Cherchi and Montandert*, 1982; *Beccaluva et al.*, 1989; *Gorini et al.*, 1994; *Seranne*, 1999]. From the late Aquitanian, oceanic spreading took place [*Burrus*, 1984], and the Corsica–Sardinia block rotated counterclockwise by about 25–30°, between 21 and 16 Ma [*Van der Voo*, 1993]. After a few million years, extension shifted in the Southern Tyrrhenian

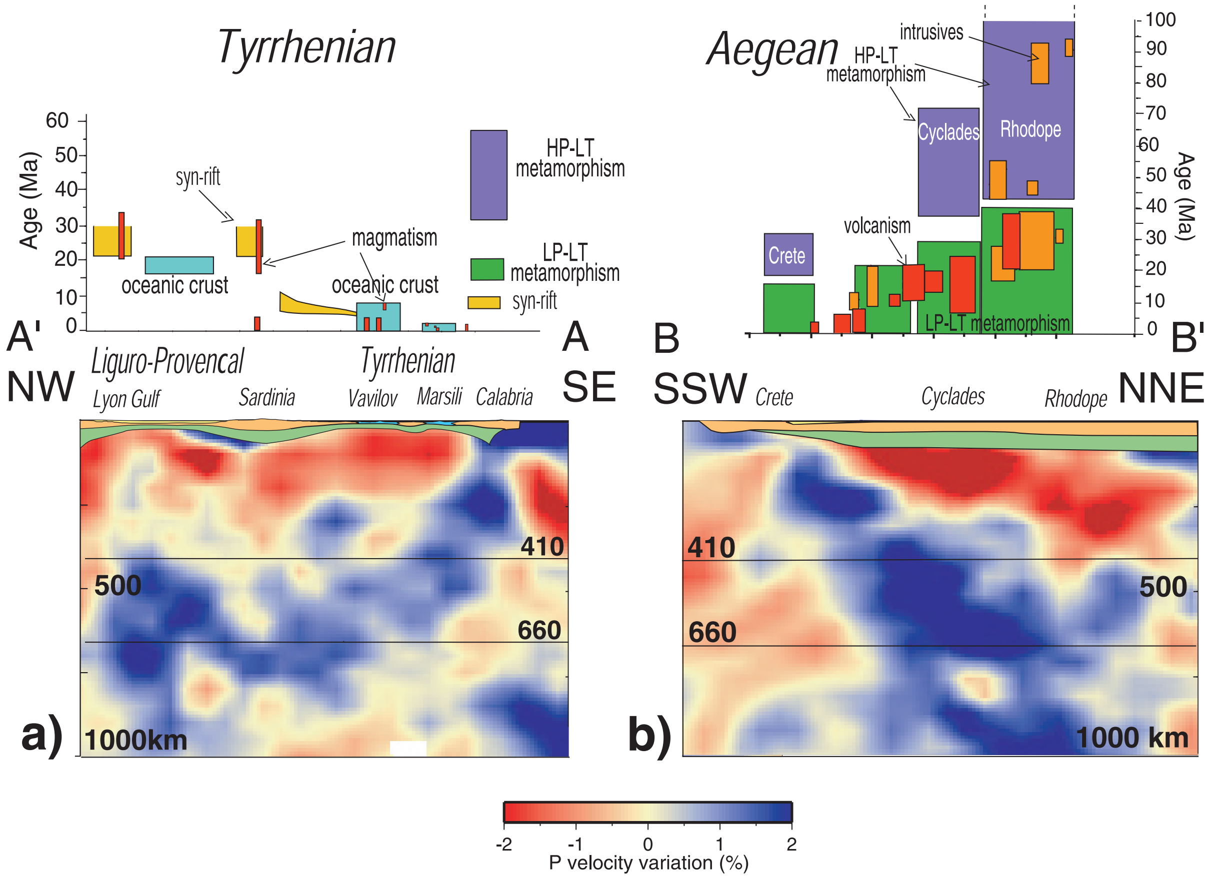

Figure 2. Cross-sections of the studied area (compare to Figure 1). (a) From the Gulf of Lyon to Calabria and (b) from Rhodope Massif to Crete. Crustal structure of section AA′ is from from *Finetti and Del Ben* [1986] and *Chamot-Rooke et al.* [1999], of section BB′ from *Makris* [1978]. Lithospheric structure is from *Suadolch and Panza* [1989]. Tomographic cross-sections are from model PM0.5 [*Piromallo and Morelli*, 2002]. The upper panels show the age and distribution of the geological record related to subduction (see text for references): metamorphism (blue and green box represent blueschist, HP-LT facies and greenschist LP-LT facies, respectively), magmatism (red and orange box represent volcanic and intrusive rocks, respectively), syn-rift deposits filling extensional basins (yellow box) and oceanic crust (light blue box).

basin (Figure 2a): syn-rift deposition started at ∼10–12 Ma in both eastern Sardinia shelf and Calabria [*Kastens and Mascle*, 1990; *Sartori*, 1990], followed by the formation of localized spreading centers (at 4–5 Ma, Vavilov basin, and at 2 Ma, Marsili basin), and drifting and arching of the Calabria block [*Sartori*, 1990]. In the Tyrrhenian side, back arc extension was superimposed on contractional structures formed in the Paleogene and Oligocene time. During extension and rotation of the Corsica–Sardinia block, the thrust front of the accretionary wedge migrated eastward to its present position at the foot of the Apennines [*Patacca et al.*, 1990]. The present and recent Apennine chain is different in style from the Paleogene one and formed during the subduction and closure of a narrow Jurassic oceanic basin (Ligurian ocean) [e.g., *Dercourt et al.*, 1986]. The older mountain belt is very reminiscent of the Alps, with stacking of continental basement units and oceanic nappes during a northeastward directed thickening event [*Knott*, 1987; *Dietrich*, 1988; *Rossetti et al.*, 2001]. In Calabria, radiometric ages of the exposed high pressure–low temperature (H*P*–L*T*) metamorphic rocks related to the subduction process range from Paleocene to early Miocene time (Figure 2a) [*Borsi and Dubois*, 1968; *Shenk*, 1980; *Rossetti et al.*, 2001]. Therefore, H*P*–L*T*, subduction-related metamorphism is indicative of subduction and underthrusting active before and during the back arc extension, from Paleocene onwards. The continuous formation of blueschist units and their structural architecture indicates that the present-day subduction initiated during the Late Cretaceous–Paleocene, consuming the Ligurian oceanic basin first, then a small (few hundreds of km) fragment of the Apulian continental-transitional lithosphere and, finally, most of the present-day Ionian lithosphere [*Faccenna et al.*, 2001b].

2.2. Aegean Region

[8] Figure 2b shows the section BB′ in the eastern Mediterranean, running NNE from the Hellenic trench to Crete and to the Rhodope Massif. This cross-section is usually considered representative, as it strikes parallel to the stretching direction [*Jolivet*, 2001, and references

therein] and because of the fair tomographic picture of the slab along this profile [e.g., *Spakman et al.*, 1993; *Karason and Van der Hilst*, 2000]. The crust is particularly thin along the Crete Sea (16 km) and beneath the Cyclades (30 km), with respect to the eastern and western regions where the crust is 40–45 km thick [*Makris*, 1978]. Since the Oligocene, extension started in the Aegean area, causing the collapse of the previously formed mountain belt and the formation of deep basins [*Lister et al.*, 1984; *Jolivet and Patriat*, 1999; *Gautier et al.*, 1999]. The first outcropping syn-rift sediments date back to the Aquitanian but the onset of extensional process is probably older [*Gautier et al.*, 1999; *Jolivet and Faccenna*, 2000], as attested by the radiometric dating of green-schist L*P*–L*T* metamorphism fabric (Figure 2b) related to the extensionally driven exhumation process. Extensional processes in the Aegean area are superimposed on a previously formed mountain belt of the Hellenic chain. The analysis of these disrupted mountain belts allows the reconstruction of different geodynamic events [*Bonneau*, 1982; *Dercourt et al.*, 1986]. The orogenic wedge formed during the Cretaceous after the closure of the Vardar ocean and the subsequent collision and underthrusting of the Apulia microplate below the southern margin of Eurasia [*Jakobshagen et al.*, 1978; *Bonneau*, 1982; *Dercourt et al.*, 1986]. A doubly vergent orogen formed, with north-verging thrust in the Northern Rhodope and south-verging thrusting in the accreting northern margin of the Apulia, constituted by carbonate platforms and pelagic basins. The H*P*–L*T* blueschist units now outcropping in the Cyclades formed within this subduction/accretionary complex and are mainly derived from the Pindus pelagic basin (Figure 2b). Accretion and orogenic wedging then continued moving progressively southward with the formation of the Crete and Peloponnese blueschist H*P*–L*T* units (Figure 2b), where peak pressure is dated at 25 Ma [*Jolivet et al.*, 1996]. The age of the oldest high-pressure event in the Rhodope is not precisely constrained but a Late Cretaceous–Paleocene or Early Eocene age is possible (Figure 2b). U/Pb SCHRIMP ages for zircon yield ages between 73 (far east Rhodope) and 42 Ma (far west Rhodope) [*Liati and Gebauer*, 1999]. The Cyclades high-pressure blueschist units also show scattered ages, from the Late Cretaceous for some eclogite (70 Ma for the eclogite stage of Syros [*Bröcker and Enders*, 1999]) to the Eocene for most of the blueschists [*Wijbrans and McDougall*, 1986, 1988]. Finally, from the Late Miocene, the consumption and accretion of the Apulian continental block was followed by the subduction of the Ionian oceanic domain. The age-distribution of H*P*–L*T* units and of magmatism (Figure 2b) indicates the trench remained rather fixed for a long time span in the Rhodope–Cyclades region during the orogenic accretion of crustal continental block, and then swept backward to the present-day location.

[9] Available tectonic reconstructions propose the evolution of the region as related to a sequence of successive northward-dipping subductions zones, from the Jurassic–Cretaceuos Tethyan subduction in the Vardar suture to the Paleogene Pindos subduction and finally the present-day Ionian subduction [*Dewey et al.*, 1973; *Dercourt et al.*, 1986; *Bonneau*, 1982; *Gealey*, 1988]. In these models, the present-day subduction zone represents the southernmost and youngest one [*Bonneau*, 1982] and its initiation has been dated at 13 Ma [*Le Pichon and Angelier*, 1979] or 10–5 Ma [*McKenzie*, 1978], accounting for the depth of the Wadati–Benioff zone. *Spakman et al.* [1988] and *Wortel et al.* [1990], combining tomographic images and paleotectonic reconstruction, proposed that the present-day subduction initiated in the late Eocene. Comparing geological and tomographic data, we propose here that the present-day subduction represent the ultimate evolution of a single subducting system active since the Mesozoic, involving the lithospheres of the Vardar and Ionian oceans and of the Apulian delaminated continental lithosphere.

3. Images of the Subducting Slabs

[10] Figures 2 and 3 show images from a recent high-resolution tomographic model of the mantle beneath the Euro-Mediterranean region obtained by inversion of the International Seismological Centre (1964–1995) P wave delay times [*Piromallo and Morelli*, 2002]. Summary residuals of carefully selected regional and teleseismic rays from shallow earthquakes are used as input data to the inversion and the model is parameterized with linear splines over a three-dimensional grid [*Piromallo and Morelli*, 1997]. Horizontal node spacing is roughly 55 km in both directions and vertical spacing is 50 km, down to 1000 km depth. The perturbation to the velocity field is computed and displayed with respect to the global reference velocity model *sp6* [*Morelli and Dziewonski*, 1993]. For a comprehensive description of the model and its reliability the reader is referred to Piromallo and Morelli (submitted manuscript, 2001).

[11] The cross-section AA′ from Calabria to the Gulf of Lyon (Figure 2a) shows an almost continuous high-velocity body extending from the surface below Calabria, with a NW dip of 70°–80°, and then turning horizontally in the transition zone. The estimated total length of the high-velocity zone, interpreted as subducted lithosphere is ~1200–1400 km, measured from the base of the lithosphere and including its lowermost flat portion. Using different data sets and techniques, *Spakman et al.* [1993] and *Lucente et al.*, [1999] have obtained velocity models for the Mediterranean yielding a feature similar in both geometry and total length, giving confidence to our earlier interpretation [*Faccenna et al.*, 2001a]. The high-velocity anomaly below the Calabrian region lines up with a continuous, NW-dipping Wadati–Benioff zone. Seismicity is distributed in a 200 km wide and 40–50 km thick volume, plunging down to a depth of ~450 km, with a 70° dip [*Isacks and Molnar*, 1971; *Giardini and Velonà*, 1988; *Selvaggi and Chiarabba*, 1995].

[12] In the Aegean area, the present-day slab is marked by a northward dipping Wadati–Benioff plane down to a depth of 180 km [*Hatzfeld*, 1994; *Papazachos et al.*, 2000]. The tomographic images show a marked positive velocity anomaly that follows the Hellenic Arc and continues, at shallow depth, below the Dinaric chain (Figure 3). Cross-section BB′ (Figure 2) shows continuous fast anomaly from shallow lithospheric depths down to the bottom of the transition zone. At transition zone the slab appears thicker than in its upper portion. In the lower mantle, especially in the W–SW portion of the Hellenic Arc, the high-velocity anomaly can

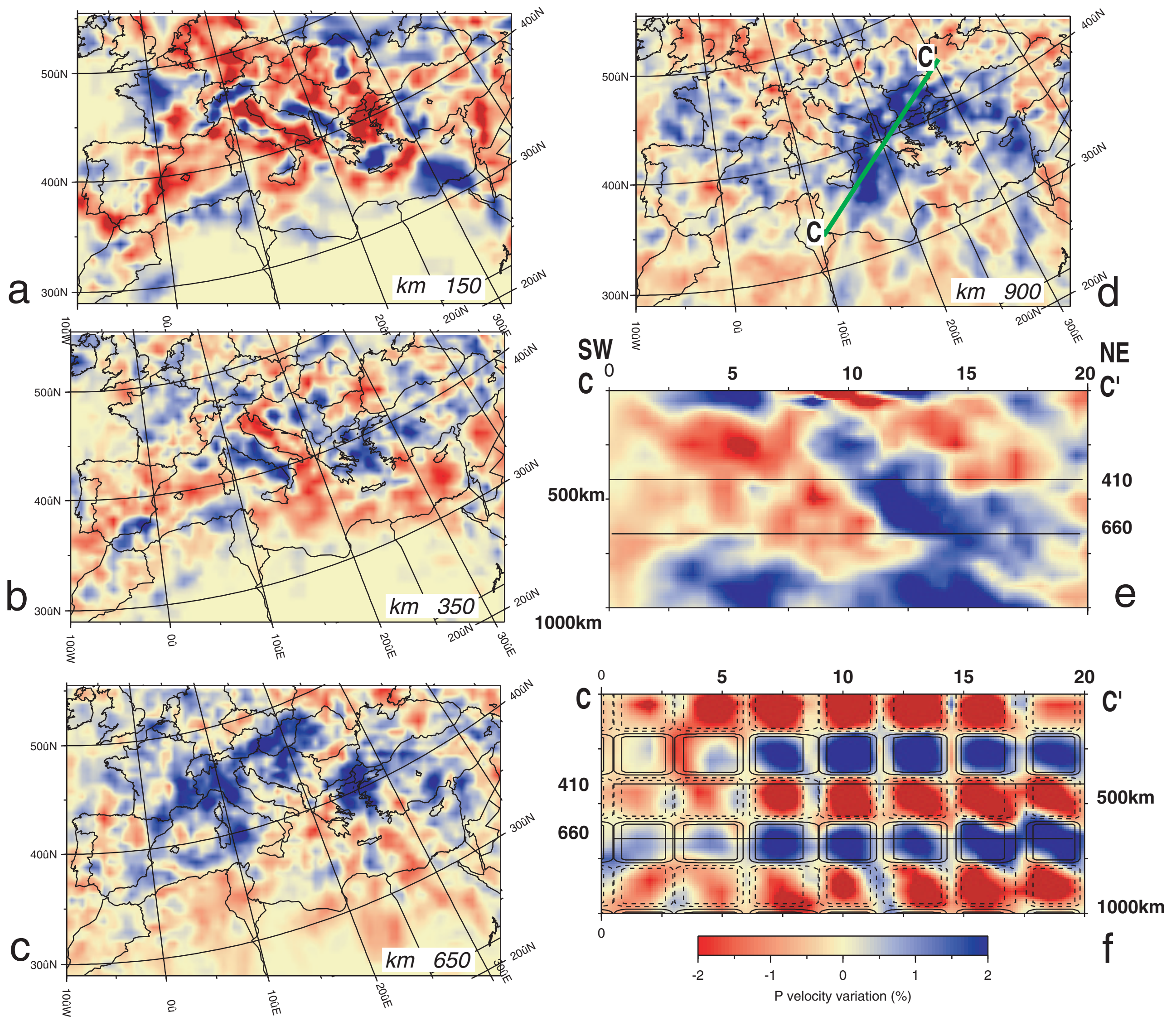

Figure 3. Map views (a–d) of tomographic results at 150, 350, 650 and 900 km and (e) cross-section *CC′* from model PM0.5 (Piromallo and Morelli, submitted manuscript, 2001). Velocity anomalies are displayed in percentages with respect to the reference model sp6 [*Morelli and Dziewonski*, 2001]. Section *CC′* intersects the deep positive velocity anomaly showing an apparent continuity between the upper and the midmantle positive velocity anomalies. The bottom right panel (f) illustrates a slice, along the same trace of *CC′*, resulting from a three-dimensional box-car recovery test, to estimate spatial resolution. In general, recovery test analyses are aimed at checking the ability of the inversion scheme in retrieving an input model (exactly known in spatial location, geometrical shape and amplitude of anomalies), given the same ray coverage used for the real data inversion. Here, input box-car heterogeneities of opposite sign (±4%), approximately 220 km in each direction, are alternately superimposed on the ambient velocity profile. Gaussian random noise is added to the data. Input is shown by thin lines (positive) and dashed lines (negative), with contouring at 1% and 3%; output is shown in colors. The simulated input is nicely resolved in the inversion, both in sign and shape of the anomaly (except for the south-westernmost portion of the cross-section) and the edges of the box-car are also fairly detected in the best resolved part (except for its northeasternmost portion where some smearing occurs).

be traced down to 1000 km, bottom of the model (Figure 3). The slab sinks at an angle of about 45° in the upper mantle, while its shallower portion appears to dip on a less inclined plane [*Hatzfeld*, 1994; *Papazachos and Nolet*, 1997]. Similar results have been obtained by *Spakman et al.* [1993], *Bijwaard et al.* [1998] and *Karason and Van der Hilst* [2000], showing that the high-velocity anomalies can be followed down to 1500 km depth.

[13] In map view at a depth of 900 km (Figure 3d), the positive velocity anomaly is identified below the western portion of the arc and shows a NE striking ellipsoidal shape, approximately centered on mainland Greece. Its major axis

extends from the Black Sea, to the Northeast, to the Sirte Gulf, to the Southwest, about 1500 km long. Therefore, the southern termination of the velocity anomaly is located to the south with respect to the present-day position of the trench. Cross-section CC′ (Figure 3e), along the major axis of the ellipsoid, does show that the high-velocity anomaly dips toward NE down to 700–800 km depth and then seems to fold and turn southwestward. Sections BB′ and CC′ show that the tip of the upper mantle high-velocity anomaly is well located in correspondence with the lower mantle one. However, our tomographic analysis is maybe unable to distinguish if the upper mantle high-velocity anomaly is directly connected or not with the lower mantle one.

[14] Interpreting the high-velocity anomalies as a subducted slab and considering the results of other deeper tomographic images [*Van der Voo et al.*, 1999a; *Bijward et al.*, 1998; *Karason and Van der Hilst*, 2000], it is possible to estimate that the amount of material consumed at trench is more than 2000 km along the BB′ anomaly. This value can double along the section CC′, that is considering the continuation of the velocity anomaly to the southwest of the slab.

4. Absolute and Relative Velocity and the Amount of Subduction

[15] In the following, we first estimate the amount and rate of subduction at trench, summing the amount of back arc extension and the amount of relative convergence of the African plate with respect to stable Eurasia, from the Late Cretaceous onward. We then reconstruct the position of the plates in the hot spot reference frame to estimate the position of the trenches in time with respect to the lower mantle.

4.1. Amount of Subduction

[16] Estimations of the rate and the amount of back arc extension have been performed restoring back to their previous supposed thickness and length the crustal cross-sections of Figure 2. This has been done by subtracting the oceanic-floored area of each basin and then, using an area balancing technique, restoring the crust to the thickness of the surrounding undeformed domain, assuming that the locus of extension at the surface corresponds to the locus of maximum crustal thinning and neglecting lower crustal flow. Results of this analysis are shown in Figure 4b.

[17] The result of the central Mediterranean area restoration has been already presented by *Faccenna et al.* [2001b]. In the Liguro-Provençal and Tyrrhenian region, we have calculated that the total amount of extension (∼780 km) is partitioned roughly equally between the two basins, with alternating episodes of rifting (∼7 Myr) and oceanic spreading (∼5 Myr) (Figure 4). The rate of extension is on average 2.6 cm/yr, with a peak of 5.6 cm/yr during the last few million years and with a pause between 15 and 10 Ma, when the velocity of retreat drastically decreased. Our estimates are in good agreement with previous evaluations [*Burrus*, 1984; *Malinverno and Ryan*, 1986; *Patacca et al.*, 1990; *Chamot-Rooke et al.*, 1999; *Mauffret et al.*, 1995; *Spadini et al.*, 1995; *Guegen et al.*, 1998].

[18] The amount of extension in the Aegean area has been performed restoring the crustal section of Figure 2b to the

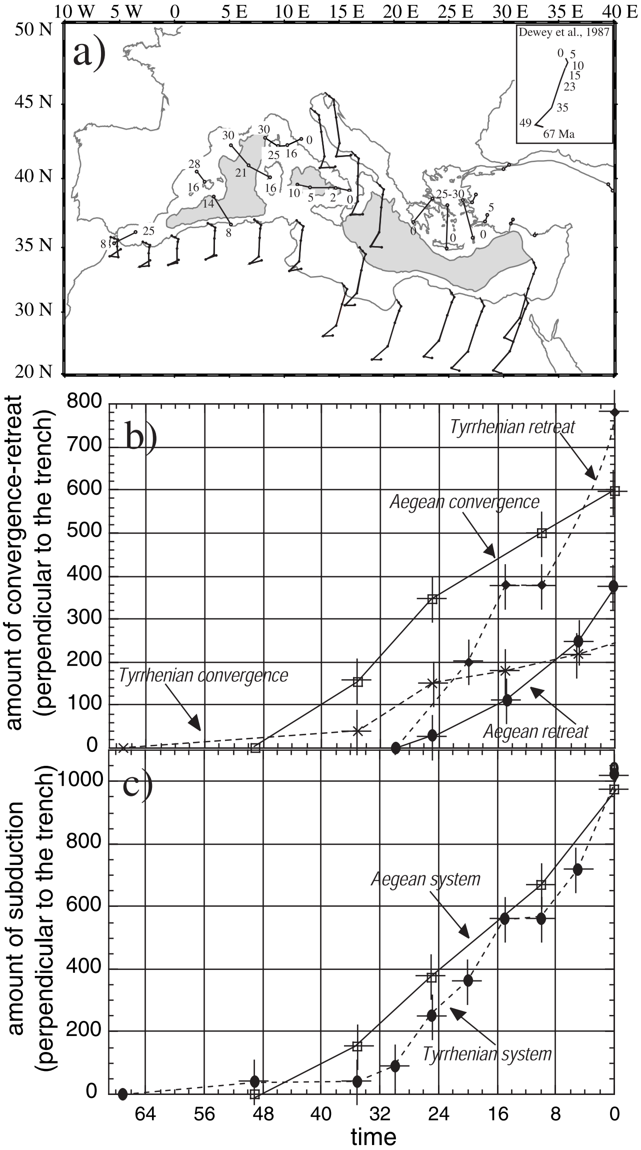

Figure 4. (a) Displacement trajectories of Africa and Apulia motion with respect to stable Eurasia (calculated from *Dewey et al.* [1989], see inset for stages division) and displacement trajectories related to back-arc extension and Anatolia motion (numbers are million years). (b) Amount of relative convergence, extension and (c) amount of subduction calculated along the cross-section of Figure 2 perpendicular to the trench in the last 64 Myr.

thickness of the shoulder about ∼45 km [*Makris*, 1978]. The total amount of extension of the Aegean Sea is about 320 km with an average velocity of 1.1 cm/yr (Figure 4). To estimate the amount of trench retreat, this value should be summed with the amount of southwestward rigid extrusion of the Anatolia microplate (Figure 4a). This event occurred most probably during the last few million years. The amount of extrusion can be assumed to be of about 50 km, as estimated from the average slip measured along the North Anatolia fault system [*Barka*, 1992; *Armijo et al.*, 1999]. The total amount of trench retreat measured along the Figure 2b cross-section is in good agreement with the

Gautier et al. [1999] calculation and with the paleo-restoration of the Hellenic arc, as deduced by paleomagnetic data [*Kissel and Laj*, 1988].

[19] The net amount of relative convergence of Africa with respect to stable Eurasia plate during the Tertiary also shows remarkable difference moving from the Tyrrhenian trench to the Hellenic trench. This is mainly due to the fact that the trench in the central Mediterranean was mostly oriented parallel to the relative African motion [*Faccenna et al.*, 2001b] whereas the Hellenic trench was always oriented rather perpendicular to the Africa–Eurasia relative motion (Figure 4a). Using the *Dewey et al.* [1989] model for Africa–Eurasia, it is possible to estimate the amount of subducted material at trench measured perpendicular to the paleo-strike of the trench for the two regions (Figure 4). *Jolivet and Faccenna* [2000] show that for this purpose, there is no substantial difference between the *Dewey et al.* [1989] and other relative models [*Savostin et al.*, 1986; *Ricou*, 1994]. During the last 67 Ma, the amount of convergence over the Tyrrhenian trench is on the order of 200 km, whereas in the Aegean is three times as large (Figure 4). Summing these values with the estimate of trench retreat, it is possible to evaluate the total amount of subduction during the Tertiary. Figure 4c shows that the total amount of subduction during the Tertiary for the two systems is roughly similar, on the order of 1000 km, but is partitioned in a different manner, with a more efficient retreat in the Tyrrhenian (800 km) with respect to the Aegean (400 km). In the Late Cretaceous interval (67–90 Ma; not shown in Figure 4a), it is also possible to evaluate that due to plate convergence, an additional 1000 km of material should have been consumed at the Aegean trench. In the Tyrrhenian region, conversely, the subduction process was just initiating [*Faccenna et al.*, 2001b] and no significant convergence occurred at the infant plate boundary.

4.2. Absolute Motion

[20] We use the pole of rotation of *Gordon and Jurdy* [1986] for the Tertiary and *Lithgow-Bertelloni and Richards* [1998] for the oldest time lapses to calculate the positions of the African and Eurasia plates in the hot spot reference frame. Figure 5 illustrates the path of both the African and Eurasia plates back to 94 Ma. Africa moved to the Northeast by about 2300 km, decreasing quite sharply its rate during the last 35–30 Ma from 3 to about 1 cm/yr [*O'Connor and Duncan*, 1990; *Müller et al.*, 1993; *Burke*, 1996; *Silver et al.*, 1998]. Europe also moved to the Northeast but only about 1200 km in the last 94 Ma, with an average rate of about 1.3 cm/yr. From this reconstruction, we define the position of the trench with respect to the lower mantle, as shown in Figures 6d–6f. For the case of the Aegean region, it is reasonable to assume that in the interval between 94 and 30 Ma the trench advanced toward the Northeast, following the Europe motion (trench advancing toward the upper plate). This assumption is based on the fact that during the considered time lapse, no major extensional episode took place behind the trench. During the last 30 Ma, conversely, back arc extension and the Anatolia extrusion took place and induced about 400 km of southward retreat of the trench with respect to Eurasia. Therefore, in the latter time lapse, the absolute position of the trench remained quite stationary as a consequence of the velocity vectors composition along the considered section (southward trench retreat due to back arc extension has to be subtracted from the northeastward absolute motion of Europe). Along the NNE trending section BB′ (Figure 2b), trench retreated southward by about 200 km as the northward component of absolute motion of Europe is about 150–200 km, whereas back arc extension is in the order of 350–400 km. Along the section CC′, conversely, the trench advanced about 100 km, as the full component of absolute Europe motion is larger than the extensional component due to back arc extension. In Figure 5, we also sketch the location of the velocity anomalies as shown in Figure 3d at lower mantle depth of 900 km. We note that at about 64 Ma, the Hellenic trench was lined up with the southern end of the high-velocity anomaly.

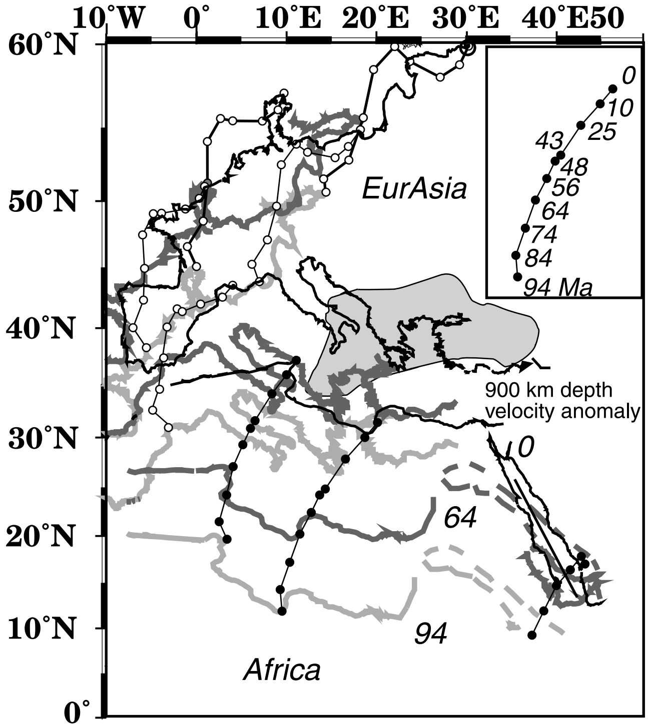

Figure 5. Absolute motion of Eurasia and Africa reconstructed using the pole of rotation of *Gordon and Jurdy* [1986] for the 64-Myr stage and *Lithgow-Bertelloni and Richards* [1998] for the 94-Myr stage. The image of the midmantle positive velocity anomaly below the Aegean at a depth of 900 km (Figure 3d) is shown for reference.

[21] Three considerations can be drawn from the kinematic analysis of the plate system. First, in the Tyrrhenian margin, the amount of subduction estimated from the velocity anomaly (1200–1400 km) is not far from what is calculated by summing the amount of back arc extension and the convergence due to plate motion during the Tertiary (1050 km). Second, in the Aegean margin, the amount of subduction estimated from the velocity anomaly (including its lower mantle portion) is far larger than the one calculated by summing the amount of back arc extension and the convergence due to plate motion during the Tertiary (1000 km). These values can be reconciled by either assuming that the present-day subduction in the Aegean

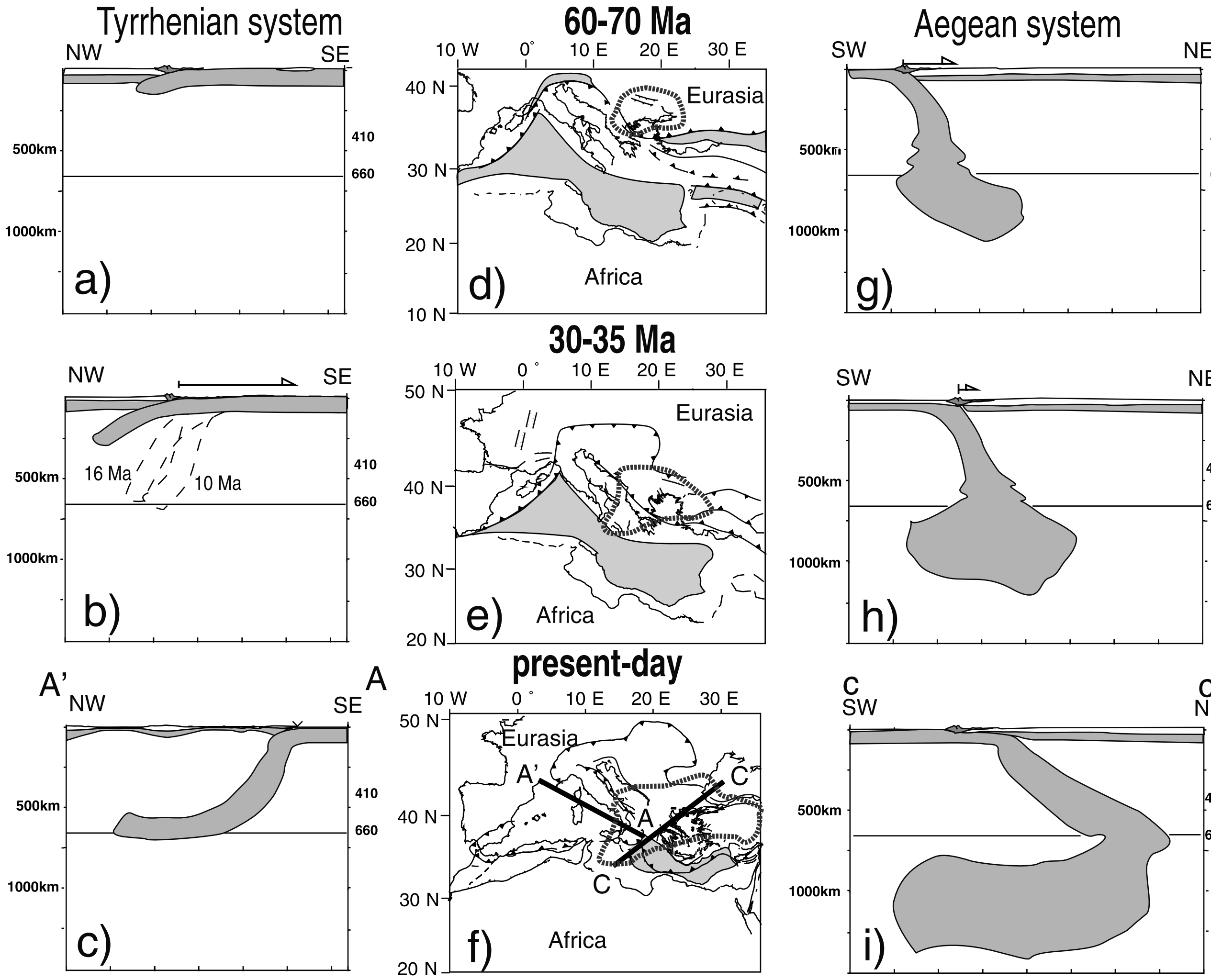

Figure 6. Diagrams (d, e, f) showing our reconstruction of the evolution of the Mediterranean region in absolute reference frame in three stages, at the base of the Tertiary (60–70 Ma), at the beginning of back-arc extension (30 Ma) and present-day setting. Mesozoic oceanic domains are marked in grey. The contour line of the evolving deep (900 km) high velocity anomaly of Figure 3d is also projected for reference (dashed gray). Two cross-sections (compare Figure 1 with f) illustrate the evolution of the subduction process along the Tyrrhenian (a, b, c; based on the Figure 2a tomographic image) and from the Aegean (g, h, i; based on the Figure 3e tomographic image) at the same time intervals. White arrows indicate the net motion of the trench.

region started at least 100 Ma ago or by assuming that the lower mantle velocity anomaly does not belong to the present-day subduction system. Third, the Aegean trench system mainly advanced northeastward following the path of Europe. The absolute path shows that in the Early Tertiary–Late Cretaceous the trench is favorably located with the southern termination of the lower mantle velocity anomaly. For the case of the Tyrrhenian, conversely, the absolute reconstruction is not significant as slab never penetrated to lower mantle depth.

5. Toward an Evolutionary Scenario

[22] Geological data set, tomographic images, and plate motion reconstruction indicate that the evolution of two active subduction zones in the Mediterranean has been remarkably different. The Aegean subduction system is older than the Tyrrhenian one. It probably formed during the Mesozoic, accreting crustal blocks during the persistent push of the African plate, and the trench system advanced toward the upper plate. The back arc extensional process also shows substantial difference between the two regions: intermittent, rapid, episodes of extension in the Tyrrhenian contrast with the slow and small amount of extension in the Aegean. Moreover, the lower mantle below the Aegean region is characterized by a large high-velocity anomaly, resembling ones described further east, in correspondence of the Tethyan slab [*Grand et al.*, 1997; *Bijwaard et al.*, 1998; *Van der Voo et al.*, 1999a; *Karason and Van der Hilst*, 2000]. This anomaly is absent in the whole western region of the Mediterranean, where large-scale fast anomalies are confined mainly in the transition zone [*Piromallo et al.*, 2001].

Previous authors [*Bijwaard et al.*, 1998; *Karason and Van der Hilst*, 2000] interpreted the high-velocity anomalies in the lower mantle below the Hellenic arc as cold subducted lithospheric material: in this view the Aegean slab penetrates in the midmantle at least down to 1500 km. However, the continuation of the same lower mantle anomaly to the south of the present-day location of the trench is more problematic in that the lower mantle material could not be directly related to the present-day slab. For example, *Van der Voo et al.* [1999a] distinguished two different anomalies below India and related them to two different subduction episodes. The southern one, being related to the Upper Cretaceous obduction episode (90–70 Ma), occurred along the north-African margin. However, this reconstruction cannot be applied to the Aegean, as there is no trace of obduction episode or of any other subduction episode occurred to the south of the present-day trench. On the contrary, previous paleotectonic reconstruction of the Hellenic region proposed that the suture present in the northern Aegean area marks the presence of an older subduction-collisonal episode related to the closure of the Vardar ocean [e.g., *Bonneau*, 1982]. But this alternative possibility cannot explain the location of the lower mantle anomaly and is at odds with the fact that no other high-velocity anomaly is found at depth to the north of the present-day one, in any tomographic model neither on a regional nor on a global scale.

[23] The solution proposed here reconciles the geological data, the tomographic analysis and the position of the Africa–Europe plate boundary (Figures 5 and 6). In this model, the whole evolution of the region over the last 100 Ma is related to a single, still-active subduction process. This scenario justifies also the presence of a rather continuous magmatic input in the back arc region during the last 100 Ma (Figure 2). This model implies that the entrance of the large Apulian continental block at trench after the Late Cretaceous closure of the Vardar ocean did not cause subduction to cease. In this case, it is possible that off-scraping of light upper crustal slices permitted the continuation of subduction of the delaminated, dense mantle lithospheric portions.

[24] Our reconstruction starts in the Late Cretaceous (70–80 Ma) and is illustrated in the form of a cartoon in Figure 6, comparing the evolution of two subduction systems in three time steps. In this reconstruction, we use the tomographic cross-section CC′ of Figure 3e for the Aegean, which better highlights the main characters of the subduction scenario. At that time, the trench was favorably located in correspondence of the southern termination of the lower mantle, high-velocity anomaly. Therefore, the Aegean slab already accumulated material at the 660-km in a manner to initiate its travel into the midmantle. In fact, from 90 to 70 Ma more than 1000 of km was already consumed below the Rhodope massif. At that time the slab was probably steeper than the present-day one, accomplishing for the absolute advancing motion of the trench with respect to its tip. In the central Mediterranean, conversely, where small convergence took-place, the subduction process was only in its infant stage [*Faccenna et al.*, 2001b]. During much of the Paleogene, the trench advanced northeastward, and left backward trace of its motion. At the same time, during the continuous subduction process, a mountain belt was forming, piling up slices of crustal material.

[25] At about 30 Ma the absolute motion of the African plate decreased and halved in few million years. The decrease in the absolute motion of the downgoing plate is likely to cause a decrease of the in-plane compressional stress favoring the initiation of retreating motion of the two slabs [*Jolivet and Faccenna*, 2000]. The whole Mediterranean region underwent large-scale extension: the presence of oceanic portion of the lithosphere locked in between collisional belts allowed a complete extensional collapse of the previously formed orogenic belt [*Le Pichon*, 1982; *Jolivet and Faccenna*, 2000]. However, in the Aegean, the rate of extension was quite slow (1–2 cm/yr in average). The trench remained quite stationary in the lower mantle reference frame (Figure 6). Only in its more pronounced portion of the arc (Crete) we estimated a southward retreat of the trench of about 200 km, whereas the other part of the extensional process is related to the continuous northeastward motion of Europe away from the trench. It is possible that during this extensional phase the shallow portion of the Aegean slab decreased its dip to the present-day attitude. At the time extension initiated (30 Ma), conversely, the Tyrrhenian slab, was still sinking into the upper mantle (Figure 6). During the quite rapid opening of the Liguro-Provençal basin more than 400 km subducted in 15 Ma. Considering the previously subducted material due to plate convergence (about 180 km) it is then plausible to imagine that the tip of the Tyrrhenian slab reached the transition zone. This can be the cause of the drastic reduction of the retreat velocity for about 5 Myr observed in the area. In fact, extension resumed at about 10 Ma, in the more advanced position of the Tyrrhenian basin. It is then possible to imagine, as proposed by *Faccenna et al.* [2001a], at that time the slab bent and reaccelerated again during the opening of the Tyrrhenian Sea reaching its steep present-day geometry.

[26] This reconstruction of course suffers from some oversimplifications. First, the reconstruction of the subduction process in the Mediterranean is eminently three-dimensional, due to the complexity of the inherited paleogeographic scenario. In addition, we did not take into consideration the continuity of the slabs in their shallower portion (topmost 150–200 km), which is still under debate particularly in the Apenninic sector (see *Wortel and Spakman* [2000] for a review). Tomographic results show lateral variations in the continuity of shallow high-velocity anomalies along the Apenninic chain [*Spakman et al.*, 1993; *Piromallo and Morelli*, 1997; *Lucente et al.*, 1999]. In particular, the lack of high-velocity anomalies, detected by all models, in correspondence to the Central–Southern Apennines is interpreted as due to slab detachment [*Wortel and Spakman*, 1992, 2000] or as evidence of a different nature (continental rather than oceanic) of the subducted lithosphere [*Lucente et al.*, 1999]. We also neglect the recent evolution of the regions. Along the Apennines, for example, the rate of subduction decreased during the Pleistocene and the whole belt underwent a large-scale uplift [e.g., *D'Agostino and McKenzie*, 1999]. In the Aegean, the locus of extension shifted toward the Aegean basin shoulders [*Jolivet*, 2001] and a temporal change in the stress field occurred [e.g., *Le Pichon and Angelier*, 1979; *Meijer and Wortel,*, 1996]. Nevertheless, considering the time- and the length-scales of the process

analyzed here, we are confident that these complexities do not have strong implications on our main results.

6. Implications for the Style of Mantle Convection in the Mediterranean

[27] The comparison between those two subduction systems, where boundaries and geological conditions are rather well defined, sheds light on the long-standing debate concerning the depth of convection and on the way slab interacts with the 660-km discontinuity. For the case of the Mediterranean, we identify two parameters that could have played a dominant role allowing for the penetration of the slab in the Aegean mantle. The first is the motion of the upper plate–trench system. In correspondence to the Hellenic region the trench advanced as the upper plate moved northward, like the African plate did. This condition could facilitate piling up of lithospheric material at the 660-km discontinuity. Similarly, the motion of the Philippine plate system away from the trench, has been proposed to be the cause of the partial penetration of the Mariana slab in the midmantle [*Van der Hilst and Seno*, 1993]. Conversely, the Tyrrhenian trench retreated and material is likely lying on the 660-km over a wider area, decreasing the effective force that favors penetration, as suggested by laboratory and numerical experiments [*Christensen and Yuen*, 1984; *Kincaid and Olson*, 1987; *Griffiths et al.*, 1995; *Christensen*, 1996]. The other concurring factor is the duration of subduction. Continuous downwelling processes (~100 Myr), in fact, should favor the accumulation of lithospheric material at the upper-lower mantle boundary making it easier to overcome the effect of the viscosity jump and of the gravitational forces at the 660-km phase change [e.g., *Tackley et al.*, 1994; *Davies*, 1995; *King and Ito*, 1995; *Zhong and Gurnis*, 1995]. The amount of material in the lower mantle below the Aegean, as imaged by tomography is quite large (~4000 km), suggesting that subduction in the area was already active during the Cretaceous time, possibly the Jurassic (no constraints are available to define the age of initiation of the subduction system). Subduction process in the Tyrrhenian, and more generally in the whole western Mediterranean region, is younger, developed mostly during the Tertiary [*Dercourt et al.*, 1986], and the trench started to retreat while slab was still descending into the upper mantle. In this condition the subducted material is likely to be temporarily halted at the 660-km discontinuity because mass flux has neither the time (duration and amount of subduction) nor the favorable geometry (subducted material horizontally lying over a wider region) to penetrate in the lower mantle.

[28] The geometry of the subducted slab below the Aegean mantle resembles the one imaged by tomography below India [*Van der Voo et al.*, 1999a]. In our interpretation, the presence of lower mantle subducted material to the back of the present-day upper mantle slab represents the deep trace of the advancing slab. This implies that the slab tip was not anchored to the lower mantle but moved northward coherently with trench, possibly sustained by the presence of an upper mantle flow coupled to the African plate [*Silver et al.*, 1998]. In the case of an effective anchoring, in fact, we should expect a backward reclined slab, like the one described in the western Himalaya [*Van der Voo et al.*, 1999a]. This also implies that the subducted material in the lower mantle is not directly connected with its upper mantle feeding source. This view is also supported by the images of the Aegean slab (Figures 2a and 3e) that is thickened and thus deformed at transition region.

[29] From the reconstruction proposed here, we cannot define the timescale and the kinematics of the downwelling process. This is because we do not know either the exact duration of subduction in the Aegean or the effective amount of subducted material. In fact, the ellipsoidal shape of the high-velocity anomaly suggests that lithospheric material could be channeled from the side toward the central portion of the deep Aegean slab, resembling the results of 3-D convection numerical models [*Bunge et al.*, 1997]. In this sense, the amount of subducted material estimated along the 2D section (~4000 km) can be largely overestimated. Nevertheless, from reconstruction it is possible to deduce that the present-day upper mantle slab is constituted by lithospheric material subducted mainly during the Cenozoic (~1000 km), whereas the lower mantle one is subducted during the Mesozoic. In fact, by the time the slab penetrated into the lower mantle (Late Cretaceous, Figure 6g), at least 1000 km of lithosphere was already subducted. Assuming an average rate of plate convergence of ~2 cm/yr, one can estimate the minimum age for the initiation of subduction is Late Jurassic. If this is correct, the southern and deeper portion of the lower mantle material could represent the lithosphere of the Vardar ocean. The possibility to identify lithospheric materials into the lower mantle some ~150 Myr after they have been subducted is not surprising. Examples of fast tomographic anomalies referred to lithosphere subducted in the Jurassic and Cretaceous have been already proposed [*Van der Voo et al.*, 1999b; *Bunge and Grand*, 2000] and tested by convection models [*Bunge et al.*, 1998]. Therefore, we can deduce that material now at a depth of 1500 km descends into the mantle at an average rate on the order of ~1 cm/yr. The rate of downwelling estimated here is similar to the one calculated for the Mesozoic slab under Siberia [*Van der Voo et al.*, 1999b]. This velocity is thus sufficiently high to ensure that the slab is not eroded away by the conductive heating. If our reconstruction is correct, we can also infer that lithosperic material accumulates and stagnates over the 660-discontinuity for at least ~50 Myr before entering in the lower mantle. This prevision is in the range of what proposed by previous geodynamic models [*Zhong and Gurnis.*, 1995; *Ito and King*, 1998].

[30] In our reconstruction, the different style of convection envisaged below the two Mediterranean regions creates a different geological expression also at surface, looking at the style of back arc deformation. Rapid (up to ~5 cm/yr) and short episodes of back arc extension observed in the Tyrrhenian have been related to slab reshaping when it reached the 660-km discontinuity [*Faccenna et al.*, 2001a]. They occurred on a timescale of $\sim 10^6 - 10^7$ Myr and possibly characterize a region where the convection process is restricted to the upper mantle. In the Aegean region, in fact, the extensional process is slower (~1–2 cm/yr), and preserved its characteristics over much of its history [*Jolivet*, 2001]. We suggest that the different rate and style of back arc deformation are somehow related to the different scale of the (time-dependent) convection process in the two regions. Fast and intermittent motion of the slab is probably promoted if the convection

process is restricted to the upper mantle, while slow and uniform motion is possibly favored for larger scale downwellings in the lower mantle.

[31] Finally, it is difficult to predict the fate of the subducted slabs in the central Mediterranean region. In the long-term, from the comparison with the Aegean region, it is reasonable to suppose that under the continuous push of the African plate, the amount of material lying over the 660-km discontinuity will increase to a level that viscous and gravitational forces will be overcome. Then, cold lithospheric material will start its slow downwelling into the lower mantle. In this case, the lower mantle signature of the Tethyan slab [*Grand et al.*, 1997; *Van der Voo et al.*, 1999a] over the whole Alpine–Himalayan belt, from the very far east to Gibraltar, will be complete.

7. Conclusion

[32] We use geological data, plate motion reconstructions and seismic tomography to study the tectonic of the eastern and central Mediterranean. We find that the evolution of presently active subduction zones are remarkably different. The Aegean slab is characterized by a shallow dip and its history started at least during the Cretaceous. The evolution of the slab was controlled by the motion of the Eurasia plate, which mostly moved northeastward away from the trench, and of the African plate, which also moved northward, causing the trench to advance toward the upper plate. Tomography shows a long slab-like feature that penetrates in the midmantle. We propose that this feature can be reconciled with a single subduction process running from at least the Cretaceous, consuming first the Vardar oceanic domain, the large continental block and presently the Ionian ocean. The history of subduction reconstructed for the Aegean trench is different from the one observed further to the west, in the central Mediterranean. Below Calabria the slab is steep and then it bends lying over the 660-km discontinuity, without traces of past or present large-scale midmantle penetration. We infer that the depth of penetration in the mantle of the two slabs depends on the amount of the subducted material and on the way it piled up at the 660-km discontinuity. In the Aegean the advancing motion of trench, and the duration of continuous downwelling favor a large accumulation of cold material at the transition zone and further on its penetration in the midmantle, that should be initiated around the Late Cretaceous. In this model the deeper, lower-mantle, fast velocity anomaly as detected by tomography can be related to the lithosphere of the Vardar ocean subducted in the Jurassic. Conversely the retreating Tyrrhenian slab mainly evolved during the Tertiary and did not have either the time or the geometry to penetrate into the midmantle. We also suggest that the style of back arc extension, fast and episodic in the central Mediterranean contrast with the slow one observed in the Aegean are consequences of the two different styles of convection. The example of the Mediterranean contributes to the general understanding of the style of present-day mantle convection in that they further substantiate the view [e.g., *Van der Hilst and Karason*, 1999; *Becker and Boschi*, 2002] that the 660-km discontinuity represents an impediment but not long-term barrier to flow.

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