



Lateral slab deformation and the origin of the Western Mediterranean arcs

C. Faccenna, C. Piromallo, A. Crespo-Blanc, Laurent Jolivet, F. Rossetti

► To cite this version:

C. Faccenna, C. Piromallo, A. Crespo-Blanc, Laurent Jolivet, F. Rossetti. Lateral slab deformation and the origin of the Western Mediterranean arcs. *Tectonics*, 2004, 23, pp.1-21. 10.1029/2002TC001488 . hal-00022411

HAL Id: hal-00022411

<https://hal.science/hal-00022411>

Submitted on 11 Feb 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Lateral slab deformation and the origin of the western Mediterranean arcs

Claudio Faccenna,¹ Claudia Piromallo,² Ana Crespo-Blanc,³ Laurent Jolivet,⁴ and Federico Rossetti¹

Received 6 December 2002; revised 31 July 2003; accepted 15 October 2003; published 3 February 2004.

[1] The western Mediterranean subduction zone (WMSZ) extends from the northern Apennine to southern Spain and turns around forming the narrow and tight Calabrian and Gibraltar Arcs. The evolution of the WMSZ is characterized by a first phase of orogenic wedging followed, from 30 Ma on, by trench retreat and back-arc extension. Combining new and previous geological data, new tomographic images of the western Mediterranean mantle, and plate kinematics, we describe the evolution of the WMSZ during the last 35 Myr. Our reconstruction shows that the two arcs form by fragmentation of the 1500 km long WMSZ in small, narrow slabs. Once formed, these two narrow slabs retreat outward, producing back-arc extension and large scale rotation of the flanks, shaping the arcs. The Gibraltar Arc first formed during the middle Miocene, while the Calabrian Arc formed later, during the late Miocene-Pliocene. Despite the different paleogeographic settings, the mechanism of rupture and backward migration of the narrow slabs presents similarities on both sides of the western Mediterranean, suggesting that the slab deformation is also driven by lateral mantle flow that is particularly efficient in a restricted (upper mantle) style of mantle convection. **INDEX TERMS:** 8120

Tectonophysics: Dynamics of lithosphere and mantle—general; 8102 Tectonophysics: Continental contractional orogenic belts; 8158 Tectonophysics: Plate motions—present and recent (3040); 8150 Tectonophysics: Plate boundary—general (3040);

KEYWORDS: Mediterranean, subduction, arcuate belt, tomography.

Citation: Faccenna, C., C. Piromallo, A. Crespo-Blanc, L. Jolivet, and F. Rossetti (2004), Lateral slab deformation and the origin of the western Mediterranean arcs, *Tectonics*, 23, TC1012, doi:10.1029/2002TC001488.

1. Introduction

[2] Arcs are characteristic features of subduction systems. Most of them face the overriding plate reflecting undula-

tions in the subducting slab, as detected by earthquake hypocenters distribution [e.g., *Isacks and Molnar*, 1971]. The Mediterranean area shows a large number of unusually narrow arcs, defining an irregular and rather diffuse plate boundary. In particular, the boundary between Africa and Eurasia runs parallel to the north African coast and then turns northward forming the tight arcs of Gibraltar and Calabria, at the western and eastern sides of the western Mediterranean, respectively (Figure 1). The external domain of the two arcs is constituted by foreland thrust belts, whereas the inner domain is occupied by extensional basins. Hence the genesis of both arcs should be related to the transfer and migration of crustal material outward for some hundreds of kilometers, while preexisting structures are passively rotated along the two flanks. The migration rate is high, reaching 5–6 cm/yr, in the Calabrian-Tyrrhenian system [*Patacca et al.*, 1990] and is higher than the rate of convergence, which is of the order of 1–2 cm/yr [e.g., *Dewey et al.*, 1989]. Hence their formation cannot be related to the kinematics of the plate system in a rigid escape fashion [e.g., *Tapponnier*, 1977] but should be somehow connected with the deep internal dynamics of the system. The presence of a back-arc-trench system also suggests that those arcs can be related to the retreat of the subduction zone. *Malinverno and Ryan* [1986] first proposed that the Calabrian Arc formed by trench retreat in correspondence of the narrow Ionian oceanic lithosphere. However, the radius of curvature of the western Mediterranean arcs is one order of magnitude smaller than other trench curvatures (10° on average [*Tovish and Schubert*, 1978; *Jarrad*, 1986]). Hence it is difficult to imagine that those structures can simply form as a consequence of slab bending. For example, three-dimensional laboratory experiments fail to reproduce the narrow radius of curvature of the Calabrian Arc [*Faccenna et al.*, 1996]. *Nur et al.* [1991] overcome this limitation suggesting that the arcs of the Tyrrhenian system formed as a consequence of the retreat of a narrow slab, and *Dworkin et al.* [1993] analyze the possibility that slab mantle material can flow around the slab sides, enhancing the retreat velocity. The hypothesis of slab retreat has been also extended to the case of the Gibraltar Arc [*Royden*, 1993; *Lonergan and White*, 1997]. However, application of the retreat model to this area has been criticized [*Vissers et al.*, 1995; *Calvert et al.*, 2000] as the formation of the Gibraltar region occurred during continental convergence. An alternative hypothesis for the formation of this structure stems from the possibility to generate radial compression by removing the dense and thickened mantle portion of the lithosphere in the inner side of the arc [*Platt and Vissers*,

¹Dipartimento di Scienze Geologiche, Università di Roma Tre, Rome, Italy.

²Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy.

³Istitut Andaluz de Ciencias de la Tierra, Granada, Spain.

⁴Laboratoire de Tectonique, Université Paris VI, Paris, France.

1989; *Vissers et al.*, 1995]. On the other hand, this scenario is not realistic for the case of the Calabrian Arc as the well-defined Wadati-Benioff zone suggests the presence of an active subduction [*Isacks and Molnar*, 1971; *Giardini and Velonà*, 1988; *Selvaggi and Chiarabba*, 1995].

[3] Despite the similarity in the geometry and in the structure of the two arcs (Figure 1), it is then evident that a unique, simple explanation for their genesis has not yet been proposed. However, it seems inescapable, when looking at the tectonic evolution of the western and central Mediterranean, that the formation of the Gibraltar and Calabrian Arcs results from the same process. It is thus tempting to look for a single mechanism which would adequately explain the evolution of both.

[4] We reconstruct the Tertiary evolution of the western Mediterranean exploring the kinematics of the subducting system. We use geological data, seismic tomography of the lithosphere-mantle and plate kinematics to formalize a geological consistent tectonic scenario at the scale of the upper mantle. From this reconstruction we conclude that the mechanism leading to the formation of the two arcs is similar, deriving from the fragmentation in narrow tongues of a single, wider subduction zone.

2. Geology of the Western Mediterranean Subduction Zone

[5] The western Mediterranean subduction zone (WMSZ) shows along its length common geological features in terms of tectonic architecture, age, and style of deformation. Three distinct domains can be distinguished. The inner orogenic domain, outcropping in northern Apennines, Calabria, Kabylie and in Rif-Betic belt, is constituted by metamorphic units and preserves the oldest trace of a subduction process. It separates the extensional back-arc domain (Tyrrhenian, Liguro-Provençal, Valencia, Algerian and Alboran basins) from the external domain, where slices of the sedimentary cover derived from the paleomargins are piled up (Apennines, Magrebides, Atlas, external Rif and sub-Betics). Over the whole WMSZ, the extensional back-arc domain deforms contemporaneously with the external domain. Only a small portion of this once vigorous subduction zone is now active: a rather well-defined Wadati-Benioff zone is present only below the Calabrian Arc [*Selvaggi and Chiarabba*, 1995].

2.1. Inner Orogenic Wedge

[6] Boudins of the Alpine metamorphic belt, stretched and drifted apart during the Neogene extensional episodes represent the oldest remnants of the subduction process. They are present along the WMSZ in the Calabrian Arc, in the Kabylie and in the Betic-Rif belt (Figures 1, 2, and 3). The metamorphic belt is constituted by the stacking of slices of continental Variscan basement and its cover, continental, oceanic and metasedimentary rocks. Extensive outcrops of ophiolites are present only in the Calabria belt, suggesting that the Jurassic ocean narrows westward [*Dercourt et al.*, 1986]. Alpine metamorphism overprint covers the entire range of possibilities from greenschist to blueschist facies, and, locally, to eclogitic. Pressure-temperature (P-T) cali-

bration for the main metamorphic units reveals an increasing thermal gradient moving westward along the WMSZ. In Calabria, pressure estimates range from 0.5 to 1.2 GPa while temperatures are less than 350°–450°C [*Piccarreta*, 1981; *Cello et al.*, 1991; *Rossetti et al.*, 2001]. In the Kabylie and in the Alboran domain, temperatures up to 600°C are documented for rocks that have suffered pressures up to 1.0–1.4 GPa [*Goffé et al.*, 1989; *Bouybaouene et al.*, 1995; *Saadallah and Caby*, 1996; *Azañon et al.*, 1998; *Caby et al.*, 2001]. Geological and radiometric data indicate that the Alpine metamorphic signature occurs between the Paleogene and the early Miocene (Calabria [*Borsi and Dubois*, 1968; *Shenk*, 1980; *Beccaluva et al.*, 1981; *Rossetti et al.*, 2001], Kabylie [*Monié et al.*, 1988; *Saadallah and Caby*, 1996; *Caby et al.*, 2001], and Rif-Betic [*DeJong*, 1991; *Monié et al.*, 1991; *Zeck et al.*, 1992; *Vissers et al.*, 1995; *Sánchez-Rodríguez et al.*, 1996; *Balanyá et al.*, 1997; *Martinez-Martinez and Azañon*, 1997; *Platt et al.*, 1998; *Platt and Whitehouse*, 1999; *Azañon and Crespo-Blanc*, 2000]).

[7] The architecture of the wedge shows common characters along the WMSZ. Its current structure, however, has been modified significantly from its original geometry. In fact, the late Neogene evolutionary stages of the belt, related to the extensional processes, obliterate the structures associated with the early thickening event. The most evident expression of the extensional process is the formation of large-scale detachments that place high-pressure units (HP) below nonmetamorphosed or slightly metamorphosed units. Kinematic indicators related to the thickening event are rare and have been found only in Calabria where a northeast directed shear sense has been described [*Dietrich*, 1988; *Monaco*, 1993; *Rossetti et al.*, 2001] (Figure 2). In the Alboran domain, the synmetamorphic exhumation-related linear fabric shows an overall northward directed sense of shear turning around the arc from NE in the Betics to NNW in the Rif [*Balanyá and García-Dueñas*, 1988] (Figure 3). They have been related either to a compressive [*Tubía et al.*, 1992; *Simancas and Campos*, 1993] or to an extensional regime [*Platt and Vissers*, 1989; *Vissers et al.*, 1995; *Balanyá et al.*, 1997; *Martinez-Martinez and Azañon*, 1997; *Platt et al.*, 1998; *Azañon and Crespo-Blanc*, 2000].

2.2. Back-Arc Extensional Domain

[8] Over the whole western Mediterranean, back-arc extensional processes affected both the inner orogenic belt and the Iberian domain [*Faccenna et al.*, 1997]. The extensional regime is contemporaneous with the accretion of the external fold-and-thrust belt and is more vigorous moving eastward along the WMSZ. Indeed, in the central Mediterranean, two triangular oceanic basins open: the Liguro-Provençal first and the Tyrrhenian afterward (Figures 1 and 2). Cross section AA' of Figure 4, running from Calabria to the Gulf of Lyon and parallel to the main extensional direction, shows the lithospheric structure and the age (Figure 4, top) of these two basins separated by the Sardinia block [*Finetti and Del Ben*, 1986; *Suhadolc and Panza*, 1989; *Chamot-Rooke et al.*, 1999]. In the Liguro-Provençal basin, extensional processes started at about

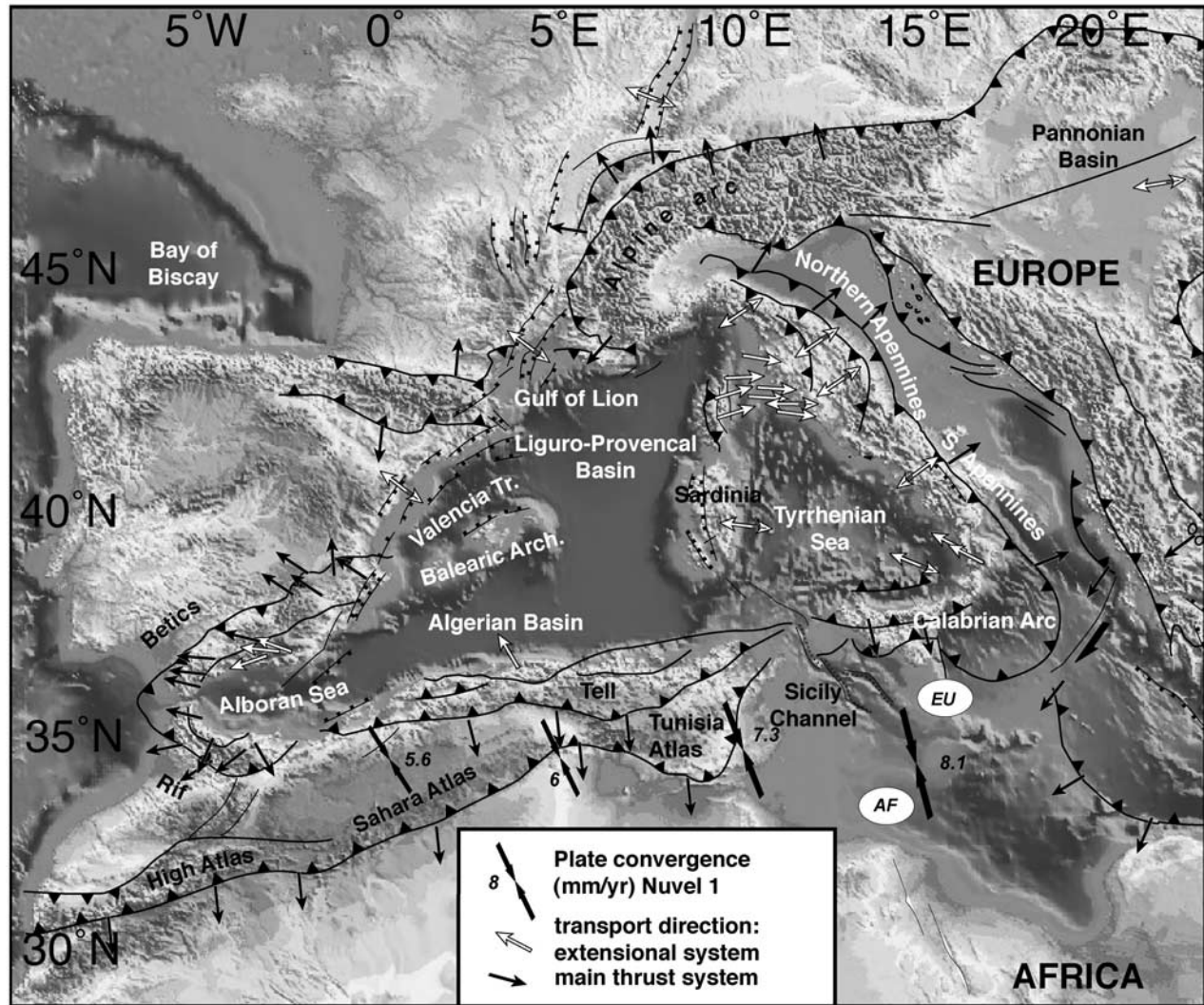


Figure 1. Tectonic map of the western Mediterranean region. Sense of transport along main thrust fronts (black arrows) and along the main extensional detachments (white arrows) is shown (see text for references).

30 Ma [Cherchi and Montandert, 1982; Gorini *et al.*, 1994; Seranne, 1999], and from 21 to 16 Ma, oceanic spreading took place [Burrus, 1984] during the counterclockwise rotation of the Corsica-Sardinia block [Van der Voo, 1993]. After a pause of a few million years, extension shifted eastward to the southern Tyrrhenian basin (Figure 4), leading to the complete collapse of the Calabrian orogenic wedge by large-scale extensional detachment [Rossetti *et al.*, 2001] (Figure 2). In this region, synrift deposition started at ~ 10 –12 Ma on both the eastern Sardinia shelf and Calabria margin [Kastens and Mascle, 1990; Sartori, 1990; Mattei *et al.*, 2002]. It was followed by the formation of localized spreading centers (at 4–5 Ma, Vavilov basin, and at 2 Ma, Marsili basin) [Sartori, 1990]. In a similar way, the volcanic arc migrated southeastward from the Provençal and Sardinia margin, where calc-alkaline suites erupted from 34–32 Ma up to 13 Ma [Beccaluva *et al.*, 1989], to the Tyrrhenian basin at about 5 Ma (5–

2 Ma), reaching its present-day position in the Eolian Island (Figure 2) [Beccaluva *et al.*, 1989; Kastens *et al.*, 1988; Argnani and Savelli, 1999]. In Sardinia, a new phase of magmatic activity occurred during the Pliocene with the eruption of alkaline to tholeiitic suites [e.g., Lustrino *et al.*, 2000].

[9] The Valencia trough represents the westward continuation of the Provençal basin (Figure 1). Cross section BB' (Figure 4) runs from the Kabylie massif to Iberia. In the Valencia trough, the extensional process occurred between 26 and 16 Ma [Verges and Sabat, 1999] during the clockwise rotation of the Balearic Islands [Parés *et al.*, 1992]. Thrusting in the Balearic Island also occurred at that time, from the upper Oligocene [Sabat *et al.*, 1988] to 15–12 Ma [Verges and Sabat, 1999]. During this stage, the extensional process was also localized in the inner orogenic domain, causing the collapse of the Kabylie belt with the formation of extensional detachments with a top-to-north sense of

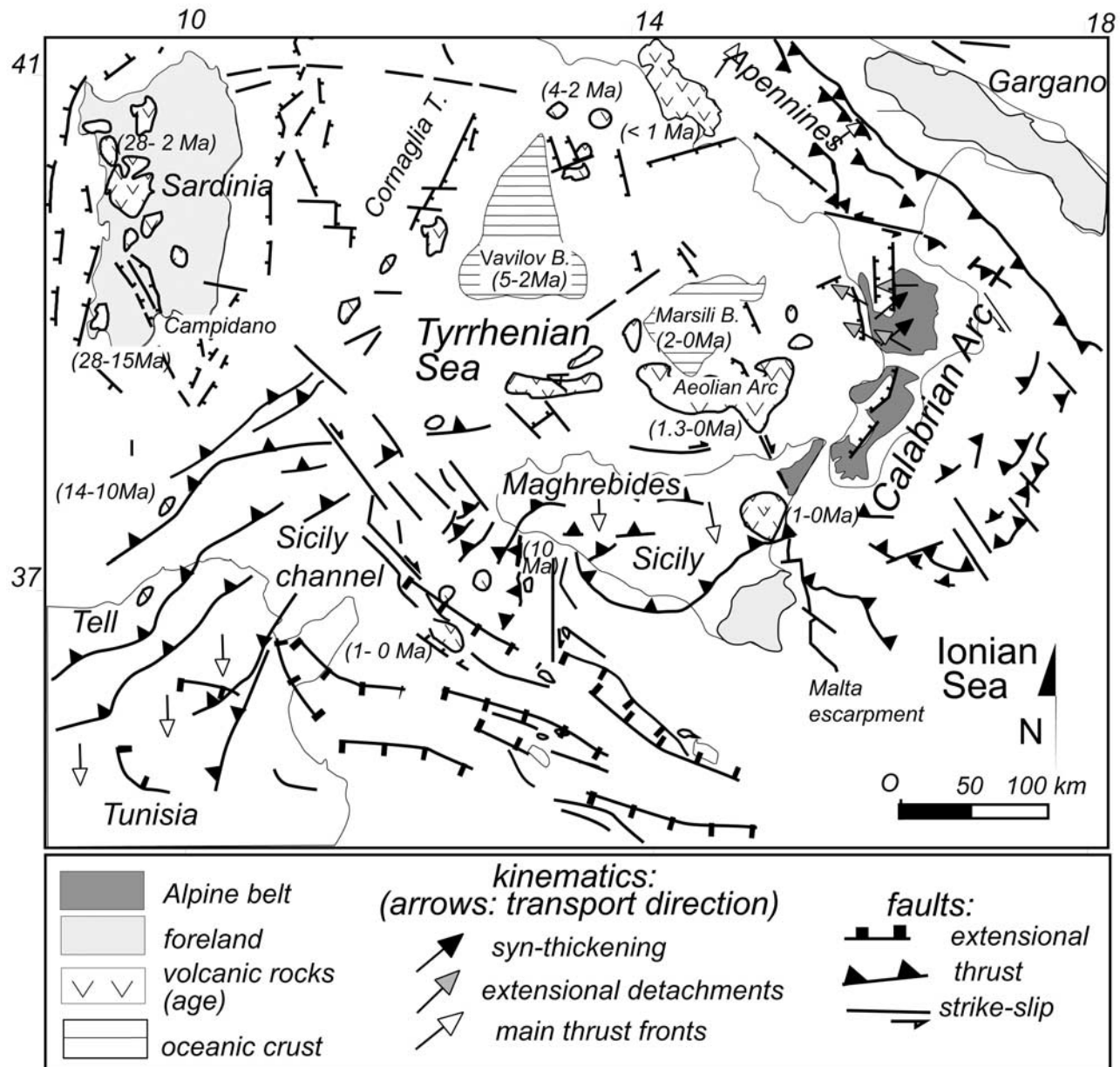


Figure 2. Tectonic map of the Calabrian Arc region. Sense of transport along the main thrust front (white and black arrows for the external and internal domain, respectively) and extensional detachments (grey arrows) are shown (see text for references).

shear (Figure 1) [Saadallah and Caby, 1996; Caby et al., 2001].

[10] A few million years after, extension shifted in the Algerian basin. The exact timing of the Algerian basin opening is not known. It should have occurred before 6–7 Ma, the age of the evaporites overlying the oceanic crust [Verges and Sabat, 1999] and possibly after the compressional episode present in the Balearic archipelago (12 Ma). The volcanic arc also shifted southward following the trench system. Calc-alkaline suite volcanism, 25–13 Ma in age, first occurred in the Valencia trough and then migrated along the north African coast, while in the Valen-

cia region alkaline volcanism took place since 10 Ma [Marti et al., 1992]. In central Algeria, the subduction-related volcanic activity spanned from 16 to 10 Ma, first with the eruption of low-K arc tholeiites and then with the emplacement of granitoids and acidic lavas with a strong crustal signature [Maury et al., 2000; Fourcade et al., 2001].

[11] Further to the west, extensional processes affected the orogenic wedge of the Alboran domain. The ages of synrift sediments and radiometric dating indicate that extension in the Alboran region started around 27–25 Ma [Comas et al., 1999]. Cross section CC' (Figure 4) strikes

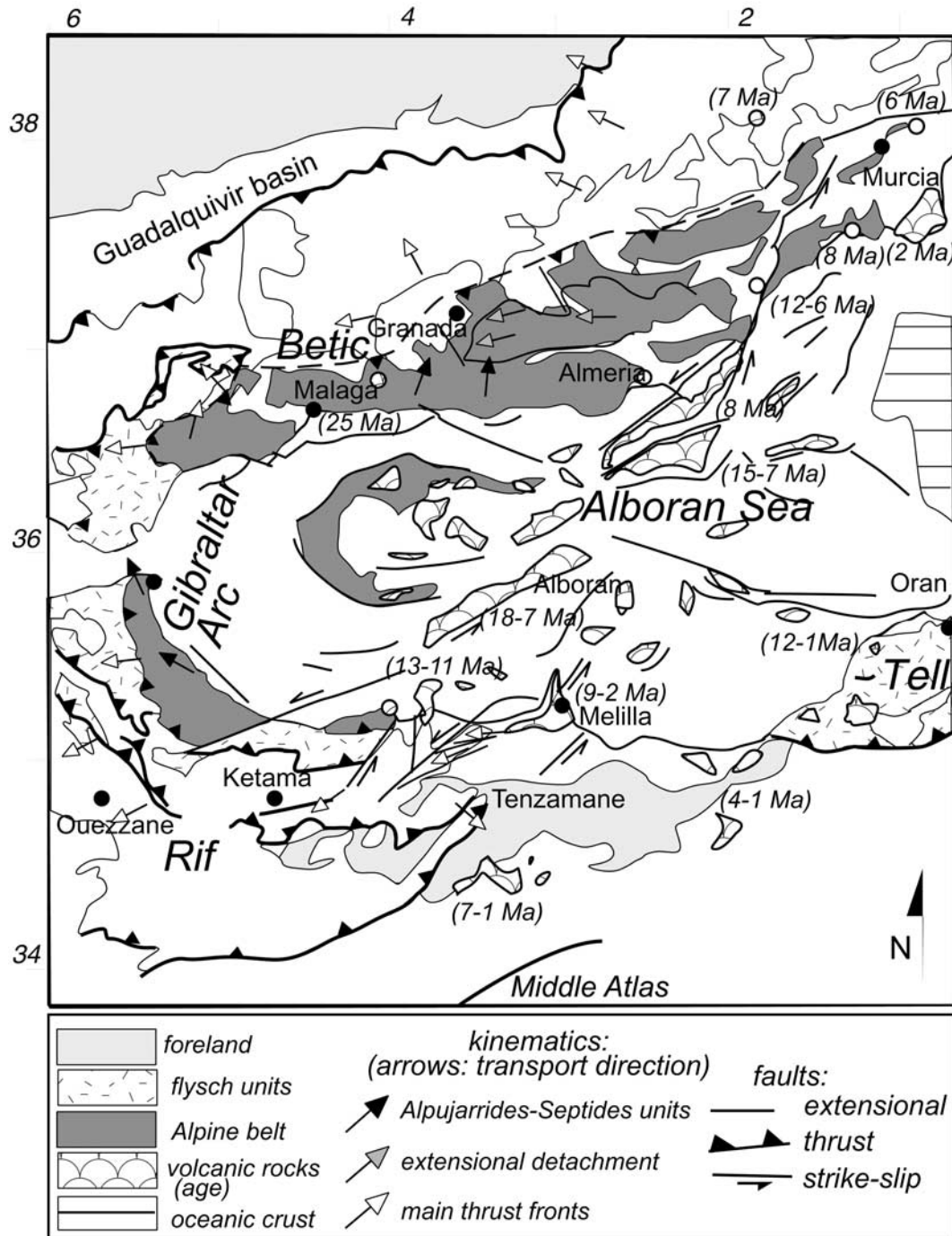


Figure 3. Tectonic map of the Gibraltar Arc region. Sense of transport along the main thrust front (white and black arrows for the external and internal domain, respectively) and extensional detachments (grey arrows) are shown (see text for references).

WSW-ENE, that is, parallel to the stretching direction associated with the Alboran rifting [García-Dueñas *et al.*, 1992; Comas *et al.*, 1992, 1999]. It shows that both the crust and the mantle lithosphere are strongly thinned below the Alboran basin with respect to the outer region of the compressional fronts (2.5 times according to Torné *et al.*

[2000]). The extensional process in the Alboran domain is marked by the formation of a large-scale postorogenic extensional shear zone with a westward-southwestward sense of shear (Figure 3) [Galindo-Zaldívar *et al.*, 1989; Platt and Vissers, 1989; García-Dueñas *et al.*, 1992; Jabaloy *et al.*, 1993; Martínez-Martínez and Azañón,

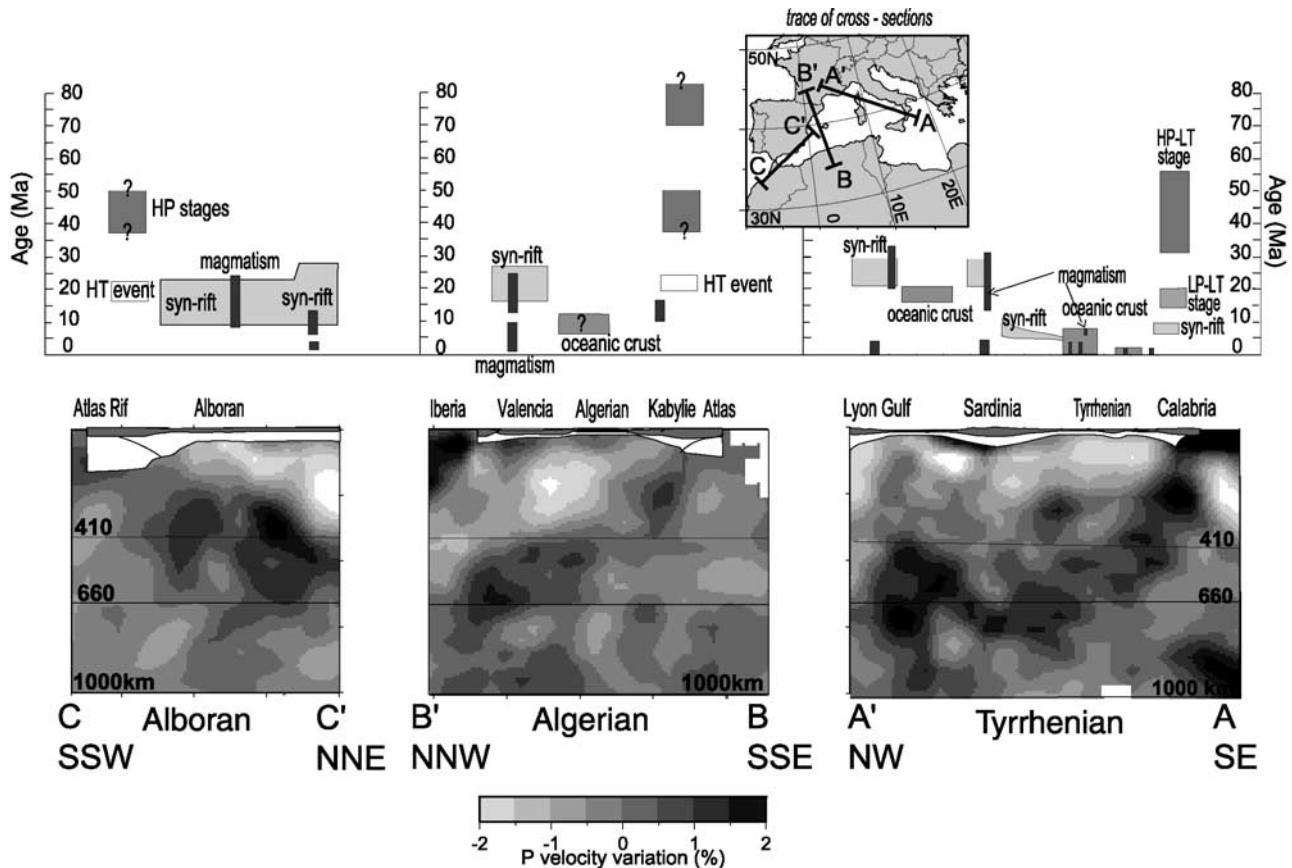


Figure 4. (bottom) Cross sections of the studied area (locations in the inset). AA' is from Calabria to the Gulf of Lyon, BB' is from Algeria to Iberia, and CC' is from southwestern Morocco to Cartagena. Crustal structure of section AA' is from *Finetti and Del Ben* [1986] and *Chamot-Rooke et al.* [1999], of section BB' is from *Verges and Sabat* [1999], and of section CC' is from *Torné et al.* [2000]. Lithospheric structure is from *Suhadolc and Panza* [1989] and *Torné et al.* [2000]. Tomographic cross sections are from model PM0.5 [*Piromallo and Morelli*, 2003]. (top) Age and distribution of the geological record related to subduction (see text for references): metamorphism (blue and green boxes represent blueschist and greenschist facies, respectively), magmatism (red boxes represent volcanic and intrusive rocks), synrift deposits filling extensional basins (yellow box), and oceanic crust (light blue box). See color version of this figure at back of this issue.

1997]. Extension was associated with a thermal event, as revealed by magmatism and by the clustering of most radiometric ages around 22–18 Ma (Figure 4) [*Sánchez-Rodríguez et al.*, 1996; *Monié et al.*, 1991; *Zeck et al.*, 1992; *Monié et al.*, 1994; *Platt and Whitehouse*, 1999; *Zeck*, 1999; *Sánchez-Rodríguez and Gebauer*, 2000; *López Sánchez-Vizcaíno et al.*, 2001]. Volcanism started in the early Miocene with the tholeiitic dike swarm of Malaga [*Turner et al.*, 1999] and inside the Alboran basin (20 Ma) with a calc-alkaline signature [*Comas et al.*, 1999]. Afterward, it migrated northward in southeastern Spain [*Benito et al.*, 1999; *Turner et al.*, 1999] and southward, along the Morocco-Algerian border [*El Bakkali et al.*, 1998; *El Azzouzi et al.*, 1999; *Maury et al.*, 2000; *Coulon et al.*, 2002]. In both areas, the transition from calc-alkaline products to transitional, in the Tortonian, and to alkali basaltic from the Pliocene is documented [*El Azzouzi et al.*, 1999; *Maury et al.*, 2000]. In particular, in Morocco, volcanism spans from

15 Ma to Quaternary [*El Bakkali et al.*, 1998; *El Azzouzi et al.*, 1999; *Maury et al.*, 2000; *Coulon et al.*, 2002]. It must be stressed that the Miocene-to-Pliocene volcanic centers are scattered along a NNE-SSW directed belt extending from the inner back-arc region to the external foreland region, both on the Maghrebien and the Iberian margin (Figure 3) [*Piqué et al.*, 1998].

[12] Over the whole WMSZ the decay of extensional processes migrated progressively in time and space, from west to east. The recent tectonic evolution of the Gibraltar Arc area is marked by north-south convergence from lower Messinian onward. Kilometric-scale open folds formed, together with large-scale strike-slip structures and minor N-S normal faults [*Comas et al.*, 1999] (Figure 3). From the Pliocene onward a NW-SE trending compressional regime and a complex pattern of active strike-slip structures affected also the internal zones and passive Algerian margin [*Pondrelli et al.*, 1995; *Meghraoui et al.*, 1996]. Finally, in

the back-arc region of the Calabria subduction zone, extension is presently diminishing as indicated by the seismically active strike-slip and compressive structures [Pondrelli *et al.*, 1995].

2.3. External Foreland Thrust Belt

[13] The external envelop of the orogenic wedge is constituted by a stack of Meso-Cenozoic sedimentary units derived from the African-Iberian-Adria margin (Figure 1). These foreland fold-and-thrust belts formed during the Neogene and turn around both arcs. The southern Apennine is constituted by a system of NW-SE directed thrusts with a NE directed sense of transport (Figures 1 and 2) [Patacca *et al.*, 1990; Roure *et al.*, 1991; *Consiglio Nazionale delle Ricerche*, 1991], while the Sicilian Maghrebian thrust belt trends regionally E-W across Sicily with a mainly southward sense of transport (Figure 2). The timing of deformation of the Apennine-Maghrebian thrust belt is bracketed between the Tortonian and the lower to middle Pleistocene [Patacca *et al.*, 1990] (Figure 2). After a sharp bend in Tunisia, probably due to the reactivation of preexisting structures [Ottami *et al.*, 1995], the fold-and-thrust belt continues all along North Africa. The E-W directed thrust front of both the internal Tell and external Atlas shows a main southward transport direction active in the more external portion up to Pleistocene time [Frizon de Lamotte *et al.*, 2000].

[14] Around the Gibraltar Arc, the internal zone overthrusts the African and Iberian paleomargins and the upper Cretaceous to lower Miocene flysch deposits (Figure 3). These fold-and-thrust belts formed during the middle and late Miocene. The sense of transport during this episode is globally W-SW directed in the western Rif [Morley, 1992; Frizon de Lamotte *et al.*, 1991], west directed in the Flysch units [Luján *et al.*, 2000], and WNW in the Betics (Figure 3) [Frizon de Lamotte *et al.*, 1991; Platzman *et al.*, 1993; Crespo-Blanc and Campos, 2001]. Platt *et al.* [2003] recently presented the pattern of stretching lineations around the arc and their orientation if restored for vertical axis rotation and shortening. The main conclusion of this study is that the outer front of the belt shows that the Betics and the Rif show a WNW and WSW motion, respectively. The transport direction in the external Rif is also attested by the presence WSW trending left-lateral shear zones [Frizon de Lamotte *et al.*, 1991] acting as lateral ramp and separating the Rif from the Tell belt (Figures 1 and 3). As described before, the Algerian Tell thrust belt at that time underwent a prevalently southward directed shear (Figure 1). Therefore, during the middle Miocene the Rif and the Tell belts separated following diverging transport directions. In the late Miocene the deformational front propagated in the more external portion. However, the outer deformational front of the Atlas shows a rather continuous E-W striking direction over the whole African margin, from Morocco to Tunisia, apart from the Middle Atlas which strikes obliquely due to the orientation of preexisting structures [Gomez *et al.*, 1998]. The southward transport direction of the Atlas front is consistent with the major plate convergence direction [Frizon de Lamotte *et al.*, 2000; Gomez *et al.*, 2000].

Recently, Gutscher *et al.* [2002] showed evidence west of Gibraltar of an active accretionary prism.

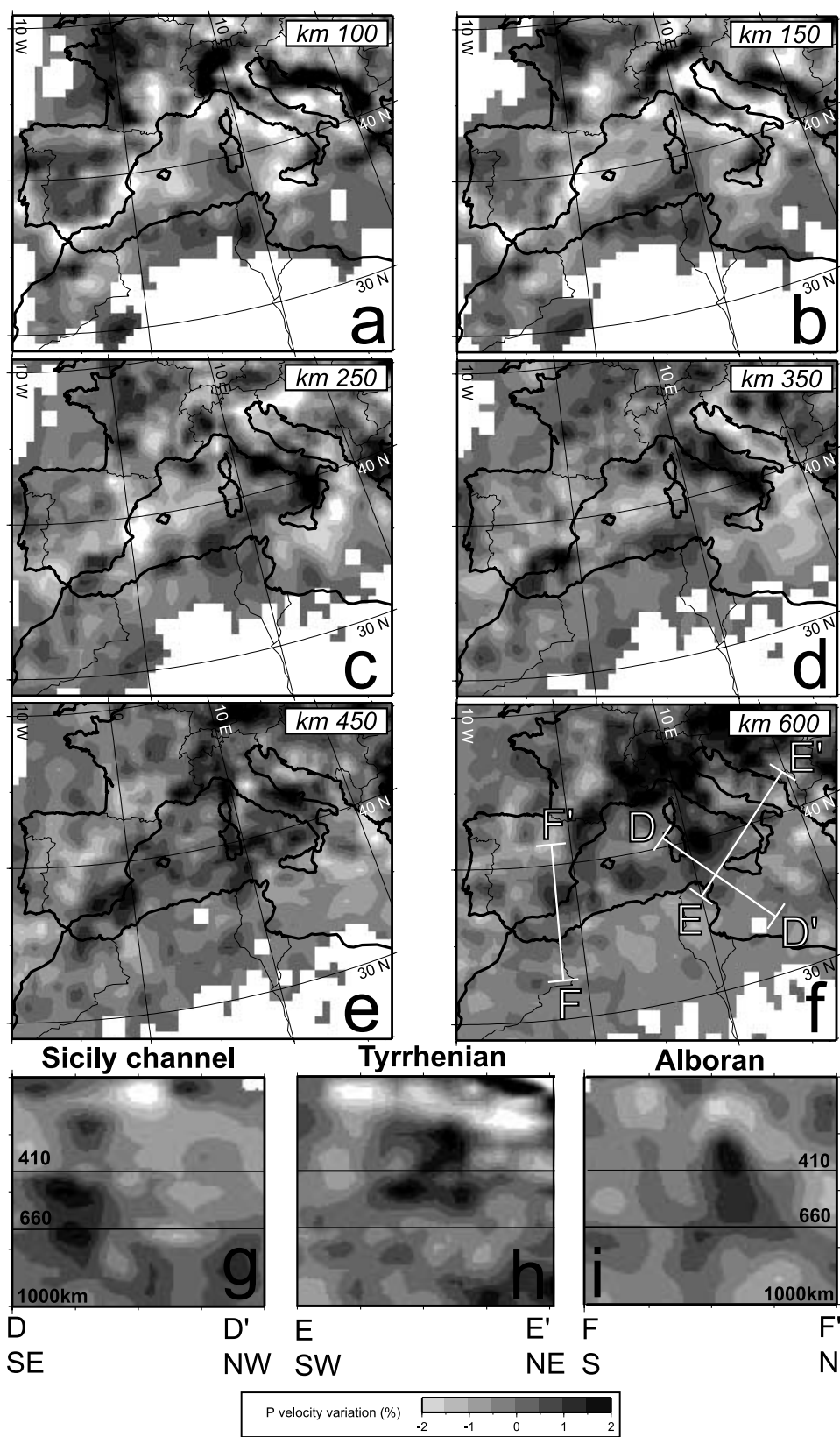
2.4. Evidences of Lateral Discontinuities in the WMSZ

[15] In the previous paragraph, we outline how the WMSZ extends from northern Apennine to Southern Spain. Nevertheless, the continuity in the geological features related to the WMSZ is interrupted. Along the northern Apennines, Royden *et al.* [1987] first documented the lateral segmentation of the subducting lithosphere on the base of the Pliocene foredeep architecture. Here we focus on the presence of two slab ruptures placed along the southern portion both arcs. The first is located in the Sicily channel, whereas the second interruption lies in the Oranie-Melilla region (Figures 1, 2, and 3).

[16] In the Sicily channel, the Maghrebian foreland thrust belt is crosscut by a system of NW trending faults and related basins [Tricart *et al.*, 1994], active from the late Miocene-Pliocene onward (Figure 2) [Illies, 1981; Jongsma *et al.*, 1987; Argnani, 1990, 1993; Tricart *et al.*, 1994]. The rift system is better developed in the African foreland region, where extensional basins and magmatic activity spread over a 200 km wide belt from northern Tunisia to Sicily. The kinematics of the rift system is characterized by the superposition of Pleistocene strike slip [Cello *et al.*, 1985; Jongsma *et al.*, 1987; Grasso *et al.*, 1990] over late Messinian-Pliocene extension [Illies, 1981; Jongsma *et al.*, 1987; Grasso *et al.*, 1990; Argnani, 1993]. Magmatic activity is mainly Quaternary in age [Consiglio Nazionale delle Ricerche, 1991], but traces of Tortonian volcanic rocks have been dredged off of southern Sicily [Argnani, 1990]. The northwestern continuation of the rift belt can be observed in Southern Sardinia, in the Campidano graben (Figure 2). The Sicily channel rift system therefore could represent the surface manifestation of a break in the WMSZ: it crosscut the fold and thrust belt running from the foreland to the inner extensional domain, and opened contemporaneously with the opening of the Tyrrhenian basin from the late Messinian-Pliocene onward.

[17] Gvirtzman and Nur [1999] suggest that the Malta escarpment fault zone (Figures 1 and 2) also represents the surficial evidence of a lateral break in the subducting system. Indeed, the Malta escarpment is a major Mesozoic discontinuity, as it represents the passive margin of the Ionian basin [Catalano *et al.*, 2001]. However, this structure was not active during the main Neogene phases of activity of the WMSZ, and has been partly reactivated only during the upper Pleistocene [Cernobori *et al.*, 1996; Hirn *et al.*, 1997; Monaco *et al.*, 1997; Doglioni *et al.*, 2001; Argnani *et al.*, 2003].

[18] At the Oranie-Melilla region (Algeria-Morocco border) (Figure 3) it is possible to identify the other major discontinuity in the WMSZ [Frizon de Lamotte *et al.*, 1991; Lonergan and White, 1997]. It is attested to mostly by the presence of large-scale sinistral NE trending lateral ramps on the eastern Rif (Jebha, Nekor, Tamsamani). These structures accommodate the diverging transport direction of the Rif-Tell system. In fact, around the Gibraltar Arc, both the external middle Miocene thrust front and the



internal extensional detachment show an overall westward sense of transport [Frizon de Lamotte *et al.*, 1991]. This different sense of transport then separates the Betic-Rif from the Tell domain, where southward transport direction is instead documented. The timing of this rupture episode is bracketed in the middle Miocene. In fact, prior to (during the collision) and after this episode, the convergence process between the major plates dominates the whole system imposing a major north-south shortening [Gomez *et al.*, 2000; Beauchamp *et al.*, 1999; Frizon de Lamotte *et al.*, 1991, 2000].

2.5. When Did the Arcs Form?

[19] The precise timing of formation of the WMSZ Gibraltar and Calabrian Arcs is still uncertain, but it is tempting to imagine that their formation is coeval with the opening of back-arc basins [Royden, 1993]. This is the case of the well-documented Calabrian Arc, which attained its shape mostly between the late Miocene and the Pleistocene, during the opening of the Tyrrhenian Sea (Figure 2). Significant counterclockwise rotation of the southern Apennines, in fact, occurred after the opening of the Liguro-Provençal basin [Mattei *et al.*, 2002; Gattacceca and Speranza, 2002], and part of this rotation (25°, according to Sagnotti [1992] and Scheepers *et al.* [1993]) should have occurred after the early Pleistocene. The Calabrian region itself rotated clockwise by about 15°–25° during the Plio-Pleistocene [Scheepers *et al.*, 1993; Scheepers and Langereis, 1994; Speranza *et al.*, 2000]. Moreover, an overall clockwise rotation has been detected in the Sicilian belt [Channell *et al.*, 1980, 1990; Aifà *et al.*, 1988; Scheepers and Langereis, 1993], but its timing and magnitude are still uncertain, as it could be related to the complex rotational pattern of single thrust sheets [Speranza *et al.*, 1999].

[20] The age of formation of the Gibraltar Arc is less defined, but according to the pattern of rotation sense, it occurred during the Alboran rifting. Indeed, paleomagnetic data show that the external zone of the Betics thrust belt has rotated approximately 60° clockwise [Osete *et al.*, 1988; Platzman, 1992; Platzman and Lowrie, 1992; Allerton *et al.*, 1993; Platt, 1995; Fainberg *et al.*, 1999], whereas in the Rif, counterclockwise rotations up to 100° have been reported [Platzman *et al.*, 1993; Platt *et al.*, 2003]. Nevertheless, the timing of these rotations has not been established. In the internal middle Miocene basins, no significant patterns of rotation have been observed [Allerton *et al.*, 1994; Calvo *et al.*, 1997].

3. Images of Western Mediterranean Subducting Slab

[21] Figures 4 and 5 show images of a recent tomographic model of the upper mantle beneath the Euro-Mediterranean

region, obtained by inversion of *P* wave delay times from the International Seismological Centre [Piromallo and Morelli, 2003]. The model is parameterized with linear splines over a three-dimensional Cartesian grid, whose nodes are spaced $0.5^\circ \times 0.5^\circ$ horizontally and 50 km vertically, down to 1000 km depth. Regional and teleseismic rays from carefully selected shallow earthquakes are grouped into summary rays whose residuals are inverted via the LSQR algorithm [Nolet, 1985]. The resulting perturbation to the velocity field is computed and displayed with respect to the reference velocity model sp6 [Morelli and Dziewonski, 1993]. A thorough description of the resulting model and its reliability are given by Piromallo and Morelli [2003].

[22] From horizontal slices through the tomographic model (Figure 5), it is possible to observe a high-velocity anomaly running from the northern Apennine to the Gibraltar Arc, turning around the Calabrian Arc. This fast belt corresponds to the WMSZ, although it shows some discontinuities. Indeed, at a depth of 100 and 150 km (Figures 5a and 5b), the high-velocity anomaly is located beneath the northern Apennines, Calabria, northern Algeria and the Gibraltar Arc. Clear interruptions of this belt occur in three regions of low velocity: beneath the southern Apennines, the Sicily channel and the Oranie-Melilla region. At a depth of 250 km (Figure 5c), the first two gaps visible at shallower depth are not present anymore, and the Calabria high-velocity anomaly joins both the Apennine and the Algerian anomalies. The westernmost interruption, conversely, persists down to a depth of 400–450 km (Figures 5e and 5f). At greater depths (Figure 5f), the high-velocity anomaly spreads horizontally over the whole western Mediterranean area. No evident trace of high-velocity anomaly is present below the transition zone [Piromallo and Morelli, 2003].

[23] Vertical cross sections through the model are shown in Figure 4. These sections are oriented parallel to the extensional direction of the back-arc basins. Cross section AA' from Calabria to the Gulf of Lyon (Figure 4) shows an almost continuous high-velocity body below Calabria, with a dip of 70°–80° toward the NW and then turning horizontally in the transition zone. The estimated total length of the fast velocity zone, interpreted as subducted lithosphere, is about 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 *P* wave velocity models for the Mediterranean yielding a feature similar in both geometry and total length. The high-velocity anomaly below the Calabrian region lines up, down to a depth of about 450 km, with a continuous, northwestward, 70°-dipping Wadati-Benioff zone, in which seismicity is distributed in a 200 km wide and 40–50 km thick volume [e.g., Selvaggi and Chiarabba, 1995].

Figure 5. (a–f) Map views of tomographic results at 100, 150, 250, 350, 450, and 600 km depth and (g–i) cross sections from model PM0.5 [Piromallo and Morelli, 2003]. Velocity anomalies are displayed in percentages with respect to the reference model sp6 [Morelli and Dziewonski, 1993]. Sections EE' and FF' intersect the deep positive velocity anomalies of Calabrian and the Alboran slab, respectively, parallel to the strike of the slab to show their limited lateral extent. See color version of this figure at back of this issue.

[24] Cross section BB' from the Kabylie to the Valencia Gulf (Figure 4) shows a less pronounced anomaly contrast, due to reduced ray coverage caused by a paucity of stations along the northwestern African margin [Piromallo and Morelli, 2003]. Though resolution is not optimal, it is possible to observe a high-velocity anomaly dipping toward the NNW. It presents a rather steep dip in the first 300 km where it gets thinner. In correspondence of the 410 km discontinuity, the high-velocity anomaly apparently kinks, and then becomes flat in the transition zone, while its thickness increases. No intermediate or deep seismicity is recorded along this cross section. The total length of the anomaly measured from the base of the lithosphere is about 1000 km. Above the slab, a pronounced low-velocity anomaly is located below the Algerian and Valencia basins.

[25] Cross section CC' runs from northwest Morocco to south Spain (Cartagena) (Figure 4) and shows a rather continuous high-velocity anomaly dipping 40° ENE down to 400 km. It turns then horizontally and thickens near the bottom of the upper mantle. Deep seismic events in the region cluster near this deeper anomaly [Blanco and Spakman, 1993; Seber et al., 1996]. The total length of the anomaly is on the order of 800 km, while its lateral width is a few hundreds of km (Figure 5). As observed below the other back-arc basins, a low-velocity anomaly is present at shallow depth below the thinned Alboran region. This section is similar to the EW one presented by Calvert et al. [2000], Blanco and Spakman [1993], and Gutscher et al. [2002]. As already noted by Calvert et al. [2000], shallow and intermediate south dipping seismicity clusters inside the low-velocity anomaly.

[26] In Figure 5, three additional cross sections better illustrate the lateral distribution of the velocity anomaly. Section DD' (Figure 5g) runs across the Sicily channel, where a rather well-defined shallow (from the surface down to 150–200 km) low-velocity anomaly corresponds to the area where volcanic centers are distributed, whereas no high-velocity anomaly (which could indicate continuity with the north African margin) is present. Cross section EE' (Figure 5h), approximately perpendicular to DD', shows the same structure below the Sicily channel. In addition, the section crosscuts the Calabrian slab along strike in its middle portion, hence illustrating the limited lateral extent (about 350 km) of the subducted lithosphere. To the north, the Calabrian slab is also limited by a low-velocity window located below the southern Apennines [Lucente et al., 1999; Wortel and Spakman, 2000; Piromallo and Morelli, 2003]. Section FF' runs N-S over the Oranie-Melilla region and then crosses the Alboran basin (Figure 5i). It illustrates the presence of a low-velocity anomaly in the topmost layers below the Alboran region. Below this region, an elongated subvertical high-velocity anomaly is observed from approximately 300 km depth down to the 660 km discontinuity. This cross section, usually selected as the most representative [Blanco and Spakman, 1993; Spakman et al., 1993; Calvert et al., 2000], has been used in tectonic reconstructions as an indication of slab detachment [Blanco and Spakman, 1993; Carminati et al., 1998; Zeck, 1999]. However, it must be stressed that the N-S section, crossing

the Gibraltar Arc, strikes subperpendicular to the dip of slab and can be used only to assess its width, which for the Alboran case does not exceed about 250 km.

[27] Summing up, tomographically detected high-velocity anomalies can be followed discontinuously below the WMSZ. The high-velocity anomaly belt is laterally broken beneath the southern flank of the Gibraltar and Calabrian Arcs. The deep slab breaks line up with the main discontinuities in the geological trends, the Sicily channel and the Oranie-Melilla region. Below the arcs we observe a narrow (250–350 km), rather planar, and continuous high-velocity anomaly descending from the surface to the transition zone. The length of the high-velocity anomaly, mainly confined to the upper mantle, varies from 1200–1400 to 800 km, and decreases westward.

4. Amount of Subduction

[28] The total amount of subduction along the three sections of Figure 4 can be evaluated by summing the amount of back-arc extension to the amount of net convergence related to Africa/Eurasia convergence along the WMSZ trench. This value can be compared with the length of the high-velocity anomalies obtained from the tomographic sections.

[29] Estimates of the rate and the amount of back-arc extension are performed by restoring the thickness and length of the crustal cross sections of Figure 4. This is done by subtracting the oceanic-floored area of each basin and then, using an area balancing technique, by restoring the crust to the thickness of the surrounding undeformed domain. The results of this exercise are shown in Figure 6b.

[30] Restoration of the Calabrian section (Figure 4) has been already presented by Faccenna et al. [2001a]. In the Liguro-Provençal and Tyrrhenian region the total amount of back-arc extension (~780 km) is partitioned roughly equally between the two basins (Figures 1 and 4), with alternating episodes of rifting (~7 Myr) and oceanic spreading (~5 Myr). The rate of extension has an average of 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 (Figure 6b). Our estimates are in good agreement with previous evaluations [Burrus, 1984; Malinverno and Ryan, 1986; Mauffret et al., 1995; Spadini et al., 1995; Gueguen et al., 1998; Chamot-Rooke et al., 1999].

[31] Restoration of the Algerian section (Figure 4) has been performed by Verges and Sabat [1999]. The total amount of extension (~340 km) is also partitioned between the Valencia trough (~80 km) and the Algerian basin (~260 km). The mean rate of extension is around 1.7 cm/yr, but extension also occurred episodically, with a peak rate of about 4 cm/yr during the opening of the Algerian basin, with a pause between 16 and 12 Ma (Figure 6b). We should remark, however, that the exact timing of Algerian basin oceanic accretion is only inferred.

[32] Restoration of the Alboran section (Figure 4) to a crustal thickness of about 40 km (stretching factor of 2.5, according to Torné et al. [2000]) leads to ~210 km of extension and an average rate of 1 cm/yr. This value

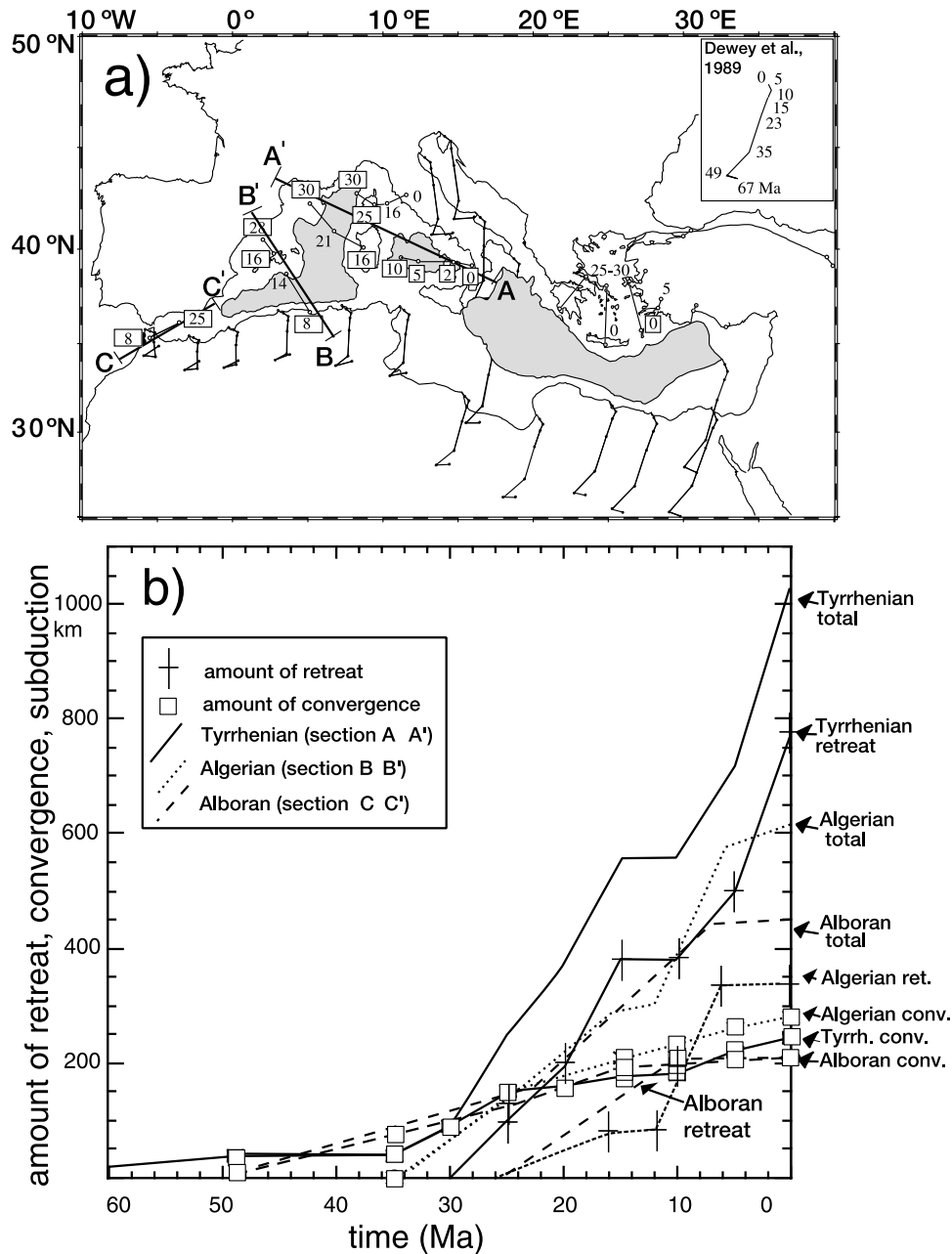


Figure 6. (a) Displacement trajectories of Africa and Apulia motion with respect to stable Eurasia (calculated from Dewey *et al.* [1989], see inset for stages division), assuming that Adria moved coherently with Africa. The displacement trajectories related to back-arc extension (numbers are million years) are also shown. Details of the calculation are in the text. A, B, C refer to the traces of the Tyrrhenian, Algerian, and Alboran cross sections, respectively. (b) Amount of relative plate convergence and back extension calculated along the Tyrrhenian, Algerian, and Alboran cross sections (indicated in Figure 6a as A, B, and C, respectively). Calculations have been performed by measuring the component of relative convergence (as shown in Figure 6a) and extension perpendicular to the trench during the last 64 Myr. The total amount of subduction is derived by summing up the amount of convergence with the amount of back-arc extension.

represents a minimum estimate as it is not possible to state if the westernmost portion of the Algerian basin belongs to the Alboran stretching regime (Figure 6b). This value is in agreement with what estimated by Platt *et al.* [2003]

palinspastic restoration (about 250 km) and is far lower than the one estimated by Lonergan and White [1997].

[33] The amount of subducted material due to Africa-Eurasia plate convergence is calculated using the Dewey *et*

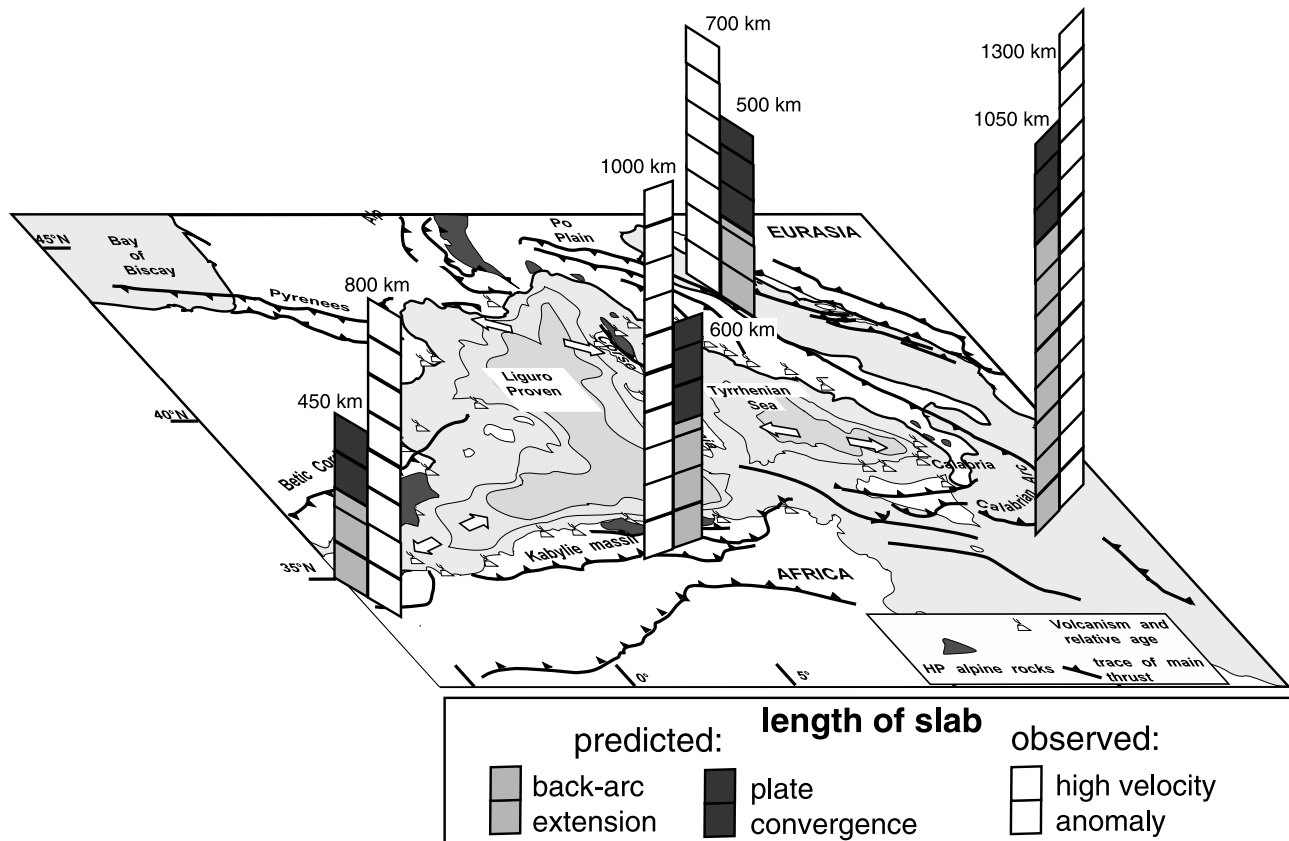


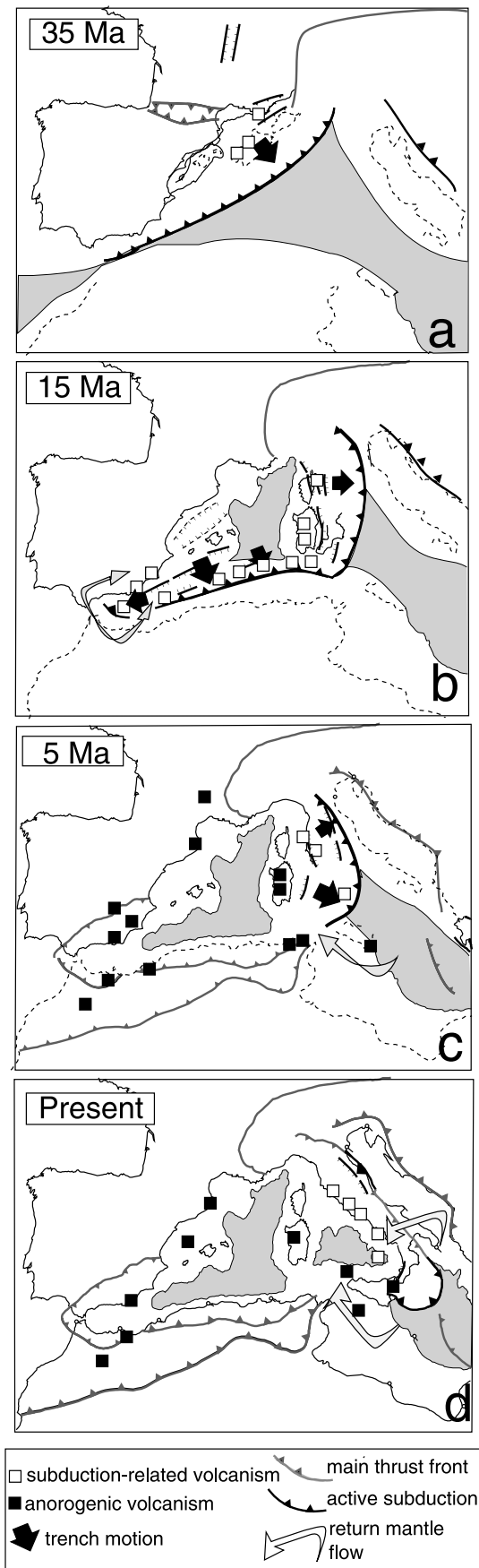
Figure 7. Comparison between predicted (see Figure 6b) and observed (see tomographic sections of Figure 4 and *Piomallo and Morelli* [2003] slab length). The observed length is always higher than the predicted length, notably on the westernmost area.

al. [1989] model for the last 67 Myr, by measuring the net convergence perpendicular to the western Mediterranean trench (Figure 6a). To this purpose, no substantial difference exists between *Dewey et al.* [1989] model and other ones [*Savostin et al.*, 1986; *Ricou*, 1994]. During the last 67 Myr, the amount of convergence along the western Mediterranean trench ranges from the 200 km of the Gibraltar to the 300 km of the Algerian region and is mostly attained during the last 35 Myr (Figure 6b). This is because prior to that time lapse, the trench was oriented parallel to the Africa-Eurasia convergence vector.

[34] The total amount of subduction during the Tertiary can be then estimated summing these values to those related to back-arc extension (Figure 6b). The amount of subduction during the Tertiary progressively decreases westward from the 1050 km of the Tyrrhenian to 600 km of the Algerian and to the 450 km of the Alboran system. Figure 7 shows the comparison between these values and the length of the high-velocity anomalies as measured from Figure 4 cross sections. We also note that the length of the high-velocity anomaly is always greater than the predicted length, especially on the western side of the subduction system.

[35] No definitive answers can be proposed to justify this misfit. Smearing of high-velocity anomalies in regions of insufficient ray sampling could in principle lead to overes-

timate the slab length. However, according to the sensitivity analyses performed to assess the tomographic model reliability [*Piomallo and Morelli*, 2003], this region is fairly resolved and smearing along rays can hardly explain a misfit in length larger than 200 km. A possible explanation is that the high-velocity anomaly reflects chemical (rather than thermal) differences in the mantle, and therefore is not representative of subducted material. This possibility, however, is at odds with the geological and seismological data. Conversely, assuming that the high-velocity anomalies derive from the thermal contrast, it is possible that a significant amount of lithosphere was consumed at the trench during the Late Cretaceous. This solution would also explain the Late Cretaceous high-pressure metamorphism found in the Kabylie [*Monié et al.*, 1988]. However, the models of Africa/Eurasia relative motion [see also *Jolivet and Faccenna*, 2000] show that at that time the convergence vectors were subparallel to the trench, which precludes the possibility that a large amount of subduction occurred. Another possibility is to consider that the slab is significantly stretched or even broken. This was proposed for the Algerian section by *Carminati et al.* [1998], and it can indeed account for the reduced thickness of the high-velocity anomaly at an intermediate depth of about 200–300 km observed along the westernmost segments (Figure 4). Severe stretching or breaking of the slab has been commonly observed in



subduction simulations [e.g., *Tao and O'Connell*, 1993; *Becker et al.*, 1999] and appears to be a common feature throughout the Mediterranean [*Wortel and Spakman*, 2000]. A reasonable solution to explain the difference in length between the high-velocity anomaly and the estimated amount of subduction along the WMSZ consists in evoking both the presence of a late Cretaceous to early Tertiary slab, thought to be immature, which is stretched and eventually broken in its middle portion during its latest evolution stage [*Wortel and Spakman*, 2000].

5. Reconstruction of the Western Mediterranean Subduction

[36] On the basis of the geological and kinematic constraints and of the tomographic images, we are able to reconstruct the evolution of the WMSZ in four main steps from 35 Ma to present-day. The main assumption behind this model is that the high-velocity anomalies, imaged by tomography, are related to cold subducted material.

[37] Around 35 Ma, the WMSZ extended for more than 1500 km from southern Iberia to the Ligurian region (Figure 8a). It was NW dipping and consumed the land-locked Jurassic oceanic basin (Figure 9a) [*Le Pichon et al.*, 1988]. The position of the trench, running along the Iberia margin, has been reconstructed by restoring the amount of back-arc extension. The trench terminated to the northeast in correspondence to the Ligurian region, where subduction flipped dipping southward beneath the Alps, and to the southwest in correspondence with the Gibraltar region where the Tethyan seaway got narrow or even disappeared (Figure 8a). At this time, the WMSZ was probably continuous and already well developed, reaching a depth of 300–400 km and dipping at rather shallow angle (Figure 9a). Therefore the infant stage of the slab should be traced back at least to the Paleogene, as attested to by evidences of HP metamorphism in Calabria, Kabylie and in the Betics. The velocity of subduction decreased westward. In the Betics, it is probably reduced to a few millimeters per year (Figure 6b) and collision is nearly occurred. This difference in subduction rate is attested to by the thermal gradient recorded by the metamorphic assemblages, which is lower in Calabria with respect to the Betics-Rif region. At about 30 Ma, the back-arc extensional process started throughout the Mediterranean [*Jolivet and Faccenna*, 2000]. It initiates in the northeastern sector, in the Liguro-Provençal area. Calc-alkaline volcanism spreads over the region, attesting to the efficiency of the subduction process. This large-scale reorganization of the subduction process over the whole Mediterranean region is related to an increment of the retrograde motion of the slab under the concurrent action

Figure 8. Reconstruction of the evolution of the Mediterranean region in relative (Eurasia fixed) reference frame in four stages, from 35 Ma to present-day. Deep basin domains are marked in grey. The locations of the magmatic centers and their bearing with subduction process are marked with solid (anorogenic) and open (subduction-related) squares.

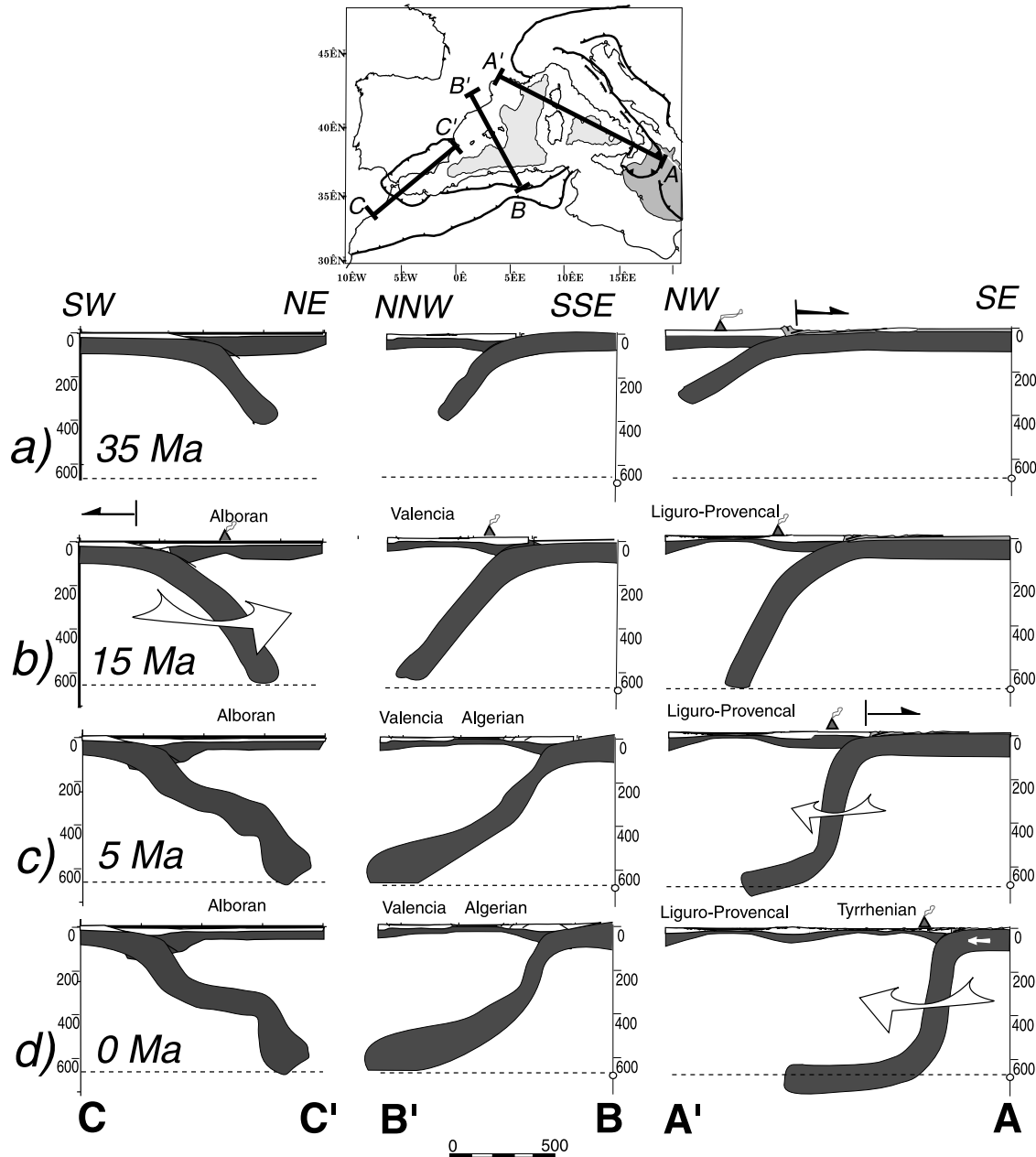


Figure 9. Three cross sections (locations in the inset) illustrate the evolution of the subduction process along the Alboran (inspired from tomographic cross section CC' of Figure 4), the Algerian (inspired from tomographic cross section BB' of Figure 4), and the Tyrrhenian (inspired from the tomographic cross section AA' of Figure 4) at the same four time stages of Figure 8. Solid arrows indicate the net motion of the trench, large open arrows indicate the lateral flow of the mantle. Small volcanoes indicate the approximate position of the arc, if any.

of increased slab pull level and decreased Africa rate of motion [Jolivet and Faccenna, 2000].

[38] From 30 to 23 Ma, back-arc extensional processes propagated southward from the Liguro-Provençal basin to the Valencia and the Alboran basin. Extensional processes localized not only in the back-arc region, but also in the orogenic wedge by means of large-scale extensional detachments in Calabria [Rossetti et al., 2001], Kabylie [Saadallah and Caby, 1996; Caby et al., 2001], and Betics [García-

Dueñas et al., 1986; Jabaloy et al., 1993]. The velocity of subduction, mainly related to the slab retrograde motion, progressively increased, reaching its maximum in southern Sardinia (Figures 6b and 8b), and produced the formation of a first smooth arc in front of the oceanic seaway. In the western sector, retreat occurred during subduction of the African paleomargin. There, it is possible that continental subduction occurred, scraping off the crustal layer and delaminating it from the dense mantle material [Serri et al., 1993; Jolivet et

al., 1999; Calvert *et al.*, 2000]. Calc-alkaline subduction related volcanism was widespread over the whole area from Sardinia to the Valencia and Alboran region.

[39] Between 23 and 15 Ma (Figure 8b), the Liguro-Provençal and Valencia trough basin completed their opening. At that time the entire Alboran domain is strongly extending toward WSW. The Alboran domain motion then diverged from the Algerian slab, which underwent southward retreat. The transition between the two areas was localized in the Melilla-Oranie region, where NE-SW left-lateral shear belt is activated, accommodating the diverging motion of the two belts. The initial rupture and the formation of a 200–300 km wide segment of slab at the western termination of the WMSZ could be achieved at that time. Once broken, this small slab was free to retreat toward the W-SW independently from the rest of the eastern, larger, Algerian slab. The formation of a narrow slab tongue likely produced a complex pattern of mantle circulation around it. An expected consequence of this new configuration is that subslab mantle material can rapidly flow laterally around the slab during its retrograde migration reaching the inner back-arc region [Funicello *et al.*, 2003]. The vigor of this lateral flow, coupled with the return flow generated by the delaminating continental lithosphere, not only can accelerate extension in the back-arc region [Dworkin *et al.*, 1993] but can also produce thermal erosion at the base of the overriding lithosphere and consequently, the sudden increase of the thermal gradient below the area. This can explain the impulse of heating observed in metamorphic units which floor the Alboran region between 22 and 18 Ma [Platt *et al.*, 1998]. Magmatism, however, still preserves the imprinting of a mantle metasomatized by subduction of crustal material also in the region where the rupture of the slab occurred [El Bakkali *et al.*, 1998; Maury *et al.*, 2000; Coulon *et al.*, 2002].

[40] Around 16–15 Ma (Figure 8b), the retrograde migration of the western Mediterranean slab stopped. Back-arc extensional processes produced two triangular-shaped back-arc basins facing each other: the oceanic floored Liguro-Provençal basin and the smaller Valencia trough. No appreciable extension took place during this time interval in the central western Mediterranean basins, except in the Alboran basin, which followed an independent drift path. The geometry of the WMSZ already attained a sharp curvature in the proto-Calabrian area possibly related to the lateral extent of the Tethyan oceanic seaway. Reconstruction of slab geometry reveals that in the central portion of the subduction zone (Algeria and Calabria), subducted lithosphere already reached and interacted with the deeper part of the transition zone (Figure 9b). The interaction and deformation of the slab at its arrival at the 660 km discontinuity is proposed as a primary cause for the decrease in the rate of rollback [Faccenna *et al.*, 2001a]. The whole WMSZ was still characterized by the presence of calc-alkaline volcanism whose melt was generated from crustal contamination of a mantle metasomatized melt [El Bakkali *et al.*, 1998; Benito *et al.*, 1999; Maury *et al.*, 2000; Fourcade *et al.*, 2001; Coulon *et al.*, 2002].

[41] Around 12–10 Ma, the locus of extension jumped southward from the Liguro-Provençal to the Tyrrhenian

region and probably also from the Valencia trough to the Algerian basin. In this frame, calc-alkaline magmatism was present nearly over the whole Algerian margin up to 10 Ma. In the southern Alboran region, between Melilla and Oranie, transitional alkali-basalt volcanism took place.

[42] Between 10 and 5 Ma (Figure 8c), rifting migrated eastward within the Tyrrhenian domain. There, the velocity of extension increased and led to the emplacement of isolated oceanic spreading centers from about 5 Ma onward. The increase in the extensional velocity began during the break of the slab along the Sicily channel. From this moment, the two portions of the slab retreated in different directions: southward in northern Africa and southeastward in Calabria, where trench retreat was faster, consuming the oceanic seaway lithosphere. The formation of the slab window was marked by a change in the nature of volcanism, and alkali-basalts erupted during the late Miocene-Pliocene in northern Tunisia, in Sardinia, and along the southern Tyrrhenian seamounts. Extension ceased in the Algerian and Alboran basin, around 7 Ma, probably because of the large amount of continental material consumed at trench (Figure 9c). In the Alboran region, alkali basalts and basanites erupted along a 100 km corridor located above the slab window. Contemporaneously, the whole Alboran region was submitted to a convergence process, producing a network of strike-slip faults and a renewed phase of underthrusting [Morales *et al.*, 1999; Calvert *et al.*, 2000].

[43] At present (Figure 8d), the remnant of the once vigorous WMSZ is preserved only in the narrow tongue below Calabria and partly in the northern Apennine [Selvaggi and Amato, 1992]. Despite the slab is still defined by the narrow Wadati-Benioff zone below Calabria [Selvaggi and Chiarabba, 1995], the trench should have nearly stopped its retrograde motion as suggested by geotectonic data [Hollenstein *et al.*, 2003]. This suggests that subduction in the central Mediterranean is decaying.

6. Uncertainties and Comparisons With Previous Models

[44] Although the general outline of the paleogeographic models of Figure 8 is widely accepted [Dercourt *et al.*, 1986; Dewey *et al.*, 1989; Gueguen *et al.*, 1998; Jolivet and Faccenna, 2000], the tectonic pattern and the vergence of subduction in the western Mediterranean system have been subjects of debate. From our reconstruction it turns out that the extensional process in the Mediterranean is driven by the retreat of the subducting slab. Hence the model proposed here, though based on different data sets, is similar to that proposed, for example, by Malinverno and Ryan [1986], Royden [1993], Lonergan and White [1997], Wortel and Spakman [2000], and Faccenna *et al.* [2001a, 2001b]. A common criticism that has been put forward against these models is that the subducted lithosphere in the westernmost region is continental [Platt and Vissers, 1989; Calvert *et al.*, 2000]. The lack of unquestionably identified oceanic remnants, the nappe pile stacked in the orogenic wedge, and the paleogeographic reconstruction all indicate that in the Alboran area more than 400 km of continental material

belonging to the north African paleomargin has been subducted during the last 35 Myr. In fact, although the consumption of continental lithosphere has been described in many regions, it is not common for continental lithosphere to produce slab rollback in a western Pacific-like fashion. A viable solution for that, already proposed for the northern Apennines [Serri *et al.*, 1993; D'Offizi *et al.*, 1994; Jolivet *et al.*, 1999; Faccenna *et al.*, 2001b], is that the light crustal portion of the lithosphere is off-scraped from the denser mantle lithosphere which can readily sink into the mantle. This mechanism can be favored if oceanic lithosphere is attached to continental lithosphere, driving with its negative buoyancy the process of delamination of the mantle lithosphere. Indeed, in the Betic-Rif wedge both sedimentary pile and basement slices scraped off from the underlying mantle are involved in the construction of the orogenic prism.

[45] An alternative to the slab rollback mechanism to explain the Alboran region evolution is the possibility of a convective removal of the roots of a previously thickened mantle lithosphere [Platt and Vissers, 1989; Seber *et al.*, 1996]. This model, however, is not supported by the tomographic images which show the presence of a slab-like feature [Blanco and Spakman, 1993; Calvert *et al.*, 2000; Piromallo and Morelli, 2003; Gutscher *et al.*, 2002]. An alternative to this model is the possibility that extension of the Alboran region occurred as a consequence of slab break off [Carminati *et al.*, 1998; Zeck, 1999]. This latter model is based on the N-S oriented tomographic section (FF' of Figure 5). However, this section is not representative of the subduction processes in the region, as the narrow slab dips ENE. Zeck [1999] proposes that the high-velocity anomaly depicted along this section could represent the remnant of the subducted slab, vertically detached from the north African plate around 20–25 Ma. If this is the case, the rate of sinking of the detached portion into the mantle should have been of the order of only 1 mm/yr. This rate is actually too low: it implies an anomalous upper mantle viscosity (one or two orders of magnitude higher than predicted [e.g., Hager, 1984; Mitrovica and Forte, 1997]) and the possible smearing out by thermal erosion of the high seismic velocity [e.g., de Jonge *et al.*, 1994].

[46] The model presented here emphasizes the lateral deformation of the WMSZ. Three points of rupture along the WMSZ are observed: a window below the southern Apennines, a second rather vertical window below the Sicily channel and another larger rupture along Morocco-Algeria border. The southern Apennine break probably formed in the middle Pleistocene, while the Sicily channel tear formed from the Pliocene. It is more difficult to define the exact timing of slab rupture along the Morocco-Algerian border, although it could have occurred during early Miocene. Indeed, the 22–19 Ma timing of the heating episode observed in the metamorphic rocks of the Alboran basin basement and the divergent sense of shear recorded in the Betic-Rif region with respect to the Kabilie-Tell can be interpreted as the result of the initial phase of rupture. If this is the case, the transition from calc-alkaline (derived from a slab-metasomatized mantle source) to alkali (derived from a mantle source) magmatism would have occurred only some

10 Myr after the slab break, during the late Miocene [Maury *et al.*, 2000]. We are then left to suppose that the arrival of alkali magmatism at the surface reflects the complete opening of the slab window to the point that the subslab mantle material predominates over the supraslab metasomatized one. Geodynamic models [Thorkelson, 1996; van de Zedde and Wortel, 2001], indeed, show that the occurrence of a rapid and transient heating pulse should occur only a few millions years after the break off of the slab.

[47] The mechanism suggested here predicts the presence of a lateral and, most probably, also vertical slab deformation. In this sense, our model contains ingredients of previous works of Royden *et al.* [1987], Carminati *et al.* [1998], and Wortel and Spakman [1992, 2000], who identify both styles of slab deformation in the western Mediterranean. In particular, Carminati *et al.* [1998] propose that the slab detached vertically from the African plate during the Langhian, inducing the opening of the Algerian basin. Resolution of our tomographic model (BB' section of Figure 3) is unable to distinguish if the slab is still attached or not to the African plate.

[48] Finally, the model proposed here is based on the idea that the recent history of these narrow and deformed slabs represents the mature evolution of a once longer and older subduction system. Alternatively, several authors proposed that the present-day subduction in the western Mediterranean initiated only at about 35 Ma, after a subduction reversal of a southern dipping subduction zone [Doglioni *et al.*, 1997; Frizon de Lamotte *et al.*, 2000]. Our data do not support this model. Radiometric and structural data collected in key regions such as Calabria and Northern Tyrrhenian suggest that the Neogene subduction process initiated at least in the Paleocene [Faccenna *et al.*, 2001b; Rossetti *et al.*, 2001]. The high-velocity anomalies shown here indicate the presence of a long-running single subduction event producing a slab-shaped mantle signature with an average length of about 1000 km.

7. Arc Formation as a Consequence of Restricted Upper Mantle Convection

[49] The model proposed here identifies lateral slab fragmentation as the key process for the formation of the arcs. The zones of slab rupture, identified both by geological signatures and tomographic images, are positioned at the southern flanks of both arcs and developed during the formation of extensional back-arc basins.

[50] The reason the WMSZ is deformed and segmented forming narrow tongues similar to those sketched in Figure 10 is nontrivial. In fact, this pattern requires either the entrance at the trench of lithospheric discontinuities, which are likely to segment the slab, or a horizontal stretching of the slab. The first scenario, however, contrasts with the fact that the lateral rupture of the Calabrian Arc does not occur in correspondence with the preexisting Mesozoic margin of the Ionian ocean but within the undeformed Pelagian plateau. Therefore we are left to speculate on the possible mechanism for horizontally deforming the slab. Our preferred solution is that the deformation of the slab derives

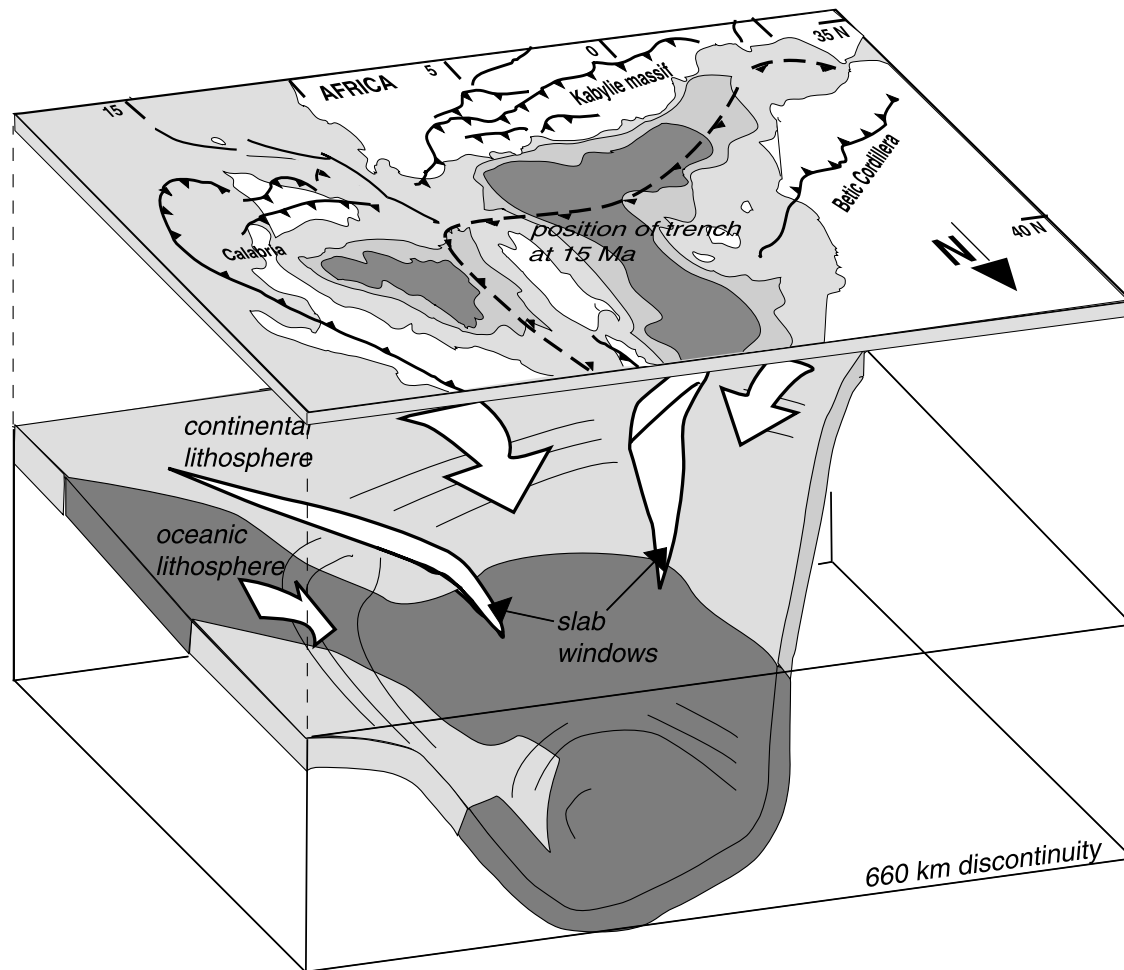


Figure 10. Cartoon of the present-day setting of the western Mediterranean slab, inspired by the tomographic images of Figures 4 and 5, emphasizing the Sicily channel and the Oranie-Melilla slab windows.

from the internal dynamic of a stratified viscous mantle. Subduction simulations [Garfunkel *et al.*, 1986; Faccenna *et al.*, 2001a; Funiciello *et al.*, 2003] show that the retrograde motion of the slab produces overpressure in the subslab mantle material. Once the slab interacts with the deep upper-lower mantle transition zone, the overpressure in the sub-mantle material is high enough to stop the slab retrograde motion [Garfunkel *et al.*, 1986; Faccenna *et al.*, 2001a] and to induce the lateral deformation and break of the slab itself [Funiciello *et al.*, 2003]. From this moment on, the retreat of the slab can be achieved by the lateral escape of subslab mantle material from the sides of the deformed slab. This characteristic sequence of events has been systematically observed in laboratory experiments, under different boundary conditions [Funiciello *et al.*, 2003]. After a first phase of retreat, the slab arrives at the 660 km discontinuity and then stops, for a few million years, while deforming. The second phase of retreat can be achieved only if the slab is deformed enough (arcuating and creating slab window) to permit the lateral escape of submantle material.

[51] The application of this model to the natural case of the WMSZ can be done only under the assumption that the

convection process in the western Mediterranean is confined to the upper mantle. Tomographic images show a large-scale high-velocity anomaly placed in the transition zone below the WMSZ [Piromallo *et al.*, 2001]. The distribution of the velocity anomaly then supports the idea that the direct slab penetration into the lower mantle is inhibited by the combined effects of the endothermic phase change and of the viscosity increase at depth.

[52] The evolutionary scenario presented in Figures 8 and 9 fulfils the sequence of deformations predicted by our model. In fact, we observe a first phase of retreat that terminates after the slab encounters the 660 km discontinuity. This is followed by a second phase of retreat that is achieved during the lateral break of the slab. In a layered convecting system, this is the only possibility that a slab can have to continue its retrograde motion [Garfunkel *et al.*, 1986]. The fact that both slab windows, the Sicily Channel and the Oranie-Mellila, formed with the main opening phases of the back-arc basins supports this hypothesis. In addition, as indeed observed, the rate of trench retreat of a narrow slab should be further enhanced by the presence of this induced lateral side flow [Nur *et al.*, 1991; Dworkin *et al.*, 1993].

[53] The consequence of slab rupture is the progressive release of pressure of the subslab mantle material, as it flows inside the windows. The formation of the slab window should be then imagined as a progressive process that may propagate from the initial point of rupture downward and foreland-ward in the subducting plate. A consequence of the formation of slab window is the mixing between the subslab and supraslab mantle reservoirs. This can cause a decrease in hydration and an increase in temperature in the latter reservoir [Thorkelson, 1996]. Thermal and chemical anomalies are then expected. Tholeiitic to alkali magmatism may supplant calc-alkaline volcanism, and its distribution should be elongated from the forearc to the retroarc. The second effect is the increase in the temperature of the overriding lithosphere. Both effects are documented in the studied areas, substantiating this model.

[54] We are nonetheless aware that this model presents several oversimplifications. For example, the western arc forms nearby the westernmost slab tip, and therefore it is likely that lateral flow existed even before the break of the slab. In addition, it is not clear if the slab window tomographically identified below the southern Apennines represents the trace of the northern side flow of the escaping mantle material beneath the Calabrian Arc or if it is a younger middle Pleistocene feature, as attested to by the uplift of the foreland region [Bordoni and Valensise, 1998].

[55] Finally, the role of the advancing African plate in terms of entrained mantle flow is not taken into account, mostly because the rate of this process is significantly lower than the one related to the internal slab dynamics. However, the kinematic pattern observed in the Gibraltar Arc shows that after an episode of westward retreat, compression took place again from late Miocene onward, nearly parallel to the main direction of plate motion. In this sense, a decrease in the rate of subduction, due, for example, to the entrance at trench of continental material, may cause a surge of compression related to plate convergence, causing a further tightening of the arc. The Calabrian Arc is probably experiencing a similar episode at present, suggesting that in a near future the retreat process of the Calabrian slab will end and the plate convergence could regain over the dynamic of the system. In this sense the Calabrian Arc is probably evolving to a stage similar to the one that characterized the late Miocene evolution of the Gibraltar Arc.

8. Conclusion

[56] We have described the evolution of the western Mediterranean mantle over the last 35 Myr. The key of this analysis is that the two tight arcs that characterize the

subduction zone, that is the Gibraltar and the Calabrian Arc, result from the lateral segmentation of the WMSZ. The timing and extent of this slab break are analyzed and defined using both deep tomographic images and surface geological data. Two major points are worth recalling. First, we show that the arcs form as a consequence of the retreat of two narrow (200–300 km wide) tongues that separate from a wider WMSZ. The lateral slab deformation and the consequent formation of these narrow and fast retreating structures occur during the opening of the inner back-arc basin. The Gibraltar Arc forms first in the middle Miocene and the Calabrian Arc in the late Miocene. Second, the deformation and consequent fragmentation of the slab take place after a main episode of retreat and subduction, once the slab tip interacts with the deep transition zone in the mantle. We speculate that the sealing of the upper mantle convecting cell by the retreating subduction can generate a local overpressure in the subslab mantle, producing a large component of lateral mantle flow. This flow, in turn, can induce horizontal deformation in the slab, stretching it up to the point of rupture. Once this mechanism is achieved, the newly formed narrow slabs can rapidly and independently retreat, forming the unusually tight arcs that dominated the western Mediterranean basin.

[57] The mechanism presented here gives insights into the long-term deformation of subducting slab and into the style of mantle convection. First, this model suggests that the evolution of the WMSZ took place in a restricted convecting scenario, as shown by the high-velocity anomalies confined in the upper 700 km [Lucente *et al.*, 1999; Piromallo *et al.*, 2001; Wortel and Spakman, 2000]. This convection pattern is probably due to the quite recent (mainly Neogene) evolution of the WMSZ [Faccenna *et al.*, 2003]. In this rather unique layered context, we should expect a complex pattern of mantle convection, dominated by intermittent and fast stages of deformation and by important components of lateral flow. Second, this model proposes that the slab is a rather weak entity, prone to be deformed under the concurrent action and reaction between the density anomalies and the flowing mantle. This further corroborates the general picture of a slab which can be shaped and deformed by the convecting mantle [Hager and O'Connell, 1978; Tao and O'Connell, 1993].

[58] **Acknowledgments.** This paper is the results of a long-term collaboration between Università Roma TRE, Université de Paris VI, and the Universidad de Granada encouraged by R. Funicello and J. P. Cadet. The model presented is inspired by the laboratory experiments performed by F. Funicello. We thank J. M. Azanon, J. C. Balanya, M. Comas, V. G. Duenas, D. Giardini, M. Mattei, A. Morelli, J. I. Soto, and F. Speranza for discussions and constructive criticism. L. Royden and an anonymous reviewer are acknowledged for their constructive comments. C. P. also gratefully acknowledges encouragement by E. Boschi.

References

- Aifa, T., H. Feinberg, and J. P. Pozzi (1988), Pliocene-Pleistocene evolution of the Tyrrhenian arc: Paleomagnetic determination of uplift and rotational deformation, *Earth Planet. Sci. Lett.*, **87**, 438–452.
- Allerton, S., L. Lonergan, J. P. Platt, E. S. L. Platzman, and E. McClelland (1993), Paleomagnetic rotations in the eastern Betic Cordillera, southern Spain, *Earth Planet. Sci. Lett.*, **119**, 225–241.
- Allerton, S., K. Reicherter, and J. P. Platt (1994), A structural and paleomagnetic study of a section through the eastern Subbetics, southern Spain, *J. Geol. Soc.*, **151**, 659–668.
- Argnani, A. (1990), The Strait of Sicily rift zone: Foreland deformation related to the evolution of a back-arc basin, *J. Geodyn.*, **12**, 311–331.
- Argnani, A. (1993), Neogene basins in the Strait of Sicily (central Mediterranean): Tectonic setting and geodynamic implications, in *Recent Evolution*

- and *Seismicity of the Mediterranean Region*, edited by E. Boschi et al., pp. 173–187, Kluwer Acad., Norwell, Mass.
- Argnani, A., and C. Savelli (1999), Cenozoic volcanism and tectonics in the southern Tyrrhenian sea: Space-time distribution and geodynamic significance, *J. Geodyn.*, **27**, 409–432.
- Argnani, A., C. Bonazzi, and the MESC 2001 Crew (2003), Tectonics of eastern Sicily off-shore: Preliminary results from MESC 2001 marine seismic cruise, *Boll. Geofis. Teorica Appl.*, in press.
- Azañón, J. M., and A. Crespo-Blanc (2000), Exhumation during a continental collision inferred from the tectonometamorphic evolution of the Alpujarride Complex in the central Betics (Alboran Domain, SE Spain), *Tectonics*, **19**, 549–565.
- Azañón, J. M., V. García-Dueñas, and B. Goffé (1998), Exhumation of high-pressure metapelites and coeval crustal extension in the Alpujarride Complex (Betic Cordillera), *Tectonophysics*, **285**, 231–252.
- Balayá, J. C., and V. García-Dueñas (1988), El cabalgamiento cortical de Gibraltar y la tectónica de Béticas y Rif, in *Actas, Segundo Congreso Geológico de España (Simposios)*, pp. 35–44, Soc. Geol. de España, Granada, Spain.
- Balayá, J. C., V. García-Dueñas, J. M. Azañón, and M. Sánchez-Gómez (1997), Alternating contractional and extensional events in the Alpujarride nappes of the Alboran Domain (Betics, Gibraltar Arc), *Tectonics*, **16**, 226–238.
- Beauchamp, W. R., A. Allmendinger, M. Barazangi, A. Demnati, M. El Alji, and M. Dahmani (1999), Inversion tectonics and the evolution of the High Atlas mountains, Morocco, based on a geological-geophysical transect, *Tectonics*, **18**, 163–184.
- Beccaluva, L., S. Chiesa, and M. Delaloye (1981), K/Ar age determinations on some Tethyan ophiolites, *Rend. Soc. Ital. Miner. Pet.*, **37**, 869–880.
- Beccaluva, L., P. Brotzu, G. Macciotta, L. Morbidelli, G. Serri, and G. Traversa (1989), Cainozoic tectonomagmatic evolution and inferred mantle sources in the Sardo-Tyrrhenian area, in *The Lithosphere in Italy: Advances in Earth Science Research*, edited by A. Boriani et al., pp. 229–248, Accad. Naz. dei Lincei, Rome.
- Becker, T., C. Faccenna, R. O'Connell, and D. Giardini (1999), The development of slabs in the upper mantle: Insights from numerical and laboratory experiments, *J. Geophys. Res.*, **104**, 15,207–15,226.
- Benito, R., J. Lopez-Ruiz, J. M. Cebria, J. Hertogen, M. Doblas, R. Oyarzun, and D. Demaiffe (1999), Sr and O isotopic constraint on source and crustal contamination in the high-K calc-alkaline and shoshonitic neogene volcanic rocks of SE Spain, *Lithos*, **46**, 773–802.
- Blanco, M. J., and W. Spakman (1993), The *P*-wave velocity structure of the mantle below the Iberian Peninsula: Evidence for subducted lithosphere below southern Spain, *Tectonophysics*, **221**, 13–34.
- Bordoni, P., and G. Valensise (1998), Deformation of the 1235 ka marine terrace in Italy: Tectonic implications, in *Coastal Tectonics*, edited by I. S. Stewart and C. Vita Finzi, *Geol. Soc. Spec. Publ.*, **146**, 71–110.
- Borsi, S., and R. Dubois (1968), Données géochronologiques sur l'histoire hercynienne et alpine de la Calabre centrale, *C. R. Acad. Sci., Ser. P*, **266**, 72–75.
- Bouybaouene, M. L., B. Goffé, and A. Michard (1995), High-pressure, low-temperature metamorphism in the Sebide S nappes, northern Rif, Morocco, *Geogaceta*, **17**, 117–119.
- Burrus, J. (1984), Contribution to a geodynamic synthesis of the Provençal basin (north-western Mediterranean), *Mar. Geol.*, **55**, 247–269.
- Caby, R., D. Hammor, and C. Delor (2001), Metamorphic evolution, partial melting and Miocene exhumation of lower crust in the Edough metamorphic core complex, west Mediterranean orogen, eastern Algeria, *Tectonophysics*, **342**, 239–273.
- Calvert, A., E. Sandvol, D. Seber, M. Barazangi, S. Roecker, T. Mourabit, F. Vidal, G. Alguacil, and N. Jabour (2000), Geodynamic evolution of the lithosphere and upper mantle beneath the Alboran region of the western Mediterranean: Constraints from travel time tomography, *J. Geophys. Res.*, **105**, 10,871–10,898.
- Calvo, M., R. Vegas, and M. L. Osete (1997), Paleomagnetic results from upper Pliocene and Pliocene rocks from the internal zone of the Iberian Peninsula, *Tectonophysics*, **277**, 271–283.
- Carminati, E., M. J. R. Wortel, W. Spakman, and R. Sabadini (1998), The role of slab detachment processes in the opening of the western-central Mediterranean basins: Some geological and geophysical evidence, *Earth Planet. Sci. Lett.*, **160**, 651–665.
- Catalano, R., C. Doglioni, and S. Merlini (2001), On the Mesozoic Ionia basin, *Geophys. J. Int.*, **144**, 49–64.
- Cello, G., G. M. Crisci, S. Marabini, and L. Tortorici (1985), Transverse tectonics in the Strait of Sicily: Structural and volcanological evidence from Island Pantelleria, *Tectonics*, **4**, 311–322.
- Cello, G., L. Morten, and A. M. De Francesco (1991), The tectonic significance of the Diamante-Terranova unit (Calabria, southern Italy) in the Alpine evolution of the northern sector of the Calabrian Arc, *Boll. Soc. Geol. Ital.*, **110**, 685–694.
- Cernobori, L., et al. (1996), Crustal image of the Ionian basin and its Calabrian margins, *Tectonophysics*, **264**, 175–189.
- Chamot-Rooke, N., J.-M. Gaulier, and F. Jestin (1999), Constraints on Moho depth and crustal thickness in the Liguro-Provençal basin from a 3D gravity inversion: Geodynamic implications, in *The Mediterranean Basins: Tertiary Extension Within the Alpine Orogen*, edited by B. Durand et al., *Geol. Soc. Spec. Publ.*, **156**, 37–61.
- Channell, J. E. T., R. Catalano, and B. D'Argenio (1980), Paleomagnetism and deformation of the Mesozoic continental margin in Sicily, *Tectonophysics*, **61**, 391–407.
- Channell, J. E. T., J. S. Oldow, R. Catalano, and B. D'Argenio (1990), Paleomagnetically determined rotations in the western Sicilian fold and thrust belt, *Tectonics*, **9**, 641–660.
- Cherchi, A., and L. Montandert (1982), Oligo-Miocene rift of Sardinia and the early history of the western Mediterranean basin, *Nature*, **298**, 736–739.
- Comas, M. C., V. García-Dueñas, and M. J. Jurado (1992), Neogene tectonic evolution of the Alboran Sea from MCS data, *Geo Mar. Lett.*, **12**, 157–164.
- Comas, M. C., J. P. Platt, J. I. Soto, and A. B. Watts (1999), The origin and tectonic history of the Alboran basin: Insights from leg 161 results, *Proc. Ocean Drill. Program Sci. Results*, **161**, 555–579.
- Consiglio Nazionale delle Ricerche (1991), Progetto Finalizzato geodinamica, structural model of Italy, map, scale 1:500000, Rome.
- Coulon, C., M. Megaritsi, S. Fourcade, R. C. Maury, H. Bellon, A. Louni-Hacini, J. Cotton, A. Coutelle, and D. Hermitte (2002), Post-collisional transition from calc-alkaline to alkaline volcanism during the Neogene in Oranie (Algeria): Magmatic expression of a slab breakoff, *Lithos*, **62**, 87–110.
- Crespo-Blanc, A., and J. Campos (2001), Structure and kinematics of the South Iberian paleomargin and its relationship with the Flysch Trough units: Extensional reactivation within the Gibraltar Arc fold-and-thrust belt (western Betics), *J. Struct. Geol.*, **23**, 1615–1630.
- DeJong, K. (1991), Tectonometamorphic studies and radiometric dating in the Betic Cordilleras (SE Spain): With implications for the dynamics of extension and compression in the western Mediterranean area, Ph.D. dissertation, 204 pp., Free Univ., Amsterdam.
- de Jonge, M. R., M. J. R. Wortel, and W. Spakman (1994), Regional scale tectonic evolution and the seismic velocity structure of the lithosphere and upper mantle: The Mediterranean region, *J. Geophys. Res.*, **99**, 12,091–12,108.
- Dercourt, J., et al. (1986), Geological evolution of the Tethys belt from the Atlantic to the Pamir since the Lias, *Tectonophysics*, **123**, 241–315.
- Dewey, J. F., M. L. Helman, E. Torco, D. H. W. Hutton, and S. Knott (1989), Kinematics of the Western Mediterranean, in *Alpine Tectonics*, edited by M. P. Coward and D. Dietrich, *Geol. Soc. Spec. Publ.*, **45**, 265–283.
- Dietrich, D. (1988), Sense of overthrust shear in the Alpine nappes of Calabria (southern Italy), *J. Struct. Geol.*, **10**, 373–381.
- D'Offizi, S., G. Minelli, and G. Pialli (1994), Foredeeps and thrust systems in the Northern Apennines, *Boll. Geofis. Teorica Appl.*, **36**, 91–102.
- Doglioni, C., E. Gueguen, F. Sàbat, and M. Fernandez (1997), The western Mediterranean extensional basins and the Alpine orogen, *Terra Nova*, **9**, 109–112.
- Doglioni, C., F. Innocenti, and G. Mariotti (2001), Why Mt Etna?, *Terra Nova*, **13**, 25–31.
- Dworkin, J., A. Nur, G. Mavko, and Z. Ben-Avraham (1993), Narrow subducting slabs and the origin of backarc basins, *Tectonophysics*, **227**, 63–79.
- El Azzouzi, M., J. Bernard-Griffiths, H. Bellon, R. C. Maury, A. Piqué, S. Fourcade, Cotten, and J. Hernandez (1999), Evolution des sources du volcanisme marocain au cours du Neogene, *C. R. Acad. Sci., Ser. II*, **329**, 95–102.
- El Bakkali, S., A. Gourgaud, J. L. Bourdier, and N. Gundogdu (1998), Post-collision neogene volcanism of the Eastern Rif (Morocco): Magmatic evolution through time, *Lithos*, **45**, 523–543.
- Faccenna, C., P. Davy, J.-P. Brun, R. Funicello, D. Giardini, M. Mattei, and T. Nalpas (1996), The dynamics of back-arc extensions: An experimental approach to the opening of the Tyrrhenian Sea, *Geophys. J. Int.*, **126**, 781–795.
- Faccenna, C., M. Mattei, R. Funicello, and L. Jolivet (1997), Styles of back-arc extension in the central Mediterranean, *Terra Nova*, **9**, 126–130.
- Faccenna, C., R. Funicello, D. Giardini, and P. Lucente (2001a), Episodic back-arc extension during restricted mantle convection in the central Mediterranean, *Earth Planet. Sci. Lett.*, **187**, 1–2, 105–116.
- Faccenna, C., T. W. Becker, F. P. Lucente, L. Jolivet, and F. Rossetti (2001b), History of subduction and back-arc extension in the central Mediterranean, *Geophys. J. Int.*, **145**, 809–820.
- Faccenna, C., L. Jolivet, C. Piromallo, and A. Morelli (2003), Subduction and the depth of convection in the Mediterranean mantle, *J. Geophys. Res.*, **108**(B2), 2099, doi:10.1029/2001JB001690.
- Fainberg, H., O. Saddiqi, and A. Michard (1999), New constraints on the bending of the Gibraltar arc from paleomagnetism of the Ronda peridotites (Betic cordilleras, Spain), in *Paleomagnetism and Tectonics of the Mediterranean Region*, edited by A. Morris and H. Tarling, *Geol. Soc. Spec. Publ.*, **105**, 43–52.
- Finetti, I., and A. Del Ben (1986), Geophysical study of the Tyrrhenian opening, *Boll. Geofis. Teorica Appl.*, **28**, 75–155.
- Fourcade, S., R. Capdevilla, A. Oubadi, and F. Martineau (2001), The origin and geodynamic significance of the Alpine cordierite-bearing granitoids of northern Algeria: A combined petrological, mineralogical, geochemical and isotopic (O, H, Sr, Nd) study, *Lithos*, **57**, 187–216.
- Frizon de Lamotte, D., J. Andrieux, and J. C. Guézou (1991), Cinématique des chevauchements Néogènes dans l'arc bético-Rifains, discussion sur les modèles géodynamiques, *Bull. Soc. Geol. Fr.*, **4**, 611–626.
- Frizon de Lamotte, D., B. Saint Bezar, R. Bracène, and E. Mercier (2000), The two main steps of the Atlas building and geodynamics of the western Mediterranean, *Tectonics*, **19**, 740–761.
- Funicello, F., C. Faccenna, D. Giardini, and K. Regenauer-Lieb (2003), Dynamics of retreating slabs: 2. Insights from three-dimensional laboratory experiments, *J. Geophys. Res.*, **108**(B4), 2207, doi:10.1029/2001JB00896.

- Galindo-Zaldívar, J., F. González-Lodeiro, and A. Jabaloy (1989), Progressive extensional shear structures in a detachment contact in the Western Sierra Nevada (Betic Cordillera, Spain), *Geodin. Acta*, 3, 73–85.
- García-Dueñas, V., J. M. Martínez-Martínez, and F. Navarro-Vilá (1986), La zona de falla de Torres Cartas, conjunto de fallas normales de bajo ángulo entre Nevado-Filábrides y Alpujarrides (Sierra Alhamilla, Béticas orientales), *Geogaceta*, 1, 17–19.
- García-Dueñas, V., J. C. Balanya, and J. M. Martínez-Martínez (1992), Miocene extensional detachments in the outcropping basement of the northern Alboran Basin and their tectonic implications, *Geo Mar. Lett.*, 12, 88–95.
- Garfunkel, Z., C. A. Anderson, and G. Schubert (1986), Mantle circulation and the lateral migrating of subducted slabs, *J. Geophys. Res.*, 91, 7205–7223.
- Gattacceca, J., and F. Speranza (2002), Paleomagnetism of Jurassic to Miocene sediments from the Apenninic carbonate platform (southern Apennines, Italy): Evidence for a 60° counterclockwise Miocene rotation, *Earth Planet. Sci. Lett.*, 201, 19–34.
- Giardini, D., and M. Vela (1988), La sismicità profonda del Mar Tirreno, *Mem. Soc. Geol. Ital.*, 41, 1079–1087.
- Goffé, B., et al. (1989), First evidence of high pressure, low temperature metamorphism in the Alpujarride nappes, Betic Cordillera (SE Spain), *Eur. J. Mineral.*, 1, 139–142.
- Gomez, F. W., R. Allmendinger, M. Barazangi, A. Er-Raji, and M. Dahmani (1998), Crustal shortening and vertical strain partitioning in the Middle Atlas Mountains of Morocco, *Tectonics*, 17, 520–533.
- Gomez, F. W., W. R. Beauchamp, and M. Barazangi (2000), Role of the Atlas Mountains (northwest Africa) within the African-Eurasian plate-boundary zone, *Geology*, 28, 775–778.
- Gorini, C., A. Mauffret, P. Guennoc, and A. Le Marrec (1994), Structure of the Gulf of Lions (northwestern Mediterranean Sea): A review, in *Hydrocarbon and Petroleum Geology of France*, edited by A. Mascle, pp. 223–243, Eur. Assoc. of Pet. Geol., Houten, Netherlands.
- Grasso, M., A. De Dominicis, and G. Mazzoldi (1990), Structures and tectonic setting of the western margin of the Hylean-Malta shelf, Central Mediterranean, *Ann. Tectonicae*, 4, 140–145.
- Gueguen, E., C. Doglioni, and M. Fernandez (1998), On the post-25 Ma geodynamic evolution of the western Mediterranean, *Tectonophysics*, 298, 259–269.
- Gutscher, M.-A., J. Malod, J.-P. Rehault, I. Contrucci, F. Klingelhoefer, L. Mendes-Victor, and W. Spakman (2002), Evidence for active subduction beneath Gibraltar, *Geology*, 30, 1071–1074.
- Gvirtzman, Z., and A. Nur (1999), The formation of Mount Etna as the consequence of slab rollback, *Nature*, 401, 782–785.
- Hager, B. H. (1984), Subducted slab and the geoid: Constraints on mantle rheology and flow, *J. Geophys. Res.*, 89, 6003–6015.
- Hager, B. H., and R. J. O'Connell (1978), Subduction zone dip angles and flow derived by plate motion, *Tectonophysics*, 50, 111–133.
- Hirn, A., et al. (1997), Roots of Etna volcano in faults of great earthquakes, *Earth Planet. Sci. Lett.*, 148, 171–191.
- Hollenstein, C., H. G. Khale, A. Geiger, S. Jenny, S. Goes, and D. Giardini (2003), New GPS constraints on the Africa-Eurasia plate boundary zone in southern Italy, *Geophys. Res. Lett.*, 30(18), 1935, doi:10.1029/2003GL017554.
- Illies, J. H. (1981), Graben formation: The Maltese Island—A case history, *Tectonophysics*, 73, 151–1678.
- Isacks, B., and P. Molnar (1971), Distribution of stresses in the descending lithosphere from a global survey of focal mechanism solutions of mantle earthquakes, *Rev. Geophys.*, 9, 103–174.
- Jabaloy, A., J. Galindo-Zaldívar, and F. González-Lodeiro (1993), The Alpujarride-Nevado-Filábride extensional shear zone, Betic Cordillera, SE Spain, *J. Struct. Geol.*, 15, 555–569.
- Jarrad, R. D. (1986), Relations among subduction parameters, *Rev. Geophys.*, 24, 217–284.
- Jolivet, L., and C. Faccenna (2000), Mediterranean extension and the Africa-Eurasia collision, *Tectonics*, 19(6), 1095–1106.
- Jolivet, L., C. Faccenna, N. d'Agostino, M. Fournier, and D. Worrall (1999), The kinematics of back-arc basins, examples from the Tyrrhenian, Aegean and Japan Seas, in *The Mediterranean Basins: Tertiary Extension Within the Alpine Orogen*, edited by B. Durand et al., *Geol. Soc. Spec. Publ.*, 156, 21–53.
- Jongsma, D., J. M. Woodside, G. C. P. King, and J. E. van Hinte (1987), The Medina wrench: A key to the kinematics of the central and eastern Mediterranean over the past 5 Ma, *Earth Planet. Sci. Lett.*, 82, 87–106.
- Kastens, K. A., and J. Mascle (1990), The geological evolution of the Tyrrhenian Sea: An introduction to the scientific results of ODP Leg 107, *Proc. Ocean Drill. Program Sci. Results*, 107, 3–26.
- Kastens, K. A., J. Mascle, and O. L. S. Party (1988), ODP Leg 107 in the Tyrrhenian Sea: Insights into passive margin and backarc basin evolution, *Geol. Soc. Am. Bull.*, 100, 1140–1156.
- Le Pichon, X., F. Bergerat, and M.-J. Roulet (1988), Plate kinematics and tectonics leading to the Alpine belt formation: A new analysis, *Spec. Pap. Geol. Soc. Am.*, 218, 111–131.
- Loneragan, L., and N. White (1997), Origin of the Betic-Rif mountain belt, *Tectonics*, 16, 504–522.
- López Sánchez-Vizcaíno, V., D. Rubatto, M. T. Gómez-Pugnaire, V. Trommsdorff, and O. Müntener (2001), Middle Miocene high-pressure metamorphism and fast exhumation of the Nevado-Filábride Complex, SE Spain, *Terra Nova*, 13, 327–331.
- Lucente, P. F., C. Chiarabba, G. B. Cimini, and D. Giardini (1999), Tomographic constraints on the geodynamic evolution of the Italian region, *J. Geophys. Res.*, 104, 20,307–20,327.
- Luján, M., J. C. Balanya, and A. Crespo-Blanc (2000), Contractual and extensional tectonics in Flysch and Penibetic units (Gibraltar Arc, SW Spain): New constraints on emplacement mechanisms, *C. R. Acad. Sci., Ser. II*, 330, 631–638.
- Lustrino, M., L. Melluso, and V. Morra (2000), The role of lower continental crust and lithospheric mantle in the genesis of Plio-Pleistocene volcanic rocks from Sardinia (Italy), *Earth Planet. Sci. Lett.*, 180, 259–270.
- Malinverno, A., and W. Ryan (1986), Extension in the Tyrrhenian Sea and shortening in the Apennines as result of arc migration driven by sinking of the lithosphere, *Tectonics*, 5, 227–245.
- Marti, J., J. Mitjavila, E. Roca, and A. Aparicio (1992), Cenozoic magmatism of the Valencia trough (western Mediterranean): Relationship between structural evolution and volcanism, *Tectonophysics*, 203, 145–165.
- Martínez-Martínez, J. M., and J. M. Azañón (1997), Mode of extensional tectonics in the southeastern Betics (SE Spain): Implications for the tectonic evolution of the peri-Alboran orogenic system, *Tectonics*, 16, 205–225.
- Mattei, M., P. Cipollari, D. Cosentino, A. Argentieri, F. Rossetti, F. Speranza, and L. Di Bella (2002), The Miocene tectono-sedimentary evolution of the southern Tyrrhenian Sea: stratigraphy, structural and palaeomagnetic data from the on-shore Amantea basin (Calabrian Arc, Italy), *Basin Res.*, 14, 147–168.
- Mauffret, A., G. Pascal, A. Maillard, and C. Gorini (1995), Tectonics and deep structure of the northwestern Mediterranean Basin, *Mar. Pet. Geol.*, 12, 645–666.
- Maury, R. C., et al. (2000), Post-collisional Neogene magmatism of the Mediterranean Maghreb margin: A consequence of slab breakoff, *C. R. Acad. Sci., Ser. II*, 331, 159–173.
- Meghraoui, M., J. L. Morel, J. Andrieux, and M. Dahmani (1996), Tectonique Plio-Quaternaire de la chaîne tello-rifaine et de la Mer d'Alboran: Une zone complexe de convergence continent-continente, *Bull. Soc. Geol. Fr.*, 167, 147–157.
- Mitrovica, J. X., and A. M. Forte (1997), Radial profile of mantle viscosity: Results from the joint inversion of convection and postglacial rebound observables, *J. Geophys. Res.*, 102, 2751–2769.
- Monaco, C. (1993), Le unità Liguridi nel confine Calabro-Lucano (Appennino meridionale): Revisione dei dati esistenti, nuovi dati ed interpretazione, *Boll. Soc. Geol. Ital.*, 112, 751–769.
- Monaco, C., P. Tapponnier, L. Tortorici, and P. Y. Gillot (1997), Late Quaternary slip rates on the Acireale-Piedimonte normal faults and tectonic origin of Mt. Etna (Sicily), *Earth Planet. Sci. Lett.*, 147, 125–139.
- Monié, P., H. Maluski, A. Saadallah, and R. Cabyl (1988), New $^{40}\text{Ar}/^{39}\text{Ar}$ ages of Hercynian and alpine thermotectonic events in Grande Kabylie (Algeria), *Tectonophysics*, 152, 53–69.
- Monié, P., F. G. Lodeiro, B. Goffé, and A. Jabaloy (1991), $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of alpine tectonism in the Betic Cordillera (southern Spain), *J. Geol. Soc. London*, 148, 289–297.
- Monié, P., R. L. Torres-Roldán, and A. García-Casco (1994), Cooling and exhumation of the western Betic Cordillera, $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronological constraints on a collapsed terrane, *Tectonophysics*, 238, 353–379.
- Morales, J., I. Serrano, A. Jabaloy, J. Galindo-Zaldívar, D. Zhao, F. Torcal, F. Vidal, and F. González-Lodeiro (1999), Active continental subduction beneath the Betic Cordillera and Alboran Sea, *Geology*, 27, 8735–8738.
- Morelli, A., and A. Dziewonski (1993), Body wave travel times and a spherically symmetric P- and S-wave velocity model, *Geophys. J. Int.*, 112, 178–194.
- Morley, C. K. (1992), Tectonic and sedimentary evidences for synchronous and out-of-sequence thrusting Larache-Acila area, western Morocco, Rif, *J. Geol. Soc. London*, 149, 39–49.
- Nolet, G. (1985), Solving or resolving inadequate and noisy tomographic system, *Geophys. J. Int.*, 112, 178–194.
- Nur, A., J. Dvorkin, G. Mavko, and Z. Ben Avraham (1991), Speculation on the origin and fate of back-arc basins, *Ann. Geofis.*, 36, 155–163.
- Osede, M. L., R. Freeman, and R. Vegas (1988), Preliminary paleomagnetic results from the subbetic zone (Betic cordillera): Kinematic and structural implications, *Phys. Earth Planet. Inter.*, 52, 283–300.
- Ottami, F., B. Addoum, E. Mecier, D. Frizon de La Motte, and J. Andrieux (1995), Geometry and kinematics of the south Atlas front, Algeria and Tunisia, *Tectonophysics*, 249, 233–248.
- Parés, J. M., R. Freeman, and E. Roca (1992), Neogene structural development in the Valencia trough margins from paleomagnetic data, *Tectonophysics*, 203, 111–124.
- Patacca, E., R. Sartori, and P. Scandone (1990), Tyrrhenian basin and Apenninic arcs: Kinematic relations since late Tortonian times, *Mem. Soc. Geol. Ital.*, 45, 425–451.
- Piccarreta, G. (1981), Deep-rooted overthrusting and blueschistic metamorphism in compressive continental margins: An example from Calabria (southern Italy), *Geol. Mag.*, 118, 539–544.
- Piqué, A., L. Brahim, M. El Azzouzi, R. C. Maury, H. Bellon, B. Semroud, and E. Laville (1998), Le pinceau maghrébin: Contraintes structurales et géochimiques, *C. R. Acad. Sci., Ser. II*, 326, 575–581.
- Piomallo, C., and A. Morelli (2003), P wave tomography of the mantle under the Alpine-Mediterranean area, *J. Geophys. Res.*, 108(B2), 2065, doi:10.1029/2002JB001757.
- Piomallo, C., A. P. Vincent, D. A. Yuen, and A. Morelli (2001), Dynamics of the transition zone under Europe inferred from wavelet cross-spectra of seismic tomography, *Phys. Earth Planet. Inter.*, 125, 125–139.

- Platt, J. P. (1995), Origin of the western subbetic arc (southern Spain): Paleomagnetic and structural evidence, *J. Struct. Geol.*, **17**, 765–775.
- Platt, J. P., and R. L. M. Vissers (1989), Extensional collapse of thickened continental lithosphere: A working hypothesis for the Alboran Sea and Gibraltar arc, *Geology*, **17**, 540–543.
- Platt, J. P., and M. J. Whitehouse (1999), Early Miocene high-temperature metamorphism and rapid exhumation in the Betic Cordillera (Spain): Evidence from U-Pb zircon ages, *Earth Planet. Sci. Lett.*, **171**, 591–605.
- Platt, J. P., J. I. Soto, M. J. Whitehouse, A. J. Hurford, and S. P. Kelley (1998), Thermal evolution, rate of exhumation, and tectonic significance of metamorphic rocks from the floor of the Alboran extensional basin, western Mediterranean, *Tectonics*, **17**, 671–689.
- Platt, J. P., S. Allerton, A. Kirker, C. Mandeville, A. Mayfield, E. S. Platzman, and A. Rimi (2003), The ultimate arc: Differential displacement, oroclinal bending, and vertical axis rotation in the External Betic-Rif arc, *Tectonics*, **22**(3), 1017, doi:10.1029/2001TC001321.
- Platzman, E. (1992), Paleomagnetic rotations and the kinematics of the Gibraltar arc, *Geology*, **20**, 311–314.
- Platzman, E., and W. Lowrie (1992), Paleomagnetic evidence for rotation of the Iberia peninsula, and the External Betic Cordillera, southern Spain, *Earth Planet. Sci. Lett.*, **108**, 45–60.
- Platzman, E. S., J. P. Platt, and P. Olivier (1993), Paleomagnetic rotations and fault kinematics in the Rif of Morocco, *J. Geol. Soc. London*, **150**, 707–718.
- Pondrelli, S., A. Morelli, and E. Boschi (1995), Seismic deformation in the Mediterranean area estimated by moment tensor summation, *Geophys. J. Int.*, **122**, 106–140.
- Ricou, L. E. (1994), Tethys reconstructed: Plates, continental fragments and their boundaries since 260 Ma from Central America to south-eastern Asia, *Geodi. Acta*, **7**, 169–218.
- Rossetti, F., C. Faccenna, B. Goffé, P. Monié, A. Argentieri, R. Funicello, and M. Mattei (2001), Alpine structural and metamorphic signature of the Sila Piccola Massif nappe stack (Calabria, Italy): Insights for the tectonic evolution of the Calabrian Arc, *Tectonics*, **20**, 112–133.
- Roure, F., P. Casero, and R. Vially (1991), Growth process and melange formation in the southern Apennines accretionary wedge, *Earth Planet. Sci. Lett.*, **102**, 395–412.
- Royden, L. H. (1993), Evolution of retreating subduction boundaries formed during continental collision, *Tectonics*, **12**, 629–638.
- Royden, L., E. Patacca, and P. Scandone (1987), Segmentation and configuration of subducted lithosphere in Italy: An important control on thrust-belt and foredeep-basin evolution, *Geology*, **15**, 714–717.
- Saadallah, A., and R. Caby (1996), Alpine extensional detachment tectonics in the Grande Kabylie metamorphic core complex of the Maghrebides (northern Algeria), *Tectonophysics*, **267**, 257–273.
- Sábat, F., J. A. Muñoz, and P. Santanach (1988), Transversal and oblique structures at the Sers de Llevant thrust belt: 4. Mallorca Island, *Geol. Rundsch.*, **77**, 529–538.
- Sagnotti, L. (1992), Paleomagnetic evidence for a Pleistocene counterclockwise rotation of the Sant'Arcangelo basin, southern Italy, *Geophys. Res. Lett.*, **19**, 135–138.
- Sánchez-Rodríguez, L., and D. Gebauer (2000), Mesozoic formation of pyroxenites and gabbros in the Ronda area (southern Spain), followed by early Miocene subduction metamorphism and emplacement into the middle crust: U-Pb sensitive high resolution ion microprobe dating of zircon, *Tectonophysics*, **316**, 19–44.
- Sánchez-Rodríguez, L., D. Gebauer, J. M. Tubía, J. I. Gil Ibarguchi, and D. Rubatto (1996), First shrimps ages on pyroxenites, eclogites and granites of the Ronda complex and its country-rocks, *Geogaceta*, **20**(2), 487–489.
- Sartori, R. (1990), The main results of ODP Leg 107 in the frame of Neogene to recent geology of peritethyan areas, *Proc. Ocean Drill. Program Sci. Results*, **107**, 715–730.
- Savostin, L. A., J.-C. Sibuet, L.-P. Zonenshain, X. Le Pichon, and M.-J. Roulet (1986), Kinematic evolution of the Thethys belt from the Atlantic Ocean to the Pamir since the Triassic, *Tectonophysics*, **123**, 1–35.
- Scheepers, P. J. J., and C. G. Langereis (1993), Analysis of NRM directions from Rossello composite: Implication for tectonic rotation of the Caltanissetta basin, Sicily, *Earth Planet. Sci. Lett.*, **119**, 243–258.
- Scheepers, P. J. J., and C. G. Langereis (1994), Paleomagnetic evidence for counter-clockwise rotations in the southern Apennines fold-and-thrust belt during the late Pliocene and middle Pleistocene, *Tectonophysics*, **239**, 43–59.
- Scheepers, P. J. J., C. G. Langereis, and F. J. Hilgen (1993), Counter-clockwise rotations in the southern Apennines during the Pleistocene: Paleomagnetic evidences from the Matera area, *Tectonophysics*, **225**, 379–410.
- Seber, D., M. Barazangi, A. Ibenbrahim, and A. Demnati (1996), Geophysical evidence for lithospheric delamination beneath the Alboran Sea and Rif-Betic mountains, *Nature*, **379**, 785–790.
- Selvaggi, G., and A. Amato (1992), Subcrustal earthquakes in the northern Apennines (Italy): Evidence for a still active subduction?, *Geophys. Res. Lett.*, **19**, 2127–2130.
- Selvaggi, G., and C. Chiarabba (1995), Seismicity and P-wave velocity image of the southern Tyrrhenian subduction zone, *Geophys. J. Int.*, **122**, 818–826.
- Seranne, M. (1999), The Gulf of Lion continental margin (NW Mediterranean) revisited by IBS: An overview, in *The Mediterranean Basins: Tertiary Extension Within the Alpine Orogen*, edited by B. Durand et al., *Geol. Soc. Spec. Publ.*, **156**, 21–53.
- Serri, G. F., F. Innocenti, and P. Manetti (1993), Geochemical and petrological evidence of the subduction of delaminated Adriatic continental lithosphere in the genesis of the Neogene-Quaternary magmatism of central Italy, *Tectonophysics*, **223**, 117–147.
- Shenk, V. (1980), U-Pb and Rb-Sr radiometric dates and their correlation with metamorphic events in the granulite facies basement of the Serre, southern Calabria (Italy), *Contrib. Mineral. Petrol.*, **73**, 23–38.
- Simancas, J. F., and J. Campos (1993), Compresión NNW-SSE tardi- a postmetamórfica y extensión subordinada en el Complejo Alpujárride (Dominio de Alborán, Orógeno bético), *Rev. Soc. Geol. España*, **6/1-2**, 23–36.
- Spadini, G., S. Cloetingh, and G. Bertotti (1995), Thermo-mechanical modeling of the Tyrrhenian Sea: Lithospheric necking and kinematics of rifting, *Tectonics*, **14**, 629–644.
- Spakman, W., S. van der Lee, and R. van der Hilst (1993), Travel-time tomography of the European-Mediterranean mantle down to 1400 km, *Phys. Earth Planet. Inter.*, **79**, 3–74.
- Speranza, F., R. Maniscalco, M. Mattei, A. Di Stefano, R. W. H. Butler, and R. Funicello (1999), Timing and magnitude of rotations in the frontal thrust systems of southwestern Sicily, *Tectonics*, **18**, 1178–1197.
- Speranza, F., M. Mattei, L. Sagnotti, and F. Grasso (2000), Rotational differences between the northern and southern Tyrrhenian domains: Paleomagnetic constraints from the Amantea basin (Calabria, Italy), *J. Geol. Soc. London*, **157**, 327–334.
- Suhadolc, P., and G. F. Panza (1989), Physical properties of the lithosphere-asthenosphere system in Europe from geophysical data, in *The Lithosphere in Italy: Advances in Earth Science Research*, edited by A. Boriani, M. Bonafede, G. B. Piccardo, and G. B. Vai, pp. 15–40, Accad. Naz. dei Lincei, Rome.
- Tao, W. C., and R. J. O'Connell (1993), Deformation of a weak subducted slab and variation of seismicity with depth, *Nature*, **361**, 626–628.
- Tapponnier, P. (1977), Évolution tectonique du système alpin en Méditerranée: Poinçonnement et écrasement rigide-plastique, *Bull. Soc. Geol. Fr.*, **19**, 437–460.
- Thorkelson, D. J. (1996), Subduction of diverging plates and the principles of slab window formation, *Tectonophysics*, **255**, 47–63.
- Torné, M., M. Fernández, M. C. Comas, and J. Soto (2000), Lithospheric structures beneath the Alboran Basin: Results from three-dimensional gravity modeling and tectonic relevance, *J. Geophys. Res.*, **105**, 3209–3228.
- Tovish, A., and G. Schubert (1978), Island arc curvature, velocity of convergence and angle of subduction, *Geophys. Res. Lett.*, **5**, 329–332.
- Tricart, P. L., P. L. Torelli, A. Argnani, F. Rekhiss, and N. Zitellini (1994), Extensional collapse related to compressional uplift in the Alpine chain off northern Tunisia (central Mediterranean), *Tectonophysics*, **238**, 317–329.
- Tubía, J. M., J. Cuevas, F. Navarro-Vilá, F. Alvarez, and F. Aldaya (1992), Tectonic evolution of the Alpujárride Complex (Betic Cordillera, southern Spain), *J. Struct. Geol.*, **14**, 193–203.
- Turner, S. P., J. P. Platt, R. M. M. George, S. P. Kelley, D. G. Pearson, and G. M. Nowell (1999), Magmatism associated with orogenic collapse of the Betic-Alboran domain, SE Spain, *J. Petrol.*, **40**(6), 1011–1036.
- Van der Voo, R. (1993), *Paleomagnetism of the Atlantic Thethys and Iapetus Oceans*, Cambridge Univ. Press, New York.
- van de Zedde, D. M. A., and M. J. R. Wortel (2001), Shallow slab detachment as a transient source of heat at midlithospheric depths, *Tectonics*, **20**(6), 868–882.
- Verges, J., and F. Sabat (1999), Constraints on the Neogene Mediterranean kinematic evolution along a 1000 km transect from Iberia to Africa, in *The Mediterranean Basins: Tertiary Extension Within the Alpine Orogen*, edited by B. Durand et al., *Geol. Soc. Spec. Publ.*, **156**, 63–80.
- Vissers, R. L. M., J. P. Platt, and D. Van der Wal (1995), Late orogenic extension of the Betic Cordillera and the Alboran domain: A lithospheric view, *Tectonics*, **14**, 786–803.
- Wortel, M. J. R., and W. Spakman (1992), Structure and dynamic of subducted lithosphere in the Mediterranean, *Proc. K. Ned. Akad. Wet.*, **95**, 325–347.
- Wortel, M. J. R., and W. Spakman (2000), Subduction and slab detachment in the Mediterranean-Carpathian Region, *Science*, **290**, 1910–1917.
- Zeck, H. P. (1999), Alpine kinematic evolution in the W Mediterranean: A W-ward directed subduction regime followed by slab roll-back and slab detachment, in *The Mediterranean Basin: Tertiary Extension Within the Alpine Orogen*, edited by B. Durand et al., *Geol. Soc. Spec. Publ.*, **156**, 109–120.
- Zeck, H. P., P. Monié, I. M. Villa, and B. T. Hansen (1992), Very high rates of cooling and uplift in the Alpine belt of the Betic Cordilleras, southern Spain, *Geology*, **20**, 79–82.

A. Crespo-Blanc, Departamento de Geodinámica, Institut Andaluz de Ciencias de la Tierra, Universidad - CSIC, Fuentenueva s/n, E-18071, Granada, Spain. (acrespo@ugr.es)

C. Faccenna and F. Rossetti, Dipartimento di Scienze Geologiche, Università di Roma Tre, L. S. R. Murialdo 1, Rome, I-00146, Italy. (faccenna@uniroma3.it; rossetti@uniroma3.it)

L. Jolivet, Laboratoire de Tectonique, UMR 7072, Université Pierre et Marie Curie, 4 Place Jussieu, F-75252, Paris, cedex 05 France. (laurent.jolivet@lgs.jussieu.fr)

C. Piromallo, Istituto Nazionale di Geofisica e Vulcanologia, Via Di Vigna Murata, 605, Rome, I-00143 Italy. (piromallo@ingv.it)

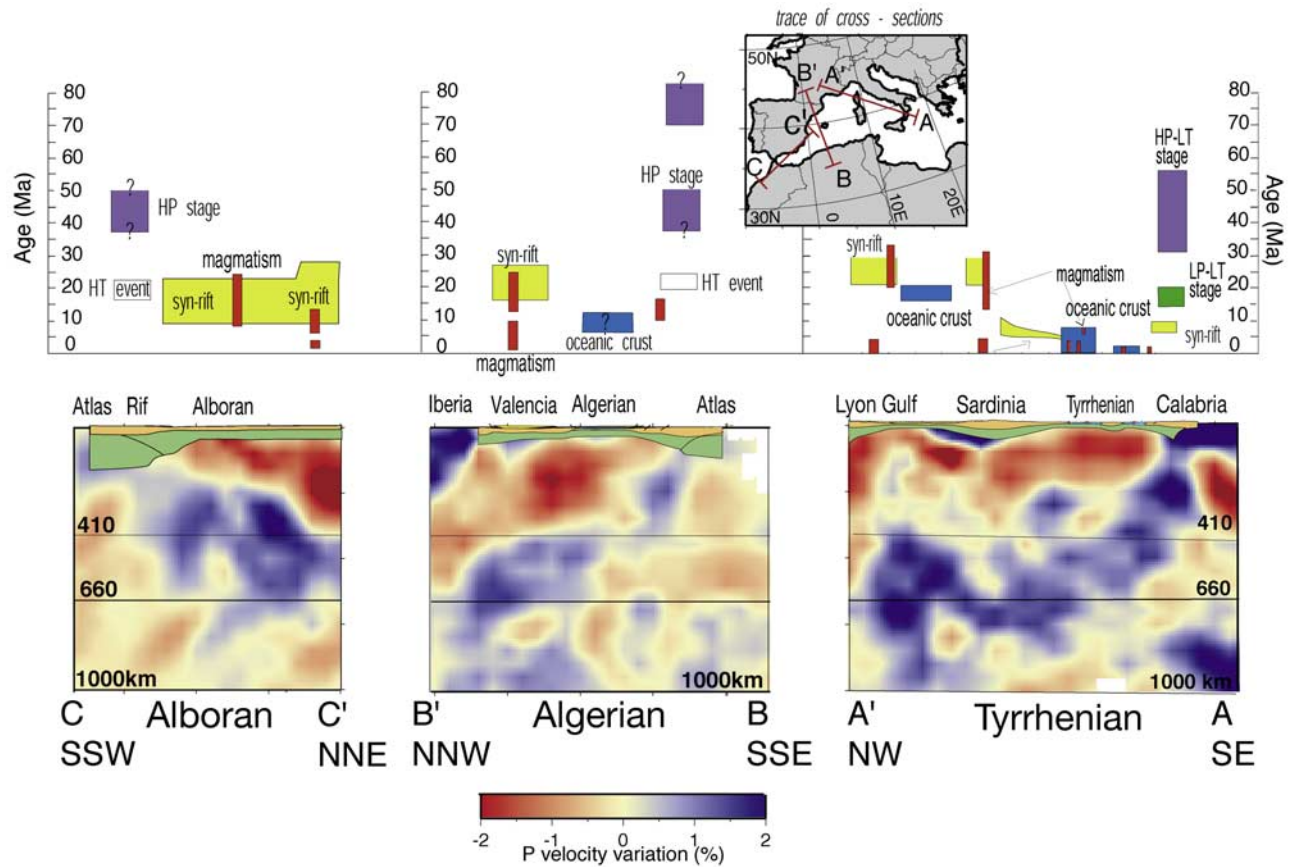


Figure 4. (bottom) Cross sections of the studied area (locations in the inset). AA' is from Calabria to the Gulf of Lyon, BB' is from Algeria to Iberia, and CC' is from southwestern Morocco to Cartagena. Crustal structure of section AA' is from *Finetti and Del Ben* [1986] and *Chamot-Rooke et al.* [1999], of section BB' is from *Verges and Sabat* [1999], and of section CC' is from *Torné et al.* [2000]. Lithospheric structure is from *Suhadolc and Panza* [1989] and *Torné et al.* [2000]. Tomographic cross sections are from model PM0.5 [*Piromallo and Morelli*, 2003]. (top) Age and distribution of the geological record related to subduction (see text for references): metamorphism (blue and green boxes represent blueschist and greenschist facies, respectively), magmatism (red boxes represent volcanic and intrusive rocks), synrift deposits filling extensional basins (yellow box), and oceanic crust (light blue box).

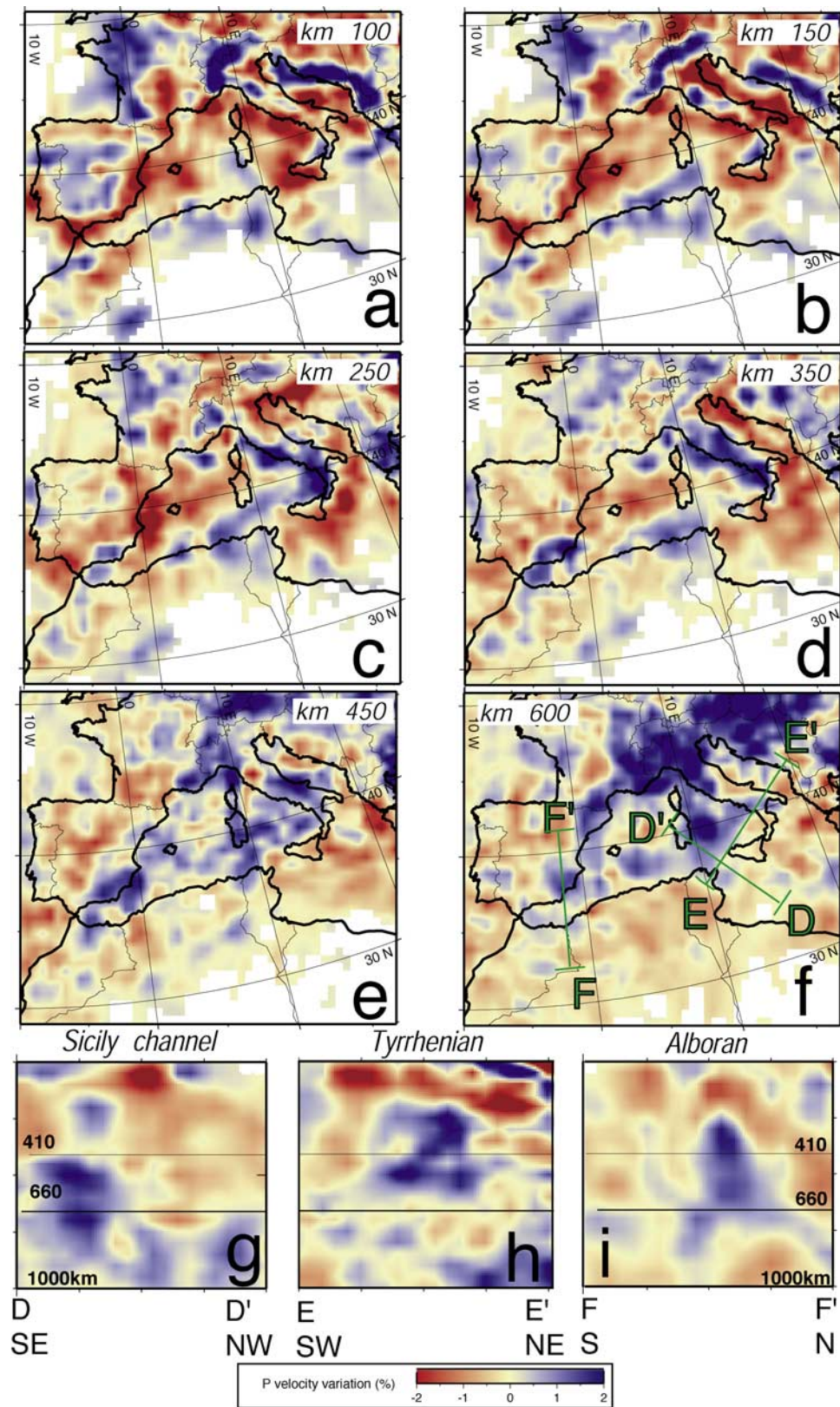


Figure 5.

Figure 5. (a–f) Map views of tomographic results at 100, 150, 250, 350, 450, and 600 km depth and (g–i) cross sections from model PM0.5 [Piromallo and Morelli, 2003]. Velocity anomalies are displayed in percentages with respect to the reference model sp6 [Morelli and Dziewonski, 1993]. Sections EE' and FF' intersect the deep positive velocity anomalies of Calabrian and the Alboran slab, respectively, parallel to the strike of the slab to show their limited lateral extent.