

RESEARCH ARTICLE

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Key Points:

- Western Mediterranean subduction was very slow between 85 and 30 Ma
- Subduction rollback started when the slab was no more than 150 km long
- Subduction rollback resulted from slab foundering at the inception of slab pull

Supporting Information:

- Readme
- Figure S1
- SWMediterranean_November2013.rot
- SWMediterranean_November2013.gpml

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Origin and consequences of western Mediterranean subduction, rollback, and slab segmentation

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Abstract The western Mediterranean recorded subduction rollback, slab segmentation and separation. Here we address the questions of what caused Oligocene rollback initiation, and how its subsequent evolution split up an originally coherent fore arc into circum-southwest Mediterranean segments. We kinematically reconstruct western Mediterranean geology from subduction initiation to present, using Atlantic plate reconstructions as boundary condition. We test possible reconstructions against remnants of subducted lithosphere imaged by seismic tomography. Transform motion between Africa and Iberia (including the Balears) between ~120 and 85 Ma was followed by up to 150 km convergence until 30 Ma. Subduction likely initiated along the transform fault that accommodated pre-85 Ma translation. By the ~30 Ma inception of rollback, up to 150 km of convergence had formed a small slab below the Balears. Iberia was disconnected from Sardinia/Calabria through the North Balearic Transform Zone (NBTZ). Subduction below Sardinia/Calabria was slightly faster than below the Balears, the difference being accommodated in the Pyrenees. A moving triple junction at the trench-NBTZ intersection formed a subduction transform edge propagator fault between the Balears and Calabria slab segments. Calabria rolled back eastward, whereas the Balears slab underwent radial (SW-S-SE) rollback. After Kabylides-Africa collision, the western slab segment retreated toward Gibraltar, here reconstructed as the maximum rollback end-member model, and a Kabylides slab detached from Africa. Opening of a slab window below the NBTZ allowed asthenospheric rise to the base of the fore arc creating high-temperature metamorphism. Western Mediterranean rollback commenced only after sufficient slab-pull was created from 100 to 150 km of slow, forced subduction before ~30 Ma.

1. Introduction

The western Mediterranean region underwent a complex, young evolution of subduction initiation, slab fragmentation, and rollback, with an associated intense but well-studied crustal deformation evolution [e.g., *Loneragan and White*, 1997; *Gueguen et al.*, 1998; *Rosenbaum et al.*, 2002a; *Faccenna et al.*, 2004; *Mauffret et al.*, 2004; *Jolivet et al.*, 2006, 2009; *Carminati et al.*, 2012], within a context of slow Africa-Iberia and Africa-Europe convergence [e.g., *Seton et al.*, 2012; *Torsvik et al.*, 2012; *Vissers and Meijer*, 2012b]. The region overlies a structurally complex mantle imaged by seismic tomography with clear evidence of remnants of subducted lithosphere [*Spakman*, 1991; *Spakman et al.*, 1993; *Carminati et al.*, 1998; *Wortel and Spakman*, 2000; *Gutscher et al.*, 2002; *Piomallo and Morelli*, 2003; *Spakman and Wortel*, 2004; *Wortel et al.*, 2009; *Bezada et al.*, 2013]. The western Mediterranean region therefore provides an excellent opportunity to reconstruct the dimensions of the slab at the onset of rollback and the evolution of slab segmentation that initiated during the Oligocene. To this end, it is essential to develop quantitative plate-kinematic restorations that are consistent with the imaged mantle structure as well as with key geological observables such as style and timing of thrusting, extension, metamorphism, exhumation, and volcanism.

Although published reconstructions of the western Mediterranean region are broadly similar, differences exist on two important issues that affect the restoration of the slab dimension through time. The first issue of debate concerns the age of the onset of convergence, and subduction initiation inferred from that, between Africa (and its northern promontory Adria) and Iberia. Different scenarios are predominantly the result of the choice of plate circuit based on restorations of marine magnetic anomalies and fracture zones of the Atlantic Ocean and the Bay of Biscay [e.g., *Savostin et al.*, 1986; *Dewey et al.*, 1989; *Srivastava et al.*, 1990; *Olivet*, 1996; *Müller et al.*, 1999; *Rosenbaum et al.*, 2002b; *Sibuet et al.*, 2004; *Vissers and Meijer*, 2012a, 2012b]. Variations between circuits published in the past decades result from different interpretations of the geological

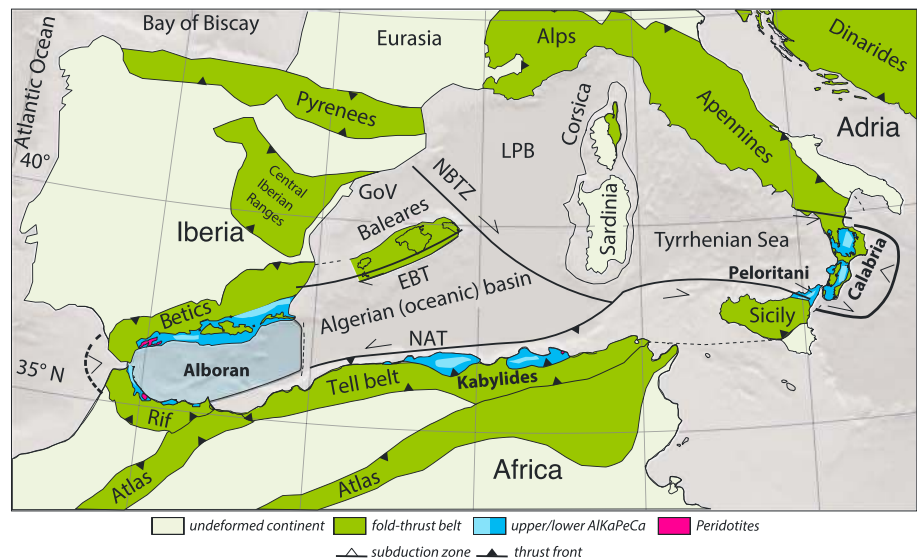


Figure 1. Schematic tectonic map of the western Mediterranean region. EBD=Emile Baudot Transform; LPB=Liguro-Provençal Basin; GoV=Gulf of Valencia; NAT=North African Transform; NBTZ=North Balearic Transform Zone.

evolution of the Pyrenees, the inclusion or omission of paleomagnetic data from Iberia in the analysis, and from updates of marine geophysical records (see *Vissers and Meijer* [2012a, 2012b] for a review). Resulting interpretations of the timing of western Mediterranean subduction initiation vary from as old as ~120 Ma [*Handy et al.*, 2010] and ~80 Ma [*Faccenna et al.*, 2001b] to as young as ~35 Ma [*Rosenbaum et al.*, 2002a]. In addition, scenarios for western Mediterranean subduction vary strongly in the predicted amount of rollback of the Gibraltar slab and, when compared to the slab length imaged by seismic tomography, imply a total amount of subduction prior to the start of slab rollback varying from ~400 km [*Faccenna et al.*, 2001b, 2004] to almost 0 km [*Rosenbaum et al.*, 2002a] along a single, northwest dipping slab, or a pre-35 Ma southeast dipping subduction zone that changed polarity to a northwest dipping zone around 40–35 Ma [*Handy et al.*, 2010; *Carminati et al.*, 2012].

Agreement exists on the oldest volcanic and volcanoclastic arc deposits in the Provence, Sardinia, and in the highest structural units of the Alboran domain (Figure 1), with ages of ~38–32 Ma [*Beccaluva et al.*, 2011; *Lustrino et al.*, 2011], suggesting that subduction below Iberia and southern France was active since at least late Eocene time. This was followed by the inception of widespread overriding plate extension, opening the Liguro-Provençal basin since ~30 Ma and the Valencia basin several million years thereafter [*Séranne*, 1999]. There is also consensus that since this time the western Mediterranean region has been characterized by widespread fore-arc and back-arc extension associated with major regional vertical axis rotations, exhumation of metamorphic rocks, and in places eventually back-arc ocean spreading, all during retreat of the subducting slab relative to Iberia and Eurasia [*Lonergan and White*, 1997; *Faccenna et al.*, 2004; *Spakman and Wortel*, 2004; *Handy et al.*, 2010]. During rollback, the length of the Africa-Iberia plate contact increased dramatically. This was associated with stretching and fragmentation of the original, pre-30 Ma fore-arc and accretionary prism, relics of which are now distributed over four regions: the Alboran region (Betics, Spain; and Rif, Morocco), the Kabyliides (Algeria), the Peloritani mountains (Sicily), and Calabria (southwestern mainland Italy) binned in the conceptual ALKAPECA terrane [*Boullin et al.*, 1986] (Figure 1).

A second issue of ongoing debate concerns the lateral extent of the western Mediterranean subduction zone at the onset of rollback. This is an important issue, since the length and lateral extent of a slab at the inception of rollback form an essential ingredient for understanding the dynamics of slab rollback and segmentation. The disagreement stems from the interpretation of the opening direction of the oceanic Algerian Basin, with one school of thought assuming dominant N-S opening leading to a presently inactive slab under the North African margin [e.g., *Gueguen et al.*, 1998; *Carminati et al.*, 1998; *Wortel and Spakman*, 2000; *Rosenbaum and Lister*, 2004b; *Schettino and Turco*, 2006], followed by relatively minor (~200 km) westward rollback in the Gibraltar region accommodated in the Alboran domain [*Faccenna et al.*, 2004; *Jolivet et al.*, 2009;

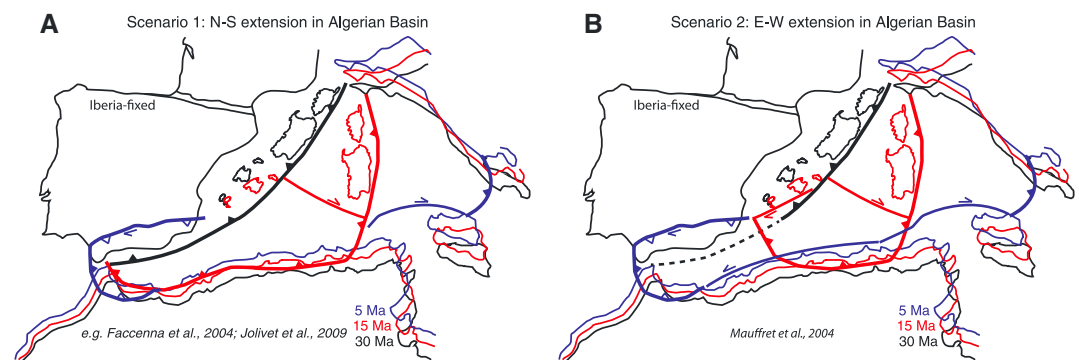


Figure 2. Schematic illustration of the effects in subduction zone configurations in the Oligo-Miocene assuming (a) N-S extension or (b) E-W extension in the Algerian Basin. In the case of E-W extension, ~700 km of subduction accommodated by westward rollback occurred, in addition to ~150 km pre-Miocene subduction, consistent with seismic tomographic images (see Figure 4).

Rossetti et al., 2013]. A second school assumes dominant E-W opening [Royden, 1993; Lonergan and White, 1997; Rosenbaum et al., 2002a] associated with slab rupture along and removal of slab under the North African margin [Gutscher et al., 2002; Mauffret et al., 2004; Spakman and Wortel, 2004; Duggen et al., 2003, 2004, 2005] (Figure 2). In the first case, a wide slab from Gibraltar to Corsica started to roll back, in the second case the slab that started to roll back was confined to the Balearic-Sardinia/Corsica segment while it propagated westward only since the early Miocene. The northern African margin has been postulated to be the site of southward subduction initiation since the Pliocene [Deverchere et al., 2005; Stich et al., 2006; Baes et al., 2011; Billi et al., 2011] and the two scenarios for the opening of the Algerian Basin lead to very different boundary conditions for that subduction initiation as well, with the first scenario suggesting subduction initiated along a E-W trending collisional zone, whereas the second scenario argues for subduction initiation along a fossil transform (subduction transform edge propagator (STEP)) fault.

In this paper, we present a kinematic restoration of the western Mediterranean region and explore the amount and timing of Africa-Iberia convergence using the Eurasia-Iberia-North America-Africa plate circuit. This forms a quantitative backbone for the mid-Cenozoic tectonic setting and for estimating amounts of subduction along the south and east Iberian margin prior to the start of early Miocene rollback. We subsequently test kinematic models with different choices for the opening direction of the Algerian Basin against the amount and location of subducted lithosphere imaged by seismic tomography of the western Mediterranean mantle. Finally, the rocks of the ALKAPECA terrane have a unique metamorphic geological record, which includes anomalously high-temperature metamorphic rocks, that are unexpected in fore arcs above active subduction zones which are normally cooled from below by subducting slabs [e.g., Brun and Faccenna, 2008]. A successful kinematic reconstruction should correctly predict the timing and location of such anomalous metamorphism, and we use the metamorphic record to test our kinematic restoration. We will use this reconstruction to explore the feasibility for geodynamic scenarios that may explain the origin of western Mediterranean rollback.

2. Amount of Convergence Along the South and East Iberian Margin Prior to 30 Ma

Kinematic boundary conditions for the restoration of the western Mediterranean region come from the relative motions of Eurasia, Iberia, and Africa, as constrained by marine magnetic anomalies of the central and northern Atlantic Oceans and the Bay of Biscay. We here use Euler rotations for the opening of the central Atlantic Ocean between Africa and North America of Müller et al. [1999] and Labails et al. [2010], and for North America-Europe of Gaina et al. [2002], with modifications as in Vissers and Meijer [2012a], as recently summarized in Gaina et al. [2013]. An important constraint for our analysis comes from the reconstruction of Iberia-Europe and consequently Iberia-North America motion. Since the 1980s, two contrasting models were proposed for the motion of Iberia relative to Eurasia during the Cretaceous opening of the Bay of Biscay (see Vissers and Meijer [2012a] for a detailed discussion). In the first model, Iberia rotated relative to Eurasia around a pole in the eastern Bay of Biscay, leading to Early Cretaceous Iberia-Eurasia convergence at the longitude of

Table 1. Kinematic Constraints Used for the Reconstruction of Figure 4

Reconstructed Phenomenon	Amount	Time Span	Reference
High Atlas mountains	30 km N-S shortening (reconstructed)	50–35 Ma	<i>Beauchamp et al.</i> [1999], <i>Brede</i> [1992], and <i>Teixell et al.</i> [2003]
High Atlas mountains	10 km N-S shortening (alternative)	50–35 Ma; 2–0 Ma	<i>Frizon de Lamotte et al.</i> [2008]
Tunesian Atlas mountains	20 km	10–7 Ma	<i>Creuzot et al.</i> [1993]
middle Atlas mountains	5 km	10–7 Ma	<i>Gomez et al.</i> [1998]
Central Iberian Range	20 km N-S shortening (reconstructed)	30–15 Ma	<i>De Vicente et al.</i> [2007]
Central Iberian Range	65 km N-S shortening (alternative)	Tertiary	<i>Guimera et al.</i> [2004]
Alboran domain	100 km E-W extension	25–10 Ma	<i>Faccenna et al.</i> [2004]
Alboran domain	110 km E-W extension	18–10 Ma	<i>Vissers et al.</i> [1995] and <i>Martinez-Martinez et al.</i> [2002]
Tyrrhenian Sea	up to 390 km NE-SW extension	10–0 Ma	<i>Faccenna et al.</i> [2004]
Gulf of Valencia	80 km NW-SE extension; clockwise rotation Balears	25–16 Ma	<i>Verges and Sabat</i> [1999] and <i>Séranne</i> [1999]
Balearic islands (Mallorca)	~85 km NW-SE shortening	25–16 Ma	<i>Sabat et al.</i> [2011]
Balearic islands (Mallorca)	~20° clockwise rotation	25–16 Ma	<i>Pares et al.</i> [1992]
Algerian Basin (scenario 1)	560 km E-W extension	16–8 Ma	<i>Mauffret et al.</i> [2004]
Algerian Basin (scenario 2)	260 km N-S extension	25–16 Ma	<i>Verges and Sabat</i> [1999]
Gulf of Lyon	up to 390 km NE-SW extension	~30–16 Ma	<i>Faccenna et al.</i> [2004]
Sardinia-Corsica block	~40° counterclockwise rotation	21–16 Ma	<i>Gattacceca et al.</i> [2007]

the Pyrenees [e.g., *Dewey et al.*, 1989; *Rosenbaum et al.*, 2002b; *Sibuet et al.*, 2004; *Vissers and Meijer*, 2012a, 2012b]. Following marine magnetic anomaly constraints of the Bay of Biscay, almost all pre-Eocene Africa-Europe convergence in the Iberian segment was accommodated in the Pyrenees, and Africa-Iberia convergence slowly started around 85 Ma, becoming significant after ~45 Ma. In the second model, Iberia moved since the Early Cretaceous along a transtensional left-lateral strike-slip system from a position adjacent to the northern margin of the Bay of Biscay into its modern position [e.g., *Savostin et al.*, 1986; *Olivet*, 1996]. This model was used by, e.g., *Handy et al.* [2010] to suggest continuous subduction between Iberia and Adria since the Early Cretaceous, as it predicts ~150–200 km of Iberia-Africa convergence between 100 and 80 Ma (even though it also predicts no convergence or even some extension between Iberia and Adria/Africa between 80 Ma and ~45 Ma).

Recent work has shown that the second model predicts a significantly smaller total amount as well as an incorrect timing of vertical axis rotation of Iberia compared to paleomagnetic data [*Van der Voo*, 1967; *Gong et al.*, 2008], provides incorrect predictions for paleomagnetic fits of 200 Ma basalts and mafic dikes in Iberia and Morocco [*Ruiz-Martinez et al.*, 2012], and is inconsistent with marine magnetic anomaly data in the Atlantic Ocean between Iberia and Newfoundland and the Bay of Biscay [*Vissers and Meijer*, 2012a, 2012b]. In contrast, the first model predicts all these constraints correctly. We therefore adopt the Eurasia-Iberia-North America plate circuit of the first model, as elaborated in *Vissers and Meijer* [2012a, 2012b], in combination with central Atlantic poles from *Müller et al.* [1999].

Our reconstruction framework is made with *GPlates* free software (<http://www.gplates.org> [*Boyden et al.*, 2011]). (*GPlates* rotation and shape files of this reconstruction are available in the supporting information.) Kinematic constraints on the Cenozoic formation and dispersion of ALKAPECA, discussed below, are listed in Table 1. For details of the reconstruction approach of nonrigid deforming terranes, we refer to *van Hinsbergen et al.* [2011] and *van Hinsbergen and Schmid* [2012]. Most importantly, our reconstruction allows for burial of sediments that are now metamorphosed (i.e., units disappear from the surface) and their subsequent exhumation (i.e., units reappear to the surface). This approach differs from recent reconstructions that apply standard plate reconstruction approaches using rigid blocks that can only move along the surface [*Schettino and Turco*, 2006; *Turco et al.*, 2012] in that area occupied by a single, now intensely deformed domain such as the Alboran region can change its surface area over time, which is more realistic given the widespread evidence for low-angle detachment faulting in such regions (see review below).

First, we constrain the timing and amount of Africa-Iberia convergence that is accommodated within the Piemonte-Ligurian Ocean, which opened in Jurassic time between Iberia and Adria/Africa [*Frisch*, 1979; *Vissers et al.*, 2013]. Therefore, we first compensate the Africa-Iberia convergence as constrained by the plate circuit for N-S shortening accommodated in the Atlas Mountains of NW Africa. The Atlas Mountain range formed by intracontinental shortening accommodated in an intracontinental rift that formed in early-middle Mesozoic

time [Frizon de Lamotte *et al.*, 2008, 2011] and was reconstructed as ~30 km between 50 and 35 Ma following Brede [1992], Beauchamp *et al.* [1999] and Teixell *et al.* [2003], although Frizon de Lamotte *et al.* [2008] suggested a smaller total amount on the order of ~10 km (Table 1). In addition, part of the shortening was accommodated since the Pleistocene [Frizon de Lamotte *et al.*, 2008], which is not specifically reconstructed here. NW-SE shortening in the Central Iberian Ranges was reconstructed at 20 km between 35 and 20 Ma [De Vicente *et al.*, 2007] (see Table 1), although Guimera *et al.* [2004] estimated as much as 65 km. The estimates of total intraplate shortening thus vary from 30 to 95 km and were reconstructed as ~50 km. The resulting convergence history since 85 Ma, in 5 Ma time steps between Africa and Iberia, is illustrated in Figure 3. Prior to 85 Ma, Africa-Iberia motion occurs along a small-circle more or less parallel to the southern and eastern Iberian margin, which thus likely formed a transform fault cutting now-subducted lithosphere. The sense of shear along that transform fault, as well as the total displacement during the Cretaceous Normal Superchron (CNS; ~121–83 Ma), is difficult to constrain because there are no magnetic anomalies on the seafloor to assess changes in rate of seafloor spreading, and from that, relative Africa-Iberia motion. During the superchron, Iberia rotated counterclockwise relative to Europe around a pole in the eastern Bay of Biscay, and the rate and timing (Aptian-Albian, ~121–110 Ma [Gong *et al.*, 2008]) of this rapid rotation has been constrained by biostratigraphically dated paleomagnetic data. Similar data for Africa are sparse [Torsvik *et al.*, 2012], but assuming constant Africa-North America spreading rates throughout the CNS would result in ~600 km right-lateral strike-slip between Africa and Iberia during the Iberian rotation (~121–110 Ma [Gong *et al.*, 2008; Vissers and Meijer, 2012a]), followed by some extension (perhaps reflected by recently documented N-S Albian-Santonian extension in Tunisia [Gharbi *et al.*, 2013]) and ~300 km of left-lateral strike-slip until ~85 Ma (Figure 3). Future work may shed further light on the exact Africa-Iberia kinematics during the Cretaceous superchron, but it seems nevertheless likely that the subduction zone below Iberia/Baleares formed along a former transform plate boundary. Independent of the noted uncertainties in relative motion between Iberia and Africa, the plate reconstruction from ocean magnetic anomalies does not allow for any convergence between Iberia and Africa during the ~121–83 Ma CNS, rather a modest amount of extension was accommodated in the plate contact zone.

After ~85 Ma, the motion between Africa and Iberia slowly and gradually changed toward convergence. The total amount of Africa-Iberia convergence at the position of the North Balearic Transform Zone (NBTZ, Figure 3) since 85 Ma was ~280 km, of which ~150 km occurred before the ~30 Ma inception of rollback. The total Africa-Iberia convergence since the Cretaceous at the position of Gibraltar is on the order of 55–120 km (taking the uncertainties in intracontinental shortening estimates in the Atlas and Central Iberian Ranges into account), of which ~50 km pre-dates 30 Ma (Figure 3). There are no error bars available for the magnetic anomaly positions of the Bay of Biscay, or the restorations of the Central Iberian ranges and the Atlas mountains, but typical error bars for seafloor reconstructions in the Atlantic are on the order of several tens of kilometers [e.g., Doubrovine and Tarduno, 2008].

The bulk of Africa-Europe convergence occurred after 45 Ma (~220 km). Although some contraction (up to 60 km) may have occurred between 85 and 45 Ma, rates were very low and it is unlikely that a subducting slab had formed by 45 Ma below Iberia. Between 45 Ma and 30–25 Ma, when incipient rollback and extension in the Gulf of Valencia started, some 90–150 km of Africa-Iberia convergence had occurred at the position of the NBTZ. At this stage, it is not possible to accurately constrain the total slab length below Sardinia at the time rollback started due to uncertainties in the partitioning of convergence to the north and south of the Corsica-Sardinia block and due to uncertainties in kinematic change from northwestward subduction below the Baleares to southeastward subduction prior to ~35 Ma on Corsica [Brunet *et al.*, 2000]. The total amount of 65–35 Ma Africa-Europe convergence at the position of Sardinia is on the order of 250 km. The inception of arc volcanism in the Provence and Sardinia around 38–34 Ma suggests that by this time, a slab reached ~100–150 km of depth below Sardinia, which is consistent with the plate circuit constraints. There is evidence, however, that some convergence was accommodated to the north of Corsica-Sardinia in the Provence (southern France) in Eocene time [Lacombe and Jolivet, 2006; Andreani *et al.*, 2010], when the continental basement of Corsica started to be involved in the Alpine, southward dipping subduction zone [Maggi *et al.*, 2012]; the total amount of documented shortening in the Provence is only on the order of 15–20 km [Espurt *et al.*, 2012], but the amount of convergence accommodated between Corsica and Sardinia hidden in the now-extended passive margins of the Liguro-Provençal Basin and in the western Alps remains to be reconstructed. Paleomagnetic data demonstrate that since Jurassic time, the Sardinia-Corsica block

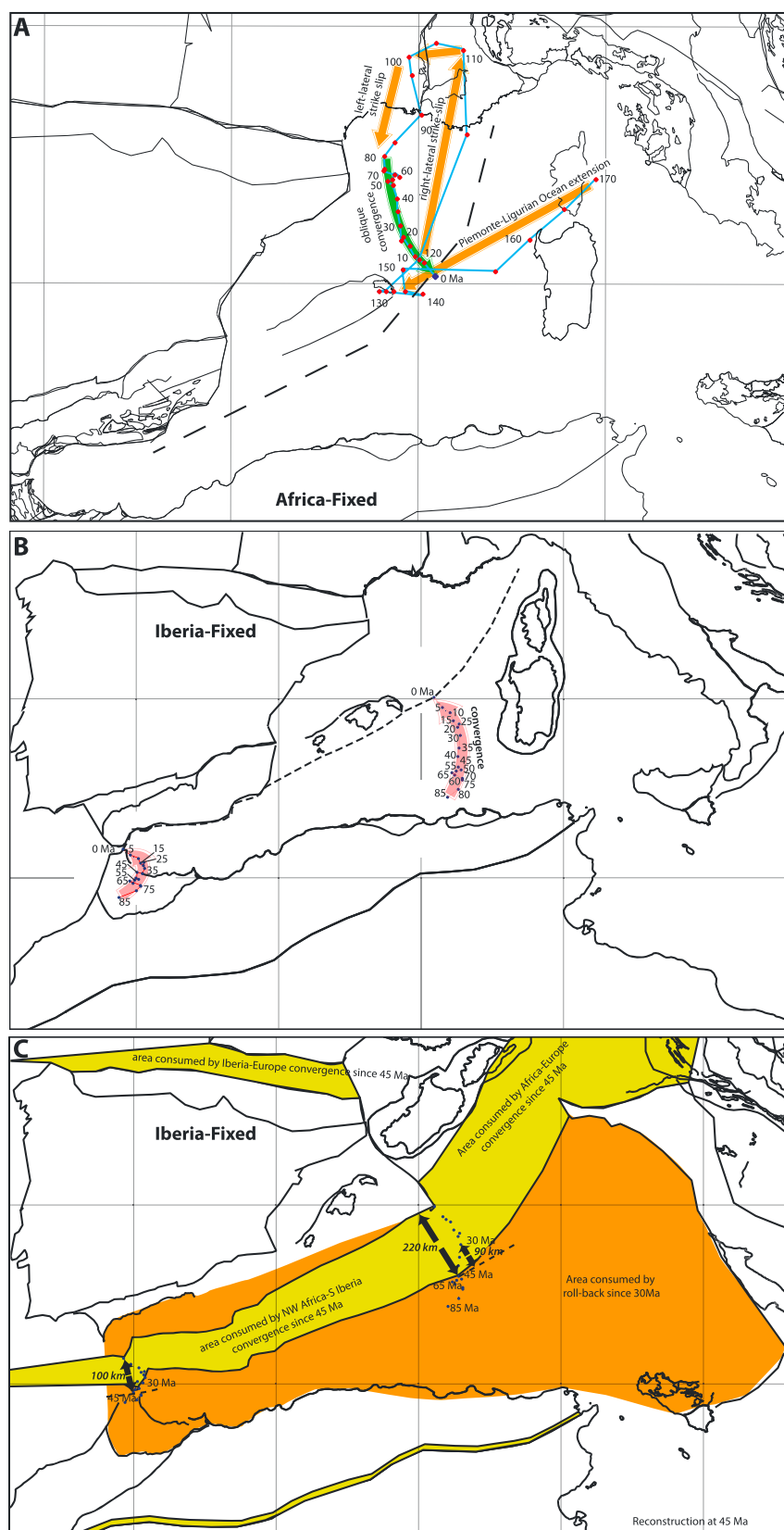


Figure 3. Africa-Iberia convergence relative to a fixed southern Iberian plate, using Central Atlantic reconstructions of Müller *et al.* [1999] and Bay of Biscay and North Atlantic reconstructions of Vissers and Meijer [2012], corrected for shortening in the Central Iberian Ranges and Atlas mountains (see text and Table 1).

rotated $\sim 90^\circ$ counterclockwise [Kirscher *et al.*, 2011], of which $\sim 50^\circ$ occurred in Miocene time [Speranza *et al.*, 2002; Gattacceca *et al.*, 2007]. We incorporated information from unpublished paleomagnetic results (E. L. Advokaat *et al.*, Eocene rotation of Sardinia, and the paleogeography of the Mediterranean region, submitted to *Earth and Planetary Science Letters*, 2014) that suggest that the pre-Miocene $\sim 40^\circ$ counterclockwise rotation of Sardinia occurred in the Eocene and was likely accommodated by contraction between the Sardinia-Corsica block and Eurasia, as documented in the Provence. This would suggest that Sardinia and Iberia rotated at different times and were hence disconnected, as previously suggested by Rosenbaum *et al.* [2002b], which we adopted in the reconstructions shown here. Since our new paleomagnetic data are not published yet, we focus the main quantitative estimates of the amount of subduction in the western Mediterranean on the Balearic segment, and the quantitative subduction evolution of the Sardinia segment is tentative, and maximum estimates only.

Summarizing, the length of a northwestward dipping slab at the inception of western Mediterranean rollback some 30 Ma may have been ~ 250 km below Sardinia but not more than ~ 150 km below the Balears, whereas at the location of Gibraltar, only some tens of kilometers of convergence had occurred and probably no well-developed slab existed (Figure 3).

3. Review: Structure and Metamorphism of ALKAPECA

Before reconstructing the rollback process in the western Mediterranean since the Early Miocene, we focus on some key geological markers of that evolution. Relics of the fore-arc and accretionary prism of the western Mediterranean subduction zone that existed prior to the inception of rollback in Late Oligocene time are preserved in the ALKAPECA terranes, which now overlie thrust and locally metamorphosed passive margin sediments of Iberia, North Africa, and Adria (Figure 1). Here we restore the ALKAPECA terranes into their Late Eocene configuration prior to their dispersion.

There are two main ALKAPECA units (here termed “upper and lower”) that are internally thrust and overprinted by extension. The upper ALKAPECA units show at best low-grade Alpine metamorphism and consist of Hercynian basement relics with a Mesozoic-Paleogene cover (Betics: Malaguide [Loneragan and Platt, 1995; Vissers *et al.*, 1995; Vissers, 2012], Rif: Ghomaride [Chalouan and Michard, 1990; Michard *et al.*, 2006; Zaghloul *et al.*, 2010], Kabylides: Upper Unit, [Monié *et al.*, 1984, 1988; Peucat *et al.*, 1996; Saadallah and Caby, 1996; Michard *et al.*, 2006]; Peloritani-Calabria: Aspromonte-Stilo [Graessner *et al.*, 2000; Rossetti *et al.*, 2001, 2004; Langone *et al.*, 2006; Heymes *et al.*, 2008, 2010]). These units are unconformably overlain by ~ 30 – 20 Ma clastics probably belonging to a fore-arc basin [Cavazza, 1989; Weltje, 1992; Loneragan, 1993], which appears to have been contiguous from Calabria, where they formed during NE-SW, trench-parallel extension [Heymes *et al.*, 2008], to the Rif and Betics [Bonardi *et al.*, 2003].

The lower ALKAPECA units are \sim NW-SE shortened Paleozoic to Triassic metasedimentary rocks with Eo-Oligocene eclogite-blueschist or carpholite-bearing assemblages (Betics: Alpujarride [Goffé *et al.*, 1989; Monié *et al.*, 1991; Sanchez-Vizcaino *et al.*, 1991; Tubia and Gil Ibarra, 1991; Vissers *et al.*, 1995; Booth-Rea *et al.*, 2002; Platt *et al.*, 2005; Vissers, 2012], Rif: Sebtide [Bouyabouene *et al.*, 1995; Michard *et al.*, 1997; Chalouan *et al.*, 2001], Kabylides: Lower Unit [Mahjoub *et al.*, 1997; Michard *et al.*, 2006], Peloritani-Calabria: Africo-Polsi [Platt and Compagnoni, 1990; Wallis *et al.*, 1993; Ortolano *et al.*, 2005; Heymes *et al.*, 2010]). The high-pressure, low-temperature (HP-LT) metamorphic parageneses suggest that these rocks were buried in a subduction zone, and the lower ALKAPECA units were interpreted to have undergone at least part of their exhumation in a subduction channel [Avigad *et al.*, 1997; Jolivet *et al.*, 2003].

The Triassic and older metasediments of the Alpujarride units of the Betics were locally intruded by gabbros with mid-ocean ridge basalt (MORB) geochemical signatures [Martin-Rojas *et al.*, 2009; Tubia *et al.*, 2009]. A zircon age from these of 183 ± 3 Ma is interpreted as the intrusion age, with a 19.9 ± 1.7 Ma old rim related to a Miocene HT metamorphic overprint (see below) [Sanchez-Rodriguez and Gebauer, 2000]. In addition, the Alpujarride, Sebtide, and lower Kabylides units are tectonically intercalated with peridotites derived from subcontinental lithospheric mantle (Betics: Ronda, Rif: Beni Bousera, Kabylides: Edough [Pearson *et al.*, 1989; Davies *et al.*, 1993; van der Wal and Vissers, 1996; Balanyá *et al.*, 1997; Lenoir *et al.*, 2001; Michard *et al.*, 2006; Bruguier *et al.*, 2009; El Atrassi *et al.*, 2011]). Following decompression from diamond-facies depth at an unknown time [Pearson *et al.*, 1989; Davies *et al.*, 1993], a thermal pulse overprinted the Ronda peridotite at conditions of 16 ± 2 kbar/1180–1225°C, decreasing structurally upward. Mapped facies boundaries of the

Ronda peridotite are approximately parallel to those in the overlying metasedimentary rocks of the Alpujarride unit in which the deepest units experienced ~15 kbar/800°C [Loomis, 1972; Obata, 1980; Argles *et al.*, 1999; Lenoir *et al.*, 2001]. These facies boundaries, however, separate rocks with different deformational and thermal histories. The structurally highest rocks in the mantle section are garnet peridotite mylonites delineating a shear zone of some 500 m thick, which is concordant with the overlying high-grade crustal rocks. The mineral assemblages are consistent with pressures of around 18 kbar [van der Wal and Vissers, 1993], or 19.5–20 kbar [Garrido *et al.*, 2011]. These mylonites overprint a prekinematic garnet-bearing assemblage indicating pressures of 24–27 kbar [Garrido *et al.*, 2011]. Pyroxenite dikes in the garnet-bearing assemblages yielded zircons with ~180–130 Ma U/Pb core ages, interpreted as ages of the protolith, with rims of 19–22 Ma interpreted to reflect Miocene HT metamorphism [Sanchez-Rodriguez and Gebauer, 2000].

The parallel arrangement of the mylonitic rocks in the Ronda peridotite and the overlying metasedimentary rocks, as well as microstructural evidence [e.g., van der Wal and Vissers, 1996], suggests that a single thermal pulse overprinted both the Ronda peridotite and the overlying country rock, with HT metamorphism prevailing when the metasedimentary rocks immediately overlying the Ronda peridotites were under pressures of 15 kbar (equivalent to ~50 km depth). The peridotite mylonite, however, is clearly associated with the displacement that juxtaposed the peridotite with the crustal rocks, suggesting that the mylonitization and the formation of the overlying gneisses are Early Miocene in age and may have operated under pressure conditions decreasing from 18 kbar or higher to around 16 kbar. Hercynian zircons in the country rocks consistently contain zircon rim U/Pb ages of ~22–19 Ma [Sánchez-Gómez, 1998; Platt and Whitehouse, 1999; Michard *et al.*, 2006] and similar ages are found in leucocratic dikes crosscutting the peridotites [Esteban *et al.*, 2011] as well as in HT-LP metasedimentary rocks of the Alpujarride unit that were recovered from the seafloor of the Alboran Sea [Kelley and Platt, 1999]. The lower Kabylides units underwent a similar, albeit slightly earlier history, with ~25 Ma ages for HT metamorphism and granitoid intrusion [Michard *et al.*, 2006]. These data demonstrate that there was Miocene HT-LP metamorphism and that subcontinental mantle peridotites at that time must have been in contact with, or within only several kilometers of Paleozoic-Triassic sedimentary rocks, perhaps locally still associated with some Hercynian basement slivers [Michard *et al.*, 1997]. Numerical modeling results of Platt *et al.* [1998] demonstrated that to reach the HT-LP metamorphic conditions in the rocks recovered from the Alboran seafloor, asthenospheric temperatures pertained at depths as shallow as ~60 km.

Argles *et al.* [1999] demonstrated attenuation of the metamorphic field gradient between the deepest metasedimentary units overlying the Ronda peridotite and the highest structural units, still exposed in the Betic Cordillera of the Malaguide complex. This attenuation requires thinning of the Alboran crust by a factor of 10 after the Early Miocene peak metamorphic conditions in the Alpujarride rocks. We stress, however, that the contrast in pressures between the Ronda plagioclase peridotites (~16 kbar [Lenoir *et al.*, 2001; Platt *et al.*, 2003c]) and the basal metasedimentary units (~15 kbar [Argles *et al.*, 1999]) during the HT metamorphic overprint was marginal. We will return to the significance of this observation later in this paper. All lower ALKAPECA units were affected by extension-related exhumation, dominantly E-W directed in AL and KA, NE-SW in PE and CA, with exhumation finalized by late Early to Middle Miocene time shown by unconformable sedimentary cover units and fission track data [Loneragan and Platt, 1995; Vissers *et al.*, 1995; Platzman and Platt, 2004; Michard *et al.*, 2006; Heymes *et al.*, 2008; Esteban *et al.*, 2013]. The contact between the upper and lower ALKAPECA units is in its latest motion an extensional detachment (e.g., the Malaguide-Alpujarride Contact in the Betics [Platzman and Platt, 2004], the Aspromonte-Stilo detachment in Calabria [Heymes *et al.*, 2008], and the Kabylid detachment [Saadallah and Caby, 1996]). In the Rif, Kabylides, and Peloritani Mountains, finally, a stack of nonmetamorphosed, rootless thrust sheets of Mesozoic-Cenozoic carbonates ("Dorsale Calcaire" unit) is found, thrust at the front of and structurally below the upper ALKAPECA units [Michard *et al.*, 2006; Chalouan *et al.*, 2008]. The Dorsale Calcaire unit probably formed the sedimentary cover of part of the lower ALKAPECA units, which decoupled upon arrival in the subduction zone to form rootless nappes [Frizon de Lamotte *et al.*, 2000; El Kadiri *et al.*, 2006].

In summary, at the inception of rollback, the lower ALKAPECA units were in a buried position decoupled from their original lower crustal and lithospheric underpinnings, and located immediately above a subducting slab, and were shortly after the inception of rollback overprinted by HT metamorphism and extensional exhumation. The upper ALKAPECA units were at shallow depth in a fore-arc position and have never been deeply buried in Cenozoic time.

The now-dispersed ALKAPECA fragments eventually overthrust the continental margins of Iberia, Africa, and Adria. The Kabylides overlie thrust and folded African margin sediments (Maghrebian flysch and Tell

belt) with the contact pierced by 16–15 Ma granites, interpreted to result from slab break-off after collision [Maury *et al.*, 2000; Coulon *et al.*, 2002; Benaouali-Mebarek *et al.*, 2006; Michard *et al.*, 2006]. Calabria overlies in places Oligo-Miocene HP-LT, ocean-derived metasediments and metabasites and became thrust onto a paleogeographically complex margin of Adria (with nappes representing from top to bottom the Apennine platform, Lagonegro basin, and Apulian platform units) forming the southern Apennines, with the Peloritani Mountains overthrusting the African basement of Sicily [Pescatore *et al.*, 1999; Rossetti *et al.*, 2001, 2004; Speranza *et al.*, 2003; Heymes *et al.*, 2008; Maffione *et al.*, 2013; Vitale and Ciarcia, 2013], whereas subduction of oceanic crust below central Calabria continues today [Palano *et al.*, 2012].

In the Betics, exhumed Iberian margin units (Nevado-Filabride units) have 18–14 Ma metamorphic ages [Platt *et al.*, 2006; Behr and Platt, 2012; Gómez-Pugnaire *et al.*, 2012]. These units consist of Variscan basement relics and a Paleozoic-Triassic stratigraphic cover [Gómez-Pugnaire *et al.*, 2012; Vissers, 2012], tectonically overlain by Jurassic metabasic and serpentinitic rocks and possibly Cretaceous calcareous micaschists metamorphosed at HP-LT [Bodinier *et al.*, 1987; Puga *et al.*, 1989, 2011], interpreted as derived from oceanic crust and sometimes called “Betic ophiolites.” The Nevado-Filabride continental units represent the underthrust Iberian margin, with the “ophiolites” being derived from the neighboring Piemonte-Ligurian Ocean. To the west and north, the Alboran domain is underlain by a nonmetamorphic, WNW-ESE shortened fold-thrust belt consisting of Triassic to upper Miocene carbonates that thrust in Miocene time [Platt *et al.*, 2003b; Crespo-Blanc, 2007; Meijninger and Vissers, 2007] and likely form the stratigraphic cover of the Nevado-Filabride units. Alboran units in the Rif overlie metamorphosed North African margin units (Temsamane unit) with ~15–12 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages and are fringed by an ESE-WNW shortened Middle-Late Miocene fold-thrust belt of the external Rif [Negro *et al.*, 2008; Di Staso *et al.*, 2010; Booth-Rea *et al.*, 2012]. The northwestern external Rif and the southwestern external Betics are overlain by flysch nappes derived from the presumably oceanic corridor between Iberia and Africa that formed as connection between the central Atlantic and Piemonte-Ligurian Oceans in the Late Jurassic [Frisch, 1979; Vissers *et al.*, 2013]. The flysch consists of Upper Jurassic to Upper Cretaceous turbidites, interpreted to have been deposited in a passive margin setting with oceanic crust consistent with Jurassic mafic lavas associated with the Rif flysch units [Durand-Delga *et al.*, 2000]. These are overlain by Upper Cretaceous to Oligocene marls and turbidites, and Upper Oligocene to Lower Miocene quartz arenites (Numidian flysch). From Upper Oligocene mica-rich deposits onward, the flysch may be collision related, older units probably were passive margin sediments, interpreted as deep-water lateral equivalents of the external Rif and the sub-Betic units [Platt *et al.*, 2003b; Lujan *et al.*, 2006]. Thrusting of the flysch units occurred since late Burdigalian time and was associated with complete detachment of these units from their original basement, which must have subducted [Lujan *et al.*, 2006].

Thrusting of the flysch nappes, as well as of the external Betic and Rif fold-thrust belts, ceased in upper Tortonian time, both onshore and offshore [Platt *et al.*, 2003b; Chalouan *et al.*, 2006]. Field evidence from Morocco and from offshore seismic lines demonstrates that the youngest thrust contacts are unconformably covered by upper Tortonian (~8 Ma) and younger sediments [Crespo-Blanc and Juan, 2001; Melialdea *et al.*, 2004; Chalouan *et al.*, 2006; Iribarren *et al.*, 2007]. These relationships suggest that the Gibraltar subduction zone has not accommodated surface convergence since ~8 Ma.

After 8 Ma, the Alboran domain, including its overlying Middle Miocene and older extensional detachments and basins, has been shortened as a result of ongoing Africa-Iberia convergence in a N-S to NW-SE direction, with deformation concentrated along sinistral N-NE trending faults, dextral W-NW trending faults, and reverse WSW-W trending faults [Aldaya *et al.*, 1991; Crespo-Blanc *et al.*, 1994; Lonergan *et al.*, 1994; Lonergan and Platt, 1995; Martínez-Martínez *et al.*, 2002; Booth-Rea *et al.*, 2003; Platt *et al.*, 2005; Meijninger and Vissers, 2006; Marin-Lechado *et al.*, 2007; Benmakhlouf *et al.*, 2013; Martínez-García *et al.*, 2013]. After 8 Ma, the region uplifted [Krijgsman *et al.*, 2006; van der Laan *et al.*, 2006; Hüsing *et al.*, 2010], with as most spectacular effect the eventual disconnection of the waters of the Mediterranean basin from the Atlantic Ocean during the Messinian salinity crisis [Krijgsman *et al.*, 1999].

4. Post 30 Ma Reconstruction of ALKAPECA Dispersion: Testing Algerian Basin Models Against Tomography

The Early-Middle Miocene dispersion and overthrusting of ALKAPECA have been linked (qualitatively) to subduction rollback of the westerly part of the Piemonte-Ligurian Ocean [Alvarez *et al.*, 1974; Boullin *et al.*, 1986;

Lonergan and White, 1997]. Here we provide a new kinematic reconstruction of the western Mediterranean in which pre-rollback convergence, as well as the effects on geological evolution of slab segmentation and lateral separation, are embedded.

The amount of subduction in the western Mediterranean region is the sum of Africa-Iberia convergence and overriding plate extension accommodated in the Liguro-Provençal Basin and the Valencia Basin, the Tyrrhenian Sea, the Algerian Basin, and the Alboran domain. Although broadly similar, existing models differ in the way the Algerian Basin is reconstructed (Figure 2). In one set of models [e.g., Gueguen et al., 1998; Carminati et al., 1998, 2012; Verges and Sabat, 1999; Faccenna et al., 2004; Schettino and Turco, 2006; Jolivet et al., 2009; Rossetti et al., 2013], it is assumed that the Algerian oceanic basin formed as a result of ~N-S extension between ~23 and ~16 Ma, around which time the Kabylides collided with northern Africa [Michard et al., 2006]. Schettino and Turco [2006] showed a map of complex magnetic anomaly patterns of the western Mediterranean region and interpreted only a small selection of anomaly picks in support of a NW-SE opening of the western and central Algerian Basin. N-S opening models of the Algerian Basin assume that a northward dipping subduction zone existed in the early Miocene from the modern Alboran domain to Sardinia-Corsica and rolled back toward the North African and Adriatic margin, resulting in a continuous, northward dipping slab along the entire North African margin [see, e.g., Jolivet et al., 2009]. In these models, westward rollback leading to an east dipping Gibraltar slab was restricted to ~200–250 km of extension accommodated within the Alboran continental domain [Faccenna et al., 2004].

Alternatively, Mauffret et al. [2004], based on geomorphological observations of the Algerian Basin floor and margins, suggested that the Algerian Basin formed as the result of 560 km of E-W extension and oceanic basin formation between 16 and 8 Ma after southward rollback had ceased upon the Kabylides-Africa collision. In this model, southward rollback led to continental extension without oceanization, accommodated in, e.g., the Alboran domain, which restores to the north and northwest of the Kabylides. The continent-ocean transition of the eastern Alboran domain [Booth-Rea et al., 2007] forms then the conjugate margin of the continent-ocean transition SW of Sardinia, and westward motion of the Alboran domain relative to the Balears and North Africa was accommodated along the Emile Baudot and North African transforms, respectively (Figure 1). A right-lateral strike-slip character of the Emile Baudot escarpment (rather than it representing a passive margin as suggested by Verges and Sabat [1999]) was inferred based on its horse-tail geometry [Mauffret et al., 1992; Acosta et al., 2001]. A similar scenario of E-W opening of the Algerian Basin was suggested by Lonergan and White [1997], Gutscher et al. [2002], Rosenbaum et al. [2002a], and Spakman and Wortel [2004], with geochemical magmatic support of Duggen et al. [2003, 2004, 2005].

Finally, Bezada et al. [2013] proposed a model arguing for ~500–600 km of westward rollback but suggesting that the Alboran domain underwent only ~200 km of westward motion, following the shortening reconstruction of Platt et al. [2003b] of the sub-Alboran fold-thrust belts of the sub-Betics and the Rif. They place the Alboran continental domain in a downgoing plate position ~200 km east of its modern position and suggested that following the first 300–400 km of rollback before ~21 Ma, the slab delaminated the Alboran block, leaving only its crust behind and generating the HT-LP metamorphism in the Alboran, followed by limited retreat of the slab after 21 Ma bringing the delaminated Alboran block into its present position.

Seismic tomographic images can help to test the predictions of these scenarios. Seismic tomographic images from the UU-P07 model [Amaru, 2007; van der Meer et al., 2010] (Figure 4) confirm inferences drawn from earlier tomography models [Gutscher et al., 2002; Piromallo and Morelli, 2003; Faccenna et al., 2004; Spakman and Wortel, 2004] in showing that the eastward dipping Gibraltar slab below the Alboran domain reaches the 660 km discontinuity and has a length of ~800 km (Figure 4). A similar number was recently estimated by Bezada et al. [2013]. The UU-P07 model has sufficient spatial resolution below the African margin for detecting subducted lithosphere (Figure S1) and corroborates earlier findings [Spakman and Wortel, 2004] (and resolution estimates therein) that between the Rif and the Kabylides, no continuous north dipping slab exists that is still attached to the African margin. The model of Piromallo and Morelli [2003], however, shows a local positive anomaly in this region. In all tomography models a blurred anomaly of faster *P* wave speeds is found under and north of the eastern Kabylides, hereafter “Kabylides slab,” which was interpreted by Spakman and Wortel [2004] as a local slab fragment under the African margin. Middle Miocene detachment of this slab would be consistent with inferences from geochemistry of plutonic rocks [Maury et al., 2000; Coulon et al., 2002; Benaouali-Mebarek et al., 2006; Michard et al., 2006].

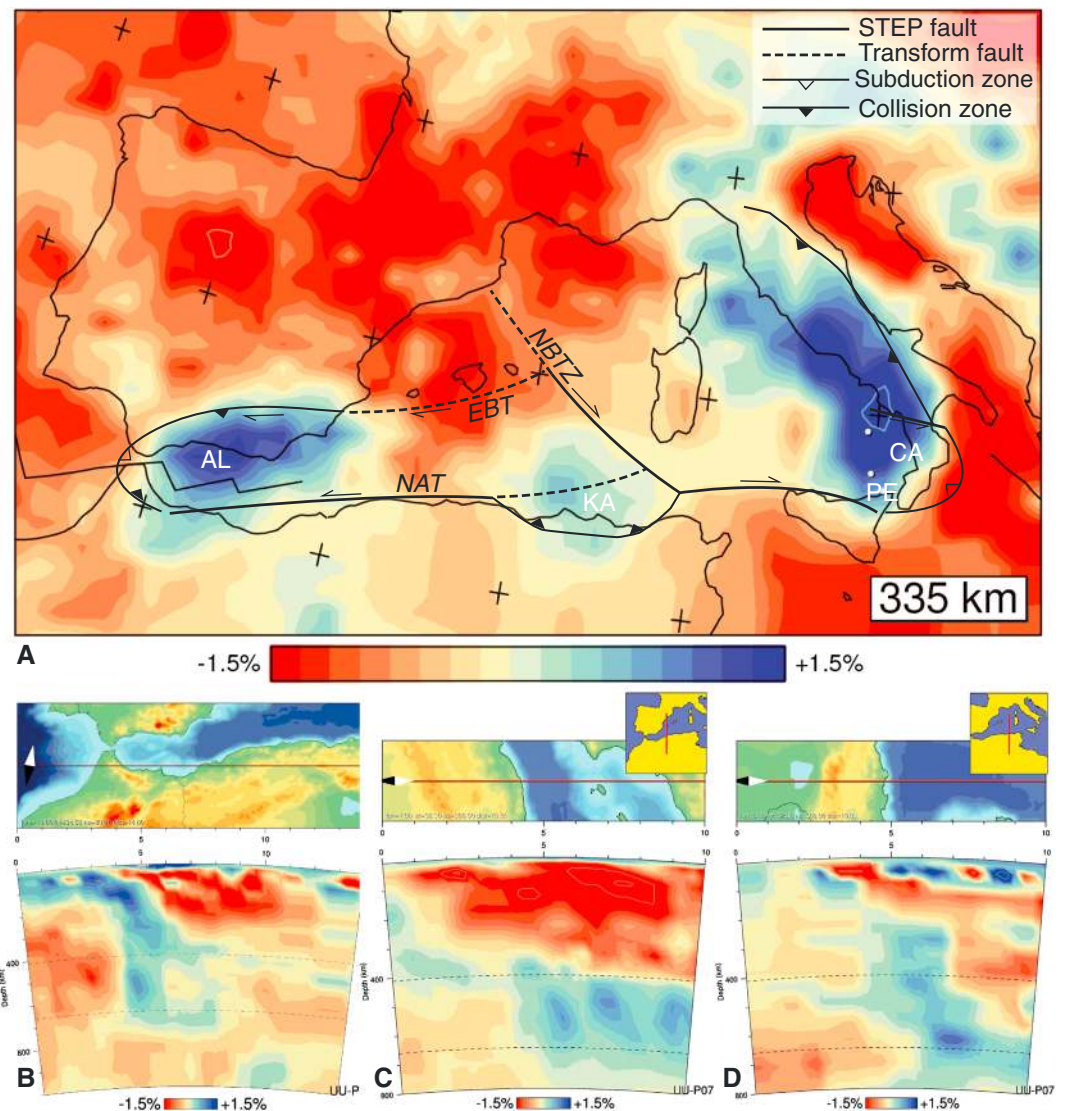


Figure 4. Seismic tomographic images from the UU-P07 model [Amaru, 2007; van der Meer et al., 2010]. (a) Horizontal seismic tomographic section at 335 km depth showing the three slab segments below the Alboran, Kabylides, and Calabria-Apennine regions, disconnected from each other, consistent with an E-W opening scenario of the Algerian Basin (Figure 2b). (b) E-W cross section close to the southern edge of the Gibraltar slab with reaching the 660 km discontinuity, requiring ~700–800 km of subduction and showing absence of slab under the African margin to the east (see Spakman and Wortel [2004] for more sections). (c) Cross section across northern Africa between the Kabylides and the Alboran region, showing no dipping slab. Instead, only horizontal subducted lithosphere overlying the 660 km discontinuity is imaged belonging to the deep portion of the Gibraltar slab [see Spakman and Wortel, 2004]. (d) Cross section across the Kabylides, showing a local northward dipping, presumably detached slab.

There is general agreement that the Calabria and Kabylides slabs are separated as a result of eastward retreat of the Calabrian slab along a subduction transform edge propagator (STEP) fault [Carminati et al., 1998; Faccenna et al., 2004; Rosenbaum and Lister, 2004a, 2004b; Spakman and Wortel, 2004; Govers and Wortel, 2005; Rosenbaum et al., 2008; Jolivet et al., 2009; Wortel et al., 2009]. As noted, the tomographic model of Piromallo and Morelli [2003] also shows an isolated zone of positive wave speed west of the Kabylides anomaly which was used in Faccenna et al. [2004] and Jolivet et al. [2009] to suggest that a largely continuous northward dipping slab was present along the North African margin as far west as the continent-ocean transition between the Alboran domain and the Algerian Basin, where it would be separated by a relatively narrow slab window from the Gibraltar slab. Such a geometry would support a scenario with predominantly N-S extension during southward rollback of a wide slab that extended as far west as the southeastern corner

of modern Iberia. The UU-P07 model (and the BS2000 model used by *Spakman and Wortel* [2004]) does not exhibit any northward dipping slab along the North African margin between the Kabylides and Gibraltar, or between the Kabylides and Calabria (Figure 4). In spite of the low density of seismic stations along the North African margin, tomographic tests with synthetic velocity anomalies suggest sufficient resolution for detecting slab remnants under the African margin (supporting information) [*Spakman and Wortel*, 2004; *Bezada et al.*, 2013]. Consequently, *Spakman and Wortel* [2004] proposed their E-W extension model for the Algerian Basin forced by westward retreat of the Gibraltar slab. There is general agreement that positive seismic anomalies in the transition zone result from a flat lying slab that draped on the 660 km discontinuity as a result of rollback.

The E-W extension model for the Algerian Basin would predict a length of the Gibraltar slab of >750 km (>100 km of extension in the Alboran domain (Table 1 and Figure 3), ~560 km of E-W extension in the Algerian Basin, ~90 km of pre-rollback subduction), which is consistent with the ~800 km imaged by seismic tomography. This slab would in this scenario have shared a pre-16 Ma rollback history with the Kabylides slab, after which it decoupled following collision of the Kabylides with Africa and rolled back westward along a STEP fault along the North African margin [*Spakman and Wortel*, 2004]. Rather than producing a northward dipping slab segment, the Piemonte-Ligurian lithosphere would have decoupled from the African margin along a vertical fault and sank into the mantle, consistent with the image arising from seismic tomography and similar to the eastern section between the Kabylides and Calabria [see also *Spakman and Wortel*, 2004]. *Faccenna et al.* [2001a, 2004] explored the consequences of a N-S opening of the Algerian Basin and assumed 220 km of E-W extension in the Alboran domain, resulting in a total amount of subduction of the Gibraltar slab of only ~400 km since ~35 Ma. Because tomographic images suggest an ~800 km long slab below Gibraltar, these authors noted that their reconstruction would suggest an ~400 km long slab at the onset of subduction rollback around 35 Ma, two to four times the total amount of Africa-Iberia convergence since the Cretaceous (whichever published plate circuit one chooses, e.g., *Savostin et al.* [1986], *Dewey et al.* [1989], *Rosenbaum et al.* [2002b], or ours based on *Müller et al.* [1999] and *Vissers and Meijer* [2012b] (Figure 3)). They suggested that the discrepancy might be explained by, e.g., stretching of the slab after its subduction (by a factor 2 or more). The maximum rollback scenario modeled by us in this paper, assuming E-W opening model of the Algerian Basin with a transform fault between the Kabylides and the Alboran along the North African margin, is consistent with the imaged slab length and does not require slab stretching.

The models of *Bezada et al.* [2013] and of *Spakman and Wortel* [2004] both explain the ~800 km length of the slab in a fashion that is consistent with the Africa-Iberia plate convergence history. In addition, the model of *Bezada et al.* [2013] obeys the shortening reconstruction of the sub-Betic and Rif fold-thrust belts, whereas the scenario of *Spakman and Wortel* [2004] implies that this shortening record significantly underestimates the total amount of subduction of the Gibraltar slab. The model of *Bezada et al.* [2013], however, treats the continental crust of the Alboran domain as a single lithospheric block before the Miocene that underwent mantle lithosphere delamination when it arrived in a Miocene, westward retreating subduction zone, whereby its crust was left behind at the surface, became extended, and metamorphosed at HT. This, however, is not consistent with the fact that the Alboran domain shows a thin-skinned fold-thrust belt that underwent HP-LT metamorphism, probably in Eo-Oligocene time, before the inception of the HT event. As noted, this HP-LT metamorphism and associated thrusting is best explained as the result of burial, and perhaps to some extent exhumation, in a subduction channel [e.g., *Avigad et al.*, 1997; *Jolivet et al.*, 2003]. Obviously, prior to their thrusting and burial, the thin-skinned thrust pile of the Alboran and Kabylides rocks must have been underlain by a lower crust and mantle lithosphere. To make an Eo-Oligocene thin-skinned nappe stack of upper crustal slices, however, these original lower crustal and mantle underpinnings must have been removed already during this time. These underpinnings in Miocene time were hence already forming (parts of) the subducted slab [*van Hinsbergen et al.*, 2005]. As a result, the lithosphere that shielded the Alboran domain from the asthenosphere prior to inception of HT metamorphism was the slab itself. In addition, the model of *Bezada et al.* [2013] cannot explain the similar HT history of the Kabylides.

We consider it therefore more likely that the post-Burdigalian (21–16 Ma) shortening that is recorded in and restored from the sub-Betic and Rif fold-thrust belts [*Platt et al.*, 2003a] significantly underestimates the amount of subduction since the early Miocene. The discrepancy between shortening and convergence may either be explained by assuming a younger inception of shortening (~15–13 Ma instead of 21–16 Ma) or by inferring wholesale underthrusting of part of the Iberian margin without leaving a shortening record. The

latter option may for instance have occurred because of the absence of a sedimentary cover and surfacing of the basal décollement ("naked basement subduction," a phenomenon not uncommon in analogue experiments of continental subduction [Willingshofer and Sokoutis, 2009]). We note that adjacent to the Miocene Betic fold-thrust belt, Variscan basement is exposed at the surface and no sedimentary cover is present. In any case, extension is not capable of removing a rock record from the surface, whereas compression buries rocks, enhances erosion, and is thus more likely to leave incomplete records. We therefore restore the opening of the Algerian Basin assuming E-W extension between 16 and 8 Ma, following Rosenbaum *et al.* [2002a], Mauffret *et al.* [2004], and Spakman and Wortel [2004], bringing the Alboran units adjacent to and north of the Kabylides in the Early Miocene. To explain the discrepancy between shortening and convergence in the sub-Betic fold-thrust belt, we assume naked basement subduction and reconstruct a ~20 Ma initiation of shortening in the sub-Betic fold-thrust belt and underthrusting of the Nevado-Filabride complex. Restoring the Tyrrhenian Sea opening (following Rosenbaum and Lister [2004a], Cifelli *et al.* [2007], and Rosenbaum *et al.* [2008]) brings the Peloritani-Calabrian units adjacent to Sardinia (Figure 5). Reconstructing the opposite Miocene rotations of Sardinia/Corsica [Speranza *et al.*, 2002; Gattacceca *et al.*, 2007] and the Balears [Pares *et al.*, 1992] and the Oligo-Miocene opening of the Liguro-Provençal Basin and the Valencia Basin [Séranne, 1999] (see Table 1) aligns ALKAPECA as a single belt along the Sardinia-Balearic margin. Schettino and Turco [2006] and Turco *et al.* [2012] suggested an Oligocene reconstruction in which the Corsica-Sardinia block is fragmented into four blocks along strike-slip faults with several tens of kilometers of displacement. Because the well-exposed islands of Corsica and Sardinia do not provide field evidence for such major strike-slip zones, we treat these islands as part of a single rigid block, as commonly portrayed [e.g., Lonergan and White, 2007; Séranne, 1999; Rosenbaum *et al.*, 2002; Faccenna *et al.*, 2004; Gattacceca *et al.*, 2007; Jolivet *et al.*, 2009]. The opposite rotations between the Corsica-Sardinia block and the Balears realm were accommodated by the North Balearic Transform Zone (NBTZ) [Séranne, 1999] (Figure 1), to the southeast occurring in tandem with trench-parallel extension, documented in the Kabylides [Saadallah and Kaby, 1996] and Calabria [Heymes *et al.*, 2008, 2010], associated with the increase in subduction zone length during radial rollback.

The different rotations, both in time and rotation angle, of the Balears and Sardinia imply Oligocene bifurcation in the west Piemonte-Ligurian Ocean subduction system along the NBTZ creating slab edges [Spakman and Wortel, 2004], and (STEP) faults [Govers and Wortel, 2005]. Following Kabylides-Africa collision around 16 Ma, the Gibraltar segment of the slab, which had rotated into a N-S orientation, rolled back westward. The extended Balearic subduction margin developed into the Emile Baudot transform and the northern African margin was formed by the North African transform, which separated the Alboran block from the Kabylides and transported it to the west (Figure 1c). We note that the Emile Baudot transform ceases to exist as a STEP fault in south-southeastern Iberia, where instead seismic tomography suggests that the slab is detached and has attained a southward dip [Spakman and Wortel, 2004; Bezada *et al.*, 2013]. Geological restorations of the fold-thrust belt underlying the "ALKAPECA" units of the Alboran in southern Spain suggest that this lithosphere formed the continental margin of Iberia and was highly obliquely subducted below the Alboran [Platt *et al.*, 2003b; Behr and Platt, 2012]. This evolution explains the apparent paradox that the Balearic islands were in an Eo-Oligocene overriding plate position above a subduction zone, whereas southern Iberia that belongs to the same plate and that has a very similar (sub-Betic) stratigraphy as the Balears [Díaz de Neira and Gil-Gil, 2013] was in a downgoing plate position to that same subduction zone only 10 Ma later. Effectively, the subduction trench rotated by more than ~90° for the Gibraltar slab segment, now striking N-S, and ~180° for the segment below Iberia which is currently in an ENE-WSW orientation [Spakman and Wortel, 2004; Bezada *et al.*, 2013]. Similar rotations were documented paleomagnetically from the Malaguide units of the Betic Cordillera [Platzman *et al.*, 2000], here reconstructed as the fore-arc above the Balearic subduction zone before the inception of rollback. In the east, the Peloritani-Calabrian slab segment rolled back eastward from Tunisia toward Sicily opening the Tyrrhenian Sea Basin (Figure 1 and Table 1). The rotational evolution of the slab that culminated in a maximum rollback rate in the south of ~8 cm/yr, along the transform parallel to the North African margin, subducting lithosphere of which the geological record preserved in the Gibraltar flyschbelt [Durand-Delga *et al.*, 2000] as well as plate kinematic reconstructions [Visser *et al.*, 2013], suggests a nature. This setting, as well as the reconstructed rollback rates, are similar for the Calabrian subduction zone [e.g., Cifelli *et al.*, 2007]. To the north, where Early to Middle Miocene HP metamorphism affected continental rocks of the Iberian margin [e.g., Behr and Platt, 2012], our reconstruction suggests rollback rates decreasing to ~1 cm/yr, for the NE Betic Cordillera, the differential

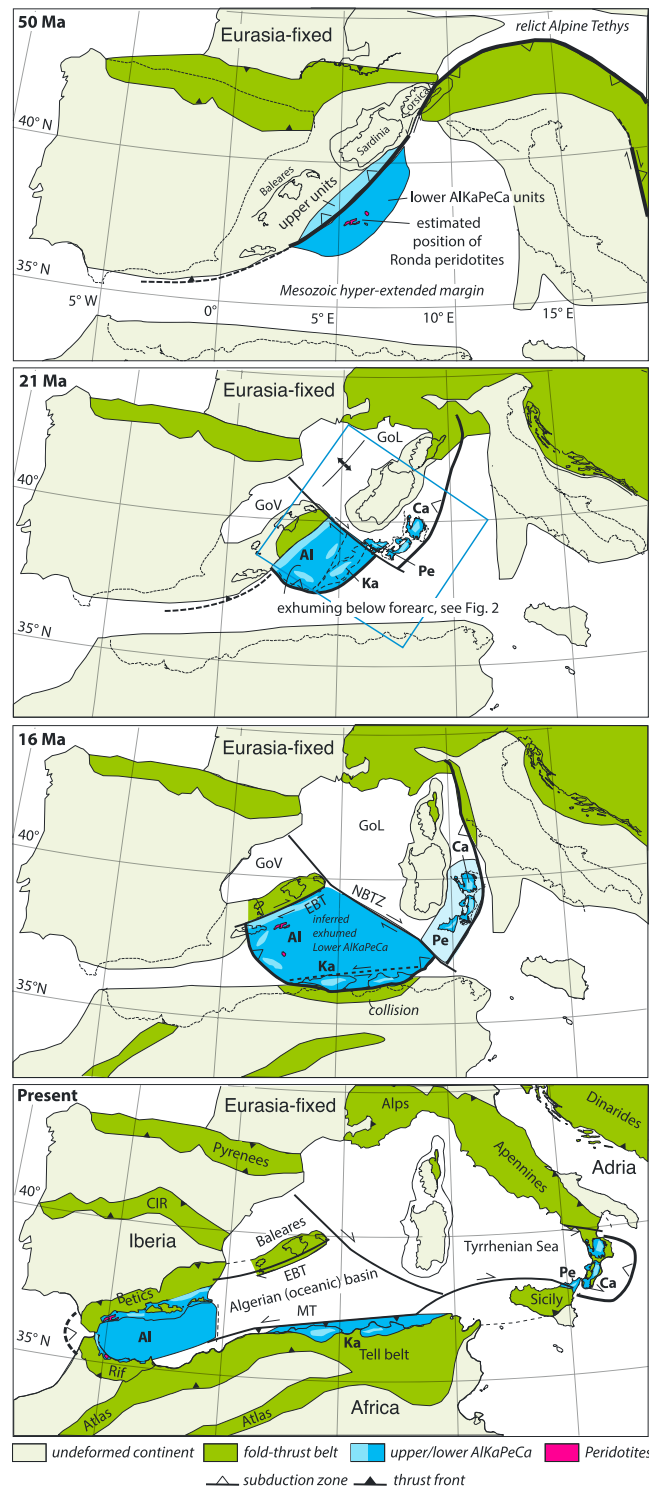


Figure 5. Reconstructed positions of ALKAPECA since 50 Ma. See Table 1 for kinematic constraints and the supporting information for a reconstruction movie. AI = Alboran; Ca = Calabria; CIR = Central Iberian Ranges; EBD = Emile Baudot Transform; GoL = Gulf of Lyon; GoV = Gulf of Valencia; Ka = Kabylides; NAT = North African Transform; NBTZ = North Balearic Transform Zone; Pe = Peloritani Mountains.

rollback rates leading to major counterclockwise rotations documented paleomagnetically [e.g., Platzman *et al.*, 2000]. Similarly, rapid rollback rates in the Calabria decreased northward, leading to major counterclockwise rotations in the southern Apennines [e.g., Cifelli *et al.*, 2008; Maffione *et al.*, 2013].

Recently, Vergés and Fernández [2012] postulated a subduction and rollback scenario that agrees on a major westward component of rollback, but in which they argue that subduction was southward below North Africa. In this scenario, the Alboran domain would represent a fore-arc remnant originally attached to the North African margin. They do not incorporate the more easterly parts of the western Mediterranean region, but their model necessitates a transform zone between this southward dipping subduction zone and a northward dipping subduction zone below the Balears where the Kabylides must have formed the fore arc. This is an interesting hypothesis, as it is possible within the plate circuit, and may also be consistent with seismic tomographic constraints of the Rif-Gibraltar-Betic domain. Our kinematic scenario, in which all ALKAPECA units stem from a single, northwestward dipping subduction zone below the Balears, provides a simpler solution and may find support in the apparent contiguity of tectonostratigraphies of the ALKAPECA units, including the Dorsale Calcaire and overlying fore-arc basin units, from the Alboran to the Kabylides and the Calabrian segment. This is to some extent a matter of choice, however, and we do not see a fundamental objection against the model of Vergés and Fernández [2012]. We would, however, expect to detect more subducted slab below the entire Kabylides range as a result of the proposed southeastward rollback of the Balears segment of the subduction system.

After the Kabylides collided with North Africa, and the Gibraltar slab started to roll back westward, the subduction zone could no longer accommodate N(W)-S(E) Africa-Europe convergence. This was accommodated in North Africa first by folding and thrusting of the Tell belt [Benaouali-Mebarek *et al.*, 2006] and subsequently by reactivation of the North African Transform as a top-to-the-north thrust that may form an incipient subduction zone of the Algerian Basin below northern Africa [Deverchere *et al.*, 2005; Stich *et al.*, 2006; Baes *et al.*, 2011; Billi *et al.*, 2011]. The Alboran domain, while undergoing E-W extension, became folded due to N-S to NW-SE shortening, folding, e.g., the extensional detachments [Aldaya *et al.*, 1991; Lonergan *et al.*, 1994; Lonergan and Platt, 1995], and compressional deformation in the Betic Cordillera as a result of Africa-Iberia convergence continues today as expressed by the transpressional Lorca earthquake of 11 May 2011 [Vissers and Meijninger, 2011].

5. ALKAPECA Dispersion and Metamorphic Evolution: Localizing the Heat Pulse

We now assess how the high-temperature metamorphism that overprinted HP-LT metamorphic rocks in the Alboran and Kabylides domains can be straightforwardly explained within the context of our reconstruction, as a critical test of its validity. Platt and Vissers [1989] were the first to discuss the problem of generating high-temperature metamorphism associated with extension and exhumation in a context of plate convergence and on a lithospheric scale in the western Mediterranean region. They suggested that the Alboran region experienced Paleogene thickening of the lithosphere in essentially a pure shear fashion, followed by convective removal of the thickened mantle lithosphere. This would lead to ascent of asthenosphere and consequent heating and rise of gravitational potential energy of the thickened crust, resulting in extensional collapse of the orogen. In this scenario, the peridotites of AL represent relics of that mantle lithosphere, and their emplacement into the crust is causally related to the high-temperature overprint.

In the decades that followed, different elements of their hypothesis met opposition. The location of crustal thickening of the Alboran region was shown to have been at least hundreds of kilometers east of its modern position [Platt *et al.*, 2003b; Mauffret *et al.*, 2004; Behr and Platt, 2012] (Figure 5). Recognition of HT metamorphism (as well as peridotites) in the Kabylides [Michard *et al.*, 2006] requires an explanation not restricted to the Alboran region. Finally, as noted before, the structural and HP-LT metamorphic history of the lower ALKAPECA units preceding the HT overprint is typical for subduction channel wedges and the presubduction lithospheric mantle and lower crustal underpinnings have subducted and are not preserved below the wedge [Avigad *et al.*, 1997; Jolivet *et al.*, 2003; Booth-Rea *et al.*, 2005]; there may be no thickened mantle lithosphere present below a HP wedge to convectively remove or delaminate. Finally, also volcanic records throughout the Oligo-Miocene of the western Mediterranean region support a continuous subduction history [Duggen *et al.*, 2004].

Thus, the explanation of the HT metamorphic overprint in the Alboran and Kabylides rocks needs to be placed within a context of subduction. A critical constraint that maintains is the inference that this metamorphism is best explained by asthenospheric temperatures at depths as shallow as 60 km [Platt *et al.*, 1998]. This constraint requires that in Late Oligocene–Early Miocene time, a slab that brought the metasedimentary rocks of the lower Kabylides, Sebtide, and Alpujarride units to a depth of ~50 km had to be removed and replaced by asthenosphere below at least part of the fore-arc, whereby our kinematic and tomographic reconstruction precludes widespread slab break-off in the western Mediterranean at this time. First, however, we will discuss the evolution of the Alboran and Kabylides peridotites to assess whether or not their tectonic emplacement into the crust needs to have occurred in Cenozoic time.

5.1. Cenozoic or Mesozoic Emplacement of the Ronda Peridotite?

Since Platt and Vissers [1989] suggested a causal relationship between the tectonic emplacement of the Ronda peridotite into the crustal metasediments of the Alpujarride unit, and the high-temperature metamorphism that affected both, alternative models that placed the HT overprint in a subduction context also attempted to accommodate the emplacement of subcontinental mantle lithosphere in the crust within a subduction context [e.g., Davies *et al.*, 1993; van der Wal and Vissers,

1996; Booth-Rea *et al.*, 2005; Mazzoli and Martin Algarra, 2011; Hidas *et al.*, 2013]. Michard *et al.* [2002], however, suggested that the exhumation of the Ronda and Beni Boussera peridotites into the crust occurred as a phase of hyperextension during the Jurassic opening of the Piemonte-Ligurian Ocean. Independent evidence for Jurassic exhumation of subcontinental mantle in the western Piemonte-Ligurian Ocean comes from the Beni Malek massif, where Upper Jurassic marine sediments rework and unconformably overlie serpentinized peridotites [Michard *et al.*, 1992]. Additionally, ~180 Ma MORB-type metagabbros intruded into Alpujarride sediments and 180–130 Ma pyroxenite dikes intruded the Ronda peridotite suggesting rapid mantle decompression in the Jurassic along the North African and Iberian margins [Sanchez-Rodriguez and Gebauer, 2000; Tubía *et al.*, 2009].

In our view, the key constraints come from the pressures at which the Ronda peridotite and the directly overlying metasediments of the Alpujarride unit were subjected at the onset of HT metamorphism (with peak pressures of 16 and 15 kbar, respectively [Argles *et al.*, 1999; Lenoir *et al.*, 2001]). These pressures suggest that the Ronda peridotite resided below, but close to the Alpujarride unit during peak HT metamorphism, at a depth of ~50–55 km. It is important to realize that bringing the subcontinental mantle peridotites of Ronda in direct contact with the Alpujarride metasediments requires removal of intervening continental lower-middle crust, prior to the inception of HT metamorphism. It is conceivable that crustal attenuation already started prior to the inception of HT metamorphism, during which time exhumation of the Ronda peridotite may have occurred from ~24 to 16 kbar [Garrido *et al.*, 2011], cutting out a crustal section of ~20 km. The Ronda peridotite is overlain by upper crustal (metasedimentary) rocks that were thickened to at least 50 km; if that shortening also involved the lower crust, a lower crustal thickness well exceeding 20 km would have resulted. From this we infer that a large part, if not all lower crust that once separated the Ronda subcontinental mantle peridotites from the Alpujarride sediments must have been excised prior to the onset of the Miocene attenuation. Shortening and convergence, which led to the burial and HP-LT metamorphism of the Alpujarride, Sebtide, and lower Kabylides rocks, can only thicken and duplicate crust but cannot excise material. Only extension can, and the extension that cut out this lower crust must have therefore occurred prior to their Eocene subduction. A scenario in which the Ronda peridotite was derived from the mantle wedge above the subducting plate is unlikely: Such wedges are normally serpentinite mélanges hydrated from the downgoing plate [e.g., García-Casco *et al.*, 2002], are cool, and are hence unlikely to emplace coherent, hot bodies of subcontinental mantle lithosphere as thrust slices into a HP wedge above a downgoing slab.

Pre-Eocene extension in the SW Mediterranean region may have occurred at multiple stages after the Variscan orogeny, but the most likely timing for exhumation of subcontinental mantle from below the Iberian (Balearic) margin is during the Jurassic breakup of Pangea and the opening of the Piemonte-Ligurian Ocean. Aside from evidence for Jurassic mantle exhumation in the Rif, exhumed subcontinental mantle is still present offshore western Iberia [e.g., Alves *et al.*, 2009] and has been reconstructed in the Pyrenees [Lagabrielle and Bodinier, 2008] and in the Alps [Mohn *et al.*, 2012]. We thus agree with suggestions of Michard *et al.* [2002] and interpret that lower crust excision and initial exhumation of peridotites of the Alboran and Kabylides domain to shallow lithospheric levels probably occurred during Jurassic extension associated with the opening of the Piemonte-Ligurian Ocean in a hyperextended margin setting (Figure 6a). The lower ALKAPECA units most likely represent Jurassic extension allochthons overlying mantle peridotites that exhumed from below SE Iberia along a Jurassic low-angle detachment. Eo-Oligocene Africa-Iberia convergence led to deep underthrusting of the lower ALKAPECA extension allochthons and associated underlying peridotites below the SE Iberian margin (Figure 6b). Recently, Jammes and Huismans [2012] carried out numerical modeling experiments of continental crust that first undergoes extension followed by inversion and subsequent subduction. Their results demonstrated that, particularly when starting with a strong crust, mantle lithosphere can exhume to close to the surface, overlain by a thin, highly extended upper crust with excision of the lower crust. Upon subsequent inversion, their models show incorporation of exhumed subcontinental mantle and remaining upper crust levels into the fold-thrust belt. We envisage a similar history for the ALKAPECA units and associated peridotite bodies. The upper ALKAPECA units, with their Hercynian basement and at best weak Alpine metamorphism, and with the Dorsale Calcaire cover of the (southern part of) the lower ALKAPECA units currently thrust below them, most likely represent the more distal hanging wall of this Mesozoic detachment, as well as of the Cenozoic subduction zone on the Iberian side (Figure 6).

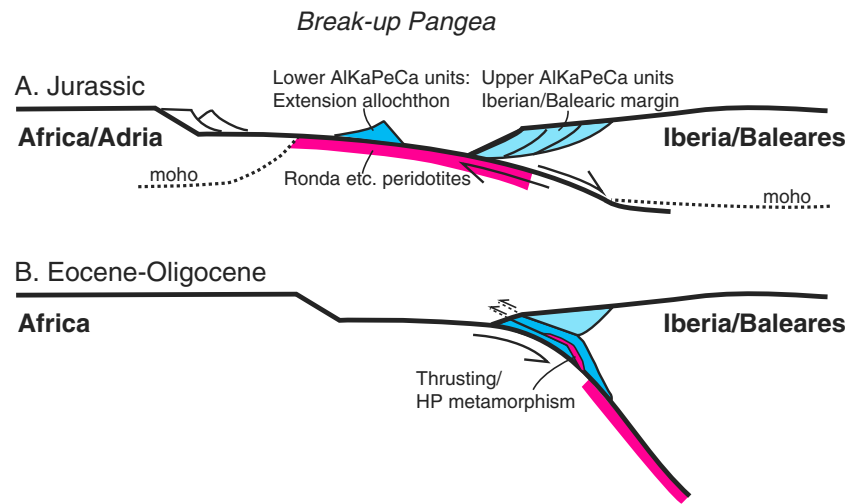


Figure 6. Scenario proposed here for the exhumation history of the Alboran and Kabyldes peridotites. The similar peak pressure conditions for the Ronda peridotite and its immediately overlying metasedimentary cover require excision of the crust once intervening sediments and peridotites prior to subduction. It is here proposed that (a) the peridotites exhumed in a hyperextended margin upon Triassic-Jurassic breakup of Pangea, with the lower ALKAPECA units of the Alboran and Kabyldes as extension allochthons directly overlying exhumed peridotites followed by (b) subduction and thrusting of both units in Paleogene times. See text for further explanation.

5.2. HT Metamorphism Due To Slab Segmentation and Slab Window Generation

Kinematic reconstructions of the western Mediterranean subduction history agree on the segmentation of an originally northwest dipping slab and the generation of slab edges along which different segments roll back at different rates (Figure 5). Following a middle Eocene inception of significant Iberia-Africa convergence, subduction segmentation started during the Oligocene activation of the NBTZ, which accommodated the SE rollback of the northern Corsica-Sardinia slab segment [e.g., *Séranne*, 1999; *Faccenna et al.*, 2004; *Rosenbaum and Lister*, 2004b]. The NBTZ propagated southeastward as a STEP fault segmenting the west Alpine-Tethyan slab. Carried by the retreating slab, the PE and CA fragments suffered only moderate NE-SW trench-parallel stretching without a major thermal overprint [*Heymes et al.*, 2008] with trench-normal extension accommodated in the Liguro-Provençal Basin [*Séranne*, 1999] (Figure 1).

Early Miocene passage of the Sardinia slab edge just NE of the Balears equally created a slab edge to the Balearic lithosphere leading to additional mechanical freedom for the short Balearic slab, still dipping NW, to go into radially growing rollback along the Balearic margin in SW direction and toward the North African margin in S-SE direction (Figure 7) [see also *Faccenna et al.*, 2005]. This is reflected in major contemporaneous trench-parallel (~E-W) extensional exhumation of the lower unit between 25 and ~16 Ma of the Kabyldes and the Alboran [*Visser et al.*, 1995; *Michard et al.*, 2006]. During this time, rollback rotated the Early Miocene Balears slab into an ~N-S orientation, moving away from the Sardinia-Corsica slab bounded by the NBTZ to the northeast (Figure 7). Because the width of the Balears slab decreases downward, radial rollback, particularly when combined with the divergence of rollback direction on either side of the NBTZ, would open a slab window below the extending fore-arc to the west of the NBTZ. The presence of such a slab window, in combination with the need for flow of asthenosphere around the Balearic and Sardinia slab edges to accommodate rollback, filled this slab window with asthenospheric mantle. The fore arc above this slab window consisted of accreted sediments (and relict exhumed subcontinental mantle emplaced against those sediments in Mesozoic time, see above) that decoupled from the subducting slab. Thrusting of these sediments created a thick crust, in particular in the subduction channel immediately above the slab, but this thick crust was no longer underlain by a lithospheric mantle: That lithosphere subducted and formed the slab. Within the slab window, asthenosphere was hence able to ascend to the base of the accretionary prism and could reach the depths of ~60 km that were modeled by *Platt et al.* [1998] to be required to explain the Early Miocene thermal pulse below the Alboran and the Kabyldes (Figure 7). As rollback matured and the subducted surface increased, asthenospheric ascent continued and contributed to the accretion of the oceanic Algerian back-arc basin while the Alboran domain was carried westward to its present location.

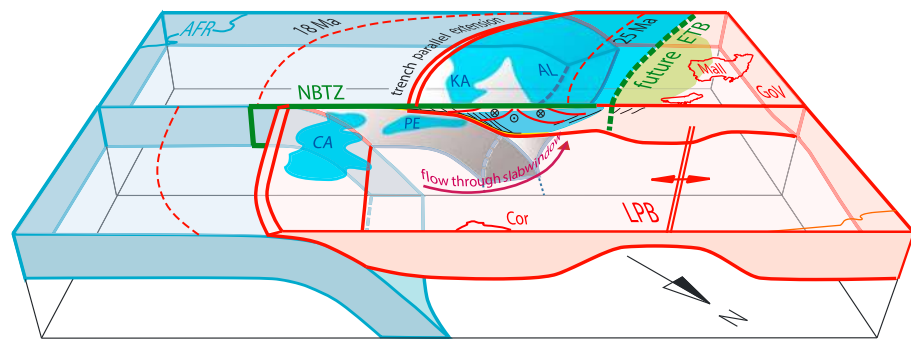


Figure 7. Cartoon showing STEP and slab window geometry along the NBTZ at 21 Ma. AFR = Africa, COR = Corsica. Other abbreviations as in Figure 1. Sardinia omitted for clarity. The future EBT cuts through the original fore arc, separating the upper (and lower) ALKAPECA unit from the Balearic block.

A similar scenario of asthenospheric flow through a slab window to explain Early Miocene granitic magmatism and metamorphism in the Alboran domain was invoked by *Rossetti et al.* [2013]; they assumed a N-S opening of the Algerian Basin, however, and consequently suggested that this slab edge was located much farther to the west, at the present-day longitude of the eastern margin of the Rif domain.

Our reconstruction, whereby the Alboran and Kabyliides rocks are located close to the NBTZ STEP fault in Late Oligocene and Early Miocene time, thus provides a straightforward explanation for the anomalously high temperatures in a narrow segment of the fore-arc. It also explains the synmetamorphic E-W extension documented in the Alboran and Kabyliides domain, which relates to the rapid increase in curvature during the early stages of rollback. This may validate our restoration further.

6. Implications for the Origin of Western Mediterranean Rollback

Our reconstruction suggests that slab rollback in the western Mediterranean started along a subduction zone that extended from Corsica to the Balears (Figure 5). Although contractional deformation accommodating Africa-Iberia convergence must have extended farther to the west (max 50 km of shortening in the Gibraltar region before ~30 Ma), the amount of convergence was apparently insufficient to create a slab that was able to roll back.

In the Balears domain, the maximum slab length around 30 Ma was ~150 km, which includes all convergence that occurred after 85 Ma constrained by the plate circuit. The maximum slab length that could have been generated at 30 Ma since the 45 Ma onset of continuous Africa-Eurasia convergence was on the order of 90 km at the intersection of the NBTZ with the trench, decreasing westward. As detailed before, the length of the slab at the inception of rollback below Sardinia may have been considerably longer, ~250 km long, although the exact length depends on the amount of Africa-Europe convergence that was accommodated to the north of the Sardinia-Corsica block in the Provence, which remains to be analyzed in detail. In any case, the amount of subduction below Sardinia was most likely larger than below the Balears, whereby the NBTZ acted as a plate boundary between Iberia and Sardinia. This slab-length contrast, decoupled at depth by the NBTZ, implies a trench-trench-transform triple junction located at the junction of the NBTZ with the trench, which moved slowly northwestward offsetting the trench along the NBTZ (Figure 8). This trench offset initiated a STEP fault that separated the Calabrian and Kabyliides slab segments. We speculate that the segmentation of the Kabyliides and Gibraltar slab, following the collision of the Kabyliides with Africa, may also have utilized a preexisting structure (e.g., a fracture or inactive transform fault) in the Piemonte-Ligurian lithosphere.

Jolivet and Faccenna [2000] argued that the onset of rollback in the western Mediterranean region could have resulted from a decrease in absolute northward motion rates of Africa resulting from the Arabia-Eurasia collision, using the then available fixed hot spot mantle reference frame [*Müller et al.*, 1993]. The latest global moving hot spot reference frame of *Dobrovine et al.* [2012], however, included error bars and shows that although an ~30 Ma decrease in African motion relative to the mantle as suggested by *Jolivet and Faccenna* [2000] is possible, it is within the reconstruction uncertainty. In addition, current kinematic constraints from the Arabia-Eurasia collision do not permit a collision age older than ~27 Ma and suggest that no correlation exists between that collision and Mediterranean rollback [*McQuarrie and van Hinsbergen*, 2013].

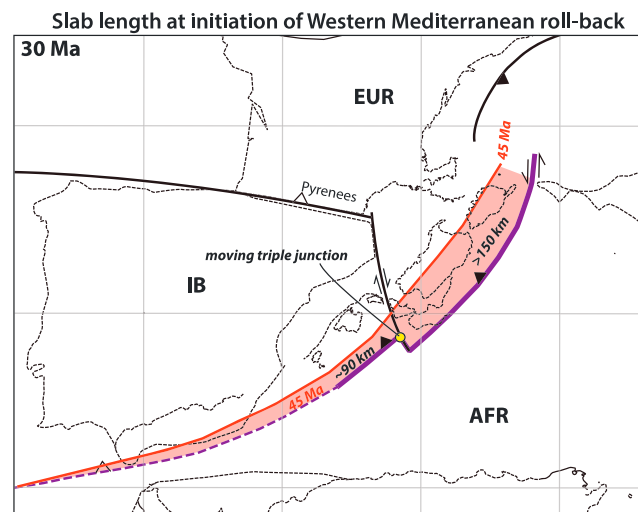


Figure 8. Slab length at the inception of western Mediterranean rollback, calculated based on the post-45 Ma Africa-Iberia convergence (see Figure 3). Slab length below the Sardinia-Corsica was more than the 150 km of post-45 Ma convergence, but the total amount of subduction below Sardinia depends on the amount of shortening accommodated north of Sardinia and Corsica, which remains to be reconstructed in future research. The presumably larger shortening in the Pyrenees than north of Sardinia would lead to a trench-trench-transform triple junction along the NBTZ, which may have provided the fundament for the STEP separating the Kabylides from the Sardinia segment.

Our reconstruction concurs with the conclusions of *Faccenna et al.* [2001a, 2001b] in that the inception of western Mediterranean rollback relates to the evolution of the slab length along the Iberian-Balearic margin until the mid-Oligocene. Numerical models of subduction initiation along a transform fault (which given the Cretaceous reconstruction of Africa-Iberia convergence (Figure 3) seems a likely scenario for the western Mediterranean region) suggest that initiation of subduction rollback requires only a small amount of ~100–150 km forced subduction, after which the negative buoyancy of the subducted slab tip leads to initially strong slab sinking initiating rollback (Figure 9) [Becker et al., 1999; Hall et al., 2003; Gurnis et al., 2004; Gerya, 2011; Leng and Gurnis, 2011; Chertova et al., 2012]. Similar results were obtained in laboratory studies, where a relatively short period of forced convergence was followed by the inception of slab pull, and

consequent rollback [Becker et al., 1999; Faccenna et al., 1999, 2001a]. Particularly, Leng and Gurnis [2011] emphasize the phase of slab sinking creating strong influx of asthenosphere above the foundering slab. Our reconstruction of central Balearic slab length at the onset of rollback in the western Mediterranean region concurs with the initial model geometry of a short slab in these numerical experiments. The higher rate of convergence below Sardinia prior to rollback may explain why inception of rollback in the Italian-Calabrian segment and the related extension in the Liguro-Provençal Basin preceded the onset of rollback in the Balearic segment and related extension in the Gulf of Valencia by several millions of years [Séranne, 1999]. We thus conclude that a small slab created by 90–150 km Africa-Iberia convergence prior to ~30 Ma was sufficient for the inception of large-scale rollback in the western Mediterranean region, without requiring further external plate tectonic forcing. This scenario may be a natural consequence of subduction initiation within a land-locked basin setting such as the Cenozoic Carpathian-Mediterranean region [Le Pichon, 1982; Wortel and Spakman, 2000].

7. Conclusions and Outlook

In this paper, we aimed to assess the origin of the western Mediterranean subduction, slab rollback, and associated slab dispersion and reconcile this with the geological evolution. The rollback history led to the dispersion of a pre-Oligocene fore arc of which relics are now found as the Alboran (southern Spain and Morocco), Kabylides (Algeria), Peloritani (Sicily), and Calabria (southern Italy) domains (known as the ALKAPECA terrane) and the opening of highly extended, partly oceanic Mediterranean back-arc basins. To this end, we reviewed and restored the dispersion of ALKAPECA and test previously hypothesized kinematic scenarios against remnants of subducted lithosphere imaged by seismic tomography of the western Mediterranean mantle.

We conclude that modern plate kinematic constraints imply that the dimension of in particular the Gibraltar slab necessitates a maximum rollback scenario for the Gibraltar slab, with an E-W opening of the Algerian Basin, which suggests a subduction zone geometry at the onset of rollback in the Oligocene (~30 Ma) that only occupied a narrow segment from the Balearic islands to Sardinia and beyond. We assess the age of subduction initiation by placing our reconstruction in the Europe-Iberia-North America-Africa plate circuit, which shows that Iberia and the Balearic Islands underwent a translational motion relative to Africa until

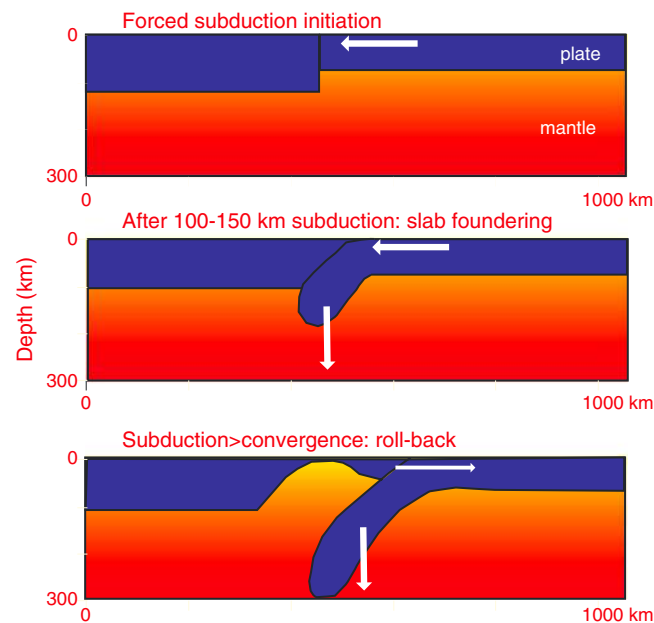


Figure 9. Schematic model for the origin of rollback in the western Mediterranean, modified from *Leng and Gurnis [2011]*. Following the first 100–150 km of forced subduction in the western Mediterranean, initiated along a transform fault that stems from the differential rotation rates of Iberia and Africa relative to Eurasia (see Figure 3), inception of slab pull leads to a subduction rate exceeding plate convergence rates, causing rollback. Slab buoyancy causes subduction through rollback to dominate over subduction resulting from plate convergence. This scenario may be typical for land-locked basins such as the Mediterranean region.

~85 Ma, followed by slow Africa-Iberia convergence. Up to ~150 km of convergence occurred below the Balearic islands before the inception of rollback ~30 Ma, of which 90 km occurred between 45 and 30 Ma.

Forced by Africa-Iberia convergence, slow subduction initiation occurred along the transform fault zone that accommodated pre-85 Ma translation. By the time of inception of rollback, ~30 Ma, a slab of no more than 150 km had formed at the position of the Balearic islands. Toward Gibraltar, the amount of convergence was only several tens of kilometer and insufficient to generate a subduction zone by negative buoyancy alone. Subduction rates below Sardinia/Calabria were slightly higher than below the Balearics, the difference being accommodated in the Pyrenees, and subduction rollback commenced a few (~3) million years earlier. A resulting moving triple junction at the trench-NBTZ intersection, decoupling Balearic rollback from Sardinia rollback, was accommodated by vertical

lithosphere tearing forming two slab segments. The Calabrian segment rolled back to the east. The Balearics slab radially rolled back, initially forming an amphitheater shape, followed after collision of the Kabylides with North Africa by segmentation of the Balearics slab into a western segment that rolled back toward Gibraltar along two STEP faults along the Balearic and African margins. Directly to the east, the Kabylides slab detached from the African margin and sank into the underlying mantle.

The early differential rollback between the Balearic and the Sardinia-Calabrian slab, in combination with initial radial rollback of the Balearics slab, opened a slab window along the NBTZ in which asthenosphere rose to the base of the fore-arc. This led to high-temperature metamorphism of the Alboran and Kabylides fore-arc rocks in latest Oligocene-Early Miocene time. Based on the metamorphic and structural history of the Alboran and Kabylides rocks, we conclude that subcontinental mantle peridotites that are found there (e.g., the Ronda and Beni Bousera peridotites) must have been exhumed to shallow lithospheric levels cutting out (a large part of) the lower crust prior to Eocene HP-LT metamorphism, most likely during Jurassic extension of the Piemonte-Ligurian Ocean.

The inception of rollback occurred when the subducted Balearics slab was not more than 150 km long. Numerical models of subduction initiation along a transform fault suggest that rollback started with initial rapid vertical slab sinking occurring after only ~100–150 km of forced subduction. We suggest that this mechanism applies to western Mediterranean subduction. Although subduction initiation occurred at low rates between Late Cretaceous and Early Eocene time as the result of slow Africa-Iberia convergence, the onset of rollback may have occurred at high rates, as a natural consequence of subduction initiation within a land-locked basin setting.

Finally, from the discussions in this paper and many other, it is clear that even after several decades of detailed geological and geophysical work, the debate on the tectonic evolution of the western Mediterranean region is still far from over. In particular, the discussion on the opening age and direction of the Algerian Basin may be forwarded by more detailed work on the magnetic anomalies in the Algerian Basin floor, in addition to

the first interpretations of Schettino and Turco [2006]. We foresee that three-dimensional numerical modeling of subduction evolution may be a new way forward to test which of the proposed scenarios for the subduction evolution result in the mantle structure below the western Mediterranean region as imaged by seismic tomography [Chertova et al., 2013].

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