TECTONICS, VOL. 25, TC3008, doi:10.1029/2005TC001885, 2006

Oppositely directed pairs of propagating rifts in back-arc basins: Double saloon door seafloor spreading during subduction rollback

A. K. Martin[1]

Received 7 July 2005; revised 7 February 2006; accepted 20 February 2006; published 24 May 2006.

[1] When a continent breaks up into two plates, which then separate from each other about a rotation pole, it can be shown that if initial movement is taken up by lithospheric extension, asthenospheric breakthrough and oceanic accretion propagate toward the pole of rotation. Such a propagating rift model is then applied to an embryonic centrally located rift which evolves into two rifts propagating in opposite directions. The resultant rhombic shape of the modeled basin, initially underlain entirely by thinned continental crust, is very similar to the Oligocene to Burdigalian back-arc evolution of the Valencia Trough and the Liguro-Provencal Basin in the western Mediterranean. Existing well and seismic stratigraphic data confirm that a rift did initiate in the Gulf of Lion and propagated southwest into the Valencia Trough. Similarly, seismic refraction, gravity, and heat flow data demonstrate that maximum extension within the Valencia Trough/Liguro-Provencal Basin occurred in an axial position close to the North Balearic Fracture Zone. The same model of oppositely propagating rifts, when applied to the Burdigalian/Langhian episode of back-arc oceanic accretion within the Liguro-Provencal and Algerian basins, predicts a number of features which are borne out by existing geological and geophysical, particularly magnetic data. These include the orientation of subparallel magnetic anomalies, presumed to be seafloor spreading isochrons, in both basins; concave-to-the-west fracture zones southwest of the North Balearic Fracture Zone, and concave-to-the-east fracture zones to its northeast; a spherical triangular area of NW oriented seafloor spreading isochrons southwest of Sardinia; the greater NW extension of the central (youngest?) magnetic anomaly within this triangular area, in agreement with the model-predicted northwestward propagation of a rift in this zone; successively more central (younger) magnetic anomalies abutting thinned continental crust nearer to the pole of rotation in the Liguro-Provencal Basin. The latter feature demonstrates that a rift also propagated northeast in the Liguro-Provencal Basin, at least in its oceanic accretion phase of development. An adaptation of an existing model for subduction slab detachment occurring along the North African margin in the late Burdigalian/Langhian, proposes propagation in opposite directions of the slab tear. The resultant rhombic slab detachment is closely associated in space and time with the rhombic form of the Algerian/Liguro-Provencal basins, suggesting a cause and effect relationship. **Citation:** Martin, A. K. (2006), Oppositely directed pairs of propagating rifts in back-arc basins: Double saloon door seafloor spreading during subduction rollback, *Tectonics*, *25*, TC3008, doi:10.1029/2005TC001885.

1. Introduction

[2] General consensus has been reached [*Dercourt et al.*, 1986; *Malinverno and Ryan*, 1986; *Dewey et al.*, 1989; *Ricou*, 1995; *Doglioni et al.*, 1997; *Lonergan and White*, 1997; *Gueguen et al.*, 1998; *Roca et al.*, 1999; *Séranne*, 1999; *Faccenna et al.*, 2001; *Roca*, 2002; *Rosenbaum et al.*, 2002; *Faccenna et al.*, 2004; *Mascle et al.*, 2004; *Rosenbaum and Lister*, 2004a] regarding plate tectonic reconstructions of the western Mediterranean (Figure 1). Rifting initiated in the mid-Oligocene at a central locus in the Gulf of Lion (Figure 2a) is followed by continued lithospheric extension of the Valencia Trough and the Liguro-Provencal Basin in the late Oligocene to the early Burdigalian (Figure 2b), whereas oceanic crust is emplaced in the Algerian and Liguro-Provencal basins in the Burdigalian/Langhian (Figure 2c). Opening of the Liguro-Provencal and Algerian basins halts when the Kabylie terranes dock with the Algerian and Tunisian margins, while the Corsica/Sardinia Block collides at its northern end with northern Italy, and at its southern end with the Galite Block and the Tunisian Platform. Extension then shifts to the northern Tyrrhenian Basin, east of Corsica and Sardinia in the upper Miocene, and finally to the southeastern Tyrrhenian Basin in the Pliocene and Quaternary (Figure 2d).

[3] Consensus does not exist regarding the mechanism for the apparent simultaneous extension in basins and compression in Mediterranean fold belts. Slab roll back [*Malinverno and White*, 1986; *Frizon de Lamotte et al.*, 1991; *Royden*, 1993; *Lonergan and White*, 1997; *Doglioni et al.*, 1997; *Gueguen et al.*, 1998; *Rosenbaum et al.*, 2002; *Faccenna et al.*, 2001, 2004] has been favored on the basis of comparison with Pacific back-arc basins, and the spatial and time relationships of extension to mainly calc-alkaline volcanism. Convective removal [*Platt and Vissers*, 1989] or delamination [*Seber et al.*, 1996; *Calvert et al.*, 2000] of the lithospheric root of a collisional ridge was proposed on the

---

[1] Repsol YPF, Madrid, Spain.

0278-7407/06/2005TC001885

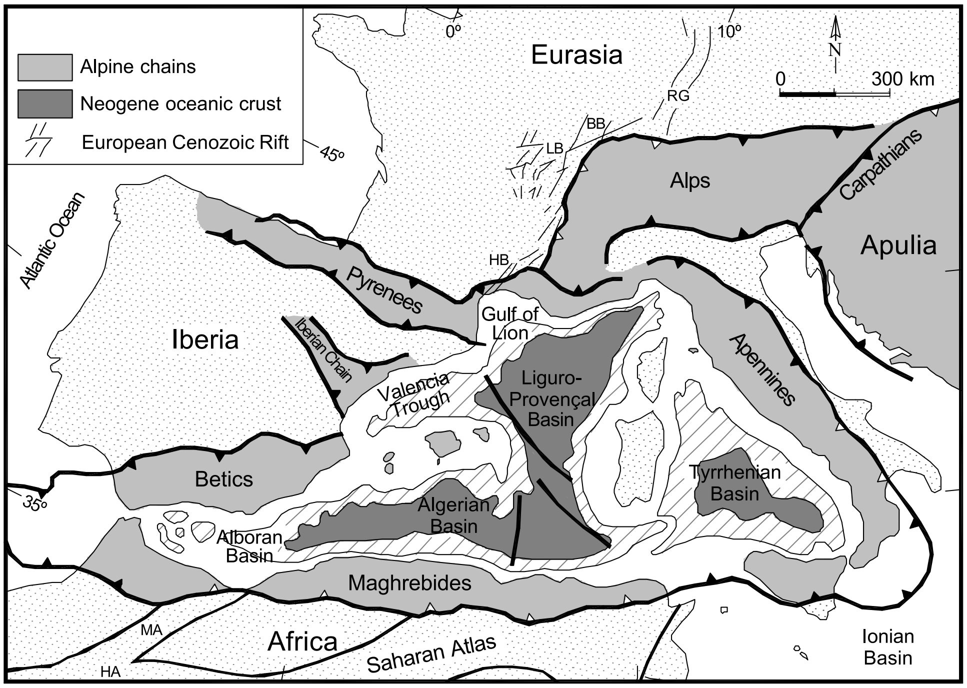

Figure 1. Simplified tectonic map of the western Mediterranean [after *Malinverno and Ryan*, 1986; *Lonergan and White*, 1997; *Roca et al.*, 1999; *Rosenbaum et al.*, 2002]. The rhombic shapes of the combined Valencia Trough/Liguro-Provencal Basin and the Algerian/Liguro-Provencal basins are outlined by the 3 and 5 ms two-way-time to basement contours from *Rehault et al.* [1984], *Rollet et al.* [2002], and *Maillard et al.* [2003]. Black barbed lines are main thrust fronts of the Betic Rif Arc, the Alps, Apennines, and Calabrian Arc. White barbed lines are areas where slab detachment has been postulated in the Alps, the Carpathians, the southern Apennines, and along the Maghrebides of northern Africa, extending to the Betics [*Patacca and Scandone*, 1989; *Carminati et al.*, 1998; *Chalot-Prat and Girbacea*, 2000; *Wortel and Spakman*, 2000]. The European Cenozoic Rift System [after *Nehlig et al.*, 2003] is shown extending over 1000 km northeast from the Gulf of Lion, via the Herault Basin (HB), Limagne Basin (LB), Bresse Basin (BB), and the Rhine Graben (RG). Note also Middle Atlas (MA), High Atlas (HA), and Saharan Atlas Mountains of North Africa.

basis of perceived near radial extension and coeval compression in the Betic Rif Arc. *Gelabert et al.* [2002] propose that arcuate fold belts and back-arc basins result from the opening of megacontinental tension gashes along preexisting faults due to compression between Africa and Eurasia. Alternatively, seismic tomography of the upper mantle velocity structure revealing apparent detachment of subducted slabs [*Blanco and Spakman*, 1993] has led to the association of detachment to rifting and extension [*Carminati et al.*, 1998; *Chalot-Prat and Girbacea*, 2000] or to cessation of extension in the detached area, with concentration of subduction rollback and extension in the area where the slab is still attached [*Wortel and Spakman*, 2000].

[4] In the subduction rollback model, the southeastward displacement of the locus of rifting and extension from the Gulf of Lion/Valencia Trough, to the Liguro-Provencal/Algerian Basin, to the northern Tyrrhenian Basin, whence to the southeast Tyrrhenian Basin is emphasized [*Malinverno and Ryan*, 1986; *Doglioni et al.*, 1997; *Gueguen et al.*, 1998; *Rosenbaum et al.*, 2002; *Sartori*, 2003; *Rosenbaum and Lister*, 2004a, 2004b]. A smaller southwestward rollback to the Betic Rif Arc is also envisaged [*Frizon de Lamotte et al.*, 1991; *Royden*, 1993; *Lonergan and White*, 1997; *Rosenbaum et al.*, 2002].

[5] In this paper, I propose that within each of the first two of these rifting episodes in the Valencia Trough/Liguro-Provencal Basin (Figures 2a and 2b) and then in the Liguro-Provencal/Algerian basins (Figure 2c), a rift initiated at a central point, and then propagated in opposite directions to the northeast and southwest. The geometry of a number of features of the western Mediterranean predicted by this simple model, appear to be borne out by existing data. These include the distribution of basin extension, the rhombic form of basins, and the orientation of magnetic anomalies.

[6] The geometry of this style of oppositely directed pairs of rifts in back-arc basins creates pairs of terranes which simultaneously rotate clockwise and anticlockwise and then accrete to nearby continents. This geometry is analogous to double saloon doors swinging open when an individual enters a bar, as in a classic “western” cowboy movie.

[7] The analogy is more than a simple metaphor to help visualize the situation. The geometry of this model has implications for the locus and relative strength of forces

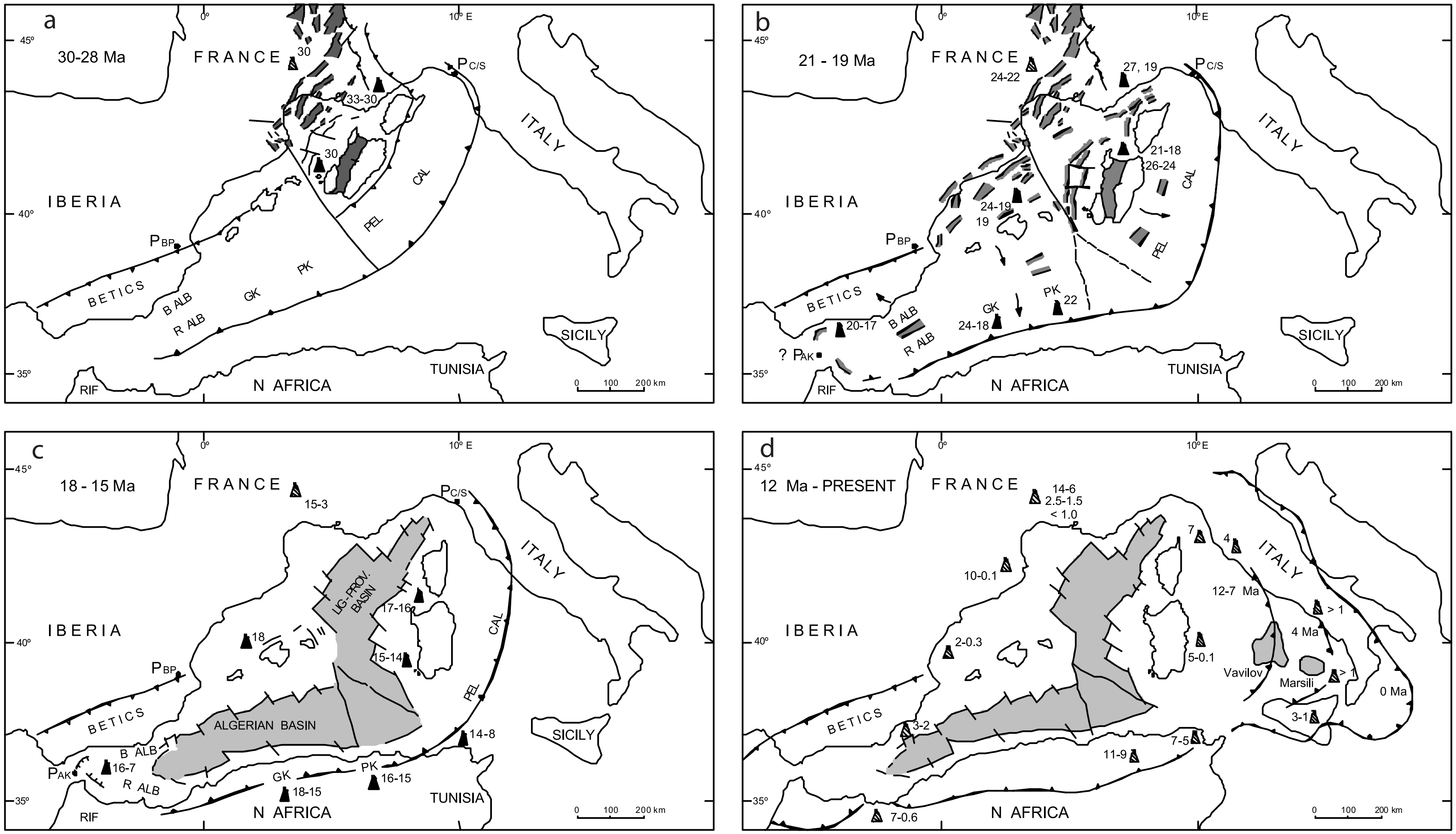
a
30-28 Ma
FRANCE
IBERIA
ITALY
SICILY
TUNISIA
N AFRICA
RIF
BETICS
B ALB
R ALB
GK
PK
PEL
CAL
P_{BP}
$P_{C/S}$
30
33-30
30
45°
40°
35°
0°
10° E
0 100 200 km
b
21 - 19 Ma
FRANCE
IBERIA
ITALY
SICILY
TUNISIA
N AFRICA
RIF
BETICS
B ALB
R ALB
GK
PK
PEL
CAL
P_{BP}
$P_{C/S}$
? P_{AK}
24-22
27, 19
21-18
26-24
24-19
19
20-17
24-18
22
45°
40°
35°
0°
10° E
0 100 200 km
c
18 - 15 Ma
FRANCE
IBERIA
ITALY
SICILY
TUNISIA
N AFRICA
RIF
BETICS
B ALB
R ALB
GK
PK
PEL
CAL
LIG.-PROV. BASIN
ALGERIAN BASIN
P_{BP}
$P_{C/S}$
P_{AK}
15-3
17-16
18
15-14
14-8
16-7
18-15
16-15
45°
40°
35°
0°
10° E
0 100 200 km
d
12 Ma - PRESENT
FRANCE
IBERIA
ITALY
N AFRICA
BETICS
14-6
2.5-1.5
< 1.0
10-0.1
2-0.3
3-2
7-0.6
11-9
7-5
5-0.1
7
4
12-7 Ma
> 1
4 Ma
Vavilov
Marsili
> 1
0 Ma
3-1
45°
40°
35°
0°
10° E
0 100 200 km

Figure 2

required to create the rotations envisaged, and thereby has ramifications for the underlying driving mechanism.

[8] Finally, an adaptation of existing slab detachment models [*Wortel and Spakman*, 2000; *Spakman and Wortel*, 2004] is proposed where slab tears propagate in opposite directions. It is shown that this is compatible with existing plate tectonic reconstructions [*Lonergan and White*, 1997; *Carminati et al.*, 1998; *Rosenbaum et al.*, 2002] and with the distribution of bimodal volcanism in the Maghrebides, and the Betic Rif and Calabrian Arcs [*Marti et al.*, 1992; *Lonergan and White*, 1997; *Maury et al.*, 2000; *Coulon et al.*, 2002; *Savelli*, 2002; *Duggen et al.*, 2004; *Rosenbaum and Lister*, 2004b; *Peccerillo and Lustrino*, 2005]. The relationship in time, space, and geometry between the resultant rhombic slab detachment and the rhombic basins produced by oppositely propagating rifts and double saloon door seafloor spreading is discussed in terms of their underlying geodynamic causes.

2. Propagating Rift Model

[9] Consider a continent about to break into two plates (Figure 3a) with rotation, following Euler's theorem, about a pole. As movement occurs (Figure 3b), point b at the southern end of the split has moved farther from b′ than point a has from a′. Let x, which equals the separation between c and c′, equal the critical separation distance where asthenosphere breaks through to the surface (Figure 3b). Therefore between a and c, separation of the two plates is accommodated by lithosphere extension, whereas between c and b, oceanic accretion occurs. As separation between the two plates increases (Figure 3c) the critical separation distance x moves north and oceanic accretion gradually extends northward toward the rotation pole. Thus propagating rifts are a natural consequence of motion about a rotation pole. Seafloor spreading isochrons abut the continent ocean boundary which is not an isochron. Note that crustal extension is equal along the length of the continental margin in this case, whereas variable extension was also modeled [*Martin*, 1984]. Moreover, the rift is assumed to proceed smoothly whereas propagation in the Woodlark Basin [*Benes et al.*, 1994; *Taylor et al.*, 1999] is interrupted for relatively short periods, while in the Gulf of Aden and Laptev Sea transitions from rifting to seafloor spreading, propagation is punctuated by lengthy periods when the rift stalls [*Manighetti et al.*, 1997; *Franke et al.*, 2001].

3. Pairs of Oppositely Propagating Rifts

[10] Taking this simple model, and applying it to a case where a rift initiates and then propagates in opposite directions from the incipient rifting point, leads to the model in Figure 4. In the original model, *Martin* [1984] recognized a rift propagating northward in the Early Cretaceous opening of the South Atlantic. Later, a southerly propagating rift was also recognized farther north in the South Atlantic [*Martin*, 1987], whereas pairs of oppositely propagating rifts have also been recognized in the Pacific [*Johnson et al.*, 1983].

[11] Consider four plates, West 1, West 2, East 1, and East 2, about to rift apart, with plates West 1 and West 2 about to open about rotation pole P_1, and plates East 1 and

Figure 2. (a) Reconstruction of the western Mediterranean at 30–28 Ma, with rifted basins (dark shading) initiating in the Gulf of Lion [after *Bouillin et al.*, 1986; *Maerten and Séranne*, 1995; *Gueguen et al.*, 1998; *Roca et al.*, 1999; *Séranne*, 1999; *Roca*, 2002; *Rosenbaum et al.*, 2002; *Nehlig et al.*, 2003]. The Balearic Peninsula, with the Minorca Promontory, is tightly closed against the Spanish Continental Margin by a 15° anticlockwise rotation about a pole at 39°N, 1°W (P_{BP}), whereas the Corsica/Sardinia Block is closed against the Ligurian Margin by a 40° clockwise rotation about a pole at 44°N, 10°W ($P_{C/S}$). Line with dark triangles represents the reconstructed subduction zone. Line with light triangles is the Betic and Alpine front. Dates of calc-alkaline volcanics (black volcano motif) and alkali volcanics (crosshatched) are taken from Figure 6 and the references therein, as well as those in Figures 2b, 2c and 2d. B Alb and R Alb, Betic and Rif parts of the Alboran Terrane; GK, Grand Kabylie; PK, Petite Kabylie; PEL, Peloritan; CAL, Calabria. (b) Reconstruction at 21–19 Ma, taking into account the model of Figures 4 and 5. The Alboran Terrane is shown southwest of the Kabylies terranes. The Balearic Peninsula is rotated clockwise 15° to its present-day position, and for symmetry, the Corsica/Sardinia Block is also rotated by 15° anticlockwise to its early Burdigalian position [*Ferrandini et al.*, 2003]. Rifts have propagated southwest into the Valencia Trough and northeast into the Liguro-Provencal Basin, but extensive accretion of oceanic crust has not yet occurred. Rifting south of the Balearic Peninsula in the Kabylies and Calabrian terranes, schematically shown as evidenced by the Oligocene-Miocene fill of the Kabylies, Peloritan and Calabria [*Bouillin et al.*, 1999a, 1999b; *Mascle et al.*, 2001, 2004]. The main phase of N-S oriented extension in the Betic and Rif areas of the Alboran Terrane, and the Alboran Basin occurred 22–18 Ma [*Comas et al.*, 1999; *Martínez-Martínez and Azañón*, 2002]. (c) Reconstruction at 18–15 Ma once the oceanic crust of the Algerian/Liguro-Provencal basins has been emplaced and the Grand and Petite Kabylies terranes have docked with North Africa. The geometry of oceanic crust in the Algerian Basin, along with rifts in the Alboran Terrane, suggests that the pole of rotation (P_{AK}) for the Rif part of the Alboran Terrane and the Kabylies Block relative to the Betic part of the Alboran Terrane should be located near the Straits of Gibraltar. Distribution and ages of volcanics are after references in Figures 2a and 6, as well as *Lonergan and White* [1997], *Maury et al.* [2000], *Coulon et al.* [2002], and *Duggen et al.* [2004]. (d) Reconstructions of the eastward and southeastward migration of the subduction zone from Sardinia to Calabria from 12 Ma to present. Late Miocene to recent alkaline volcanism is also shown, whereas the position of the subduction zone is based on compilations of calc-alkaline volcanism (after references in Figures 2a and 6, as well as *Savelli* [2001], *Sartori* [2003], *Rosenbaum and Lister* [2004b], and *Peccerillo and Lustrino* [2005]).

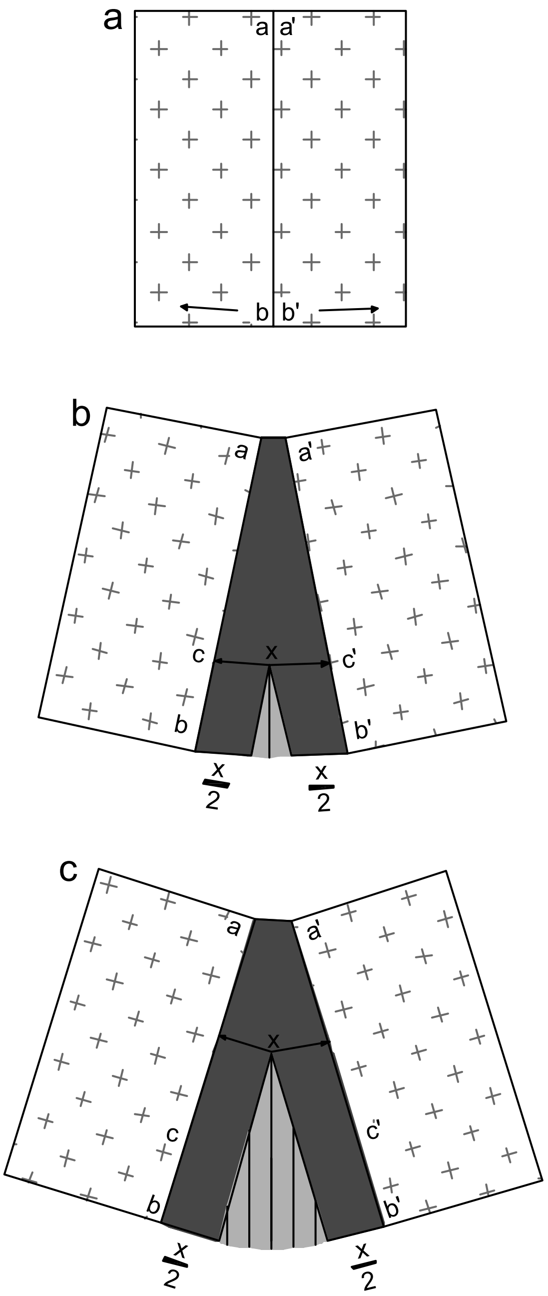

Figure 3. Propagating rift as a result of a continent splitting into two plates with rotation about a pole to the north of the continents. Initial movement is taken up by lithospheric extension, whereas asthenosphere breakthrough (oceanic accretion) occurs south of *x* [after *Martin*, 1984]. Crosses indicate continental crust; dark shaded area indicates thinned continental crust; light shaded area indicates oceanic crust within which thick vertical lines indicate seafloor spreading isochrons. Figures 3a, 3b, and 3c are further explained in section 2.

East 2 on the point of rotating about pole P_2. Rifting occurs between points a and b on plates West 1 and West 2 and between points d and e on plates East 1 and East 2, whereas between points b and g, and e and h, initial movement causes shearing (Figure 4a). The shearing motion between bg, and eh, produces a type of transform margin, but the situation is atypical because both plates West 1 and East 1 initially move to the north. However, if there is any difference in the relative rotation velocity of West 1 with respect to West 2, compared to that between plates East 1 and East 2, then a more normal transform boundary would be created. For example, if East 1 moves more rapidly relative to West 1, then the initial relative motion between bg and eh is sinistral. Should West 1 then move more rapidly and catch up with East 1, then relative motion between bg and eh is dextral.

[12] As in the previous model (Figure 3), along the rifted margins, initial movement is taken up by lithospheric extension between a and c (on West 1 and West 2), and between d and f, (on East 1 and East 2). Note therefore that in Figure 4b, extension is greater between c and c′ than it is between a and a′. A rhomb-shaped basin gradually opens, initially completely underlain by extended continental crust. When rotation of the plates reaches the situation shown in Figure 4b, extension occurring between c and b (on West 1 and West 2) and between e and f (on East 1 and East 2), is accommodated by asthenosphere breakthrough and oceanic accretion. As rifting proceeds, with greater rotation of the respective plates (Figures 4c and 4d), younger seafloor spreading anomalies extend farther west between West 1 and West 2, and farther east between plates East 1 and East 2. Younger seafloor spreading anomalies progressively abut stretched continental lithosphere closer to the rotation poles. Rotation of plate West 2 relative to West 1 is clockwise, whereas rotation of plate East 2 relative to East 1 is counterclockwise. Note also that in agreement with clockwise rotation of West 2, the curvilinear fracture zone between b and b′ is concave toward the west, whereas its equivalent between e and e′ is concave to the east, in concert with the counterclockwise rotation of plate East 2 relative to plate East 1 (Figure 4d).

[13] One of the consequences of this type of rotation of pairs of plates about rotation poles is that a north south oriented space opens between plates West 1 and East 1, and between West 2 and East 2 (Figure 4b). Between the northernmost plates West 1 and East 1, the space is narrow to the south between b and e and opens out in a triangle or fan shape to the north between g and h, whereas between the southernmost plates West 2 and East 2, the apex of the triangle is to the north between b′ and e′, and the fan shape opens up to the south between i and j.

[14] These triangular-shaped areas lie next to the fracture zones between b and b′, and e and e′ (e.g., Figure 4d). As pointed out earlier, initial movement causes shear between bg and eh (Figure 4a). With further rotation, the conjugate margins between g and h and i and j probably become rifted, particularly between their northern and southern extremes (between g and h, and i and j, respectively). Stretching of continental lithosphere off sheared continental margins is less than that off rifted continental margins (e.g., compare the Agulhas Fracture Zone sheared margin south of South Africa with the rifted South Atlantic margin off the west coast of South Africa [*Austin and Uchupi*, 1982; *Ben-*

Avraham et al., 1997]. The extent of thinned continental crust may therefore increase from b to g and from e to h (and similarly between b′ and i and between e′ and j). Assuming that the initial shear movement creates sheared margins from b to g, e to h, b′ to i and from e′ to j, narrower areas of stretched crust are shown along these margins (Figures 4c and 4d). For the sake of simplicity, the extent of thinned continental crust along these sheared margins has been considered equal along their length.

[15] Basinward of these sheared margins between plates West 1 and East 1, oceanic accretion occurs and propagates southward (compare Figures 4c and 4d), whereas between plates West 2 and East 2, the tip of oceanic crustal accretion propagates northward.

3.1. Pairs of Oppositely Propagating Rifts, With the Northerly Plates Stationary

[16] In the case of the Oligocene western Mediterranean (Figure 1), the northerly plate, West 1, would be represented by onshore Spain to the southwest of the North Balearic Fracture Zone, while plate East 1 would be represented by the Gulf of Lion and the Provencal and Ligurian coasts of France and Italy northeast of the North Balearic Fracture Zone. The Catalan coast of Spain and the Ligurian coast of Italy are oriented generally SW–NE, whereas the Gulf of Lion forms a reentrant. These plates appear not to have rotated to the northwest as depicted in Figure 4 but have stayed relatively stable. The rotations which result from two oppositely propagating rifts have therefore been modeled with the two northerly plates stationary (Figure 5).

[17] With two rifts propagating to the west and the east, the situation is very similar with regard to the rifted margins between West 1 and West 2, as well as East 1 and East 2. However, because line abed remains straight, the overall shape of the basin is triangular rather than rhombic (compare Figures 4b, 4c, and 4d with Figures 5a and 5b). Only one fan-shaped or triangular area occurs between the east side of plate West 2, and the west side of East 2 (Figures 5a and 5b). This triangle has curved sides and is therefore a spherical or Euler triangle. Oceanic crust is broadest between i and j, and narrows to an apex just south of points b and e. Oceanic accretion within this triangular area propagates northward. Between points b and b′, and points e and e′, the configuration is akin to a leaky transform fault, with increased leakage to the south.

[18] Assuming symmetrical seafloor spreading, the total rotation of West 2 relative to West 1 (angle b P_1 b^1), is bisected by the median seafloor spreading isochron lk and its extension toward P_1. In Figure 5a, line lk and its eastward extension makes a north facing obtuse angle with

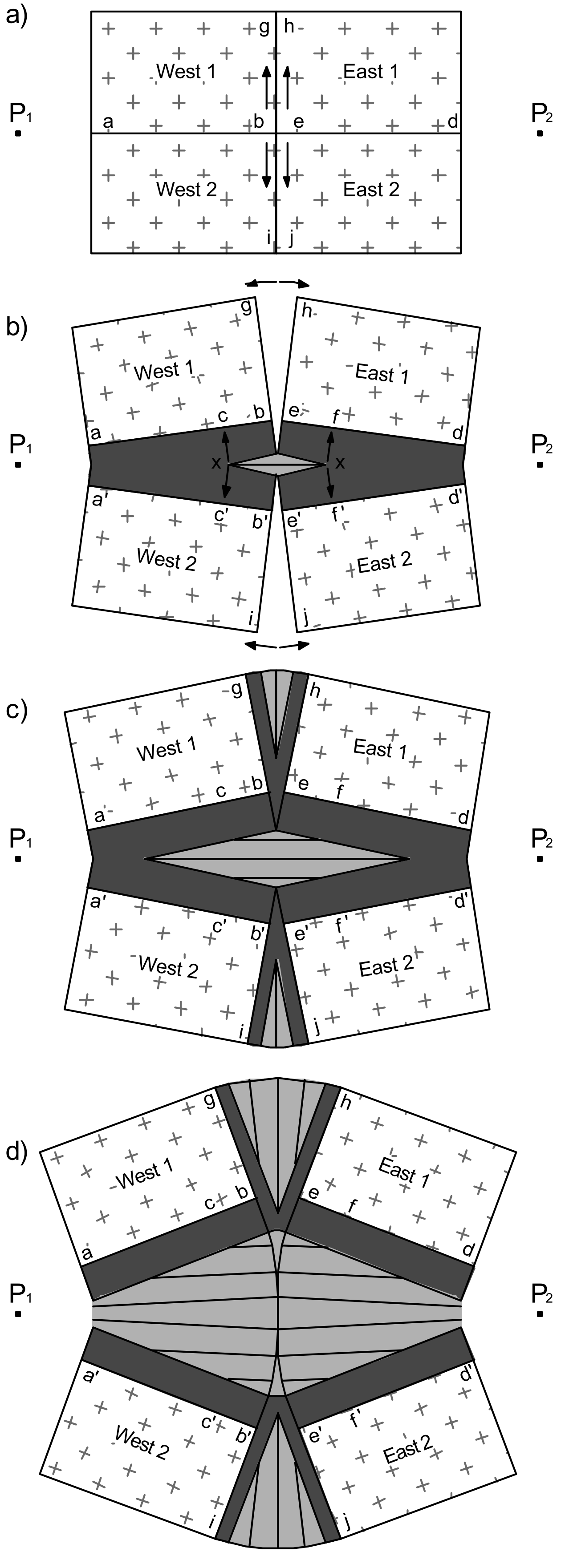

Figure 4. Taking the propagating model of Figure 3 and applying it to an initial centrally located rift which subsequently propagates in opposite directions. Legend is as in Figure 3. Plate West 2 rotates clockwise from plate West 1 about pole P1, while plate East 2 rotates anticlockwise from plate East 1 about pole P2. Figures 4a, 4b, 4c, and 4d are further discussed in section 3.

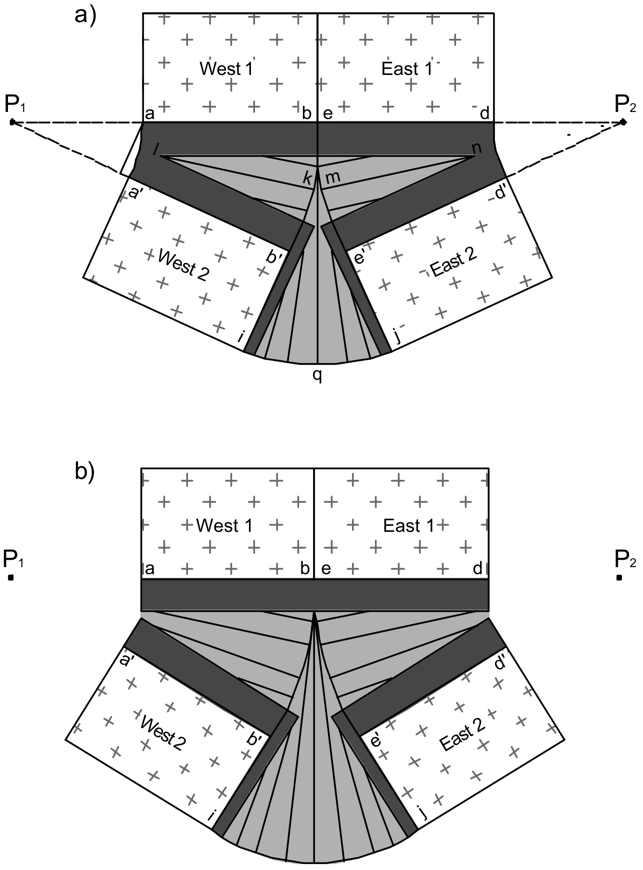

Figure 5. Two oppositely propagating rifts (as in Figure 4) but with the two northerly plates West 1 and East 1 stationary. Legend is as in Figures 3 and 4. Note the large triangular area of oceanic crust which tapers to a point south of be and opens to the south between i and j. Having curved sides, it is a spherical or Euler triangle. Figures 5a and 5b are further clarified in section 3.1.

the median seafloor spreading anomaly mn between plates East 1 and East 2. This obtuse angle is bisected by the median seafloor spreading isochron bq within the spherical triangle bij.

4. Mid-Oligocene to Recent Reconstructions of the Western Mediterranean Basin

[19] Reconstructions of the western Mediterranean [*Bouillin et al.*, 1986; *Malinverno and Ryan*, 1986; *Dewey et al.*, 1989; *Marti et al.*, 1992; *Doglioni et al.*, 1997; *Lonergan and White*, 1997; *Carminati et al.*, 1998; *Gueguen et al.*, 1998; *Roca et al.*, 1999; *Séranne*, 1999; *Faccenna et al.*, 2001; *Mascle et al.*, 2001; *Roca*, 2002; *Rosenbaum et al.*, 2002; *Faccenna et al.*, 2004; *Mascle et al.*, 2004; *Rosenbaum and Lister*, 2004a] envisage initial rifting in the Gulf of Lion in the mid-Oligocene (early Chattian 28 Ma) (Figure 2a). This is followed by an early back-arc extension phase between the mid-Oligocene and the early Burdigalian, involving the Valencia Trough and the Liguro-Provencal Basin (Figure 2b). During this stage, extension was already occurring between the Balearic Peninsula and the Kabylies terranes and between southern Sardinia and Calabria (25–22 Ma), as evidenced by the upper Oligocene–Miocene sedimentary fill of the Kabylies and the Serre, Aspromonte and Peloritani of Calabria and Sicily [*Bouillin et al.*, 1986, 1999a, 1999b; *Verges and Sábat*, 1999; *Frizon de Lamotte et al.*, 2000; *Mascle et al.*, 2001, 2004]. Also, a period of NS oriented extension occurred at 22–18 Ma in the Alboran Domain of the Betic and Rif Arc, and in the Alboran Basin [*Comas et al.*, 1992, 1999; *Martínez-Martínez and Azañón*, 2002]. In these models, oceanic crust breaks through in the Burdigalian in the Liguro-Provencal Basin, but southwest of the North Balearic Fracture Zone it is offset to the south of the Balearic Peninsula into the Algerian Basin (Figure 2c). Alternative views suggest that the rotation envisaged in Figures 2b and 2c occurred either between 21.7 and 17.6 Ma [*Montigny et al.*, 1981] or between 19 and 16 Ma [*Speranza et al.*, 2002], whereas later paleomagnetic, biostratigraphic, and isotopic age data [*Ferrandini et al.*, 2003] demonstrate that the Corsica/Sardinia Block rotation is post-late Chattian (24 Ma) and terminates around 15 Ma (post-early Langhian, 15.6 Ma). In detail, rotation begins before 21 Ma (late Aquitanian) and of a total 44° rotation, 30° occurs after the early Burdigalian [*Ferrandini et al.*, 2003], implying a significant rotation during the uppermost Chattian-Aquitanian part of the synrift period.

[20] The reconstructions (Figure 2) are based on existing literature, and are only modified to take into account the consequences of the models shown in Figures 3–5. The modeled rotation of plate West 2 (in Figures 4c and 4d and in Figures 5a and 5b) suggests that its southwest corner should rotate and collide with the area to its west. As the Balearic Peninsula Block rotated clockwise about pole P_{BP} (Figure 2b) during the mid-Oligocene-Burdigalian propagation of the Valencia Trough rift, its southwestern corner impinged on southeastern Spain. If the rotating block included the Betic part of the Alboran Terrane, then southwest of the rotation pole, westward and northwestward directed compression occurred between the Betic Alboran Terrane and the external zones of the Betic Cordillera. Similarly, in the later stages of this period, it is possible that the southern part of the Alboran Terrane together with the Kabylies terranes, also began rotating clockwise, from the Balearic Peninsula (Figure 2b). The western extent of the rift in the Alboran Sea suggests that the rotation pole was likely as far west as the Gibraltar Arc (Figure 2c). Finally, back-arc extension begins east of Corsica/Sardinia, and is displaced toward the east and southeast (Figure 2d).

5. West Mediterranean Data Corroborating the Oppositely Propagating Rift Model

5.1. Rift Initiation in the Gulf of Lion, and Subsequent Southwestward Propagation Into the Valencia Trough

[21] A number of authors have noted asynchronous initiation of rifting along the Gulf of Lion/Valencia Trough margin [*Sanz de Galdeano*, 1990; *Alvarez-de-Buergo and Melendez-Hevia*, 1994; *Roca et al.*, 1999; *Roca*, 2002].

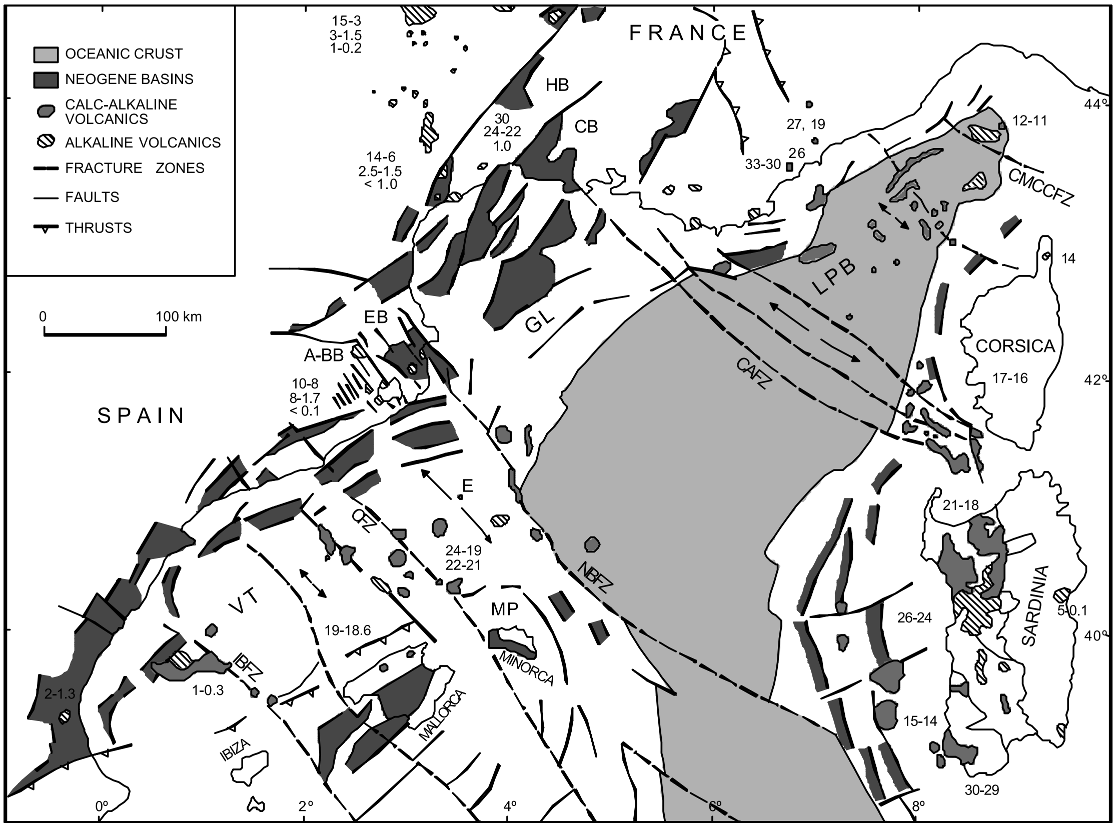

Figure 6. Map of the Valencia Trough (VT), Gulf of Lion (GL), and the Liguro-Provencal Basin (LPB) [after *Bellon*, 1981; *Rehault et al.*, 1984; *Beccaluva et al.*, 1989; *Marti et al.*, 1992; *Saula et al.*, 1994; *Maerten and Séranne*, 1995; *Mauffret et al.*, 1995; *Rossi et al.*, 1998; *Goula et al.*, 1999; *Maillard and Mauffret*, 1999; *Roca et al.*, 1999; *Séranne*, 1999; *Roca*, 2002; *Rollet et al.*, 2002; *Savelli*, 2002; *Ivaldi et al.*, 2003; *Maillard et al.*, 2003; *Nehlig et al.*, 2003]. Numbers refer to radiometric ages of volcanics. CMCCFZ, Cape Mele Cape Corse Fracture Zone; CAFZ, Cassidaigne-Asinara Fracture Zone; NBFZ, North Balearic Fracture Zone; CFZ, Central Fracture Zone; IBFZ, Ibiza Fracture Zone. Pairs of arrows increasing in length indicate increasing extension to the northeast in the Valencia Trough [after *Maillard and Mauffret*, 1999, Figure 14] and to the southwest in the Liguro-Provencal Basin (LPB) [after *Rollet et al.*, 2002, Figure 12]. HB, Herault Basin; CB, Camargue Basin. Note that individual basins within the Gulf of Lion (GL) are broader toward the southwest, as they approach the North Balearic Fracture Zone. The Empordá Basin (EB) and the basin controlled by the Amer-Brugent Fault system (A-BB) are floored by pre-lower Miocene, presumed upper Oligocene sediments and are NW-SE oriented. E, expanded spread profile 2, to the west of the NBFZ. MP, Minorca Promontory. The shaded area of oceanic crust includes the transitional and atypical oceanic domains of *Rollet et al.* [2002] in the Liguro-Provencal Basin.

Synrift sedimentation in the Herault and other subbasins of the Gulf of Lion began in the mid-Oligocene (early Chattian (30–28 Ma) [*Maerten and Séranne*, 1995; *Mauffret et al.*, 1995; *Maillard and Mauffret*, 1999; *Nehlig et al.*, 2003]. Off the Catalan coast of Spain immediately southwest of the North Balearic Fracture Zone, seismic stratigraphic analysis calibrated by well data [*Roca et al.*, 1999] shows that the synrift period began in the late Oligocene (unit O5 of late Chattian age 24 Ma), and extended into the Aquitanian. Farther to the southwest, the first synrift sediments are lower middle Miocene [*Alvarez-de-Buergo and Melendez-Hevia*, 1994] or Burdigalian [*Roca et al.*, 1999]. The implication is that a rift initiated in the Gulf of Lion and, over a period of at least 8–11 Myr from 30–28 Ma to 20–19 Ma, propagated to the southwest within the Valencia Trough.

[22] So far, a rift propagating to the northeast from the Gulf of Lion toward Liguria has not been documented in the literature [*Rehault et al.*, 1984; *Maerten and Séranne*, 1995; *Mauffret et al.*, 1995; *Maillard and Mauffret*, 1999; *Séranne*, 1999; *Rollet et al.*, 2002]. The model outlined in section 3 predicts that this is the case, while the data discussed in sections 5.3–5.5 provide supporting evidence for a NE propagating rift, at least during the Burdigalian/Langhian phase of oceanic accretion.

5.2. Central Locus of Maximum Extension

[23] The Herault and Camargue basins of the Gulf of Lion (Figure 6) are narrower to the northeast, and broaden toward the southwest, with maximum graben widths and extension occurring on the southwest side of the Gulf of Lion [*Maerten*

and Séranne, 1995; *Mauffret et al.*, 1995]. This implies that extension increases to the southwest toward the North Balearic Fracture Zone. From a compilation of seismic, volcanic and magnetic data, *Rollet et al.* [2002] show that within the Liguro-Provencal Basin, extension is least to the northeast, and increases toward the southwest (Figure 6).

[24] Within the Valencia Trough, extension increases from the southwest toward the northeast as indicated by progressively shallower depths to the Moho, increased calculated tectonic subsidence, and increasing Bouger gravity anomaly [*Torné et al.*, 1996; *Negredo et al.*, 1999]. It has been suggested [*Maillard and Mauffret*, 1999] that the northeastward increases in calculated extension occur in steps at successive fracture zones (Figure 6).

[25] In addition, during the Burdigalian/Langhian oceanic accretion phase of the Liguro-Provencal and Algerian basins (sections 5.3 and 5.4), the greatest extent of oceanic crust occurs immediately east of the North Balearic Fracture Zone, again demonstrating the central location of maximum extension.

[26] Most authors agree that the Valencia Trough is underlain entirely by thinned continental crust [e.g., *Maillard and Mauffret*, 1999]. However, the high Bouger gravity anomaly of 160 mGal in the deepest part of the Valencia Trough to the north-northwest of Minorca Island (the deepest part of the Valencia Trough shown in Figure 1) is suggestive of oceanic crust [*Negredo et al.*, 1999]. This may be due to proximity to oceanic crust on the northeast side of the North Balearic Fracture Zone (NBFZ), or it may indicate a small sliver of oceanic crust in the deepest part of the Valencia Trough immediately southwest of the NBFZ. Alternatively, the NBFZ may be acting as a leaky transform fault (compare Figure 6 with Figures 5a and 5b). Here, near Expanded spread profile 2, the crust is highly intruded and resembles oceanic crust [*Maillard and Mauffret*, 1999]. Specifically, a 1.6 km thick volcanic layer overlies basement, and without this volcanic layer, crustal thickness would be 7 km, very close to the crustal thicknesses of 5–7 km seen in the oceanic domain of the Liguro-Provencal Basin [*Maillard and Mauffret*, 1999].

[27] This suggests that after initial rifting (Figure 2a), during an early phase of extension and rift propagation between 30–28 Ma and 20–19 Ma (Figure 2b), the Valencia Trough and the Liguro-Provencal Basin evolved to a point intermediate between Figures 4a and 4b. All of the Valencia Trough is floored by thinned continental lithosphere, but there is a sliver of crust in the deepest part of the Trough, immediately southwest of the NBFZ which is similar to oceanic crust. This being the case, then the Valencia Trough/Liguro-Provencal Basin evolved almost to the situation shown in Figure 4b, with incipient oceanic breakthrough. Later, in the Burdigalian/Langhian (Figure 2c), oceanic breakthrough occurred in the Liguro-Provencal and Algerian basins (section 5.3).

5.3. Rhombic Oceanic Basins in the Liguro-Provencal and Algerian Basins

[28] On the basis of crustal thicknesses of as little as 4 km, high heat flow and magnetic anomalies, various authors have suggested that the Liguro-Provencal and Algerian Basin are underlain by oceanic crust in their central zones, whereas the margins comprise thinned continental crust, with transitional crust between the two [*Rehault et al.*, 1984; *Comas et al.*, 1999; *Séranne*, 1999; *Roca*, 2002; *Rollet et al.*, 2002; *Maillard et al.*, 2003]. The rhombic form of these combined basins (Figure 7), albeit offset along the North Balearic Fracture Zone, has been picked out by bathymetry [e.g., *Malinverno and Ryan*, 1986; *Lonergan and White*, 1997; *Wortel and Spakman*, 2000], depth to basement (Figure 1), and interpreted continent ocean boundaries [e.g., *Rehault et al.*, 1984; *Carminati et al.*, 1998; *Gueguen et al.*, 1998; *Roca*, 2002; *Rollet et al.*, 2002; *Maillard et al.*, 2003]. The region, however, is atypical insofar as, although a central basement high, the Tristanites Massif and the Median Seamount exists in part of the Liguro-Provencal Basin [*Rehault et al.*, 1984; *Rollet et al.*, 2002], it is not similar in scale to a mid-ocean ridge, and does not extend throughout the basin. For this reason, as well as the lack of coherent magnetic anomalies, and its thinness, oceanic crust in this area is considered anomalous by *Rollet et al.* [2002]. However, section 5.4 argues that the magnetic anomalies do present a coherent pattern.

5.4. Magnetic Anomalies

[29] Magnetic anomalies in the western Mediterranean provide the most compelling support for the opposite propagation of two rifts (compare Figures 4 and 5 with Figure 7). Subparallel magnetic anomalies in the Algerian Basin trend N70°E, while similar subparallel magnetic anomalies in the Liguro-Provencal Basin trend generally N30°E [*Bayer et al.*, 1973; *Rehault et al.*, 1984; *Rollet et al.*, 2002]. Liguro-Provencal Basin magnetic anomalies (N30°E) are aligned at an obtuse angle of 140° to the Algerian Basin anomalies. (See section 5.6 for more detail on geometric relationships.) In the Liguro-Provencal Basin, only the central anomalies extend to the apex of interpreted oceanic crust between Corsica and the Italian coast at Genoa. The situation is less clear cut in the Algerian Basin, but the interpreted oceanic crust does taper to its narrowest width in the East Alboran Basin between southeast Spain and Algeria between 1° and 2° west [*Comas et al.*, 1999].

[30] In the Liguro-Provencal Basin, northeast of the North Balearic Fracture Zone, magnetic anomalies are offset by curvilinear fracture zones which trend generally N115°–135°E, and are concave to the northeast. Southwest of the North Balearic Fracture Zone, similar offsetting fracture zones extend from the Valencia Trough into the Algerian Basin and trend generally N125°–165°E. In the case of the Central Fracture Zone west of Minorca, the next fracture zone west of Mallorca, and the Ibiza Fracture Zone east of Ibiza Island, the curvature is concave to the southwest (Figures 6 and 7) [see also *Rehault et al.*, 1984, Figure 9]. Farther to the west in the Algerian Basin, the fracture zone orientations are more variable.

[31] One of the most striking features of Figure 7 is the triangular or fan-shaped group of magnetic anomalies southwest of Sardinia, and southeast of Minorca. Subparallel magnetic anomalies trend N140°E from the Algerian coast toward an apex southeast of Minorca, with the central

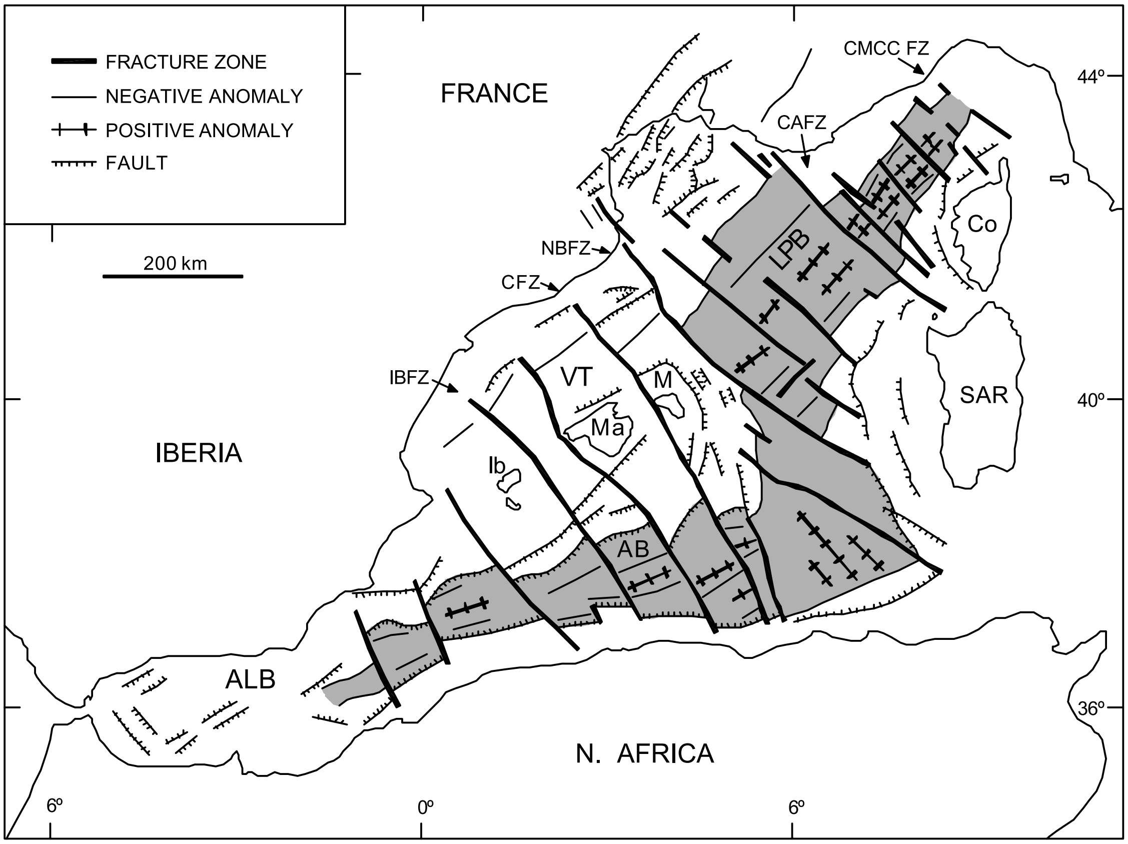

Figure 7. Fracture zones and possible seafloor spreading isochrons, as well as the extent of oceanic crust (shaded) interpreted from magnetic anomalies in the western Mediterranean [after *Bayer et al.*, 1973; *Rehault et al.*, 1984]. Fracture zone abbreviations are as in Figure 6. Co, Corsica; SAR, Sardinia; M, Minorca; Ma, Mallorca; Ib, Ibiza; VT, Valencia Trough; AB, Algerian Basin; ALB, Alboran Basin; LPB, Liguro-Provencal Basin. Note that in the case of the triangular area of N140°E oriented anomalies southwest of Sardinia, the anomalies are as shown by *Rehault et al.* [1984]. With regard to the triangular area encompassing the N140°E oriented anomalies, the original interpretation [*Rehault et al.*, 1984] showed a smaller area, whereas here a larger area is interpreted following the data of *Bayer et al.* [1973], in agreement with interpretations shown by *Carminati et al.* [1998, Figure 1] and *Gelabert et al.* [2002, Figures 5 and 6].

positive anomaly extending farthest to the northwest. The eastern boundary of this triangular zone is a N 115°E trending magnetic anomaly which corresponds to the Hamilcar anomaly of *Mauffret et al.* [2004]. The western boundary is a N165°E trending magnetic anomaly close to the Hannibal Ridge of *Mauffret et al.* [2004]. This triangular zone tapers to an apex 80 km southeast of Minorca and expands southeastward to a width of 220 km off the Algerian/Tunisian coast. Taking the original interpretation of *Rehault et al.* [1984], the triangular area is 140 km wide off the Algerian/Tunisian coast, with its apex 160 km to the southeast of Minorca Island. This triangular area of N140°E oriented anomalies corroborates the model prediction of a rift propagating northwest in this area.

[32] The northwestern apex of this triangular zone points toward the NW-SE oriented narrow graben to the northeast of Minorca Island. Here, basement descends from 1 to 6 s two-way time, in less than 50 km northeast of the graben. DSDP hole 372 shows that the 6 km wide graben is filled with pre-lower Burdigalian presumed upper Oligocene sediments [*Mauffret et al.*, 1978]. From the northeastern flank of the graben, basement descends toward the North Balearic Fracture Zone.

[33] In the mid-Oligocene–Burdigalian rifting and extension phase involving the Valencia Trough and the Liguro-Provencal Basin (Figures 2a and 2b), the combined Balearic Platform/Kabylies Block represents plate West 2 of Figures 4 and 5, whereas the combined Corsica/Sardinia/Calabria Block represents plate East 2. The margin east of Minorca Island therefore represents the margin b′i on plate West 2 during the mid-Oligocene–Burdigalian phase. During the Burdigalian/Langhian phase where oceanic crust is emplaced in the Liguro-Provencal and Algerian basins (Figure 2c), plate West 2 is represented by the Kabylies Block, while plate East 2 is still represented by the Corsica/Sardinia/Calabria Block. The margin east of Minorca Island therefore represents margin bg on plate West 1 during the Burdigalian/Langhian phase.

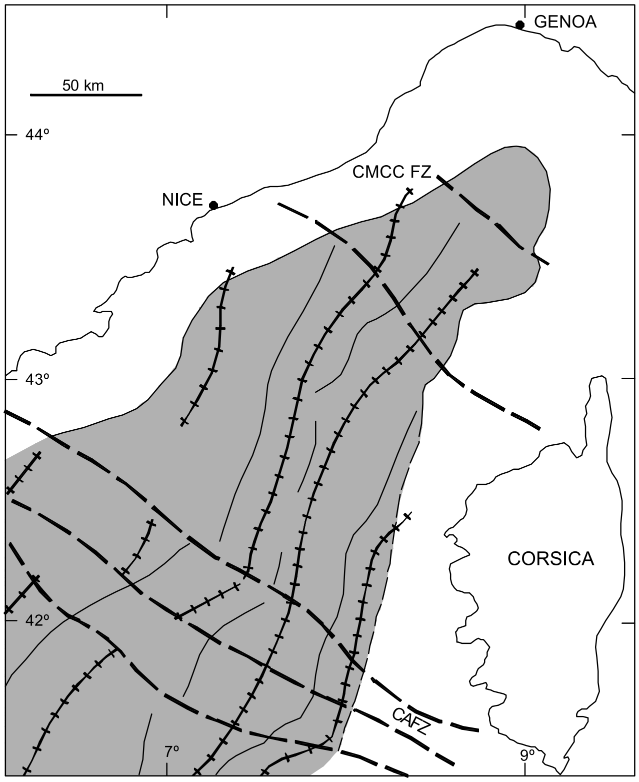

Figure 8. Simplified interpretation, following the format of Figure 7, of linear magnetic anomalies and fracture zones in the Liguro-Provencal Basin [after *Rollet et al.*, 2002]. Transitional and oceanic crust is shaded. Fracture zone abbreviations are as in Figure 6. Note that more centrally located (younger?) linear magnetic anomalies abut thinned continental crust farther northeast toward the pole of rotation. The pattern closely follows that predicted by the models of Figures 3, 4, and 5.

[34] Paleomagnetic data show that the rotation of the Corsica/Sardinia Block is post-upper Chattian (24 Ma) and continued until 15 Ma [*Ferrandini et al.*, 2003]. This 8–9 Ma period encompasses part of the synrift (Chattian–Aquitanian) and the early postrift period identified in the Gulf of Lion/Liguro-Provencal Basin [*Maerten and Séranne*, 1995; *Mauffret et al.*, 1995; *Séranne*, 1999]. Assuming that the oceanic accretion phase coincides with the Burdigalian/Langhian part of the postrift phase, then oceanic accretion lasted 6 Myr. The maximum width of oceanic crust northeast of the North Balearic Fracture Zone (250 km) implies a half-spreading rate of 2.1 cm/yr. Similarly, in the Algerian Basin the maximum width of 180 km leads to a half-spreading rate of 1.5 cm/yr, but this could have been up to 2.3 cm/yr if the 100 km northward movement of Africa is taken into account (compare Figures 2c, 2d, and 7). In the spherical triangular area off Algeria, maximum half spreading rates are 1.8 cm/yr. These values compare with rates of 1.5 cm/yr during rift propagation in the Gulf of Aden [*Manighetti et al.*, 1997] and 3.4 cm/yr in the Woodlark Basin [*Benes et al.*, 1994; *Taylor et al.*, 1999].

[35] Similarly, the dimensions of the basins (Figure 7) indicate that the Liguro-Provencal Rift (see section 5.5) propagated at a rate of 8.3 cm/yr, the Algerian Basin Rift propagated at 10.8 cm/yr, whereas the spherical triangular area rift propagated at 3.6 cm/yr. These rates compare with overall propagation rates of 8.3 cm/yr for the Woodlark Basin, and in excess of 10, possibly reaching several tens of centimeters per year for the Gulf of Aden. Furthermore, using reasonable stretching factors for thinned continental crust, *Van Wijk and Blackman* [2005] calculated propagation rates of 10–17 cm/yr.

5.5. Progressively Younger (More Central) Magnetic Anomalies (Seafloor Spreading Isochrons) Abutting Extended Continental Crust Closer to the Rotation Pole: NE Rift Propagation in the Liguro-Provencal Basin

[36] A more detailed view of the Liguro-Provencal Basin (Figure 8) shows the relationship between the continental margin and magnetic anomalies. *Rollet et al.* [2002] map the limits of thinned continental crust as the seaward limit of crust demonstrating graben and half graben morphology, which coincides with a break of slope to deeper flat-lying basement. Basement in the transitional zone is interpreted as volcanic flows sourced from nearby volcanic centers, whereas the atypical oceanic domain basement is thought to comprise discontinuous volcanoes and dikes intruded into disrupted crust.

[37] *Rollet et al.* [2002] demonstrate close correspondence between interpreted volcanism and positive magnetic anomalies. Following their interpretation, basement both in the transitional and atypical oceanic domains is related to volcanism. If the linear magnetic anomalies represent areas of preferential intrusion of volcanoes and dikes, then, despite the fact that the deep basin may be floored by "atypical ocean crust", these linear anomalies, both in the oceanic and transitional domains, may resemble seafloor spreading isochrons (Figure 8).

[38] As described in the more regional map discussed in section 5.4 (Figure 7), several prominent linear magnetic anomalies trend N30°–40°E, whereas a number of curvilinear anomalies trending N 120°–130°E have previously been interpreted as fracture zones [*Rehault et al.*, 1984]. The Cape Mele–Cape Corse Fracture Zone is the most northeasterly shown (Figure 8), whereas the triple set of offsets to the southwest comprises the Cassidaigne-Asinara Fracture Zone which trends toward the Bonifacio Strait between Corsica and Sardinia. Both Fracture Zones are associated with significant NW – SE oriented interpreted volcanic features (Figure 6), the former throughout its length, the latter as it approaches Corsica.

[39] Two N30°E oriented subparallel positive anomalies separated by a less well defined centrally located negative anomaly extend all the way from southwest of the Cassidaigne-Asinara Fracture Zone to the Cape Mele–Cape Corse Fracture Zone to the northeast (Figure 8). On either side of these are two well-defined negative anomalies. The westernmost positive anomaly, closest to the mainland coast, is associated with two large interpreted volcanic centers (Figure 6) and heads toward the coast northeast of Nice.

The easternmost positive anomaly off Corsica is less well defined, but closely follows NNE-SSW oriented volcanic features, and coincides toward the NNE with the interpreted western boundary of thinned continental crust off Corsica.

[40] The oceanic domain and the combined oceanic and transitional domains define triangular or fan-shaped areas with their apices to the northeast off the Genoa coast. The most lateral N20°–40°E oriented linear anomalies abut continental crust farther to the southwest, whereas more central anomalies abut continental crust successively farther to the northeast. This geometry (Figure 8) closely mimics the geometry predicted by the models shown in Figures 3, 4, and 5. Provided that these magnetic anomalies and the associated linear volcanic features are akin to seafloor spreading isochrons, the geometry provides evidence that a rift did propagate northeastward in the Liguro-Provencal Basin, at least during its oceanic accretion phase in the Burdigalian/Langhian.

[41] Various authors have emphasized a general southeastward younging of calc-alkaline volcanism within the western Mediterranean [*Malinverno and Ryan*, 1986; *Beccaluva et al.*, 1989; *Lonergan and White*, 1997; *Rosenbaum et al.*, 2002; *Savelli*, 2002; *Rosenbaum and Lister*, 2004a, 2004b]. Alternatively, *Marti et al.* [1992] emphasized an early calc-alkaline phase followed by a later episode of alkaline volcanism. In addition, fracture zones appear to have formed preferred areas of eruption of both calc-alkaline and alkaline volcanism (Figure 6). The model proposed here for the Liguro-Provencal Basin requires seafloor spreading (presumably of mid-ocean ridge-type basalts) to occur in a central location, and for successively younger isochrons to extend farther northeastward toward Genoa.

[42] As yet, no deep drilling has determined the age or character of deeply buried transitional and oceanic domains of the Liguro-Provencal Basin. However, on the Ligurian Margin, erupted volcanic rocks [*Ivaldi et al.*, 2003] generally young to the northeast toward Genoa, with 33–26 Ma calc-alkaline volcanics on the northeast flank of the Maures-Esterel Massif and Villeneuve-Loubet, 27 and 19 Ma volcanics farther northeast at Cap d'Ail, and finally 12–11 Ma alkali basalts at Monte Doria in the center of the Cape Mele–Cape Corse Fracture Zone (Figure 6).

[43] On the western Sardinia/Corsica Margin [*Rossi et al.*, 1998; *Rollet et al.*, 2002], dredged and outcropping volcanics young to the north toward Genoa, with 30–29 Ma calc-alkaline basalts in the southern Sardinia Rift, 26–24 Ma volcanics in the central Sardinia Rift, 21–18 Ma and 17–16 Ma rocks in the northernmost Sardinia Rift and SW Corsica, and finally 14 Ma and 12–11 Ma alkaline basalts at Sisco and NW of Corsica, respectively. This northward younging trend is broken by 5.0–0.1 Ma alkali volcanics, which have generally been associated with the Miocene opening of the Tyrrhenian Basin to the east of Sardinia [*Savelli*, 2001, 2002; *Rosenbaum and Lister*, 2004b; *Peccerillo and Lustrino*, 2005].

5.6. Geometric Relationships of Magnetic Anomalies

[44] In Figure 5a, where symmetrical seafloor spreading is depicted, the total rotation of West 2 relative to West 1 (angle b P_1 b′) is bisected by the median seafloor spreading isochron k l and its extension toward pole P_1. Line l k and its eastward extension makes a north facing obtuse angle with its equivalent median seafloor spreading isochron, line m n and its westward extension between plates East 1 and East 2. In a symmetric situation (as drawn in Figure 5a), knowing the angle between l k and m n (let it be θ), we can calculate the angle k P_1 b, = $(180 - \theta)/2$. The total rotation of plate West 2 relative to West 1 is double this, = $180 - \theta$.

[45] The reflex angle between lines l k and m n is bisected by the central seafloor spreading isochron within the spherical triangle bij (line b q in Figure 5a). Again, assuming symmetrical seafloor spreading, the heading of the median seafloor spreading isochron b q equals the heading of line m n plus half the reflex angle between l k and m n.

[46] The orientation of the Algerian Basin anomalies is N70°E. In the Liguro-Provencal Basin (Figures 7 and 8), the orientation of the anomalies varies from N20°–N50°E southwest of the Cassidaigne-Asinanra Fracture Zone, to N15°–N25°E to the northeast of the CAFZ, and finally to N40° just southeast of the Cape Mele–Cape Corse Fracture Zone. Overall, the central anomaly trends close to N30°E.

[47] The Algerian anomalies (N70°E) therefore make an obtuse angle of 140 ° with the central Liguro-Provencal anomaly (N30°E). Using the formula above, and assuming symmetry, this geometry suggests that the Corsica/Sardinia Block has rotated 40° anticlockwise, while the Kabylies Block rotated 40° clockwise.

[48] The coastline and the limit of continental crust along the Ligurian Margin trend N55°E, whereas the Corsica/Sardinia coast trends generally north, while the continental margin trends N15°E. Restoring the Corsica/Sardinia Block against the Ligurian Margin therefore also suggests a rotation of about 40° (Figure 2a).

[49] Similarly, closing the Kabylies Terrane (N85°–90°E) against the Balearic Peninsula and then against the Spanish Margin (N50°E) suggests a total rotation of just under 40°. The orientation of the northwest flank of the Balearic Peninsula suggests that of the total rotation of 40°, opening of the Valencia Trough between the Balearic Peninsula and the Catalan Margin accounts for only 15° of rotation (Figure 5a). Note that this is less than the rotation indicated by paleomagnetic data (section 6), which may mean that the Balearic Peninsula rotated farther south than its present position and then moved north commensurate with the >100 km of shortening calculated for its northern flank [*Roca*, 2002].

[50] Finally, bisecting the reflex angle between the central anomaly of the Liguro-Provencal Basin and the Algerian anomalies indicates that the central anomaly in the spherical triangle off Sardinia should be oriented at N140°E. The central anomaly within the spherical triangle does indeed trend N140°E, implying symmetrical total rotations of the Kabylies and Corsica/Sardinia blocks.

6. Pairs of Clockwise and Anticlockwise Rotated and Accreted Terranes

[51] The model (Figures 4 and 5), which appears to be corroborated by geological, geophysical, and particularly

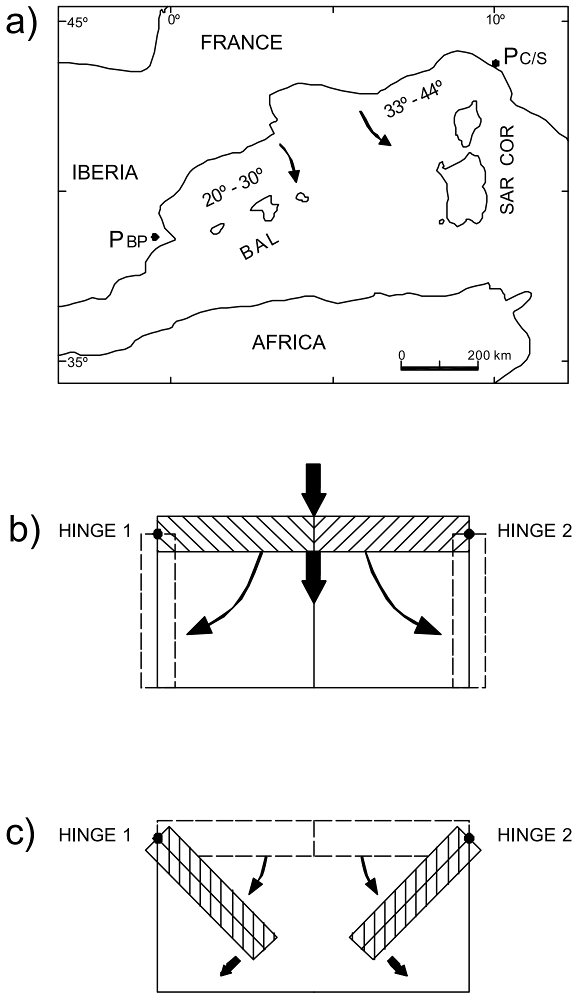

Figure 9. (a) Simplified map of the Valencia Trough/Liguro-Provencal Basin showing the paleomagnetic rotations of the Balearic Peninsula (BAL) and the Corsica/Sardinia Block [after *Montigny et al.*, 1981; *Pares et al.*, 1992; *Lonergan and White*, 1997; *Rosenbaum et al.*, 2002; *Speranza et al.*, 2002; *Ferrandini et al.*, 2003]. P_{BP} indicates pole about which the Balearic Peninsula was rotated for Figure 2, whereas $P_{C/S}$ indicates pole about which Corsica/Sardinia was rotated. (b) Plan view of double saloon doors which can swing open about their hinges. Note that initially, a single force (push or pull) is capable of opening and rotating both doors. The left door swings clockwise about its hinge, while the right door swivels anticlockwise. (Compare Figures 4, 5, and 9a.) (c) The same double saloon doors, when slightly further ajar, requiring two separate forces to continue being opened. (Compare Figures 9b and 9c with Figures 10a and 10b.)

magnetic data, as well as geometric considerations (sections 5.1–5.6), affords a mechanism for the clockwise rotation of the Balearic Peninsula, and the anticlockwise rotation of the Corsica/Sardinia Block. Paleomagnetic data (Figure 9a) demonstrate a 20°–30° clockwise rotation of the Balearic Peninsula [*Pares et al.*, 1992]. Taken with calculations made here suggesting a total rotation of 40° for the Kabylies Block, this indicates a 10–20° rotation of the Kabylies Terrane relative to the Balearic Peninsula. Paleomagnetic data evince a 33°–44° anticlockwise rotation of the Corsica/Sardinia Block [*Speranza et al.*, 2002; *Ferrandini et al.*, 2003], whereas the predrift fit of *Gueguen et al.* [1998] requires a 60° rotation, while here a 40° rotation is considered sufficient to close the Corsica Margin against the Ligurian Margin (section 5.6; Figure 2a).

[52] Rotation of the Balearic Peninsula about a rotation pole southwest of the southwestern apex of the Valencia Trough (compare Figures 2, 4, and 5) with clockwise motion taken up along concave-to-the-west fracture zones is entirely consistent with the paleomagnetic evidence (Figure 9a), and with increasing extension toward the northeast (Figure 6). Similarly, anticlockwise rotation of the Corsica/Sardinia Block about a pole near Genoa is compatible with the paleomagnetic data, concave-to-the-east fracture zones in the Liguro-Provencal Basin, and with increasing extension toward the southwest. Rotation poles of this nature are inherent both in early [e.g., *Vogt et al.*, 1971, Figure 2] and later theories [*Gelabert et al.*, 2002, Figure 4], and have been suggested in the past [*Rehault et al.*, 1984; *Dewey et al.*, 1989; *Gueguen et al.*, 1998; *Rollet et al.*, 2002], without a proposal for a model similar to that of Figures 3, 4, and 5.

[53] During the mid-Oligocene–early Burdigalian phase (Figures 2a and 2b), the combined Balearic Peninsula/Kabylies Terrane is the clockwise rotating plate, whereas the Corsica/Sardinia/Calabria Block rotates anticlockwise. In the Burdigalian/Langhian phase of oceanic accretion in the Liguro-Provencal and Algerian basins, the clockwise rotating block is the Kabylies Terrane, whereas anticlockwise rotation of the Corsica/Sardinia/Calabria Block continues.

[54] Regarding the Kabylies and southern Alboran terranes, the rotated plates or microplates have already accreted to a nearby continent, in this case, to Africa. The northern part of the Alboran Terrane has accreted to Spain. The Corsica/Sardinia/Calabria Block docked at its northern and eastern flanks with the Apennines, before a new back-arc spreading episode opened the Tyrrhenian Sea, separating Calabria and the southern Apennines from the Corsica/Sardinia Block. The Corsica/Sardinia Block has therefore also accreted to a neighboring continent, but in this case, to Eurasia/Adria. Furthermore, at its southern end, Sardinia has collided with the Galite Block and the Tunisian Plateau off the Algerian and Tunisian coasts at the Sardinian and Drepano thrust Fronts [*Bouillin et al.*, 1999a, 1999b; *Mascle et al.*, 2001, 2004; *Mauffret et al.*, 2004]. This implies that the Corsica/Sardinia Block also collided and accreted to the African plate. The Balearic Peninsula did not become fully detached from Iberia/Eurasia, and has not yet accreted to another continent, but with further convergence between Africa and Eurasia, the Balearic Peninsula may well accrete to Africa, in the region of the Kabylies and Alboran terranes. Pairs of rotated, and then accreted, terranes appear to exist in other areas too, such as the Tertiary Caribbean, and the Early Jurassic breakup of Gondwanaland (A. Martin,

manuscript in preparation, 2006), implying that this process is relatively common.

7. Empordá Basin, Catalan Coast of Spain

[55] The model shown in Figure 5 assumes that the two northern plates, West 1 and East 1 do not rotate toward the north. In the western Mediterranean, these two plates are represented by onshore Spain and onshore Provence/Liguria, respectively, and it has been assumed that they have not rotated significantly to the northwest. However, if these blocks had rotated slightly to the northwest in the manner shown in Figure 4, we would expect a northwest oriented basin extending inland from the North Balearic Fracture Zone, close to the Spanish-French border. Such a basin should be similar to or smaller than the triangular zone of magnetic anomalies southwest of Sardinia described in section 5.4 (assuming any northwest rotation of the Spanish and Ligurian coasts was less subdued than the rotation of the Balearic Peninsula/Kabylies Terrane and the Corsica/Sardinia Block). The spherical triangular area shown in Figure 7 is 220 km across the base of the triangle, and 220 km from the base of the triangle to its apex southwest of Minorca. Alternatively, using the original interpretation of *Rehault et al.* [1984] these dimensions are 140 km by 140 km.

[56] One candidate may be the series of Oligocene graben which extends northeast from the Gulf of Lion and the Herault Basin along the east side of the Massif Central via the Limagne and Bresse basins to the Rhine Graben (Figures 1 and 6). However, this system of graben extends over 1000 km into central Europe, and is oriented NE-SW.

[57] A more likely possibility is the Neogene Empordá Basin (the Tortellá-Besalú Basin of *Goula et al.* [1999]) and the Sierras Transversales (Amer-Brugent Fault system) which form NW-SE graben extending 65 km inland from where the North Balearic Fracture Zone meets the coast (Figure 6). The Roses Fault, which forms the northeast border of the 40 km wide Empordá Basin, is 65 km northeast of the southwesternmost extent of Neogene sediments associated with the Amer-Brugents faults. Basin fill comprises Plio-Quaternary and upper Miocene alluvial fans, underlain by unfossiliferous continental fluvial sediments which are presumed upper Oligocene [*Saula et al.*, 1994]. Extension of the basins occurred via listric normal faults, some of which have been active in the Quaternary. Other faults, such as the Albanyá, La Jonquera, and Sant Climent faults, also have a strike-slip component, consistent both with their close proximity to the North Balearic Fracture Zone, and to the model shown in Figures 4 and 5. The existence of uncontaminated Miocene to Recent alkaline basalts (10–0.5 Ma [*Marti et al.*, 1992]) suggests that some faults provide conduits deep into the mantle [*Saula et al.*, 1994].

8. Double Saloon Door Seafloor Spreading

[58] An analogy for the geometry of oppositely rotated terranes (Figure 9a), caused by two oppositely propagating rifts is provided by double saloon doors being opened by an individual entering a bar (Figure 9b). In this case, a single centrally placed force (push or pull) is initially capable of opening both saloon doors about their hinges. Movements of the two doors are similar to those of plates West 2 and East 2 as they initially swivel about their respective rotation poles in Figure 5. Data demonstrating that initial rifting and maximum extension occurs in a central position aligned along the North Balearic Fracture Zone (sections 5.1 and 5.2), suggest that an axially located force was the first, and the most powerful agent to act in the western Mediterranean basins. By analogy to Figure 9b, a single central force may be the only force required to cause coeval clockwise and anticlockwise rotations of the Balearic Peninsula/Kabylies Terrane Block and the Corsica/Sardinia Block, and then of the Kabylies Block and the Corsica/Sardinia Block (section 6).

[59] However, as opening proceeds (Figure 9c), a single central force is no longer capable of moving both plates because of their gradual separation. For continued rotation, two forces are required, directed to the southwest and the southeast, respectively. This geometry is very similar to the situation which results from the modified slab detachment model developed below (compare Figures 9b and 9c with Figures 10a and 10b).

9. Driving Mechanism

9.1. Existing Theories

[60] Early models for back-arc spreading in the Pacific envisaged active diapirism, passive diapirism related to subduction rollback, slab breakoff and stepwise rollback [*Karig*, 1974], or convection-driven upwelling [*Toksoz and Bird*, 1977]. Diapirism may be controlled by lithosphere composition [*Oxburgh and Parmentier*, 1978] or age and therefore density of subducting lithosphere [*Molnar and Atwater*, 1978]. In the Mediterranean, convective removal [*Platt and Vissers*, 1989] or delamination [*Seber et al.*, 1996; *Calvert et al.*, 2000] of the lithospheric root of a collisional ridge has been invoked to explain the perceived near radial form of the Gibraltar Arc. The mechanism has been criticized because it cannot explain large vertical axis rotations, and because the Gibraltar Arc is not completely radial [e.g., *Frizon de Lamotte et al.*, 1991; *Lonergan and White*, 1997; *Duggen et al.*, 2004]. Equally, slab roll back [*Malinverno and Ryan*, 1986; *Royden*, 1993; *Lonergan and White*, 1997; *Doglioni et al.*, 1997; *Gueguen et al.*, 1998; *Faccenna et al.*, 2001; *Rosenbaum et al.*, 2002; *Faccenna et al.*, 2004] has been criticized as failing to explain the temperature pressure conditions implied by peridotite bodies in the Betic and Rif areas of the Gibraltar Arc [e.g., *Calvert et al.*, 2000]. Detachment of subducted slabs [*Blanco and Spakman*, 1993] has been associated with rifting and extension [*Carminati et al.*, 1998; *Chalot-Prat and Girbacea*, 2000] and to the discontinuance of extension in the detached area, with consolidation of extension and subduction rollback where the slab remains attached [*Wortel and Spakman*, 2000]. In the latter theory, initiation of detachment, and subsequent lateral migration of the tear

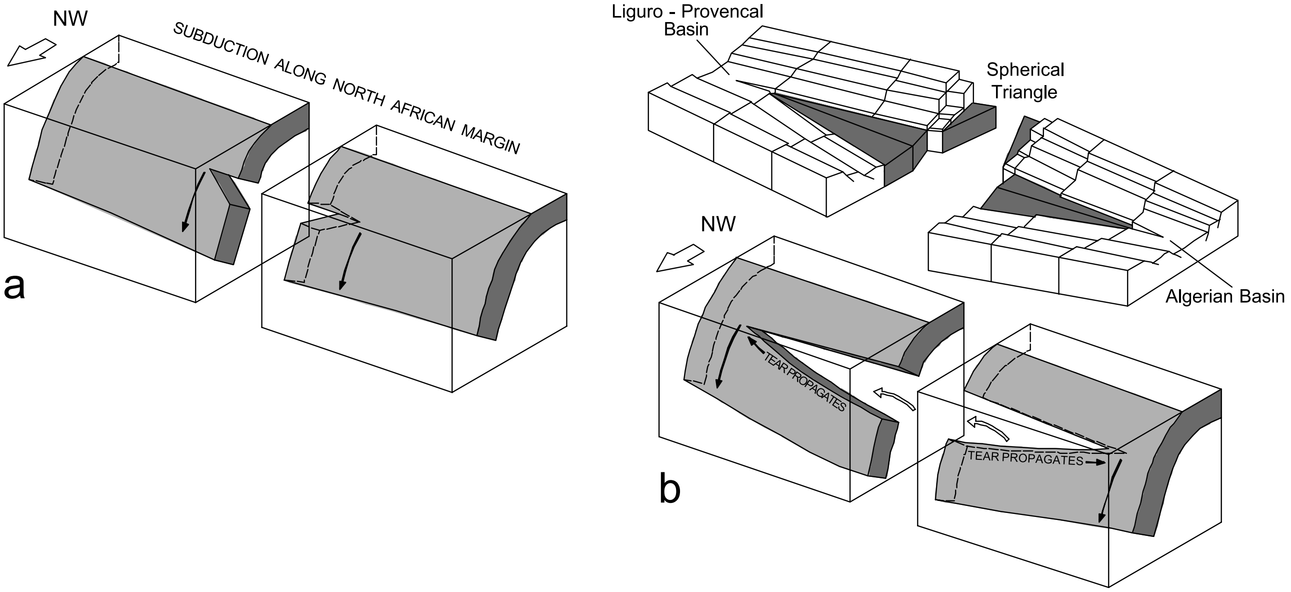

Figure 10. (a) An adaptation of the slab detachment model of *Wortel and Spakman* [2000]. As opposed to a tear extending in one direction only, the case shown here envisages a tear which initiates in a central location and then propagates in both directions. This scenario is based on existing reconstructions [*Lonergan and White*, 1997; *Carminati et al.*, 1998; *Wortel and Spakman*, 2000] which postulate slab detachment along the North African coast 18–15 Ma, whereas the slab remains attached under the Betic Rif Arc until the late Miocene (see section 9.2) and may still be attached under the Calabrian Arc [*Spakman and Wortel*, 2004]. (Compare Figure 1.) (b) Plot of more advanced case where the rhombic gap in the subducting slab grows wider as tear propagation progresses. Also shown is the rhombic basin of oceanic lithosphere created by oppositely propagating rifts in the overriding plate from 21 to 18 Ma, or from 19 to 16 Ma, or from 21 to 15 Ma (dates respectively after *Montigny et al.* [1981], *Speranza et al.* [2002], and sections 4 and 5.4, referencing *Ferrandini et al.* [2003]). The slab pull force, and therefore the subduction rollback force, is concentrated in the parts of the slab which are still attached (black arrows). This implies that a gap, where no slab pull is exerted, slowly opens and widens. (Compare to Figures 9b and 9c.) Light arrows indicate asthenosphere upwelling.

in the subducting slab has been emphasized [*Wortel and Spakman*, 2000, Figure 3].

9.2. Modified Slab Rollback/Slab Detachment: Oppositely Propagating Slab Tears

[61] In a combined subduction rollback/slab detachment model, it has been proposed that southeastern rollback of a northwesterly dipping subducting slab causes the southeastern migration of back-arc opening from the Valencia Trough/Liguro-Provencal Basin to the Algerian/Liguro-Provencal basins, hence to the northern Tyrrhenian and finally to the southern Tyrrhenian Basin [*Lonergan and White*, 1997; *Carminati et al.*, 1998; *Wortel and Spakman*, 2000; *Faccenna et al.*, 2001, 2004; *Spakman and Wortel*, 2004]. In this scheme, subduction is choked off by the collision of the continental Kabylies terranes with North Africa, leading to slab detachment along the North African coast 18–15 Ma (Figure 1). Subduction continues both to the west and east, causing more rapid and more tightly curved subduction rollback in the Betic Rif Arc and in the Calabrian Arc. Instead of a tear in the slab propagating in one direction only [*Wortel and Spakman*, 2000], the above geography mandates that slab detachment occurs off North Africa, and propagates both east and west (Figure 10), leaving an attached slab under Gibraltar until the late Miocene [*Duggen et al.*, 2004], or possibly until the Recent [*Gutscher et al.*, 2002] and an attached slab under Calabria, which may be detaching at present [*Wortel and Spakman*, 2000]. More recently, *Spakman and Wortel* [2004] emphasized both east and west slab tear propagation, whereas two separate slab tears along the North African Margin have been proposed by *Faccenna et al.* [2004] and *Rosenbaum and Lister* [2004a].

[62] This scenario is backed up by the distribution and nature of volcanism along the North African margin, in Spain, Sardinia and Calabria (Figure 2d). Many authors have noted the bimodal calc-alkaline and alkaline nature of volcanism in the western Mediterranean and the rift basins east of the Massif Central [*Froidevaux et al.*, 1974; *Bellon*, 1981; *Rehault et al.*, 1984; *Malinverno and Ryan*, 1986; *Marti et al.*, 1992; *Lonergan and White*, 1997; *Maury et al.*, 2000; *Coulon et al.*, 2002; *Rollet et al.*, 2002; *Rosenbaum et al.*, 2002; *Savelli*, 2001, 2002; *Nehlig et al.*, 2003; *Duggen et al.*, 2004; *Rosenbaum and Lister*, 2004a, 2004b; *Peccerillo and Lustrino*, 2005]. Calc-alkaline volcanism derives from subducted lithospheric mantle where metasomatism by subducted sedimentary material leads to melting. Alkali

volcanism derives from decompression melting of more enriched mantle, associated with hot spot activity, extension and rifting, or slab detachment and asthenospheric upwelling.

[63] Along the North African margin (Figure 2), calc-alkaline magmatism in the Kabylies has returned dates of 24 and 22 Ma [*Bellon*, 1981], with more widespread calc-alkaline volcanism from 18 to 15 Ma [e.g., *Savelli*, 2002], whereas significant alkaline volcanism began 11–9 Myr ago in eastern Algeria [*Lonergan and White*, 1997; *Maury et al.*, 2000]. In the Betic and Rif Arc the transition from tholeiitic and calc-alkaline magmatism to K-rich shoshonitic and lamproitic volcanism occurred 8–6 Ma, whereas alkali volcanism dates from 7–5 Ma to the Pleistocene [*Coulon et al.*, 2002; *Duggen et al.*, 2004]. Meanwhile, alkali volcanism dates from 7 to 5 Ma in Tunisia and from 5 to 0.1 Ma in Sardinia (Figures 2d and 6). Volcanism then migrated east and southeast from eastern Sardinia, with bimodal calc-alkaline and alkali volcanism in the Calabrian Arc continuing from 3 Ma into the late Pleistocene [*Savelli*, 2001, 2002; *Sartori*, 2003; *Rosenbaum and Lister*, 2004b; *Peccerillo and Lustrino*, 2005]. If the initiation of alkaline volcanism can be related to asthenospheric upwelling into a tear in a subducting slab [*Maury et al.*, 2000; *Duggen et al.*, 2004], then such upwelling began in eastern Algeria 4–6 Myr earlier than in the Betic Rif Arc and 4–7 Myr before it occurred in Tunisia and central and eastern Sardinia. From there, the magmatic arc migrated east and southeast to Calabria where slab breakoff may be occurring in modern times [*Wortel and Spakman*, 2000]. Note that a propagating slab tear has also been proposed under the Apennines on the Italian Peninsula side of the Calabrian Arc from late Miocene times [*Patacca and Scandone*, 1989; *Carminati et al.*, 1998; *Wortel and Spakman*, 2000; *Faccenna et al.*, 2001, 2004; *Rosenbaum and Lister*, 2004b; *Spakman and Wortel*, 2004].

9.3. Relationship in Space, Time, and Geometry Between Oppositely Propagating Rifts and Oppositely Propagating Slab Tears

[64] The oppositely propagating slab tear scenario (Figure 10) encompasses a number of features which are closely related in space, time and geometry to the double saloon door seafloor spreading model.

[65] First, the adapted slab detachment and slab tear propagation model (Figure 10), which is implicit in earlier reconstructions [*Lonergan and White*, 1997; *Carminati et al.*, 1998; *Wortel and Spakman*, 2000] and explicit in later syntheses [*Faccenna et al.*, 2004; *Rosenbaum and Lister*, 2004a, 2004b; *Spakman and Wortel*, 2004] dictates slab tear propagation in opposite directions along the North African Margin. This configuration closely resembles the pairs of oppositely directed propagating rifts in the double saloon door seafloor spreading episode in the Algerian and Liguro-Provencal basins (Figures 4, 5, 7, and 8).

[66] Second, following the original ideas of *Wortel and Spakman* [2000, Figure 3] but with a tear extending in both directions, the resultant gap in the subducting slab is rhombic in form (Figure 10b), again similar to the shape of the basins produced by the double saloon door model (Figures 4, 5, 7, and 8).

[67] Third, existing reconstructions [*Lonergan and White*, 1997; *Carminati et al.*, 1998; *Wortel and Spakman*, 2000] suggest that this rhombic tear in the subducting slab began to occur 18–15 Myr ago, whereas the rhombic combined Algerian/Liguro-Provencal oceanic basin accreted either 21–18 Ma [*Montigny et al.*, 1981; *Rehault et al.*, 1984; *Rosenbaum et al.*, 2002], 19–16 Ma [*Speranza et al.*, 2002], or from 21 to 15 Ma (sections 4 and 5.4, quoting *Ferrandini et al.* [2003]). The two scenarios, slab detachment and double saloon door seafloor spreading, are therefore closely related in time and space.

[68] Fourth, in the *Wortel and Spakman* [2000] model, the downward pull of the subducting slab is no longer exerted in the detached area but rather acts on that part of the slab which remains attached. The downward force of the sinking slab is therefore concentrated on the areas to the west and east of the tips of the propagating tears. This geometry (Figures 10a and 10b) is very similar to the scenario outlined in the double saloon door model as the two doors swing open on their hinges (Figures 9b and 9c). Initially, one force is capable of swinging open both doors (Figure 9b), whereas later, as the doors separate, two distinct forces are required to continue opening the doors (Figure 9c). Extending this analogy to plates West 2 and East 2 (Figure 5b) requires a more westerly positioned force acting on West 2, and a more easterly positioned force acting on East 2. During the oceanic accretion phase in the Algerian and Liguro-Provencal Basin, these plates are represented by the Kabylies terranes and the Corsica/Sardinia Block, respectively. The coincidence in space, time, and geometry of the double saloon door spreading episode and the modified slab detachment model suggests a cause and effect relationship between the two (sections 9.4 and 9.5).

9.4. Slab Detachment as the Trigger for Oppositely Directed Rifts

[69] If the slab detachment existed earlier than 18 Ma, could it be the driving mechanism for Burdigalian/Langhian double saloon door back-arc seafloor spreading in the Algerian and Liguro-Provencal basins? Such a driving mechanism has been suggested [*Carminati et al.*, 1998] for the extension of the Provencal Basin and the Valencia Trough, for the reorganization of slab rollback to the Tyrrhenian Basin, and for its concentration in the southeast Tyrrhenian Basin. The five characteristic features of *Davies and Von Blanckenburg* [1995], bimodal magmatism, uplift, regional metamorphism, extensional structures, and abundant intermontane sedimentation are considered diagnostic. Similarly, slab detachment in the Carpathians is invoked to provide asthenospheric upwelling within a subducting slab, leading to contemporaneous alkaline and calc-alkaline volcanism, respectively [*Chalot-Prat and Girbacea*, 2000].

9.5. Double Saloon Door Seafloor Spreading as a Trigger for Plate Tectonic Reorganizations, Associated With Slab Detachment in the Burdigalian/Langhian Episode

[70] The dispersed terranes of the western Mediterranean comprise Hercynian basement and Jurassic-Cretaceous

cover thickened by Cretaceous and Paleogene compressive HP LT Alpine tectonometamorphic events, the latest of which range from 38 to 25 Ma [*Monié et al.*, 1988; 1992; *Rossetti et al.*, 2001; *Roca*, 2002; *Faccenna et al.*, 2004; *Mascle et al.*, 2004; *Rosenbaum and Lister*, 2004a].The evolution of the western Mediterranean (see references in section 4) comprises a series of back-arc spreading episodes punctuated by tectonic reorganizations. First, the Valencia Trough/Liguro-Provencal Basin, floored by continental crust, opens between 28 and 20 Ma. Extension begins south of the Balearic Peninsula in the Kabylies 25–22 Ma, and oceanic crust accretes in the Liguro-Provencal and Algerian basins either from 21 to 18 Ma, from 19 to 16 Ma, or from 21 to 15 Ma. Evidence for stretching and subsidence east of Corsica dates from the Langhian, but rifting of the northern Tyrrhenian Basin dates from 9 to 5 Ma, with seafloor spreading in the Vavilov Basin from 4.3 to 2.6 Ma. Finally, extension switches to the southern Tyrrhenian Basin in the last 3 Myr, with oceanic accretion in the Marsili Basin from 1 Ma to the present. These extension and back-arc basin forming stages last from 8 to 3 Ma. The interruptions in the general eastward migration of the arc left behind areas of thickened crust termed ‘‘boudins’’ by *Gueguen et al.* [1997], which comprise the Balearic Peninsula, the Corsica/Sardinia Block, and the thicker crust of the Issel Bridge separating the Vavilov and Marsili basins [*Sartori*, 2003].

[71] In existing models [*Lonergan and White*, 1997; *Wortel and Spakman*, 2000], slab detachment is initiated by the collision of the Kabylies Block with North Africa 18–15 Ma, thereby choking the subduction process by introducing light material of continental North Africa into the subduction zone. Similarly, the arrival of the buoyant carbonate platforms of Campania-Lucania, Latium-Abruzzi, and Apulia to the east of the Calabrian Arc has been invoked to choke subduction in the southern Apennines 6.5 Ma [*Rosenbaum and Lister*, 2004b]. However, the observations of *Gueguen et al.* [1997] regarding ‘‘boudins’’ suggest an episodic process.

[72] Cold subducting slabs have a cooling effect on the mantle wedge above them and can induce convection in the overlying mantle wedge [*Peacock and Wang*, 1999]. While arc volcanics are likely due to fluid fluxing of downwelling mantle, back-arc spreading centers are probably caused by adiabatic decompression melting of upwelling mantle [e.g., *Saunders and Tarney*, 1991; *Stern et al.*, 2003]. When oceanic accretion occurs in the double saloon door seafloor spreading model, and a spherical triangular area of oceanic crust begins to develop, a rift propagates northward within this triangular area (Figures 5a and 5b). The tip of this rift is juxtaposed with the central or youngest seafloor spreading isochron between the northern plates West 1 and East 1, and the southern plates West 2 and East 2. This essentially provides a map view of the top of the upwelling cell which causes back-arc spreading. In the Burdigalian/Langhian oceanic accretion phase in the Algerian and Liguro-Provencal basins, propagation within the spherical triangular area is NW oriented (Figure 7) and is opposite to the direction of subduction rollback (Figure 2). The main locus of oceanic accretion therefore separates from the subduction zone. Such increasing separation between the cooling effect of the subducting slab and two of the limbs of an upwelling cell may lead to the mantle convection cell becoming unstable, inducing its interruption. Lateral flow of material in the direction of rift propagation [*Van Wijk and Blackman*, 2005] may contribute to the interruption of convection.

[73] Subducting slabs are heterogeneous, having variable thickness due to hot spot activity, fracture zones, and faults inherited from previous seafloor spreading phases [*Kirby*, 1995; *Kirby et al.*, 1996]. Intraslab seismicity in Wadati-Benioff zones is variable, and includes clusters of epicenters associated with heterogeneities such as fracture zones or areas of slab curvature. At depths where plastic or ductile behavior is expected, the faulting implied by this seismicity may occur because of the embrittlement effect of slab dehydration [*Kirby*, 1995]. In the Burdigalian/Langhian phase of oceanic accretion in the Algerian and Liguro-Provencal basins (Figure 7), the spherical triangular area southwest of Sardinia is located close to the area of maximum curvature of the reconstructed subduction zone (Figure 2). Furthermore, in section 5.2, it was shown that maximum extension, and by inference the maximum slab rollback force was exerted close to the North Balearic Fracture Zone (Figures 1 and 6). Coincidence of maximum curvature and maximum stress makes it likely that failure and slab detachment occur in a central locus. This geometry would be partially similar to slab detachment under Kamchatka near a sharp corner between the Pacific and North American plates [*Levin et al.*, 2002]. As noted in section 9.2, slab detachment in a central location within the Algerian and Liguro-Provencal basins is supported by the earlier eruption 11–9 Ma of alkaline volcanism in eastern Algeria than in the Betic Rif to the west, and Tunisia, Sardinia, and finally the Calabrian Arc to the east (Figure 2d).

[74] This association of alkali basalts in eastern Algeria (Figure 2d) with centrally located slab detachment, and asthenosphere upwelling (Figure 10), which in turn is related to the North Balearic Fracture Zone may suggest a link between slab detachment and the extensive alkali basalts erupted in the Empordá Basin from 10 Ma, which is here considered a northern extension of the North Balearic Fracture Zone (section 7).

10. Discussion

10.1. Propagating Rift Model

[75] The propagating rift model was developed in the context of South Atlantic rifting [*Martin*, 1984], whereas here it has been applied to back-arc extension and spreading. Rifting in the Valencia Trough, for example, occurred simultaneously with or just before compressional tectonics in the Balearic Peninsula [*Pares et al.*, 1992; *Maillard and Mauffret*, 1999; *Roca et al.*, 1999; *Roca*, 2002]. Similarly, in the Kabylies, the Sardinian Channel and Calabria, extension via low-angle detachments, and deposition of Oligocene-Miocene sediments [e.g., *Bouillin et al.*, 1999a, 1999b; *Verges and Sábat*, 1999; *Frizon de Lamotte et al.*, 2000; *Mascle et al.*, 2004] closely follows on from compressive tectonometamorphic events [*Monié et al.*, 1988, 1992;

Rossetti et al., 2001]. It is this juxtaposition which forms the basis for the reconstructions (Figure 2) propounding rollback of a subduction/forearc/back-arc system [*Malinverno and Ryan*, 1986; *Lonergan and White*, 1997; *Gueguen et al.*, 1998; *Rosenbaum et al.*, 2002]. This may infer that the propagating rift model (Figures 3, 4, and 5) is not applicable and that the southern plates West 2 and East 2 should not be shown with extended continental crust. However, back-arc spreading in the Marianas Trough over the last 5 Myr [*Kato et al.*, 2003; *Yamazaki et al.*, 2003] shows a well-imaged transition from seafloor spreading morphologies to rifted structure in arc crust, landward of the forearc trench area. This demonstrates that rifting and extension followed by seafloor spreading may be modeled in a back-arc environment.

10.2. Western Mediterranean Tectonic Reconstructions

[76] Oppositely propagating rifts are discussed here in the context of reconstructions already established in the literature (see references in section 4). Specifically, in the Burdigalian/Langhian phase (Figures 2c, 7, and 8), oceanic accretion in the Algerian Basin is considered coeval with seafloor spreading in the Liguro-Provencal Basin [e.g., *Lonergan and White*, 1997; *Gueguen et al.*, 1998; *Rosenbaum et al.*, 2002; *Mascle et al.*, 2004]. Alternatively, a younger age (Langhian to Tortonian) for the first Algerian Basin oceanic crust is preferred by *Mauffret et al.* [2004] because of thinner pre-Messinian sediment in that area compared with the Provencal Basin, and the presumed younger age of the Algerian Basin. *Carminati et al.* [1998] propose Tortonian opening of the Algerian Basin because Burdigalian oceanic accretion requires simultaneous extension both to the north and south of the Balearic Peninsula. However, early Miocene extension has been documented from the Alboran Basin in the west [*Martínez-Martínez and Azañón*, 2002], in the Kabylies, and in the Sardinian Channel [*Bouillin et al.*, 1999a, 1999b; *Verges and Sábat*, 1999; *Frizon de Lamotte et al.*, 2000; *Mascle et al.*, 2004], establishing that extension did occur both north and south of the Balearic Peninsula at this time. Furthermore, drill data show that the Alboran Basin began extending in the Burdigalian [*Comas et al.*, 1992, 1999]. A younger age for the Algerian Basin (Tortonian or Langhian/Tortonian from *Carminati et al.* [1998] or *Mauffret et al.* [2004], respectively) would imply a rift propagating east from the Alboran Basin along the Algerian Margin, in disagreement with the morphology of the Algerian Basin which narrows to the west (Figures 1, 2, and 7). The double saloon door seafloor spreading model presented here (Figures 4 and 5) and its close match to the geological, geophysical, and specifically the magnetic data, (Figures 6, 7, and 8) strongly suggests that the Liguro-Provencal Basin, the spherical triangular area southwest of Sardinia, and the western Algerian Basin all formed in one episode via an interconnected process.

10.3. Oppositely Propagating Rifts in Back-Arc Basins

[77] Here it is proposed that in the Oligocene-Burdigalian extension phase of the Valencia Trough and the Liguro-Provencal Basin, and in the Burdigalian/Langhian oceanic accretion phase in the Liguro-Provencal and Algerian basins, pairs of rifts propagated in opposite directions. If this phenomenon is common in back-arc seafloor spreading, evidence for oppositely propagating rifts may exist in various back-arc environments (A. Martin, manuscript in preparation, 2006).

[78] In the crescent-shaped Marianas Trough, a back-arc basin between the Pacific and Philippine Sea Plates, northward propagation of seafloor spreading from 18°N to 22°N over the last 5 Myr is demonstrated by successively younger anomalies abutting preexisting arc crust [*Yamazaki et al.*, 2003]. North of 22°N, seafloor spreading merges into an area of incipient rifting between the Marianas Islands arc to the east, and the West Mariana Ridge. Whereas the earliest seafloor spreading anomaly is 5 Ma between 17°N and 18°N, spreading began only 3 Ma at the southern extreme of the Marianas Trench [*Ishihara et al.*, 2001; *Kato et al.*, 2003], suggesting that a rift also propagated southward from 17°N to 13°N between 5 and 3 Ma. Although the geometry in this intraoceanic case is different, it appears that a pair of oppositely propagating rifts in a back-arc environment has been well documented by extensive magnetic and multibeam bathymetric studies.

11. Conclusions

[79] The separation of two plates about a rotation pole with initial rifting taken up by lithospheric extension (Figure 3) results in the point of first oceanic accretion propagating toward the rotation pole [*Martin*, 1984]. Applying this model to an axially positioned rift which then propagates in opposite directions, leads to the creation of a rhombic basin, initially underlain by thinned continental crust (Figures 4 and 5). The model predicts a number of features which are corroborated by geological and geophysical data from the Valencia Trough and the Liguro-Provencal and Algerian basins in the western Mediterranean (Figures 1, 2, and 6–9). Seismic stratigraphic and well data [*Alvarez-de-Buergo and Melendez-Hevia*, 1994; *Roca et al.*, 1999; *Roca*, 2002] confirm that a rift originated in the Gulf of Lion and propagated southwest into the Valencia Trough from the mid-Oligocene to the Burdigalian (28–20 Ma). Gravity, heat flow and seismic refraction data show that extension within the Valencia Trough/Liguro-Provencal Basin reached a maximum in a central location close to the North Balearic Fracture Zone [*Maerten and Séranne*, 1995; *Mauffret et al.*, 1995; *Torné et al.*, 1996; *Maillard and Mauffret*, 1999; *Negredo et al.*, 1999; *Rollet et al.*, 2002]. Regarding the Burdigalian/Langhian phase of oceanic accretion in the Liguro-Provencal and Algerian basins, the oppositely propagating rifts model predicts a number of features which are evident in data which in some cases have been available for over thirty years [*Bayer et al.*, 1973; *Rehault et al.*, 1984; *Rollet et al.*, 2002]. These include: the N70°E orientation of magnetic anomalies in the Algerian Basin, and the N30°E orientation of anomalies in the Liguro-Provencal Basin; concave-to-the-northeast fracture zones in the Liguro-Provencal Basin east of the North Balearic Fracture Zone, and concave-to-the-southwest fracture zones to its west; a spherical triangular area of NW

oriented magnetic anomalies southeast of Minorca and southwest of Sardinia; within this triangular area, the central (youngest) magnetic anomaly extends farthest to the NW, in agreement with the model prediction of northwestward propagation of a rift in this area; in the Liguro-Provencal Basin, more central (younger) magnetic anomalies successively abut thinned continental crust nearer to the rotation pole to the northeast. The latter feature illustrates the NE propagation of a rift within the Liguro-Provencal Basin, at least within its Burdigalian/Langhian phase of oceanic accretion. Geometric considerations suggest that the Kabylies Terrane and the Corsica/Sardinia Block have rotated clockwise and anticlockwise, respectively, by a total of 40°, in general agreement with paleomagnetic data (see sections 5.6 and 6 [*Montigny et al.*, 1981; *Pares et al.*, 1992; *Speranza et al.*, 2002; *Ferrandini et al.*, 2003]). Seismic tomography of the upper mantle velocity structure evinces a slab detachment along the North African margin in the late Burdigalian/Langhian [*Wortel and Spakman*, 2000]. Plate tectonic reconstructions imply that the slab tear propagated both west and east, the upshot of which is a modified slab detachment model (Figure 10) in which tears propagate in opposite directions [cf. *Spakman and Wortel*, 2004]. This is supported by the earlier (11–9 Ma) eruption of alkali basalts in the centrally located Mahgrebides [*Lonergan and White*, 1997; *Maury et al.*, 2000], whereas alkali basalts in the Betic Rif Arc date from 7 to 5 Ma [*Coulon et al.*, 2002; *Duggen et al.*, 2004], while Tunisian, Sardinian, and Calabrian Arc alkali basalts successively young from 7–5 Ma until the late Pleistocene [*Lonergan and White*, 1997; *Savelli*, 2001, 2002; *Rosenbaum and Lister*, 2004b; *Peccerillo and Lustrino*, 2005].

[80] The resultant rhombic form of the expanding slab detachment is closely associated in space and time with the rhombic geometry of the oppositely propagating rifts in the Algerian/Liguro-Provencal basins, intimating a relationship between their underlying geodynamic origins.

[81] **Acknowledgments.** I thank Angel Fernandez Lozano and Paloma Bellas Menendez for their help with artwork and literature. Reviews by Dominque Frizon de Lamotte and an anonymous reviewer helped improve the manuscript.

References

Alvarez-de-Buergo, E., and F. Melendez-Hevia (1994), Características generales de las subcuencas del margen peninsular mediterráneo (Rift del Surco de Valencia), *Acta Geol. Hisp.*, *29*(1), 67–79.

Austin, J. A., and E. Uchupi (1982), Continental-oceanic crustal transition off south west Africa, *Am. Assoc. Pet. Geol. Bull.*, *66*, 1328–1347.

Bayer, R., J. L. Le Mouel, and X. Le Pichon (1973), Magnetic anomaly pattern in the western Mediterranean, *Earth Planet. Sci. Lett.*, *19*, 168–176.

Beccaluva, L., P. Brotzu, G. Macciotta, L. Morbidelli, G. Serri, and G. Traversa (1989), Cainozoic tectono-magmatic evolution and inferred mantle sources in the Sardo-Tyrrhenian area, in *The Lithosphere of Italy*, *Adv. Earth Sci. Res.*, vol. 80, edited by A. Boriani et al., pp. 229–248, Acad. Naz. dei Lincei, Rome.

Bellon, H. (1981), Chronologie radiometrique (K-Ar) des manifestations magmatiques autour de la Mediterranee occidentale entre 33 et 1 Ma, in *Sedimentary Basins of Mediterranean Margins*, edited by F. C. Wezel, pp. 341–360, CNR Ital. Proj. of Oceanogr., Tecnoprint, Bologna, Italy.

Ben-Avraham, Z., C. J. H. Hartnady, and K. A. Kitchin (1997), Structure and tectonics of the Agulhas-Falkland Fracture Zone, *Tectonophysics*, *282*, 83–98.

Benes, V., S. D. Scott, and R. A. Binns (1994), Tectonics of rift propagation into a continental margin Western Woodlark Basin, Papua New Guinea, *J. Geophys. Res.*, *99*, 4439–4455.

Blanco, M. J., and W. Spakman (1993), The P-wave velocity structure of the mantle below the Iberian Peninsula: Evidence for a subducted lithosphere below southern Spain, *Tectonophysics*, *221*, 13–34.

Bouillin, J. P., M. Durand-Delga, and P. Olivier (1986), Betic, Rifian and Tyrrhenian Arc: Distinctive features, genesis and development stages, in *The Origin of Arcs*, edited by F. C. Wezel, pp. 281–304, Elsevier, New York.

Bouillin, J. P., T. Dumont, R. Mouterde, R. Somma, and J. C. Hippolyte (1999a), Un escarpement sous-marin permanent du Lias à l'Eocène, dans la Dorsale calcaire Péloritaine (Sicile, Italie), *C. R. Acad. Sci.*, *328*, 347–352.

Bouillin, J. P., et al. (1999b), Données géochronologiques ^{40}Ar ^{39}Ar sur les socles sarde et kabylo-péloritain submergés dans le Canal de Sardaigne (Méditerranée occidentale), *C. R. Acad. Sci.*, *328*, 529–534.

Calvert, A., E. Sandvol, D. Seber, M. Barazangi, S. Roecker, T. Mourabit, F. Vidal, and G. Alguacil (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.

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.

Chalot-Prat, F., and R. Girbacea (2000), Partial delamination of continental mantle lithosphere, uplift-related crust-mantle decoupling, volcanism and basin formation: A new model for the Pliocene-Quaternary evolution of the southern East-Carpathians, Romania, *Tectonophysics*, *327*, 83–107.

Comas, M. C., V. Garcia-Dueñas, and M. J. Jurado (1992), Neogene tectonic evolution of the Alboran Basin 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 ODP Leg 161 results, *Proc. Ocean Drill. Program Sci. Results*, *161*, 555–580.

Coulon, C., M. Megartsi, S. Fourcade, R. C. Maury, H. Bellon, A. Louni-Hacini, J. Cotten, 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*(3–4), 87–110.

Davies, J. H., and F. Von Blanckenburg (1995), Slab breakoff: A model of lithosphere detachment and its test in the magmatism and deformation of collisional orogens, *Earth and Planet. Sci. Lett.*, *129*, 85–102.

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. Turco, D. H. W. Hutton, and S. D. Knott (1989), Kinematics of the western Mediterranean, in *Alpine Tectonics*, edited by M. P. Coward, D. Dietrich, and R. G. Park, *Geol. Soc. Spec. Publ.*, *45*, 265–283.

Doglioni, C., E. Gueguen, F. Sábat, and M. Fernandez (1997), The western Mediterranean extensional basins and the Alpine orogen, *Terra Nova*, *9*, 109–112.

Duggen, S., K. Hoernle, P. van den Bogaard, and C. Harris (2004), Magmatic evolution of the Alboran region: The role of subduction in forming the western Mediterranean and causing the Messinian Salinity Crisis, *Earth Planet. Sci. Lett.*, *218*, 91–108.

Faccenna, C., T. W. Becker, F. P. Lucente, L. Jolivet, and F. Rossetti (2001), History of subduction and backarc extension in the central Mediterranean, *Geophys. J. Int.*, *145*, 809–820.

Faccenna, C., C. Piromalli, 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.

Ferrandini, J., J. Gattacceca, M. Ferrandini, A. Deino, and M.-J. Janin (2003), Chronostratigraphie et paleomagnetisme des depots oligo-miocenes de Corse: Implications geodynamiques pour l'ouverture du bassin liguro-provencal, *Bull. Soc. Geol. Fr.*, *174*, 357–371.

Franke, D., K. Hinz, and O. Oncken (2001), The Laptev Sea rift, *Mar. Pet. Geol.*, *18*, 1083–1127.

Frizon de Lamotte, D., J. Andrieux, and J. C. Guezou (1991), Cinematique des chevauchements neogenes dans l'Arc betico-rifain: Discussion sur les modeles geodynamiques, *Bull. Soc. Geol. Fr.*, *162*, 611–626.

Frizon de Lamotte, D., B. Saint Bezar, R. Bracene, and E. Mercier (2000), The two main steps of the Atlas building and geodynamics of the western Mediterranean, *Tectonics*, *19*, 740–761.

Froidevaux, C., R. Brousse, and H. Bellon (1974), Hot spot in France?, *Nature*, *248*, 749–751.

Gelabert, B., F. Sábat, and A. Rodríguez-Perea (2002), A new proposal for the late Cenozoic geodynamic evolution of the western Mediterranean, *Terra Nova*, *14*, 93–100.

Goula, X., C. Olivera, J. Fleta, B. Grellet, R. Lindo, R. L. Rivera, A. Cisternas, and D. Carbon (1999), Present and recent stress regime in the eastern part of the Pyrenees, *Tectonophysics*, *308*, 487–502.

Gueguen, E., C. Doglioni, and M. Fernandez (1997), Lithospheric boudinage in the western Mediterranean back-arc basin, *Terra Nova*, *9*, 184–187.

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*, 1072–1074.

Ishihara, T., R. J. Stern, P. Fryer, S. H. Bloomer, and N. C. Becker (2001), Seafloor spreading in the southern Mariana Trough inferred from 3-component magnetometer data, *Eos Trans. AGU*, *82*(47), Fall Meet. Suppl., Abstract T41C-0895.

Ivaldi, J.-P., H. Bellon, P. Guardia, C. Mangan, C. Muller, J.-L. Perez, and S. Terramorsi (2003), Contexte lithostructural, Ages ^{40}K ^{40}Ar et geochimie du volcanisme calco-alcalin tertiaire de Cap-d'Ail dans le tunnel ferroviaire de Monaco, *C. R. Geosci.*, *335*, 411–421.

Johnson, H. P., J. L. Karsten, J. R. Delaney, E. E. Davis, R. G. Currie, and R. L. Chase (1983), Offset of the Juan de Fuca Ridge: Evolution of a propagating rift, *J. Geophys. Res.*, *88*, 2297–2315.

Karig, D. E. (1974), Evolution of arc systems in the western Pacific, *Annu. Rev. Earth Planet. Sci.*, *2*, 51–78.

Kato, T., J. Beavan, T. Matsushima, Y. Kotake, J. T. Camacho, and S. Nakao (2003), Geodetic evidence of back-arc spreading in the Mariana Trough, *Geophys. Res. Lett.*, *30*(12), 1625, doi:10.1029/2002GL016757.

Kirby, S. (1995), Interslab earthquakes and phase changes in subducting lithosphere, *U.S. Natl. Rep. IUGG, 1991–1994, Rev. Geophys.*, *33*(S1), 287–298.

Kirby, S. H., S. Stein, E. A. Okal, and D. C. Rubie (1996), Metastable mantle phase transformations and deep earthquakes in subducting oceanic lithosphere, *Rev. Geophys.*, *34*, 261–306.

Levin, V., N. Shapiro, J. Park, and M. Ritzvoller (2002), Seismic evidence for catastrophic slab loss beneath Kamchatka, *Nature*, *418*, 763–766, doi:10.1038/nature00973.

Lonergan, L., and N. White (1997), Origin of the Betic-Rif mountain belt, *Tectonics*, *16*, 504–522.

Maerten, L., and M. Séranne (1995), Extensional tectonics in the Oligo-Miocene Hérault Basin (S. France), Gulf of Lion margin, *Bull. Soc. Geol. Fr.*, *166*, 739–749.

Maillard, A., and A. Mauffret (1999), Crustal structure and riftogenesis of the Valencia Trough (northwestern Mediterranean Sea), *Basin Res.*, *11*, 357–379.

Maillard, A., V. Gaullier, B. C. Vendeville, and F. Odonne (2003), Influence of differential compaction above basement steps on salt tectonics in the Liguro-Provencal Basin, northwest Mediterranean, *Mar. Pet. Geol.*, *20*, 13–27.

Malinverno, A., and W. B. F. 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.

Manighetti, I., P. Tapponnier, V. Courtillot, S. Gruszow, and P. Y. Gillot (1997), Propagation of rifting along the Arabia-Somalia plate boundary: The gulfs of Aden and Tadjoura, *J. Geophys. Res.*, *102*, 2681–2710.

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.

Martin, A. K. (1984), Propagating rifts: Crustal extension during continental rifting, *Tectonics*, *3*, 611–617.

Martin, A. K. (1987), Plate reorganisations around Southern Africa, hot-spots and extinctions, *Tectonophysics*, *142*, 309–316.

Martínez-Martínez, J. M., and J. M. Azañón (2002), Orthogonal extension in the hinterland of the Gibraltar Arc (Betic, SE Spain), *J. Virtual Explor.*, *8*, 1–20.

Mascle, G., P. Tricart, L. Torelli, J. P. Bouillin, F. Rolfo, H. LaPierre, P. Monie, S. Depardon, J. Mascle, and D. Peis (2001), Evolution of the Sardinia Channel (western Mediterranean): New constraints from a diving survey on Cornacya seamount off SE Sardinia, *Mar. Geol.*, *179*, 179–202.

Mascle, G. H., et al. (2004), Structure of the Sardinia Channel: Crustal thinning and tardi-orogenic extension in the Apenninic-Maghrebian orogen; results of the Cyana submersible survey (SARCYA and SARTUCYA) in the western Mediterranean, *Bull. Soc. Geol. Fr.*, *175*, 607–627.

Mauffret, A., L. Montadert, M. Lavergne, and C. Willm (1978), Geological and geophysical setting of DSDP site 372 (western Mediterranean), *Initial Rep. Deep Sea Drill. Proj.*, *42*(1), 889–897.

Mauffret, A., G. Pascal, A. Maillard, and C. Gorini (1995), Tectonics and deep structure of northwestern Mediterranean basin, *Mar. Pet. Geol.*, *12*(6), 645–666.

Mauffret, A., D. Frizon de Lamotte, S. Lallement, C. Gorini, and A. Maillard (2004), E-W opening of the Algerian Basin (western Mediterranean), *Terra Nova*, *16*(5), 257–264.

Maury, R. C., et al. (2000), Post-collisional Neogene magmatism of the Mediterranean Maghreb margin: A consequence of slab breakoff, *C. R. Acad. Sci.*, *331*, 159–173.

Molnar, P., and T. Atwater (1978), Interarc spreading and cordilleran tectonics as alternates related to the age of subducted ocean lithosphere, *Earth Planet. Sci. Lett.*, *41*, 330–340.

Monié, P., H. Maluski, A. Saadallah, and R. Caby (1988), New ^{39}Ar-^{40}Ar ages of Hercynian and Alpine thermotectonic events in Grande Kabylie (Algeria), *Tectonophysics*, *152*, 53–69.

Monié, P., R. Montigny, and H. Maluski (1992), Age burdigalien de la tectonique ductile extensive dans le massif de l'Edough (Kabylies, Algérie). Donnees radiometriques ^{39}Ar-^{40}Ar, *Bull. Soc. Géol. Fr.*, *5*, 571–584.

Montigny, R., J. B. Edel, and R. Thuizat (1981), Oligo-Miocene rotation of Sardinia: K-Ar ages and paleomagnetic data of Tertiary volcanics, *Earth Planet. Sci. Lett.*, *54*, 261–271.

Negredo, A., M. Fernandez, M. Torné, and C. Doglioni (1999), Numerical modelling of simultaneous extension and compression: The Valencia Trough (western Mediterranean), *Tectonics*, *18*, 361–374.

Nehlig, P., P. Boivin, A. De Goer, J. Mergoil, G. Prouteau, G. Sustrac, and D. Thieblemont (2003), Les Volcans du Massif Central, Num. Spec. Massif Central, pp. 1–41, Bur. de Rec. Geol. et Minieres, Orléans, France.

Oxburgh, E. R., and E. M. Parmentier (1978), Thermal processes in the formation of continental lithosphere, *Philos. Trans. R. Soc. London, Ser. A*, *288*, 415–429.

Pares, J. M., R. Freeman, and E. Roca (1992), Neogene structural development in the Valencia Trough margins from palaeomagnetic data, *Tectonophysics*, *203*, 111–124.

Patacca, E., and P. Scandone (1989), Post Tortonian mountain building in the Apennines: The role of the pressure sinking of a relic lithospheric slab, in *The Lithosphere of Italy*, *Adv. Earth Sci. Res.*, vol. 80, edited by A. Boriani et al., pp. 157–176, Acad. Naz. dei Lincei, Rome.

Peacock, S. M., and K. Wang (1999), Seismic consequences of warm versus cool subduction zone metamorphism: Examples from northeast and southwest Japan, *Science*, *286*, 937–939.

Peccerillo, A., and M. Lustrino (2005), Compositional variations of Plio-Quaternary magmatism in the circum-Tyrrhenian area: Deep versus shallow mantle processes, in *Plates, Plumes and Paradigms*, edited by G. R. Foulger et al., *Spec. Pap. Geol. Soc. Am.*, *388*, 421–434.

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

Rehault, J.-P., G. Boillot, and A. Mauffret (1984), The western Mediterranean basin geological evolution, *Mar. Geol.*, *55*, 447–477.

Ricou, L.-E. (1995), The plate tectonic history of the past Tethys Ocean, in *The Ocean Basins and Margins*, vol. 8, *The Tethys Ocean*, edited by A. E. M. Nairn, B. Vrielynck, and J. Dercourt, pp. 3–70, Springer, New York.

Roca, E. (2002), The northwest-Mediterranean basin (Valencia Trough, Gulf of Lions and Liguro-Provençal basins): Structure and geodynamic evolution, in *PeriTethyan Rift/Wrench Basins and Passive Margins*, *Peri-Tethys Mem.*, vol. 6, edited by P. A. Ziegler et al., *Mem. Mus. Natl. Hist. Nat.*, *186*, 671–706.

Roca, E., M. Sans, L. Cabrera, and M. Marzo (1999), Oligocene to middle Miocene evolution of the central Catalan margin (northwestern Mediterranean), *Tectonophysics*, *315*, 209–233.

Rollet, N., J. Déverchère, M. Beslier, P. Guennoc, J. Réhault, M. Sosson, and C. Truffert (2002), Back arc extension, tectonic inheritance, and volcanism in the Ligurian Sea, western Mediterranean, *Tectonics*, *21*(3), 1015, doi:10.1029/2001TC900027.

Rosenbaum, G., and G. S. Lister (2004a), Formation of arcuate orogenic belts in the western Mediterranean region, *Spec. Pap. Geol. Soc. Am.*, *383*, 41–56.

Rosenbaum, G., and G. S. Lister (2004b), Neogene and Quaternary rollback evolution of the Tyrrhenian Sea, the Apennines, and the Sicilian Maghrebides, *Tectonics*, *23*, TC1013, doi:10.1029/2003TC001518.

Rosenbaum, G., G. S. Lister, and C. Duboz (2002), Reconstruction of the tectonic evolution of the western Mediterranean since the Oligocene, *J. Virtual Explor.*, *8*, 107–130.

Rossetti, F., C. Faccenna, B. Goffe, P. Monie, A. Argentieri, R. Funiciello, 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, *Tectonophysics*, *20*, 112–133.

Rossi, P., et al. (1998), Importance du volcanisme calco-alcalin miocene sur la marge sud-ouest de la Corse (campagne MARCO), *C. R. Acad. Sci.*, *327*, 369–376.

Royden, L. H. (1993), Evolution of retreating subduction boundaries formed during continental collision, *Tectonics*, *12*, 629–638.

Sanz de Galdeano, C. (1990), La prolongación hacia el sur de las fosas y desgarres del norte y centro de Europa: Una propuesta de interpretación, *Rev. Soc. Geol. Esp.*, *3*, 231–241.

Sartori, R. (2003), The Tyrrhenian backarc basin and subduction of the Ionian lithosphere, *Episodes*, *26*(3), 217–221.

Saula, E., J. Picart, E. Mató, M. Llenas, M. Losantos, X. Berástegui, and J. Agustí (1994), Evolución geodinamica de la fosa del Empordá y las Sierras Transversales, *Acta Geol. Hisp.*, *29*(2–4), 55–75.

Saunders, A. D., and J. Tarney (1991), Back-arc basalts, in *Oceanic Basalts*, edited by P. A. Floyd, pp. 219–263, Blackie, Malden, Mass.

Savelli, C. (2001), Two-stage progression of volcanism (8–0 Ma) in the central Mediterranean (southern Italy), *J. Geodyn.*, *31*, 393–410.

Savelli, C. (2002), Time-space distribution of magmatic activity in the western Mediterranean and peripheral orogens during the past 30 Ma (a stimulus to geodynamic considerations), *J. Geodyn.*, *34*, 99–126.

Seber, D., M. Barazangi, B. A. Tadili, M. Ramdani, A. Ibenbrahim, and D. Ben Sari (1996), Three-dimensional upper mantle structure beneath the intraplate Atlas and interplate Rif mountains of Morocco, *J. Geophys. Res.*, *101*, 3125–3138.

Séranne, M. (1999), The Gulf of Lion continental margin (NW Mediterranean) revisited by IBS: An overview, in *The Mediterranean Basins: Ter-*

tiary Extensions Within the Alpine Orogen, edited by B. Durand et al., *Geol. Soc. Spec. Publ.*, *156*, 15–36.

Spakman, W., and M. J. R. Wortel (2004), A tomographic view on western Mediterranean geodynamics, in *The TRANSMED Atlas: The Mediterranean Region From Crust to Mantle*, edited by W. Cavazza et al., 31–52, Springer, New York.

Speranza, F., I. M. Villa, L. Sagnotti, F. Florindo, D. Cosentino, P. Cipollari, and M. Mattei (2002), Age of the Corsica-Sardinia rotation and Liguro-Provençal basin spreading: New paleomagnetic and Ar/Ar evidence, *Tectonophysics*, *347*, 231–251.

Stern, R. J., M. J. Fouch, and S. Klemperer (2003), An overview of the Izu-Bonin-Mariana subduction factory, in *Inside the Subduction Factory*, *Geophys. Monogr. Ser.*, vol. 138, edited by J. Eiler and M. Hirschmann, pp. 175–222, AGU, Washington, D. C.

Taylor, B., A. M. Goodliffe, and F. Martinez (1999), How continents breakup: Insights from Papua New Guinea, *J. Geophys. Res.*, *104*, 7497–7512.

Toksoz, N., and P. Bird (1977), Formation and evolution of marginal basins and continental plateaus, in *Island Arcs, Deep Sea Trenches and Back-arc Basins*, *Maurice Ewing Ser.*, vol. 1, edited by M. Talwani and W. C. Pitman, 379–393, AGU, Washington, D. C.

Torné, M., E. Banda, and M. Fernandez (1996), The Valencia Trough: Geological and geophysical constraints on the basin formation model, in *Structure and Prospects of Alpine Basins and Forelands*, edited by P. A. Ziegler and F. Horvath, *Mem. Nat. Hist. Mus.*, *2*, *170*, 103–128.

Van Wijk, J. W., and D. W. Blackman (2005), Dynamics of continental rift propagation: The end-member modes, *Earth Planet. Sci. Lett.*, *229*, 247–258.

Verges, J., and F. Sábat (1999), Constraints on the western Mediterranean kinematics evolution along a 1,000 km transect from Iberia to Africa, *Geol. Soc. Spec. Publ.*, *156*, 63–80.

Vogt, P. R., R. H. Higgs, and G. L. Johnson (1971), Hypothesis on the origin of the Mediterranean Basin: Magnetic data, *J. Geophys. Res.*, *76*, 3207–3228.

Wortel, M. J. R., and W. Spakman (2000), Subduction and slab detachment in the Mediterranean-Carpathian region, *Science*, *290*, 1910–1917.

Yamazaki, T., N. Seama, K. Okino, K. Kitada, M. Joshima, H. Oda, and J. Naka (2003), Spreading process of the northern Mariana Trough: Rifting-spreading transition at 22°N, *Geochem. Geophys. Geosyst.*, *4*(9), 1075, doi:10.1029/2002GC000492.

A. K. Martin, Repsol YPF, Paseo de la Castellana 280, Madrid E-28046, Spain. (kmartin@repsolypf.com)