The Geological Society of America
Special Paper 526

# *Western Alboran peridotite exhumation in an Oligocene–Miocene oblique continental rift system*

**Frédéric Gueydan***
*Géosciences Montpellier, Université Montpellier, UMR 5243 CNRS/INSU, Place E. Bataillon, CC60, 34093 Montpellier Cedex, France*

**Gianluca Frasca**
*Géosciences Montpellier, Université Montpellier, UMR 5243 CNRS/INSU, Place E. Bataillon, CC60, 34093 Montpellier Cedex, France*, and
*Géosciences Rennes, Université Rennes 1, UMR 6118 CNRS, Campus de Beaulieu, 35042 Rennes Cedex, France*

## ABSTRACT

**The western Alboran peridotites crop out across the Strait of Gibraltar (western end of the Mediterranean) and are the largest worldwide exposure of subcontinental lithospheric mantle. The present study focuses on the Cenozoic part of the long and complex metamorphic-deformation history of the western Alboran peridotites. During the Cenozoic, continental lithosphere thinning in a back-arc setting occurred and allowed the extensional exhumation of subcontinental mantle from 70–90 km depth to shallow crustal levels. Continental rift inversion at 20 Ma then triggered the final crustal emplacement of the western Alboran peridotites: the Sierra Bermeja, Alpujata, and Carratraca peridotites, which constitute the Ronda peridotites in the Betics, and the Ceuta and Beni Bousera peridotites in the Rif. A compilation of ductile shear indicators, recorded along the crust-mantle extensional shear zone during lithosphere thinning, is used here to reconstruct the three-dimensional geometry of the Oligocene–Miocene continental rift. The western Alboran peridotite bodies were back-rotated in their initial position at 20 Ma using (1) paleomagnetic data and (2) structural constraints for an ~100 km west/southwestward displacement of the Alboran Domain. A consistent NNE-SSW shear direction is found with locally opposite sense of shear. Two-dimensional numerical models of continental rifting indicate that such opposite shearing at the Moho identifies the initial position of the rift axis. On these bases, we propose an oblique rift system elongated N-S, with several NW-SE rift axes connected by NNE-SSW transform faults. The western Alboran peridotites correspond thus to different segments of this oblique rift system. These findings are then tentatively compared to the position of (1) present-day early Miocene depocenters, and (2) onshore faults, possibly reactivating transform and axis faults of the former rift.**

*Corresponding author: frederic.gueydan@umontpellier.fr.

Gueydan, F., and Frasca, G., 2017, Exhumation of western Alboran peridotites in an Oligocene–Miocene oblique continental rift system, *in* Bianchini, G., Bodinier, J.-L., Braga, R., and Wilson, M., eds., The Crust-Mantle and Lithosphere-Asthenosphere Boundaries: Insights from Xenoliths, Orogenic Deep Sections, and Geophysical Studies: Geological Society of America Special Paper 526, p. 73–87, doi:10.1130/2017.2526(04). 

## INTRODUCTION

The Ronda and Beni Bousera peridotites crop out close to the Gibraltar arc and are major features of westernmost Mediterranean geology. Although recent tomographic images show a subvertical slab below the Gibraltar arc (i.e., the Alboran high Vp anomaly; Bezada et al., 2013; Villaseñor et al., 2015), the relationship between exhumation of these peridotites bodies (hereafter called the western Alboran peridotites) and subduction slab rollback evolution is still unresolved. In the central Mediterranean (Apennines), starting from the late Oligocene, subduction slab rollback led to the successive opening of the Ligurian-Provençal basin and the Tyrrhenian Sea, from the Gulf of Genoa to the south of the Balearic system (Doglioni et al., 1997; Wortel and Spakman, 2000). In contrast, in the Western Mediterranean (Gibraltar), the amount and the timing of subduction rollback remain controversial (Lonergan and White, 1997; Wortel and Spakman, 2000; Vergés and Férnandez, 2012).

The Gibraltar region is characterized by two orogenic systems, the Betics in Spain and the Rif in Morocco (Faccenna et al., 2004; Rosenbaum and Lister, 2004; Royden, 1993; Chalouan et al., 2008; Crespo-Blanc and Frizon de Lamotte, 2006). Two Tertiary fold-and-thrust belts surround the metamorphic domain, which crops out along the coast and at the bottom of the Alboran Sea and is therefore named Alboran Domain (Didon et al., 1973; García-Dueñas et al., 1992; Hsü et al., 1973; Kornprobst, 1973; Sánchez-Gómez et al., 1999). The western portion of the Alboran Domain includes the Ronda and Beni Bousera exposures of subcontinental lithospheric mantle (western Alboran peridotites [WAP] in Fig. 1; Darot, 1974; Kornprobst, 1974; Obata, 1980). The age and the tectonic context of the exhumation of the western Alboran peridotites and their relationships with the geodynamics of the Western Mediterranean system remain controversial. The western Alboran peridotites and their surrounding Alboran continental crustal rocks have indeed experienced a polycyclic and complex history.

At least three stages of deformation have been recorded: (1) Variscan subduction and collision, testified by Variscan high-pressure and partial melting in the crustal rocks (e.g., Zeck and Whitehouse, 2002; Gueydan et al., 2015; Sánchez-Navas et al., 2014); (2) Jurassic Tethys opening, testified by Jurassic ages in aluminous pyroxenite layers within the western Alboran peridotites (Sánchez-Rodríguez and Gebauer, 2000); and (3) Alpine shortening and nappe stacking during Eocene times (e.g., Vergés and Fernández, 2012; Platt et al., 2013) followed by Oligocene–Miocene thinning in the back-arc region of the Alboran

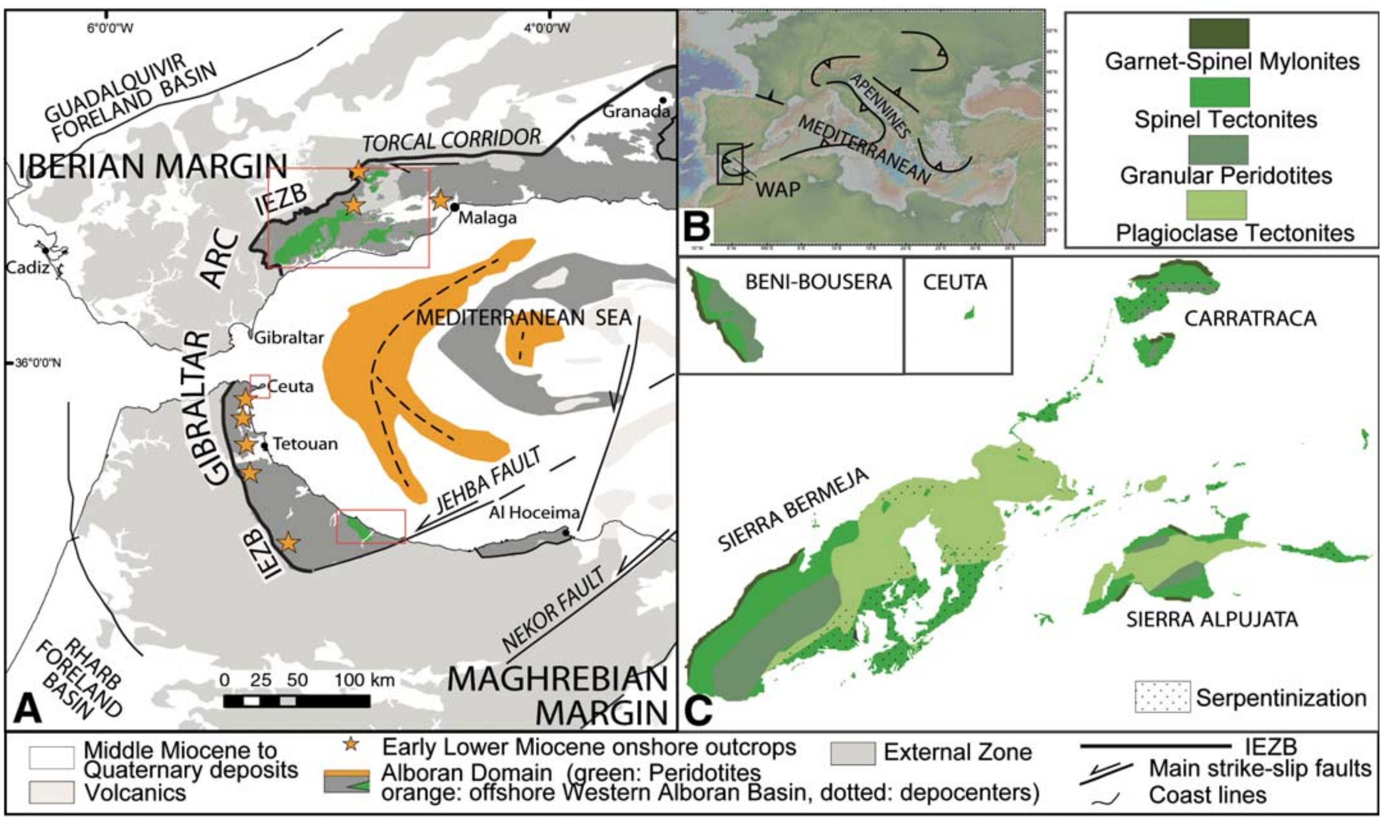



Figure 1. (A) Simplified tectonic map of the western Alboran system, with western Alboran peridotites (WAP) and late Oligocene and early Miocene sediments outlined in green and orange, respectively, within the Alboran Domain (dark gray). IEZB—Internal-External zones boundary (Platt et al., 2013).

subduction, as testified by Alpine ages in the regional foliation in peridotites and host continental crust rocks (e.g., Blichert-Toft et al., 1999; Gueydan et al., 2015), and by the ages and geochemistry of the Malaga dikes (Duggen et al., 2004; Esteban et al., 2013; Turner et al., 1999). Note that many other tectonic scenarios for Tertiary mantle exhumation have been proposed as alternative models to the back-arc exhumation, including: extrusion of a mantle wedge during transpression along a subducting slab (Mazzoli and Martín-Algarra, 2011; Tubía, 1994) or the action of successive detachments during the extensional collapse of the Betic-Rif crustal wedge (Platt et al., 2003a; Van der Wal and Vissers, 1993).

In this paper, we will focus on the Tertiary stage of exhumation of the western Alboran peridotites, from mantle depths (70–80 km) to the surface (Platt et al., 2003a; Garrido et al., 2011; Hidas et al., 2013; Van der Wal and Vissers, 1993; Mazzoli et al., 2013; Gueydan et al., 2015). The progressive rollback of the Alboran slab triggered upper continental plate thinning and hence the unroofing of the western Alboran peridotites in a back-arc setting. Subsequently, the thrusting of the former thinned lithosphere onto the Iberian and African margin led to the inversion of the back-arc (Afiri et al., 2011; Précigout et al., 2013; Frasca et al., 2015). The inversion led to the progressive westward migration of the Alboran Domain and therefore to the formation of the Gibraltar arc (Frasca et al., 2015).

The aim of this paper is to reconstruct the geometry of the Oligocene–Miocene back-arc continental rift. A compilation of ductile shear indicators occurring at the Moho during lithosphere thinning is presented here and used, together with two-dimensional (2-D) numerical models of continental rifting, to reconstruct the initial position of the rift system. Accounting for clockwise and counterclockwise rotations of the peridotite bodies during the tectonic inversion of the rift, we show that extensional unroofing of the western Alboran peridotites occurred in an oblique continental rift system elongated approximately N-S in map view.

## WESTERN ALBORAN TECTONIC FEATURES

The Internal-External zones boundary (IEZB, Platt et al., 2013; Fig. 1) shapes the western Alboran Domain across the Gibraltar arc and separates the External unmetamorphosed zone from the Internal metamorphic zone (Fig. 1). The Internal zone, called hereafter Alboran Domain, is characterized in the westernmost part by (1) the largest worldwide outcrop of subcontinental lithospheric mantle rocks (Obata, 1980) and (2) late Oligocene–early Miocene sediments, both onshore, at the base of the "Alozaina Basin" (Serrano et al., 2007), and offshore, at the base of the Western Alboran Basin (Comas et al., 1992; Watts et al., 1993; Fig. 1A). These early Miocene sediments are usually interpreted as related to a rifting phase, most probably starting at ca. 30 Ma and only registered in the western Alboran (Argles et al., 1999; Comas et al., 1999). We will show in this paper that the sediment deposition can be correlated with an Oligocene–Miocene continental rifting system, which was responsible for the extensional exhumation of the western Alboran peridotites from mantle depth to shallow crustal levels.

### Western Alboran Peridotites

The position of the western Alboran peridotites, exactly where the arcuate trend of the boundary between the Internal and External zones bends, coincides with a large positive Bouguer gravimetric anomaly (Bonini et al., 1973; Torné et al., 2000). The Ronda peridotites crop out in southern Spain and can be divided into three bodies: Sierra Bermeja (SB), Sierra Alpujata (Alp), and Carratraca (Ca), which are connected by small serpentinitic outcrops (Fig. 1B; Darot, 1974; Navarro-Vilá and Tubía, 1983; Sánchez-Gómez et al., 1999; Tubía et al., 2004). The Ceuta serpentinitic sliver links the Spanish part with the Moroccan part of the western Alboran peridotites and suggests an original continuity between the peridotitic outcrops on the two sides of the Gibraltar arc (Sánchez-Gómez et al., 1995; Sánchez-Gómez et al., 2002). The Beni Bousera body in the Moroccan Rif is smaller in size than the Ronda outcrops but has similar characteristics (Fig. 1B; Afiri et al., 2011; Frets et al., 2014; Kornprobst, 1974; Reuber et al., 1982).

The western Alboran peridotites have a roughly concentric pattern of all the three peridotite facies (i.e., garnet-, spinel-, and plagioclase-peridotite facies; Obata, 1980). Several structural-petrological studies of the Sierra Bermeja body have shown that the three traditional facies domains are related to the development of three different structural domains, coinciding partly with geochemical variations (Fig. 1; Lenoir et al., 2001; Soustelle et al., 2009; Suen and Frey, 1987; van der Wal and Bodinier, 1996; van der Wal and Vissers, 1993, 1996).

(1) Garnet-spinel-peridotites are mylonitized on a kilometer scale at the top of the mantle bodies (Figs. 1C, 2B; Précigout et al., 2013; van der Wal and Vissers, 1996). The mylonite formed by grain-size reduction and dynamic recrystallization in subcontinental mantle conditions, during decreasing pressure starting at 85 km (Argles et al., 1999; Balanyá et al., 1997; Garrido et al., 2011; Précigout et al., 2013; Tubía et al., 2004). The foliated spinel-peridotites below (Fig. 2C) are part of the same shear zone as the garnet-peridotite, as shown by Précigout et al. (2007, 2013). Crosscutting relationships between mylonite and tectonites described in Van der Wal and Vissers (1996) suggest that the spinel-tectonites were formed in a first stage of deformation and then transposed and parallelized at the base of the crust as a result of a large-scale gradient due to ductile strain localization (Précigout et al., 2013).

(2) Coarse-grained granular spinel-peridotites occur in the central part of the peridotite bodies, where Al-rich garnet pyroxenite is replaced by Al-poorer spinel-websterite (Figs. 1C and 2D). The spinel facies is separated by a "recrystallization front" defined by development of coarse granular peridotites oblique to and at the expense of the spinel-tectonite domain (van der Wal and Bodinier, 1996; Fig. 2).

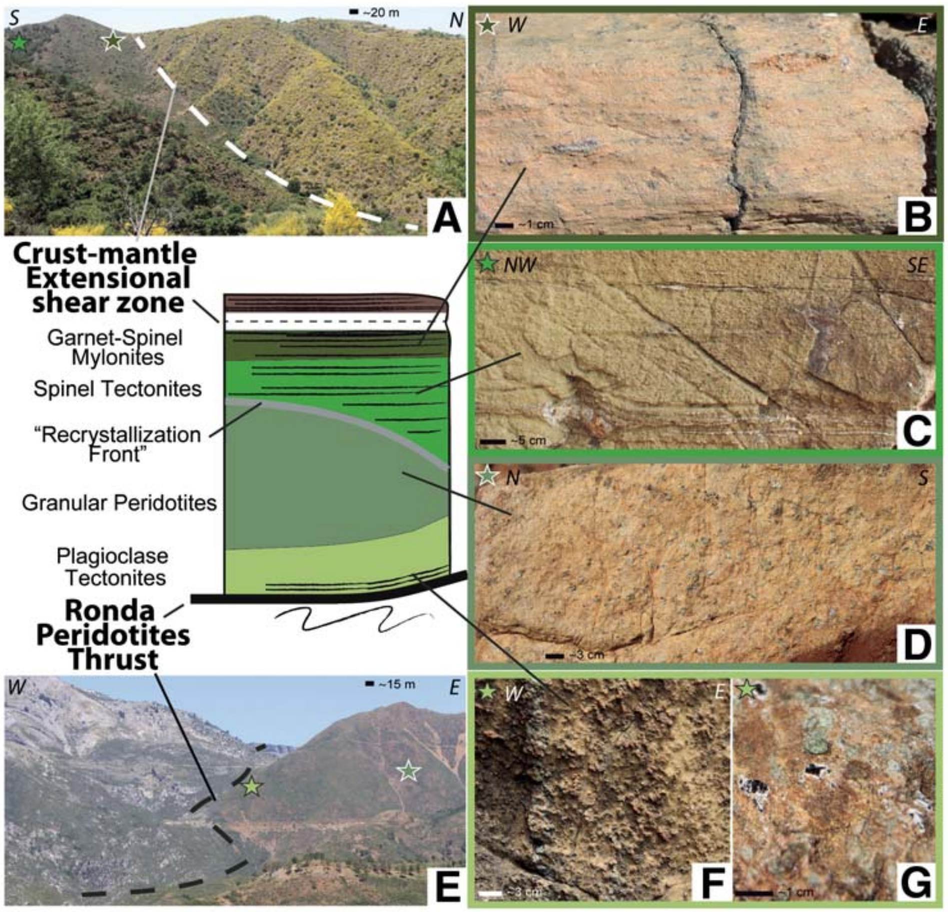



Figure 2. Main petrological and tectonic facies, presented in a schematic log with corresponding outcrop pictures, within the western Alboran peridotites (WAP) with two major tectonic contacts: (A) on top of the crust-mantle extensional shear zone (crust-mantle extensional shear zone) and (E) below the Ronda peridotites thrust (RPT). (B) Mylonitic peridotites with a pervasive foliation enclosing a centimeter-scale garnet-spinel-pyroxenite layer exhibiting strong boudinage. (C) Porphyroclastic spinel-peridotite with a decimeter-scale stretched garnet-pyroxenite layer, parallel to the peridotite foliation. (D) Coarse-granular peridotite displaying coarse black spinels and centimeter-size greenish clinopyroxenes. (E) Landscape photograph of the Ronda peridotites thrust and location of the outcrop pictures in D and F. (F) Coarse-porphyroclastic lherzolite with a foliation, marked by a strong shape preferred orientation of the pyroxenes, oblique to the vertical greenish pyroxenite. (G) Detail of the plagioclase rim around the spinel in the plagioclase tectonite.

(3) Porphyroclastic plagioclase-tectonites are at the base and developed in shallower conditions, with subordinate layers of spinel-plagioclase-olivine websterite (Figs. 1C, 2D, 2F, 2G; van der Wal and Vissers, 1996). The deformation evolved to low-temperature and low-pressure mylonites (Hidas et al., 2013). The domain contains dikes of gabbroic rocks that testify to the extreme thinning of the continental lithosphere (Hidas et al., 2015).

## Main Crust-Mantle Tectonic Contacts

Figure 3 shows tectonic maps of the western Betics and Rif with the western Alboran peridotites bodies, cropping out within the Alboran continental crust rocks, highlighted. Three types of tectonic contacts divide the western Alboran peridotites from the surrounding continental crustal rocks in the tectonic maps and cross section of Figure 3: the "Moho" contact, a thrust contact, and a high-angle fault contact.

### *"Moho" Contact*

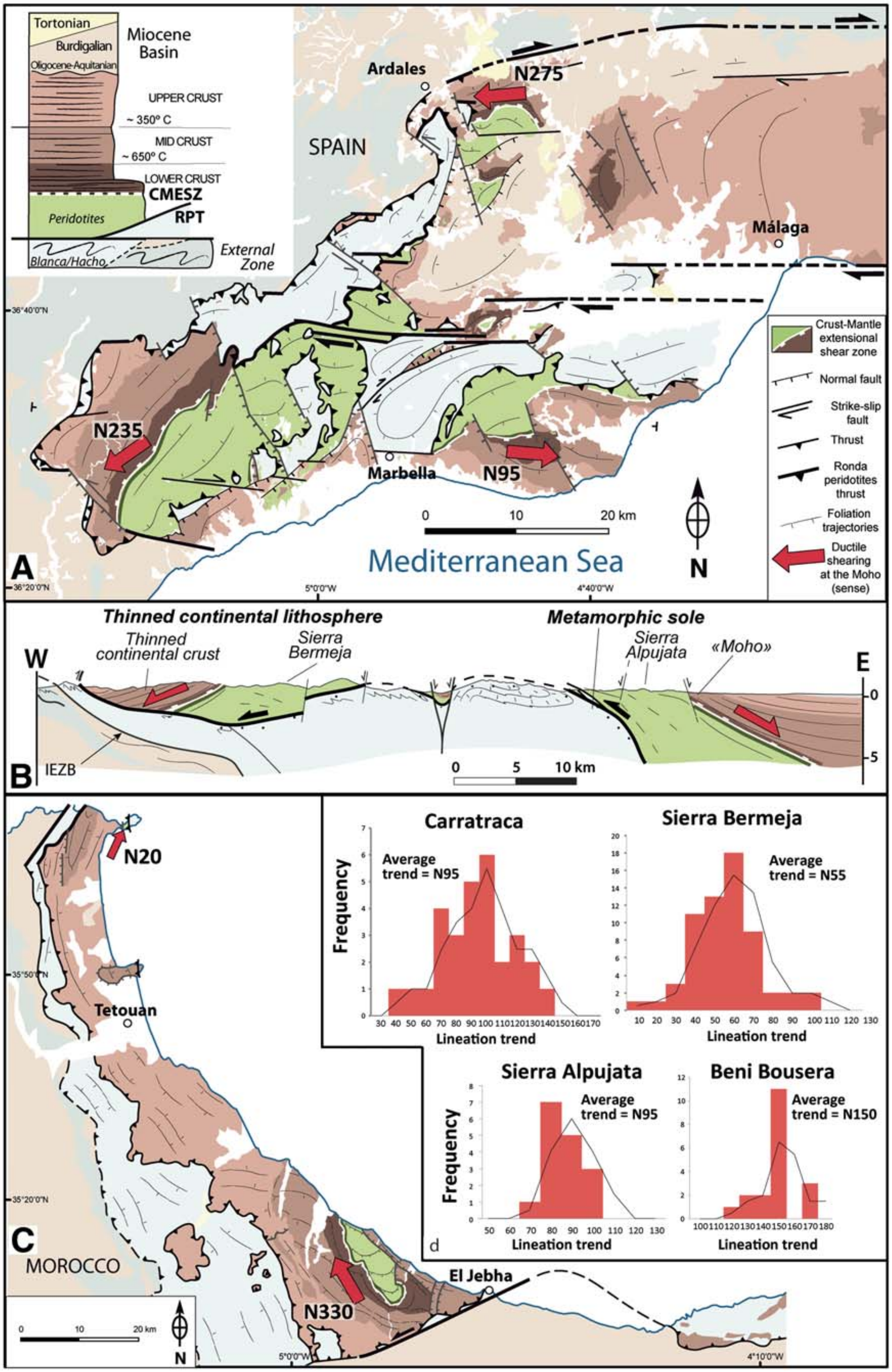
The Moho contact, at the top of the peridotites, is marked by the garnet-spinel- mylonites below and deep crust above (sheared granulites and migmatitic gneisses, Figs. 2A, 2B, 2C). In the following discussions, this contact will be called the crust-mantle extensional shear zone (thick white line in Figs. 2A, 3). Moreover, for sake of clarity, the continental rocks above the peridotites will be called the upper western Alboran (locally denoted in the past as Los Reales [Upper Alpujarrides; Tubía et al., 1997] or Filali [Lower Sebtides; Kornprobst, 1974]). We will discuss this contact in detail in the "Crust-Mantle Extensional Shear Zone" section.

### *Thrust Contact*

The thrust contact is at the bottom of the peridotites (Fig. 2E; Tubía et al., 1997, 2013). For sake of clarity, in the following, the large diversity of continental rocks below the Ronda

→

Figure 3. Tectonic maps of (A) the western Betics (modified from Frasca et al., 2015) and (C) the Rif (modified from Gueydan et al., 2015; Negro et al., 2006) with (B) an E-W cross section (location reported in A; modified from Frasca et al., 2015). The ductile shearing senses at the Moho (red arrows with mean direction of shearing in black) are inferred from the compilation of data shown in the histograms (see text for references). RPT—Ronda peridotites thrust; CMESZ—crust-mantle extensional shear zone; IEZB—Internal-External zones boundary.


Tortonian
Burdigalian
Oligocene-Aquitanian
Miocene Basin
UPPER CRUST
~ 350° C
MID CRUST
~ 650° C
LOWER CRUST
CMESZ
Peridotites
RPT
Blanca/Hacho
External Zone
Ardales
N275
SPAIN
Málaga
N235
Marbella
N95
Mediterranean Sea
0 10 20 km
N
A
Crust-Mantle extensional shear zone
Normal fault
Strike-slip fault
Thrust
Ronda peridotites thrust
Foliation trajectories
Ductile shearing at the Moho (sense)
36°40'0"N
36°20'0"N
5°0'0"W
4°40'0"W
Thinned continental lithosphere
Metamorphic sole
Thinned continental crust
Sierra Bermeja
Sierra Alpujata
«Moho»
W
E
0
5
0 5 10 km
IEZB
B
N20
Tetouan
35°50'0"N
35°20'0"N
C
MOROCCO
El Jebha
N330
0 10 20 km
5°0'0"W
4°10'0"W
Carratraca
Average trend = N95
Sierra Bermeja
Average trend = N55
Sierra Alpujata
Average trend = N95
Beni Bousera
Average trend = N150
Frequency
Lineation trend
d

peridotites will be called the lower western Alboran peridotites (locally called Ojèn—Tubía et al., 1997; Guadaiza—Esteban et al., 2008; Yunquera—Esteban et al., 2005; Blanca-Hacho—Didon et al., 1973; Dorsale—Chalouan et al., 2008; Vitale et al., 2014: "Las Nieves Unit"—Mazzoli and Martín-Algarra, 2011).

The thrust will hereafter be called the Ronda peridotites thrust (thick black line in Figs. 2E, 3) and is marked by (1) a metamorphic sole in the underlying crustal rocks (Esteban et al., 2008; Mazzoli et al., 2013; Tubía et al., 1997), and (2) top-to-the-W mylonites in the plagioclase-peridotites (Hidas et al., 2013; Frasca et al., 2015; Figs. 2 and 3). The Ronda peridotites thrust cuts through the whole lithosphere section (peridotites and crust). However, the degree of high-temperature metamorphism along the thrust is variable, from high grade (migmatites in the Ojén region) to low grade (Dorsale in Morocco). The high-grade metamorphic sole is observable onshore in Spain through tectonic windows within the peridotites (Blanca unit; Fig. 3A and cross section on Fig. 3B), while the low-grade thrust is observable in Morocco, where only the most external part of the Ronda peridotites thrust crops out (Dorsale unit; Fig. 3C).

Activity on the Ronda peridotites thrust was coeval with the formation of the Gibraltar arc and deformation in the External zone. The Ronda peridotites thrust age is well constrained by a wealth of high-temperature ages at ca. 20 Ma in leucogranite dikes associated with the "hot" Ronda peridotites thrust, and by syndeformational Burdigalian-Langhian deposits in both footwall and hanging wall of the Internal-External boundary zone (Frasca et al., 2015). The early Miocene therefore marked the onset of the main shortening event in the western Betics, as exemplified by the formation at that time of the Guadalquivir foreland basin (Férnandez et al., 1998; Fig. 1). In Morocco, the main shortening event is also proposed to have started in the early Miocene and produced a nappe stack involving the Beni Bousera peridotite (Vitale et al., 2014). Progressive westward migration of the shortening led to the formation of the Gibraltar arc and also to extensional reactivation of previously shortening zones (see Discussion in Frasca et al., 2015).

### *High-Angle Faults*

High-angle faults (with normal or strike-slip kinematics) crosscut the two former contacts and locally allow the direct juxtaposition of mantle rocks with very shallow upper-crustal rocks (north of the Sierra Alpujata massif in Spain and east of Beni Bousera in Morocco for example; Fig. 3). Frasca et al. (2015) have shown that thrusting and westward motion started at 20 Ma, took place from 20 Ma to present day, and occurred by the coeval activity of N60° frontal thrusts, N140 normal faults, and E-W strike-slip corridors that accommodated a N-S strain gradient. In the present study, we used these structural constraints to identify the direction and the amount of displacement of the Alboran Domain since 20 Ma (see details in the next section). Note also that widespread low-angle normal faults are present in the upper western Alboran and may locally mark the crust-mantle contact (Esteban et al., 2013; García-Dueñas et al., 1992; Frasca et al., 2016).

In the rest of this paper, we will discuss mainly the crust-mantle extensional shear zone and its significance for mantle unroofing. The other contacts accommodated the horizontal displacement of the unroofed mantle and are thus essential for the restoration presented in this paper.

## Crust-Mantle Extensional Shear Zone and Continental Lithosphere Thinning

In the Betics and Rif, the upper western Alboran section represents an entire continental crustal section on top of subcontinental mantle rocks (Balanyá et al., 1997; Gueydan et al., 2015), and, from bottom to top, they are composed by: (1) lower crust (dark brown in Fig. 3: granulites, migmatitic gneiss, with peak temperature higher than 650 °C; see Negro et al., 2006); (2) midcrust (brown in Fig. 3: gneiss, schists, with peak temperature between 650 °C and 350 °C; see Negro et al., 2006); and (3) upper crust (light brown in Fig. 3: low to unmetamorphosed sediments). The local names of these crustal domains are Alpujarrides and Filali (Lower Sebtides), in Spain and Morocco, respectively, for the metamorphic domain (deep and midcrust), and Malaguide and Ghomaride, for the nonmetamorphosed domain.

In Spain, the present-day thickness of this exhumed continental crust is <10 km, with minimum values at <1 km (see cross section on Fig. 3B; García-Dueñas et al., 1992; Frasca et al., 2016), and this testifies to a major crustal thinning event. In the Rif, the thickness of the exhumed continental crust is of the order to 5–10 km (see Negro et al., 2006). The crustal rocks have recorded a continuous decompression locally coeval with an increase in temperature and partial melting (Balanyá et al., 1997; Soto and Platt, 1999; Platt and Whitehouse, 1999; Barich et al., 2014; Gueydan et al., 2015).

The mantle in the upper western Alboran section has also recorded a strong decompression from mantle depth (garnet-peridotites) to low pressure (spinel- and even plagioclase-peridotites; e.g., Garrido et al., 2011; Afiri et al., 2011). Note that a former unroofing event from the diamond stability field to the garnet field may have occurred either in Variscan or Jurassic time (Pearson et al., 1989; Davies et al., 1993; Sánchez-Rodríguez and Gebauer, 2000). Deformation in the mantle shows a strain gradient from mantle to crust, suggesting a mantle-crust shear zone (Précigout et al., 2007, 2013). In Sierra Bermeja, Carratraca, and Beni-Bousera, the crust-mantle contact is characterized by garnet-spinel-mylonites, while the core of the peridotites is made of spinel-tectonites. Preservation of garnet-facies peridotites in the most deformed zone has been related to the fast cooling during deformation in the shear zone, while adiabatic evolution with retrogression may have occurred in the center of the peridotite (see discussions in Afiri et al., 2011; Garrido et al., 2011). Consistently, partial melting occurred at the end of the extensional deformation of the peridotites in the core of the massif (Précigout et al., 2013), leading to

Cr-pyroxenite generation (Marchesi et al., 2012), and the formation of the granular peridotites (recrystallization front; Van der Wal and Vissers, 1996; Van der Wal and Bodinier, 1996; Lenoir et al., 2001).

Foliation trajectories (Fig. 3) and shearing (discussed in detail in the next section) are consistent in both crust and mantle and testify to a regional extensional deformation event affecting the whole continental lithosphere (Balanyá et al., 1997; Tubía and Cuevas, 1986; Argles et al., 1999; Frasca et al., 2016; Précigout et al., 2013). The crust-mantle boundary accommodated the thinning and was responsible for the mantle unroofing from the garnet stability field to shallow depths. The crust-mantle extensional shear zone can be therefore identified in the field by garnet- and spinel-mylonite associated with granulites and migmatitic gneiss (drawn in white thick line in Figs. 3 and 4). In Spain, this association is well observed in the northern rim of Sierra Bermeja and Carratraca, and south of Sierra Alpujata. In Morocco, the crust-mantle extensional shear zone crops out only in the western rim of the Beni Bousera massif (Fig. 3). The upper western Alboran section is therefore a complete strongly attenuated continental lithosphere section, thinned in a back-arc setting (cross section in Fig. 3B; Garrido et al., 2011; Marchesi et al., 2012; Précigout et al., 2013; Gueydan et al., 2015).

## Age of the Crust-Mantle Extensional Shear Zone

The age of the continental lithosphere-thinning event is constrained mainly by three data points. (1) The Malaga tholeiite dikes, attributed to the partial melting of the peridotites during their adiabatic unroofing, intruded the thinned upper western Alboran section in Spain at ca. 30 Ma (Esteban et al., 2013). (2) High-temperature ages of zircon/monazite within the regional foliation associated with the thinning event yield ages around 23–21 Ma (Platt et al., 2003a; Gueydan et al., 2015). (3) Synrift deposits of late Oligocene/early Aquitanian age (Ciudad Granada deposits of Serrano et al., 2007) occur sparsely in both Spain and Morocco. These three data points support a Oligocene–Miocene age for the continental rifting. However, note that older ages can be found in the upper western Alboran rocks, since they have recorded a polycyclic history, from Variscan collision to Alpine thinning through Jurassic-Tethys opening (Sanchéz-Rodríguez and Gebauer, 2000). These ages led in the past to consider the mantle unroofing as Mesozoic, followed by a Tertiary nappe stacking event and then by extensional collapse of the nappe stack (Chalouan and Michard, 2004; Van der Wal and Vissers, 1993). Recent observations and geochronological ages in the upper western Alboran section lead us to propose instead an

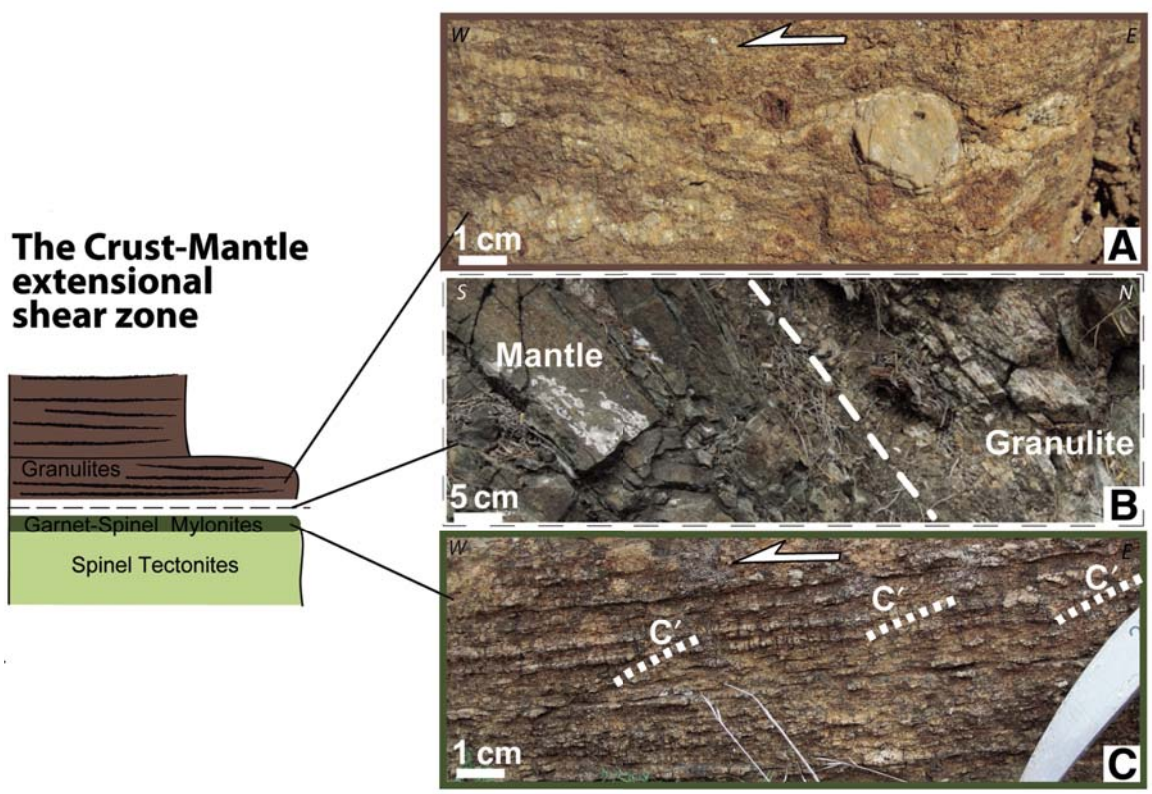



Figure 4. Outcrop pictures of shear criteria within the crust-mantle extensional shear zone (CMESZ, schematically drawn as a tectonic log to the left) in both (A) deep crust (garnet-rich mylonitic gneisses) and (C) uppermost mantle (garnet-spinel-mylonitic peridotites) within the Carratraca massif (see location on Fig. 1), where the only continuous crust-mantle extensional shear zone outcrop (B) has been reported (see Argles et al., 1999).

Oligocene–Miocene age for unroofing of the western Alboran peridotites from 70 km depths to shallow levels (Garrido et al., 2011; Afiri et al., 2011; Frasca et al., 2016; Gueydan et al., 2015). Variscan or Mesozoic extension was responsible for mantle unroofing from greater depth (100 km or larger) to 70 km. A discussion on different tectonic models is beyond the scope of the present paper and can be found in Frasca et al. (2016).

In summary, the Oligocene–Miocene tectonic activity of the western Alboran was marked by (1) strong continental lithosphere thinning, immediately followed by (2) inversion/thrusting of this thinned lithosphere. The crust-mantle extensional shear zone was responsible for unroofing of the subcontinental mantle from mantle to crustal depths, while the Ronda peridotites thrust was responsible for the inversion and final crustal emplacement of the peridotites and of the entire Alboran Domain onto the continental margin (Iberia and Morocco). This switch from slab rollback to back-arc inversion/shortening has been recently constrained by new structural and geochronological data by Frasca et al. (2017) and is consistent with the model proposed by Duggen et al. (2004) based on the analysis of magmatic products in the Alboran Domain.

### Shearing at the "Moho"

The crust-mantle extensional shear zone shows unequivocal shear criteria at regional scale, as discussed already. The histograms in Figure 3 allow us to define the mean direction of shearing along the crust-mantle extensional shear zone, hereafter called shearing at the "Moho," for the different peridotite bodies of the western Alboran system. The mean shear sense is reported in red on the tectonic maps (Fig. 3). Shear indicators are in general consistent in the mantle and deep crust and derive mainly from outcrop-scale observation of C′-type structures and porphyroclast rotation either in garnet-spinel-mylonite or in granulites (Fig. 4).

In Beni Bousera, Afiri et al. (2011) and Frets et al. (2014) have shown a remarkable consistency between deep crust (granulite, Filali migmatites and gneiss) and mantle shear criteria, with a mean shearing direction at N330. In Sierra Bermeja, Précigout et al. (2013) have shown a mean shearing direction in the mylonitic rim of the peridotites (crust-mantle extensional shear zone) at N235. In Carratraca, Frasca et al. (2016) have recently acquired new data that are compatible in trend with the data set of Argles et al. (1999), showing a mean direction of shearing in the Moho at about N275. Note that while Frasca et al. (2016) supported a top-to-the-SW shearing interpretation in the deep crust and uppermost mantle, Argles et al. (1999) suggested a top-to-the-NE or even a coaxial deformation pattern, as also suggested by Tubía et al. (2004). In the present paper, we will follow the recent work of Frasca et al. (2016), to which the readers are referred for a detailed discussion on the senses of shear at the crust-mantle boundary in the Carratraca Massif. In Sierra Alpujata, the shearing is in the opposite sense at N95 (Tubía and Cuevas, 1986). In deep crustal rocks of Ceuta and Cabo Negro, the shearing is oriented ~N25 (Didon et al., 1973; Sanz de Galdeano and Ruiz Cruz, 2016).

The compilation of data (histograms and maps; Fig. 3) shows a random distribution of shear directions and even opposite senses of shear that are difficult to interpret in the present-day configuration. Before any interpretation of these senses of ductile shearing at the Moho, rotation and horizontal displacement during the rift inversion have to be taken into account. A restoration is thus essential in order to discuss the significance of the shearing observed at the "Moho" and therefore the original geometry of the rift.

## RESTORED GEOMETRY OF THE OLIGOCENE–MIOCENE RIFT SYSTEM

### Back-Rotation of Western Alboran Peridotite Bodies from Paleomagnetic and Tectonic Data

After the rifting process that occurred from 30 to 21 Ma, the onset of thrusting (Ronda peridotites thrust) yielded to the progressive westward displacement of the Alboran Domain and to the progressive curvature of the thrust system, forming the Gibraltar arc (Platt et al., 2003b; Balanyá et al., 2007; Frasca et al., 2015). The vertical-axis rotation revealed by paleomagnetic data is an important aspect of the kinematic evolution of the Gibraltar arc (e.g., Calvo et al., 1994; Cifelli et al., 2008; Mattei et al., 2006; Osete et al., 1988; Platzman, 1992; Platzman et al., 1993, 2000; for reviews, see also Chalouan et al., 2008; Cifelli et al., 2016). In the Alboran Domain, the mantle bodies rotated clockwise about a vertical axis in the Spanish side and counterclockwise in the Moroccan side (Feinberg et al., 1996; Villasante-Marcos et al., 2003; Osete et al., 1988; Berndt et al., 2015). These data are based on magnetite in peridotites and serpentinites (Villasante-Marcos et al., 2003; Berndt et al., 2015) or from leucocratic granitic dikes inside the mantle (Feinberg et al., 1996). In this second case, the paleomagnetic declination clearly reflects the rotation after dike cooling, i.e., during rift inversion and thrusting (after 20 Ma).

In detail, the different paleomagnetic declination measurements of the western Alboran peridotites are 35° toward NE for the Sierra Bermeja (SB in Fig. 5), 55° toward NE for Carratraca (Ca in Fig. 5), 45° toward NE for the Sierra Alpujata (Alp in Fig. 5; Villasante-Marcos et al., 2003), 70° toward NW for Beni Bousera (BB in Fig. 5; Feinberg et al., 1996), and 20° toward NW for Ceuta (Ce in Fig. 5; Berndt et al., 2015). These paleomagnetic declinations are reported on Figure 5A together with the inferred senses of ductile shearing at the Moho for the western Alboran peridotites discussed in the previous section.

The clockwise rotation on the Spanish side and counterclockwise rotation on the Moroccan side are consistent with the westward migration of the Alboran Domain and a maximum of displacement in the center (close to Gibraltar), tending to decrease to the north and to the south. Regional dextral simple shearing occurred on the Spanish side, associated with the clockwise rotation, and regional sinistral simple shearing occurred in the Moroccan side, associated with counterclockwise rotation

(Frasca et al., 2015; Platt et al., 2013; Balanyá et al., 2007). This displacement field is consistent with the observed similar amounts of rotation on the two sides of the arc, if we consider a further rotation subsequent to the late Miocene of 20° counterclockwise on the Rif side of the Gibraltar arc that is not recorded in the Betic side of the western Alboran Domain (Cifelli et al., 2008), and that was responsible for the slight rotation observed in the central part of the system (Ceuta).

In the Torcal Corridor, Frasca et al. (2015) identified a major E-W dextral strike-slip lateral ramp that has accommodated the westward migration of the Alboran Domain since 20 Ma (Fig. 5A; see also Sanz de Galdeano et al., 1996; Sanz de Galdeano and López Garrido, 2012; Barcos et al., 2015). Similarly, during the Miocene, the Jebha fault in Morocco accommodated the westward motion of the Alboran Domain (Olivier, 1981; Vitale et al., 2014), although the present-day active structures are around the Nekor fault, 80 km further east (Poujol et al., 2014), while in the western Betics, they are concentrated few kilometers to the north of the Torcal area (Fig. 1; Díaz-Azpiroz et al., 2014). These two major strike-slip zones, Torcal to the north and Jebha to the south, therefore have accommodated most of the Alboran displacement during the clockwise and conterclockwise rotation observed in the peridotites and will be therefore used to constrain the direction of the horizontal motion for the retrodeformation of the western Alboran peridotites. The initial positions of the western Alboran peridotites are assumed to be at the end of the Torcal and Jebha systems and imply ~100 km of horizontal displacement. The amount of displacement estimated is slightly lower than the cross-section estimations of Platt et al. (2003b), but it is in line with the observed continuity between the Internal and External zone of the Lower Miocene sedimentary basin in the western Betics (Frasca et al., 2015).

Figure 5B presents the restored position of the western Alboran peridotites, with their associated shearing sense at the Moho. As shown by Berndt et al. (2015) and Chalouan et al. (2008), all the ultramafic bodies are aligned N-S, east of the present-day position of Malaga (Fig. 5B). The shearing directions at the Moho are almost identical after back-rotation, between N20° and N50°, and thus define a unique N-S back-arc continental rift system. The scattering in shear directions at the Moho in the present-day situation therefore reflects a nonhomogeneous horizontal rotation along a vertical axis during rift inversion. However, although the shear directions are similar after back-rotation, the senses of shear remain different, with the Carratraca–Sierra Bermeja pair showing consistent shearing direction, while Sierra Alpujata, Ceuta, and Beni Bousera show an opposite sense of shear.

We propose now to document the sense of shearing during continental rifting using a numerical model that will serve as a guide for the interpretation of the opposite shear senses along the "Moho" in the restored Oligocene–Miocene rift system.

## 2-D Numerical Models: Opposite Shearing at the Moho during Continental Lithosphere Extension

Figure 6A shows finite strain (first invariant of the strain tensor) after 140 km of horizontal extensional displacement applied at the two vertical walls of the model. This 2-D model result was extracted from the recent analysis of Gueydan and Précigout (2014), and readers are referred to that paper for model and rheological parameters. The rheology of the lithosphere mantle

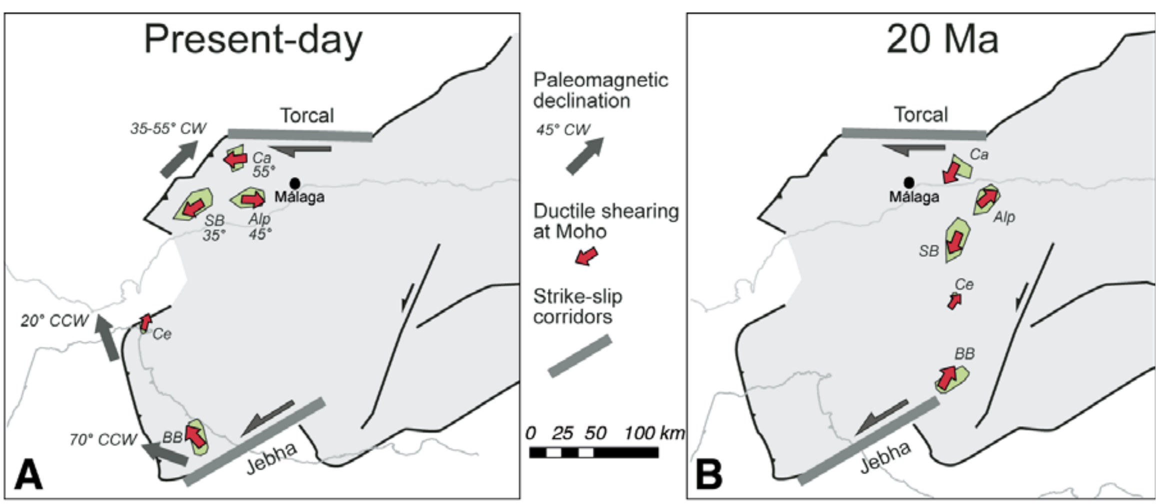



Figure 5. (A) Present-day tectonic map of the western Alboran with the main peridotite bodies in green, showing ductile senses of shear at the Moho (red arrows; from Fig. 3), paleomagnetic rotation (gray arrows with amount of rotation; see text for references), and major strike-slip corridors (Torcal in the Betics and Jebha in the Rif) accommodating the displacement during thrusting and westward/southwestward motion. Ca—Carratraca; SB—Sierra Bermeja; Alp—Sierra Alpujata; Ce—Ceuta; BB—Beni Bousera. (B) Restored geometry at 20 Ma after back-rotation of the peridotite bodies with their ductile senses of shear at the Moho (red arrows). See text for details. CW—clockwise; CCW—counterclockwise.

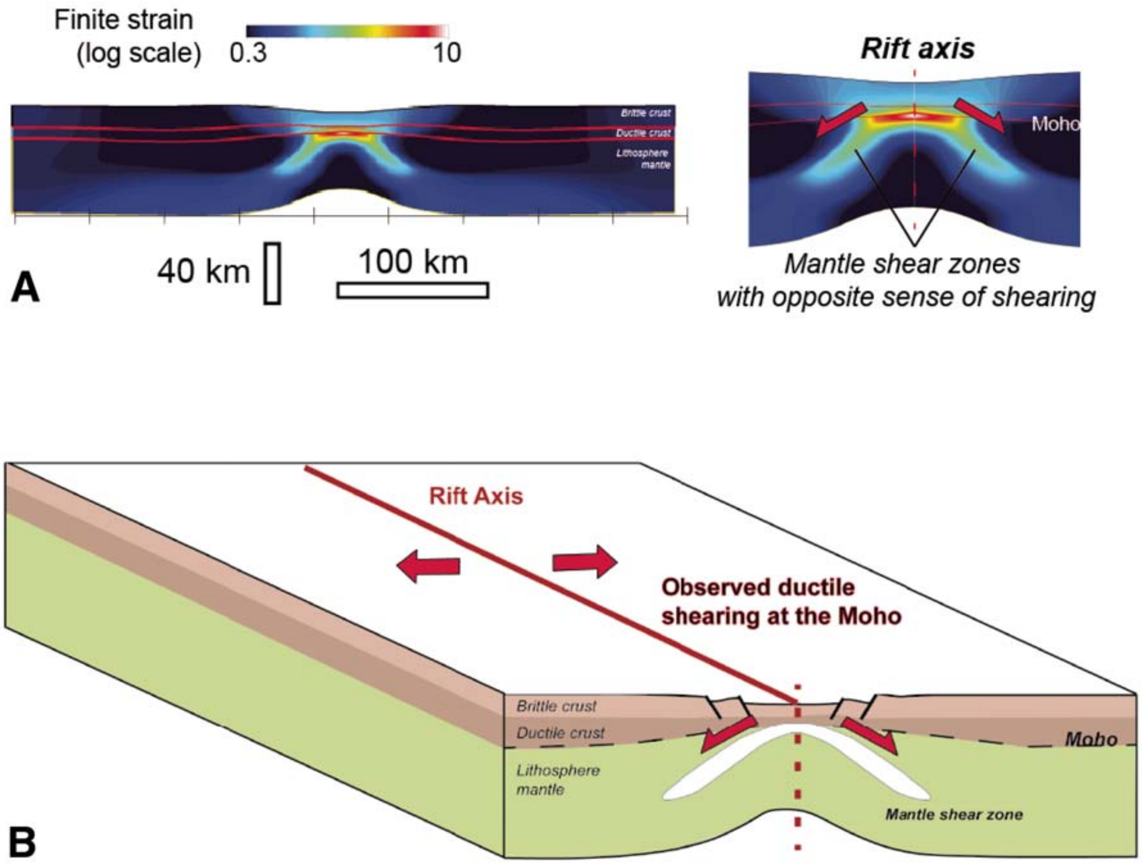



Figure 6. (A) Two-dimensional (2-D) numerical results of continental rifting (finite strain after 140 km of horizontal extensional displacement, extracted from Gueydan and Précigout, 2014) with, on the right, a focus on the rift center and associated shearing in two conjugate mantle shear zones. (B) Three-dimensional (3-D) schematic description of the continental rifting process and related ductile shearing at the Moho.

accounts for ductile strain localization since, in the western Alboran, continental lithosphere thinning is mainly controlled by ductile strain localization (Précigout et al., 2007; Précigout and Gueydan, 2009).

The high-strength subcontinental mantle, with a Moho temperature lower than 800 °C, leads to strongly heterogeneous lithospheric thinning and permits symmetric strain localization in the center of the model (Gueydan et al., 2008). This necking instability at the lithosphere scale triggers the Moho uplift below the rift center and is accommodated by two major mantle shear zones with opposite senses of shear (top to the left, left of the rift axis, and top to the right, right of the rift axis; see close-up of rift center on right side of Fig. 6A). These two mantle shear zones with opposite sense of shear allow mantle unroofing in the center and thus lithosphere thinning. In the rift center, these mantle shear zones tend to be parallel to the uplifted Moho, as it can be observed in the field in the western Alboran (crust-mantle extensional shear zone). The 2-D numerical result therefore demonstrates that, during lithosphere thinning, the senses of shear at the "Moho" were opposite on the two side of the rift system: top-to-the-outside of the rift center, as schematically drawn on Figure 6B. Note that these conclusions are valid also for most of numerical models of the rifting process.

#### *Tectonic Interpretation: Rift Axes and Rift Transforms*

These numerical findings were used to interpret the rift system after accounting for back-rotation and horizontal displacement (Fig. 7). Sierra Bermeja (SB) and Sierra Alpujata (SAlp) show opposite sense of shear: top to N20 for the Sierra Alpujata and top to N230 for the Sierra Bermeja. We can thus infer a rift axis between these two peridotite bodies, oriented perpendicular to the shearing direction, i.e., NW-SE. This hypothesis is moreover consistent with the E-W cross section of Figure 3B. At the transition between Sierra Bermeja and Sierra Alpujata, the crustal thickness reaches its minimum value (lower than a few tens of meters), which suggests the locus of the maximum crustal thinning and hence the possible locus of the rift axis. Late strike-slip faults that developed in this area moreover could not have been responsible for such a strong crustal thinning (Albornoque fault—Tubía et al., 2013; Coín corridor—Frasca et al., 2015).

Carratraca (Ca) shows the same sense of shear as the Sierra Bermeja (SB), top to N200, but in an originally different position,

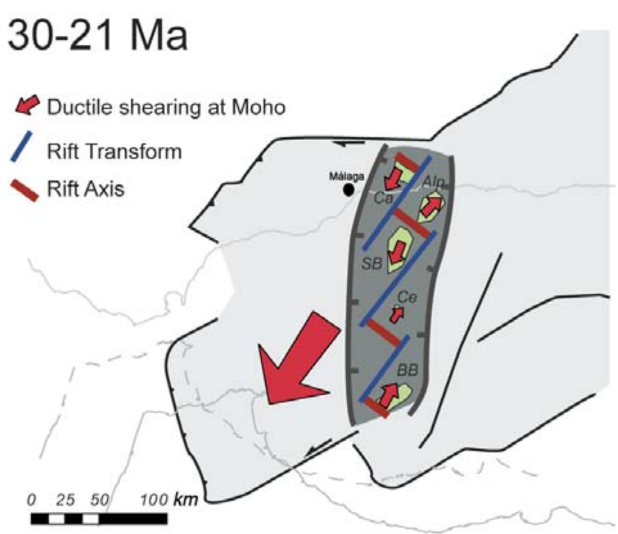



Figure 7. Geometry of the rift at 21 Ma in which the western Alboran peridotites (WAP) were exhumed: a N-S oblique rift system (in dark gray) with NW-SE rift axes (in red, perpendicular to the shearing direction at the Moho; Fig. 5B) connected with NNE-SSW transform faults (in blue). Inferred NNE-SSW direction of stretching is shown with red arrow. Ca—Carratraca; SB—Sierra Bermeja; Alp—Sierra Alpujata; Ce—Ceuta; BB—Beni Bousera.

further north of Sierra Bermeja. The rift axis of the oblique rift related to the Carratraca massif was therefore further north. Carratraca and the Sierra Bermeja–Sierra Alpujata pair were thus most probably connected by a transform fault, oriented parallel to the shearing direction (N20). Following the same procedure, we can propose that the rift axis related to Beni Bousera (BB) was to the south, as well as the rift axis related to Ceuta (Ce in Fig. 7). Two other transforms at N20 are inferred to have connected Ceuta and Beni Bousera to the rest of the rift system.

On the basis of this evidence, we define an oblique rift, with NNE-SSW direction of stretching but within a N-S–trending area of thinning, characterized by NW-SE rift axes and NNE-SSW transform faults (Fig. 7). The Sierra Bermeja–Sierra Alpujata pair belongs to the same rift axis, while Carratraca, Ceuta, and Beni Bousera correspond to other rift axes. All the different rift centers were connected by NNE-SSW transform faults.

## DISCUSSION

To discuss the implications of our interpretations, it is necessary to compare the present-day geology with our reconstruction. For that purpose, Figure 8 presents the N-S oblique rift system at 20 Ma, with synrift deposits of late Oligocene to early Miocene age (Fig. 8A), and the deformed shape of the former rift, in

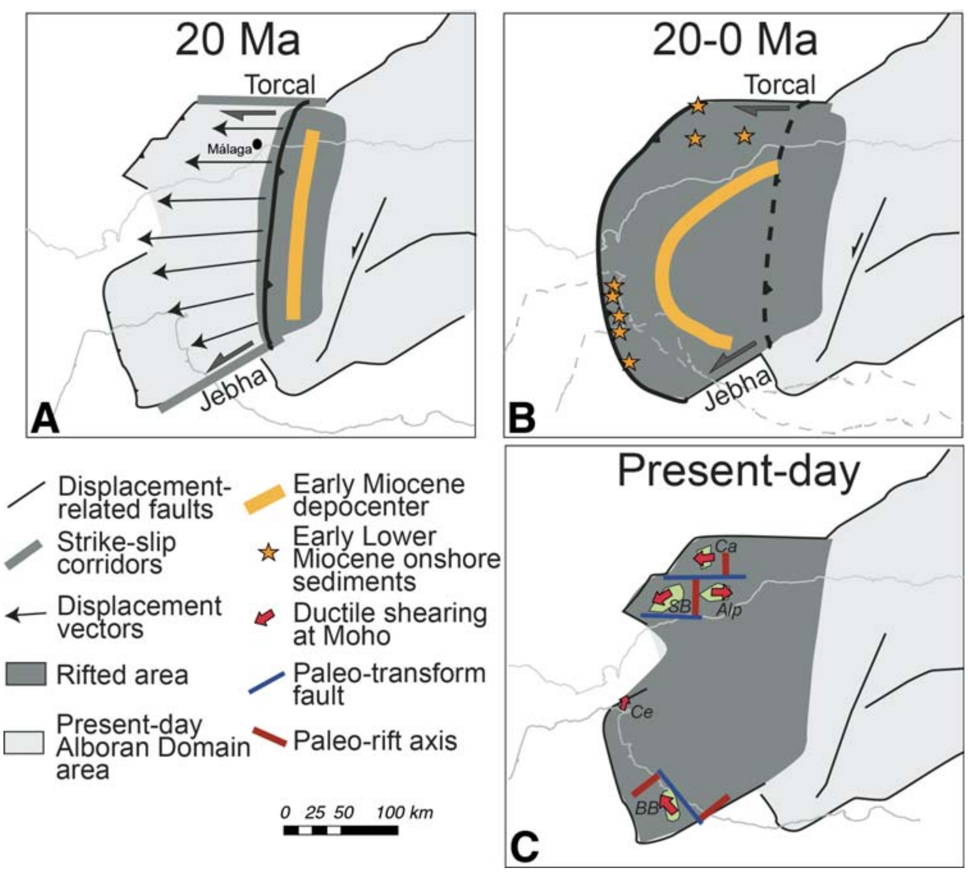



Figure 8. (A) Original position of the oblique rift system (dark gray; Fig. 7) at 21 Ma with late Oligocene and early Miocene synrift depocenters in orange, showing initial thrust position (black thick line) and displacement vectors related to westward thrusting (black arrows). (B) Deformed rift area during westward thrusting (dark gray) and related position of the Lower Miocene sediment depocenters (stars, onshore, and thick orange line, offshore). (C) Inferred orientation and position of the paleo–transform faults (blue) and of the paleo–rift axes (red) after their displacement and rotation. Ca—Carratraca; SB—Sierra Bermeja; Alp—Sierra Alpujata; Ce—Ceuta; BB—Beni Bousera.

the present-day situation, after thrusting and westward motion (Fig. 8B). As described in the previous section, the westward thrusting was accommodated at the edge of the Alboran system by two major strike-slip corridors: a dextral corridor to the north (Torcal) and sinistral corridor to the south (Jebha; Fig. 8A). This scenario implies a maximum E-W horizontal displacement in the center of the Alboran and a northward and southward decrease of the E-W horizontal displacement toward the corridors and the Iberian and African margins (Fig. 8A).

The differential displacement led to a strongly curved shape of the deformed rift system, as highlighted by the Lower Miocene offshore depositional area (Fig. 8B). The peculiar geometry of the Lower Miocene offshore depocenter is consistent with the offshore compilations of seismic data provided in Watts et al. (1993) and Comas et al. (1992) and drawn on Figure 1. Moreover, the displacement also explains the existence along the Gibraltar arc of early Aquitanian onshore deposits (see Figs. 1 and 8B), which have been interpreted as the surface expression of an extensional oblique event (Serrano et al., 2007). Note that during thrusting, the westward migration of the active front may have led to a slight spreading of the western Alboran Domain (i.e., larger outcropping area in the present-day situation [Fig. 8B] than at 20 Ma [Fig. 8A]; Frasca et al., 2015).

The hypothesis of several rift axes connected with transform faults in an oblique rift can also be compared to the present-day surface geology. Figure 8C shows the present-day position of the rift axes and transform faults in the Betics and Rif, after applying the vertical-axis rotation inferred by the paleomagnetic declinations (Fig. 5A). In the Betics, paleo–transform faults should be oriented E-W, while paleo–rift axes should be roughly N-S (Fig. 8C). As reported earlier herein, the existence of a paleo–rift axis between Sierra Bermeja and Sierra Alpujata and south of Carratraca is consistent with the inferred very low value of the thickness of the upper western Alboran crust (Fig. 3).

Frasca et al. (2015) provided detailed structural constraints that support the existence of a major E-W strike-slip corridor inside the Alboran Domain, between Carratraca and the Sierra Alpujata (Coín strike-slip corridor; see Fig. 3A; also Albornoque fault in Tubía et al., 2013). This corridor separates the western Betics into two different domains with different upper western Alboran crustal thickness that cannot be justified by the Coín strike-slip corridor kinematics. The results of the present study therefore provide a simple mechanical explanation for the partitioning of the deformation in strike-slip corridors within the Alboran Domain during the inversion (e.g., reactivation of an inherited structure, here the rift transform fault). However, note that it will be difficult to identify sinistral strike-slip indicators in the field, which would have been characteristic of the transform during rifting (Fig. 7) prior to the dextral reactivation during inversion, although sinistral kinematics have been locally identified (Sosson et al., 1998). Furthermore, anomalous mineralizations are observed along the Coín corridor (Esteban et al., 2011) and can testify to fluid circulation along the transforms, although further investigations are needed to fully justify this.

In the Rif, paleo–transform faults should be oriented NW-SE, while paleo–rift axes should be roughly NE-SW (Fig. 8C). Although it is difficult to validate a paleo–rift axis north of Beni Bousera from structural data, the late Oligocene/early Aquitanian sediments are present mainly there (Figs. 1 and 8B). A paleo–transform fault east of the Beni Bousera body striking at N150° is well correlated with a N150° highly dipping fault, which allows direct contact between upper-crustal rocks (Ghomarides) and mantle rocks (see Fig. 3C). Moreover, Rossetti et al. (2013) recently stressed the importance of N150° sinistral strike-slip faults that are parallel to our inferred paleo–transform fault orientation. More generally, the present study proposes a new tectonic framework for future studies that could identify normal or sinistral faults in upper-crustal rocks in the field that have been inherited from the oblique rifting history.

Finally, we can integrate our restoration into the plate-tectonic framework and compare our reconstruction with geodynamic models proposed in the past. The amount of slab rollback and the direction of trench migration are matters of controversy (see summaries in Chertova et al., 2014; Frasca et al., 2015). The inferred NNE-SSW direction of stretching, mainly supported by the restored direction of ductile shearing at the Moho during the oblique rifting (Fig. 7), favors a NW-dipping subduction zone along the Western Mediterranean (from Gibraltar or southeast of Iberia), which initiated in the Oligocene and rolled back mainly to the S-SW (Faccenna et al., 2004; Jolivet et al., 2006; Gueguen et al., 1998; Wortel and Spakman, 2000). This geodynamic model will nevertheless need to be amended in order to account for back-arc rifting and mantle exhumation at 20 Ma, as supported by the present study. Further studies are also required to identify the former Oligocene–Miocene magmatic arc system through structural or geophysical studies.

## CONCLUSIONS

The following conclusions can be drawn from our study.

(1) The Tertiary stage of exhumation of the western Alboran peridotites was related to extensional exhumation in a back-arc continental rift during the Oligocene–Miocene.
(2) The ductile shearing trends at the Moho in the different outcropping bodies of the western Alboran peridotites can be used to constrain the rift geometry.
(3) 2-D numerical models of continental rifting indicate that the observed opposite shearing senses at the Moho were related to different positions of the peridotite bodies relative to the rift axis.
(4) Back rotations, based on paleomagnetic and tectonic constraints, show a high consistency of N20-directed shearing at the Moho in a N-S–trending oblique rift system.
(5) The restored N-S oblique rift system was composed of several NW-SE rift axes connected by NNE-SSW transforms.
(6) Paleo–transform faults and paleo–rift axes are inherited structures and partly controlled the Miocene tectonics of the western Alboran Domain.

## ACKNOWLEDGMENTS

This work was funded by the European Union FP7 Marie Curie ITN "TOPOMOD," contract 264517. Thanks go to J.-P. Brun, A. Afiri, and J. Précigout for useful discussions. Constructive reviews from J.M. Tubía and D. Frizon de Lamotte helped to improve the manuscript.

## REFERENCES CITED

Afiri, A., Gueydan, F., Pitra, P., Essai, A., and Précigout, J., 2011, Oligo-Miocene exhumation of the Beni-Bousera peridotite through a lithosphere-scale extensional shear zone: Geodinamica Acta, v. 24, no. 1, p. 49–60, doi:10.3166/ga.24.49-60.

Argles, T., Platt, J., and Waters, D., 1999, Attenuation and excision of a crustal section during extensional exhumation: The Carratraca massif, Betic Cordillera, southern Spain: Journal of the Geological Society of London, v. 156, no. 1, p. 149–162, doi:10.1144/gsjgs.156.1.0149.

Balanyá, J.C., García-Dueñas, V., Azañón, J.M., and Sánchez-Gómez, M., 1997, Alternating contractional and extensional events in the Alpujarride nappes of the Alboran Domain (Betics, Gibraltar arc): Tectonics, v. 16, no. 2, p. 226–238, doi:10.1029/96TC03871.

Balanyá, J.C., Crespo-Blanc, A., Díaz-Azpiroz, M., Expósito, I., and Luján, M., 2007, Structural trend line pattern and strain partitioning around the Gibraltar arc accretionary wedge: Insights as to the mode of orogenic arc building: Tectonics, v. 26, no. 2, TC2005, doi:10.1029/2005TC001932.

Barcos, L., Balanyá, J.C., Díaz-Azpiroz, M., Expósito, I., and Jiménez-Bonilla, A., 2015, Kinematics of the Torcal shear zone: Transpressional tectonics in a salient-recess transition at the northern Gibraltar arc: Tectonophysics, v. 663, p. 62–77, doi:10.1016/j.tecto.2015.05.002.

Barich, A., Acosta-Vigil, A., Garrido, C.J., Cesare, B., Tajčmanová, L., and Bartoli, O., 2014, Microstructures and petrology of melt inclusions in the anatectic sequence of Jubrique (Betic Cordillera, S Spain): Implications for crustal anataxis: Lithos, v. 206–207, p. 303–320, doi:10.1016/j.lithos.2014.08.003.

Berndt, T., Ruiz-Martínez, V.C., and Chalouan, A., 2015, New constraints on the evolution of the Gibraltar arc from palaeomagnetic data of the Ceuta and Beni Bousera peridotites (Rif, northern Africa): Journal of Geodynamics, v. 84, p. 19–39, doi:10.1016/j.jog.2014.09.014.

Bezada, M., Humphreys, E., Toomey, D., Harna, M., Dávila, J., and Gallart, J., 2013, Evidence for slab rollback in westernmost Mediterranean from improved upper mantle imaging: Earth and Planetary Science Letters, v. 368, p. 51–60, doi:10.1016/j.epsl.2013.02.024.

Blichert-Toft, J., Albarède, F., and Kornprobst, J., 1999, Lu-Hf isotope systematics of garnet pyroxenites from Beni Bousera, Morocco: Implications for basalt origin: Science, v. 283, p. 1303–1306, doi:10.1126/science.283.5406.1303.

Bonini, W.E., Loomis, T.P., and Robertson, J.D., 1973, Gravity anomalies, ultramafic intrusions and the tectonics of the region around the Strait of Gibraltar: Geofizicheskie Issledovaniia, v. 78, p. 1372–1382.

Calvo, M., Osete, M.L., and Vegas, R., 1994, Palaeomagnetic rotations in opposite senses in southeastern Spain: Geophysical Research Letters, v. 21, no. 9, p. 761–764, doi:10.1029/94GL00191.

Chalouan, A., and Michard, A., 2004, The Alpine Rif Belt (Morocco): A case of mountain building in a subduction–subduction–transform fault triple junction: Pure and Applied Geophysics, v. 161, p. 489–519, doi:10.1007/s00024-003-2460-7.

Chalouan, A., Michard, A., El Kadiri, K., Frizon de Lamotte, D., Negro, F., Soto, J., and Saddiqi, O., 2008, The Rif belt, *in* Michard, A., Saddiqi, O., Chalouan, A., and de Lamotte, D.F., eds., Continental Evolution: The Geology of Morocco: Structure, Stratigraphy, and Tectonics of the Africa–Atlantic–Mediterranean Triple Junction: Berlin, Springer-Verlag, p. 203–302.

Chertova, M.V., Spakman, W., Geenen, T., Van den Berg, A.P., and Van Hinsbergen, D.J.J., 2014, Underpinning tectonic reconstructions of the Western Mediterranean region with dynamic slab evolution from 3-D numerical modeling: Journal of Geophysical Research–Solid Earth, v. 119, p. 5876–5902, doi:10.1002/2014JB011150.

Cifelli, F., Mattei, M., and Porreca, M., 2008, New paleomagnetic data from Oligocene–Upper Miocene sediments in the Rif chain (northern Morocco): Insights on the Neogene tectonic evolution of the Gibraltar arc: Journal of Geophysical Research–Solid Earth, v. 113, no. B2, B02104, doi:10.1029/2007JB005271.

Cifelli, F., Caricchi, C., and Mattei, M., 2016, Formation of arc-shaped orogenic belts in the western and central Mediterranean: A palaeomagnetic review, *in* Pueyo, E.L., Cifelli, F., Sussman, A.J., and Oliva-Urcia, B., eds., Palaeomagnetism in Fold and Thrust Belts: New Perspectives: Geological Society, London, Special Publication 425, p. 1–27.

Comas, M.C., García-Dueñas, V., and Jurado, M., 1992, Neogene tectonic evolution of the Alboran Sea from MCS data: Geo-Marine Letters, v. 12, no. 2–3, p. 157–164, doi:10.1007/BF02084927.

Comas, M.C., Platt, J.P., Soto, J.I., and Watts, A.B., 1999, The origin and tectonic history of the Alboran basin: Insights from Leg 161 results, *in* Zahn, R., Comas, M.C., and Klaus, A., Proceedings of the Ocean Drilling Program, Scientific Results, v. 161: College Station, Texas, Ocean Drilling Program, p. 555–580.

Crespo-Blanc, A., and Frizon de Lamotte, D., 2006, Structural evolution of the External zones derived from the Flysch Trough and the south Iberian and Maghrebian paleomargins around the Gibraltar arc: A comparative study: Bulletin de la Société Géologique de France, v. 177, no. 5, p. 267–282, doi:10.2113/gssgfbull.177.5.267.

Darot, M., 1974, Cinematique de l'extrusion, à partir du manteau, des peridotites de la Sierra Bermeja (Serrania de Ronda, Espagne): Comptes Rendus de l'Académie des Sciences, v. 278, p. 1673–1675.

Davies, G.R., Nixon, P.H., Pearson, D.G., and Obata, M., 1993, Tectonic implications of graphitized diamonds from the Ronda peridotite massif, southern Spain: Geology, v. 21, no. 5, p. 471–474, doi:10.1130/0091-7613(1993)021<0471:TIOGDF>2.3.CO;2.

Díaz-Azpiroz, M., Barcos, L., Balanyá, J. C., Fernández, C., Expósito, I., and Czeck, D., 2014, Applying a general triclinic transpression model to highly partitioned brittle-ductile shear zones: A case study from the Torcal de Antequera massif, external Betics, southern Spain: Journal of Structural Geology, v. 68B, p. 316–336.

Didon, J., Durand-Delga, M., and Kornprobst, J., 1973, Homologies géologiques entre les deux rives du détroit de Gibraltar: Bulletin de la Société Géologique de France, ser. 7, v. 15, no. 2, p. 77–105, doi:10.2113/gssgfbull.S7-XV.2.77.

Doglioni, C., Gueguen, E., Sàbat, F., and Fernandez, M., 1997, The Western Mediterranean extensional basins and the Alpine orogen: Terra Nova, v. 9, p. 109–112, doi:10.1046/j.1365-3121.1997.d01-18.x.

Duggen, S., Hoernle, K., van den Bogaard, P., and Harris, C., 2004, Magmatic evolution of the Alboran region: The role of subduction in forming the Western Mediterranean and causing the Messinian salinity crisis: Earth and Planetary Science Letters, v. 218, no. 1–2, p. 91–108, doi:10.1016/S0012-821X(03)00632-0.

Esteban, J.J., Cuevas, J., Tubía, J.M., Gil Ibarguchi, J.I., and Seward, D., 2005, Metamorfismo, exhumación y termocronología de la Unidad de Yunquera (Alpujárrides occidentales, Cordilleras Béticas): Revista de la Sociedad Geológica de España, v. 18, no. 1–2, p. 61–74.

Esteban, J.J., Cuevas, J., Vegas, N., and Tubía, J.M., 2008, Deformation and kinematics in a melt-bearing shear zone from the Western Betic Cordilleras (southern Spain): Journal of Structural Geology, v. 30, no. 3, p. 380–393, doi:10.1016/j.jsg.2007.11.010.

Esteban, J.J., Cuevas, J., Tubía, J.M., Velasco, F., and Vegas, N., 2011, Características petrográficas y mineralógicas de birbiritas derivadas de las peridotitas de Ronda (Cordilleras Béticas): Geogaceta, v. 50, no. 1, p. 39–42.

Esteban, J.J., Tubía, J.M., Cuevas, J., Seward, D., Larionov, A., Sergeev, S., and Navarro-Vilá, F., 2013, Insights into extensional events in the Betic Cordilleras, southern Spain: New fission-track and U-Pb SHRIMP analyses: Tectonophysics, v. 603, p. 179–188, doi:10.1016/j.tecto.2013.05.027.

Faccenna, C., Piromallo, C., Crespo Blanc, A., Jolivet, L., and Rossetti, F., 2004, Lateral slab deformation and the origin of the arcs of the Western Mediterranean: Tectonics, v. 23, TC1012, doi:10.1029/2002TC001488.

Feinberg, H., Saddiqi, O., and Michard, A., 1996, New constraints on the bending of the Gibraltar arc from paleomagnetism of the Ronda peridotite (Betic Cordilleras, Spain), *in* Morris, A.T.D., ed., Paleomagnetism and Tectonics of the Mediterranean Region: Geological Society, London, Special Publication 105, p. 43–52.

Fernández, M., Berástegui, X., Puig, C., García-Castellanos, D., Jurado, M.J., Torné, M., and Banks, C., 1998, Geophysical and geological constraints on the evolution of the Guadalquivir foreland basin, Spain, *in* Mascle, A., Puigdefàbregas, C., Luterbacher, H.P., and Fernández, M., eds., Cenozoic Foreland Basins of Western Europe: Geological Society, London, Special Publication 134, p. 29–48, doidoi:10.1144/GSL.SP.1998.134.01.03.

Frasca, G., Gueydan, F., and Brun, J.-P., 2015, Structural record of Lower Miocene westward Alboran Domain motion in the western Betics (southern Spain): Tectonophysics, v. 657, p. 1–20, doi:10.1016/j.tecto.2015.05.017.

Frasca, G., Gueydan, F., Brun, J.-P., and Monié, P., 2016, Deformation mechanisms in a continental rift up to mantle exhumation. Field evidence from the western Betics, Spain: Marine and Petroleum Geology, v. 76, p. 310–328, doi:10.1016/j.marpetgeo.2016.04.020.

Frasca, G., Gueydan, F., Poujol, M., Brun, J.-P., Parat, F., Monié, P., Maziers, S., and Pichat, A., 2017, Fast switch from extensional exhumation to thrusting of the Ronda peridotites: Terra Nova (in press).

Frets, E.C., Tommasi, A., Garrido, C.J., Vauchez, A., Mainprice, D., Targuisti, K., and Amri, I., 2014, The Beni-Bousera peridotite (Rif belt, Morocco): An oblique-slip low-angle shear zone thinning the subcontinental mantle lithosphere: Journal of Petrology, v. 55, no. 2, p. 283–313, doi:10.1093/petrology/egt067.

García-Dueñas, V., Balanyá, J.C., and Martínez-Martínez, J., 1992, Miocene extensional detachments in the outcropping basement of the northern Alboran basin (Betics) and their tectonic implications: Geo-Marine Letters, v. 12, p. 88–95, doi:10.1007/BF02084917.

Garrido, C.J., Gueydan, F., Booth-Rea, G., Précigout, J., Hidas, K., Padrón-Navarta, J.A., and Marchesi, C., 2011, Garnet lherzolite and garnet-spinel mylonite in the Ronda peridotite: Vestiges of Oligocene backarc mantle lithospheric extension in the Western Mediterranean: Geology, v. 39, no. 10, p. 927–930, doi:10.1130/G31760.1.

Gueguen, E., Doglioni, C., and Fernández, M., 1998, On the post–25 Ma geodynamic evolution of the Western Mediterranean: Tectonophysics, v. 298, no. 1–3, p. 259–269, doi:10.1016/S0040-1951(98)00189-9.

Gueydan, F., and Précigout, J., 2014, Modes of continental rifting as a function of ductile strain localization in the lithospheric mantle: Tectonophysics, v. 612–613, p. 18–25, doi:10.1016/j.tecto.2013.11.029.

Gueydan, F., Morency, C., and Brun, J.-P., 2008, Continental rifting as a function of lithosphere mantle strength: Tectonophysics, v. 460, no. 1–4, p. 83–93, doi:10.1016/j.tecto.2008.08.012.

Gueydan, F., Pitra, P., Afiri, A., Poujol, M., Essaifi, A., and Paquette, J.-L., 2015, Oligo–Miocene thinning of the Beni Bousera peridotites and their Variscan crustal host rocks, Internal Rif, Morocco: Tectonics, v. 34, no. 6, p. 1244–1268, doi:10.1002/2014TC003769.

Hidas, K., Booth-Rea, G., Garrido, C.J., Martínez-Martínez, J.M., Padrón-Navarta, J.A., Konc, Z., Giaconia, F., Frets, E., and Marchesi, C., 2013, Backarc basin inversion and subcontinental mantle emplacement in the crust: Kilometre-scale folding and shearing at the base of the proto-Alborán lithospheric mantle (Betic Cordillera, southern Spain): Journal of the Geological Society, v. 170, no. 1, p. 47–55, doi:10.1144/jgs2011-151.

Hidas, K., Varas-Reus, M.I., Garrido, C.J., Marchesi, C., Acosta-Vigil, A., Padrón-Navarta, J.A., Targuisti, K., and Konc, Z., 2015, Hyperextension of continental to oceanic-like lithosphere: The record of late gabbros in the shallow subcontinental lithospheric mantle of the westernmost Mediterranean: Tectonophysics, v. 650, p. 65–79, doi:10.1016/j.tecto.2015.03.011.

Hsü, K.J., Fox, P.J., and Ryan, W.B.F., 1973, Petrography of the western Alboran "basement," *in* Ryan, W.B.F., Hsü, K.J., et al., Initial Reports, Deep Sea Drilling Project, v. 13, Part 2: Washington, U.S. Government Printing Office, p. 753–758.

Jolivet, L., Augier, R., Robin, C., Suc, J.-P., and Rouchy, J.M., 2006, Lithospheric-scale geodynamic context of the Messinian salinity crisis: Sedimentary Geology, v. 188–189, p. 9–33, doi:10.1016/j.sedgeo.2006.02.004.

Kornprobst, J., 1973, Petrographical study of "acoustic basement" and associated breccia at Site 121—Western Alboran Basin: A comparison with the Betico-Rifean basement, *in* Ryan, W.B.F., Hsü, K.J., et al., Initial Reports, Deep Sea Drilling Project, v. 13, Part 2: Washington, U.S. Government Printing Office, p. 759–761.

Kornprobst, J., 1974, Contribution à l'Étude Pétrographique et Structurale de la Zone Interne du Rif (Maroc Septentrional): Notes et Mémoires Geological Service of Morocco 251, 256 p.

Lenoir, X., Garrido, C.J., Bodinier, J.L., Dautria, J.M., and Gervilla, F., 2001, The recrystallization front of the Ronda peridotite: Evidence for melting and thermal erosion of subcontinental lithospheric mantle beneath the Alboran basin: Journal of Petrology, v. 42, p. 141–158, doi:10.1093/petrology/42.1.141.

Lonergan, L., and White, N., 1997, Origin of the Betic-Rif mountain belt: Tectonics, v. 16, p. 504–522, doi:10.1029/96TC03937.

Marchesi, C., Garrido, C.J., Bosch, D., Bodinier, J.-L., Hidas, K., Padrón-Navarta, J.A., and Gervilla, F., 2012, A late Oligocene suprasubduction setting in the westernmost Mediterranean revealed by intrusive pyroxenite dikes in the Ronda peridotite (southern Spain): The Journal of Geology, v. 120, no. 2, p. 237–247, doi:10.1086/663875.

Mattei, M., Cifelli, F., Martín Rojas, I., Crespo Blanc, A., Comas, M., Faccenna, C., and Porreca, M., 2006, Neogene tectonic evolution of the Gibraltar arc: New paleomagnetic constraints from the Betic chain: Earth and Planetary Science Letters, v. 250, p. 522–540, doi:10.1016/j.epsl.2006.08.012.

Mazzoli, S., and Martín-Algarra, A., 2011, Deformation partitioning during transpressional emplacement of a 'mantle extrusion wedge': The Ronda peridotites, Western Betic Cordillera, Spain: Journal of the Geological Society, v. 168, p. 373–382, doi:10.1144/0016-76492010-126.

Mazzoli, S., Martín-Algarra, A., Reddy, S., Sánchez-Vizcaíno, V.L., Fedele, L., and Noviello, A., 2013, The evolution of the footwall to the Ronda subcontinental mantle peridotites: Insights from the Nieves Unit (Western Betic Cordillera): Journal of the Geological Society of London, v. 170, p. 385–402, doi:10.1144/jgs2012-105.

Navarro-Vilá, F., and Tubía, J., 1983, Essai d'une nouvelle différenciation des nappes Alpujarrídes dans le secteur occidental des Cordilléres Bétiques (Andalousie, Espagne): Comptes Rendus de l'Académie des Sciences, Paris, v. 296, p. 111–114.

Negro, F., Beyssac, O., Goffé, B., Saddiqi, O., and Bouybaouéne, M.L., 2006, Thermal structure of the Alboran Domain in the Rif (northern Morocco) and the Western Betics (southern Spain). Constraints from Raman spectroscopy of carbonaceous material: Journal of Metamorphic Geology, v. 24, no. 4, p. 309–327, doi:10.1111/j.1525-1314.2006.00639.x.

Obata, M., 1980, The Ronda peridotite: Garnet-, spinel-, and plagioclase-lherzolite facies and the *P-T* trajectories of a high-temperature mantle intrusion: Journal of Petrology, v. 21, no. 3–4, p. 533–572, doi:10.1093/petrology/21.3.533.

Olivier, P., 1981, L'accident de Jebha-Chrafate (Rif, Maroc): Revue de Géographie Physique et de Géologie Dynamique, v. 23, p. 27–106.

Osete, M., Freeman, R., and Vegas, R., 1988, Preliminary palaeomagnetic results from the Subbetic zone (Betic Cordillera, southern Spain): Kinematic and structural implications: Physics of the Earth and Planetary Interiors, v. 52, no. 3–4, p. 283–300, doi:10.1016/0031-9201(88)90121-5.

Pearson, D.G., Davies, G.R., Nixon, P.H., and Milledge, H.J., 1989, Graphitized diamonds from a peridotite massif in Morocco and implications for anomalous diamond occurrences: Nature, v. 338, p. 60–62, doi:10.1038/338060a0.

Platt, J.P., and Whitehouse, M., 1999, Early Miocene high-temperature metamorphism and rapid exhumation in the Betic Cordillera (Spain): Evidence from U-Pb zircon ages: Earth and Planetary Science Letters, v. 171, no. 4, p. 591–605, doi:10.1016/S0012-821X(99)00176-4.

Platt, J.P., Argles, T., Carter, A., Kelley, S., Whitehouse, M., and Lonergan, L., 2003a, Exhumation of the Ronda peridotite and its crustal envelope: Constraints from thermal modelling of a *P-T*-time array: Journal of the Geological Society, v. 160, no. 5, p. 655–676, doi:10.1144/0016-764902-108.

Platt, J.P., Allerton, S., Kirker, A., Mandeville, C., Mayfield, A., Platzman, E., and Rimi, A., 2003b, The ultimate arc: Differential displacement, oroclinal bending, and vertical axis rotation in the External Betic-Rif arc: Tectonics, v. 22, no. 3, 1017, doi:10.1029/2001TC001321.

Platt, J.P., Whitehouse, M., Kelley, S., Carter, A., and Hollick, L., 2003c, Simultaneous extensional exhumation across the Alboran Basin: Implications for the causes of late orogenic extension: Geology, v. 31, no. 3, p. 251–254, doi:10.1130/0091-7613(2003)031<0251:SEEATA>2.0.CO;2.

Platt, J.P., Behr, W.M., Johanesen, K., and Williams, J.R., 2013, The Betic-Rif arc and its orogenic hinterland: A review: Annual Review of Earth and Planetary Sciences, v. 41, no. 1, p. 313–357, doi:10.1146/annurev-earth-050212-123951.

Platzman, E., 1992, Paleomagnetic rotations and the kinematics of the Gibraltar arc: Geology, v. 20, no. 4, p. 311–314, doi:10.1130/0091-7613(1992)020<0311:PRATKO>2.3.CO;2.

Platzman, E., Platt, J., and Olivier, P., 1993, Palaeomagnetic rotations and fault kinematics in the Rif arc of Morocco: Journal of the Geological Society, v. 150, no. 4, p. 707–718, doi:10.1144/gsjgs.150.4.0707.

Platzman, E.S., Platt, J., Kelley, S., and Allerton, S., 2000, Large clockwise rotations in an extensional allochthon, Alboran Domain (southern Spain): Journal of the Geological Society of London, v. 157, no. 6, p. 1187–1197, doi:10.1144/jgs.157.6.1187.

Poujol, A., Ritz, J.-F., Tahayt, A., Vernant, P., Condomines, M., Blard, P.-H., Billant, J., Vacher, L., Hni, L., and Koulali, A., 2014, Active tectonics of the Northern Rif (Morocco) from geomorphic and geochronological data: Journal of Geodynamics, v. 77, p. 70–88, doi:10.1016/j.jog.2014.01.004.

Précigout, J., and Gueydan, F., 2009, Mantle weakening and strain localization: Implications for the long-term strength of the continental lithosphere: Geology, v. 37, no. 2, p. 147–150, doi:10.1130/G25239A.1.

Précigout, J., Gueydan, F., Gapais, D., Garrido, C., and Essaifi, A., 2007, Strain localisation in the subcontinental mantle—A ductile alternative to the brittle mantle: Tectonophysics, v. 445, no. 3–4, p. 318–336, doi:10.1016/j.tecto.2007.09.002.

Précigout, J., Gueydan, F., Garrido, C.J., Cogné, N., and Booth-Rea, G., 2013, Deformation and exhumation of the Ronda peridotite (Spain): Tectonics, v. 32, no. 4, p. 1011–1025.

Reuber, I., Michard, A., Chalouan, A., Juteau, T., and Jermoumi, B., 1982, Structure and emplacement of the alpine-type peridotites from Beni Bousera, Rif, Morocco: A polyphase tectonic interpretation: Tectonophysics, v. 82, no. 3–4, p. 231–251, doi:10.1016/0040-1951(82)90047-6.

Rosenbaum, G., and Lister, G.S., 2004, Formation of arcuate orogenic belts in the Western Mediterranean region, *in* Sussman, A.J., and Weil, A.B., eds., Orogenic Curvature: Integrating Paleomagnetic and Structural Analyses: Geological Society of America Special Paper 383, p. 41–56.

Rossetti, F., Dini, A., Lucci, F., Bouybaouenne, M., and Faccenna, C., 2013, Early Miocene strike-slip tectonics and granite emplacement in the Alboran Domain (Rif chain, Morocco): Significance for the geodynamic evolution of Western Mediterranean: Tectonophysics, v. 608, p. 774–791, doi:10.1016/j.tecto.2013.08.002.

Royden, L.H., 1993, Evolution of retreating subduction boundaries formed during continental collision: Tectonics, v. 12, p. 629–638, doi:10.1029/92TC02641.

Sánchez-Gómez, M., García-Dueñas, V., and Muñoz, M., 1995, Relations structurales entre les péridotites de la Sierra Bermeja et les unités Alpujarrides sous-jacentes (Benahavís, Ronda, Espagne): Comptes Rendus de l'Académie des Sciences, v. 321, no. 2, p. 885–892.

Sánchez-Gómez, M., Azañón, J.M., García-Dueñas, V., and Soto, J.I., 1999, Correlation between metamorphic rocks recovered from Site 976 and the Alpujárride rocks of the Western Betics, *in* Zahn, R., Comas, M.C., and Klaus, A., et al., Proceedings of the Ocean Drilling Program, Scientific Results, v. 161: College Station, Texas, Ocean Drilling Program, p. 307–317.

Sánchez-Gómez, M., Balanyá, J.C., García-Dueñas, V., and Azañón, J.M., 2002, Intracrustal tectonic evolution of large lithosphere mantle slabs in the western end of the Mediterranean orogen (Gibraltar arc): Journal of the Virtual Explorer, v. 8, p. 23–34, doi:10.3809/jvirtex.2002.00054.

Sánchez-Navas, A., García-Casco, A., and Martín-Algarra, A., 2014, Pre-Alpine discordant granitic dikes in the metamorphic core of the Betic Cordillera: Tectonic implications: Terra Nova, v. 26, no. 6, p. 477–486, doi:10.1111/ter.12123.

Sánchez-Rodríguez, L., and Gebauer, D., 2000, Mesozoic formation of pyroxenites and gabbros in the Ronda area (southern Spain), followed by early Miocene subduction metamorphism and emplacement into the middle crust: U-Pb sensitive high-resolution ion microprobe dating of zircon: Tectonophysics, v. 316, no. 1–2, p. 19–44, doi:10.1016/S0040-1951(99)00256-5.

Sanz de Galdeano, C., and López-Garrido, A.C., 2012, The Torcal de Antequera, an example of a structure formed by a large scale dextral transcurrent system: Estudios Geologicos, v. 68, no. 2, p. 189–202.

Sanz de Galdeano, C., and Ruiz Cruz, M.D., 2016, New lithologic and structural data of the central and eastern part of Ceuta (Rif Cordillera): Geogaceta, v. 59, p. 19–22.

Serrano, F., Guerra-Merchán, A., Kadiri, K.E., Sanz de Galdeano, C., López-Garrido, A.C., Martín-Martín, M., and Hlila, R., 2007, Tectono-sedimentary setting of the Oligocene–early Miocene deposits on the Betic-Rifian Internal zone (Spain and Morocco): Geobios, v. 40, no. 2, p. 191–205, doi:10.1016/j.geobios.2006.04.005.

Sosson, M., Morrillon, A.-C., Bourgois, J., Féraud, G., Poupeau, G., and Saint-Marc, P., 1998, Late exhumation stages of the Alpujarride complex (Western Betic Cordilleras, Spain): New thermochronological and structural data on Los Reales and Ojen nappes: Tectonophysics, v. 285, no. 3–4, p. 253–273, doi:10.1016/S0040-1951(97)00274-6.

Soto, J.I., and Platt, J.P., 1999, Petrological and structural evolution of high-grade metamorphic rocks from the floor of the Alboran Sea basin, Western Mediterranean: Journal of Petrology, v. 40, p. 21–60, doi:10.1093/petroj/40.1.21.

Soustelle, V., Tommasi, A., Bodinier, J.L., Garrido, C.J., and Vauchez, A., 2009, Deformation and reactive melt transport in the mantle lithosphere above a large-scale partial melting domain: The Ronda Peridotite Massif, southern Spain: Journal of Petrology, v. 50, p. 1235–1266, doi:10.1093/petrology/egp032.

Suen, C.J., and Frey, F.A., 1987, Origins of the mafic and ultramafic rocks in the Ronda peridotite: Earth and Planetary Science Letters, v. 85, p. 183–202, doi:10.1016/0012-821X(87)90031-8.

Torné, M., Fernández, M., Comas, M., and Soto, J., 2000, Lithospheric structure beneath the Alborán Basin: Results from 3D gravity modeling and tectonic relevance: Journal of Geophysical Research, v. 105, p. 3209–3228, doi:10.1029/1999JB900281.

Tubía, J.M., 1994, The Ronda peridotites (Los Reales nappe): An example of the relationship between lithospheric thickening by oblique tectonics and extensional deformation within the Betic Cordillera (Spain): Tectonophysics, v. 283, p. 381–398.

Tubía, J.M., and Cuevas, J., 1986, High-temperature emplacement of the Los Reales peridotite nappe (Betic Cordillera, Spain): Journal of Structural Geology, v. 8, p. 473–482, doi:10.1016/0191-8141(86)90064-7.

Tubía, J., Cuevas, J., and Ibarguchi, J.G., 1997, Sequential development of the metamorphic aureole beneath the Ronda peridotites and its bearing on the tectonic evolution of the Betic Cordillera: Tectonophysics, v. 279, no. 1–4, p. 227–252, doi:10.1016/S0040-1951(97)00124-8.

Tubía, J., Cuevas, J., and Esteban, J., 2004, Tectonic evidence in the Ronda Peridotites, Spain, for mantle diapirism related to delamination: Geology, v. 32, no. 11, p. 941–944, doi:10.1130/G20869.1.

Tubía, J., Cuevas, J., and Esteban, J., 2013, Localization of deformation and kinematic shift during the hot emplacement of the Ronda peridotites (Betic Cordilleras, southern Spain): Journal of Structural Geology, v. 50, p. 148–160, doi:10.1016/j.jsg.2012.06.010.

Turner, S.P., Platt, J.P., George, R.M.M., Kelley, S.P., Pearson, D.G., and Nowell, G.M., 1999, Magmatism associated with orogenic collapse of the Betic–Alboran Domain, SE Spain: Journal of Petrology, v. 40, no. 6, p. 1011–1036.

Van der Wal, D., and Bodinier, J.-L., 1996, Origin of the recrystallization front of the Ronda peridotite by km-scale pervasive porous melt flow: Contributions to Mineralogy and Petrology, v. 122, p. 387–405, doi:10.1007/s004100050135.

Van der Wal, D., and Vissers, R.L.M., 1993, Uplift and emplacement of upper mantle rocks in the Western Mediterranean: Geology, v. 21, no. 12, p. 1119–1122, doi:10.1130/0091-7613(1993)021<1119:UAEOUM>2.3.CO;2.

Van der Wal, D., and Vissers, R.L.M., 1996, Structural petrology of the Ronda Peridotite, SW Spain: Deformation history: Journal of Petrology, v. 37, no. 1, p. 23–43, doi:10.1093/petrology/37.1.23.

Vergés, J., and Fernández, M., 2012, Tethys-Atlantic interaction along the Iberia-Africa plate boundary: The Betic-Rif orogenic system: Tectonophysics, v. 579, no. 5, p. 144–172, doi:10.1016/j.tecto.2012.08.032.

Villasante-Marcos, V., Osete, M., Gervilla, F., and García-Dueñas, V., 2003, Palaeomagnetic study of the Ronda peridotites (Betic Cordillera, southern Spain): Tectonophysics, v. 377, no. 1–2, p. 119–141, doi:10.1016/j.tecto.2003.08.023.

Villaseñor, A., Chevrot, S., Harnafi, M., Gallart, J., Pazos, A., Serrano, I., Córdoba, D., Pulgar, J.A., and Ibarra, P., 2015, Subduction and volcanism in the Iberia–North Africa collision zone from tomographic images of the upper mantle: Tectonophysics, v. 663, p. 238–249, doi:10.1016/j.tecto.2015.08.042.

Vitale, S., Zaghloul, M.N., Tramparulo, F.D., Ouaragli, B.E., and Ciarcia, S., 2014, From Jurassic extension to Miocene shortening: An example of polyphasic deformation in the external Dorsale Calcaire unit (Chefchaouen, Morocco): Tectonophysics, v. 633, p. 63–76, doi:10.1016/j.tecto.2014.06.028.

Watts, A., Platt, J., and Buhl, P., 1993, Tectonic evolution of the Alboran Sea basin: Basin Research, v. 5, p. 153–177, doi:10.1111/j.1365-2117.1993.tb00063.x.

Wortel, M.J.R., and Spakman, W., 2000, Subduction and slab detachment in the Mediterranean-Carpathian region: Science, v. 290, p. 1910–1917, doi:10.1126/science.290.5498.1910.

Zeck, H.P., and Whitehouse, M.J., 2002, Repeated age resetting in zircons from Hercynian-Alpine polymetamorphic schists (Betic–Rif tectonic belt, S. Spain)—A U-Th-Pb ion microprobe study: Chemical Geology, v. 182, no. 275–292.

Manuscript Accepted by the Society 12 October 2016
Manuscript Published Online xx Month 2017

Printed in the USA