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Special Section:
Geodynamics, Crustal and Lithospheric Tectonics, and active deformation in the Mediterranean Regions (A tribute to Prof. Renato Funiciello)

Key Points:
- Ronda peridotite body is steeply dipping eastward and rooted in the Alboran mantle along the entire Gibraltar arc
- Continental margin obduction is defined by the thrusting of a hyper-stretched continental lithosphere onto a continental crust
- Continental margin obduction occurred at 20 Ma along the entire Gibraltar arc, explaining the exhumation of subcontinental mantle rocks

Supporting Information:
- Supporting Information S1

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Western Mediterranean Subcontinental Mantle Emplacement by Continental Margin Obduction

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Abstract Obduction is the tectonic process that results from thrusting of an oceanic lithosphere section (ophiolite) onto a continent. In contrast, thrusting of subcontinental mantle, observed in several mountain belts, remains a major unknown of plate tectonics. In the western Mediterranean, the Ronda and Beni Bousera peridotites are the largest worldwide subcontinental mantle exposure. From a geological point of view, the Ronda peridotites are exhumed by hyperstretching of the continental lithosphere in a back-arc immediately followed by thrusting, explaining their present-day position inside the Alboran crust. Using 2-D and 3-D modeling of new gravimetric data combined with local seismic tomography, we show that the Ronda peridotites are rooted inside the Alboran mantle along the entire Gibraltar arc. On these bases, we propose that the emplacement of the Ronda peridotites occurred in a back-arc setting and corresponds to the thrusting of an entire hyper-stretched continental margin onto a continent, a process that we define as continental margin obduction. This results from two successive deformation events: continental upper plate extension driven by slab roll-back, immediately followed by upper plate shortening, likely triggered when a buoyant continental domain enters the subduction. We propose that this process affected the entire western Alboran domain, with peridotite bodies embedded within the crust along the whole Gibraltar Arc. We suggest that other examples such as the Alps Ivrea mantle body could likely represent continental margin obduction at the onset of continental collision.

1. Introduction

Ophiolites are widespread in orogenic domains and well-known pieces of oceanic lithosphere thrust onto passive continental margins. Obduction is the tectonic process that allows ophiolites emplacement (Boudier et al., 1988; Coleman, 1972; Dewey, 1976). Obduction is triggered by incipient subduction in the upper oceanic plate, for example, related to the entering of a continental buoyant domain in the subduction (Coleman, 1981), hence allowing thrusting of a portion of oceanic plate onto the continental margin (Agard et al., 2007). Subcontinental mantle rocks (orogenic peridotites; Bodinier & Godard, 2014) are also common in orogenic belts, but, in contrast to ophiolites, no generic tectonic process has been proposed up to now for their emplacement.

The Mediterranean system shows numerous examples of subcontinental mantle exhumation in back-arc continental rifted margins (Figure 1). The progressive westward roll-back of the Apennines slab, starting at around 30 Ma, leads to the successive opening of the Liguro-Provencal basin and the Tyrrhenian sea (Faccenna et al., 2004), in which subcontinental mantle exhumation to the surface has been documented (Bache et al., 2010; Milia et al., 2017, Figure 1). The process of extreme continental lithosphere thinning at rifted margin is now well understood (Brun & Beslier, 1996; Gueydan et al., 2008; Gueydan & Précigout, 2014; Huismans & Beaumont, 2007) and provides a mechanism for subcontinental mantle lithosphere exhumation during lithosphere thinning, such as in the back-arc rifted margin of the central Mediterranean. In contrast, the mechanism of emplacement of large volumes of subcontinental mantle rocks (e.g., Ivrea body, Figure 1) in the Alpine collision history is still unresolved (Handy et al., 2010; Nicolas et al., 1990). The Ronda and Beni Bousera peridotites, in the western Mediterranean, are the world largest subcontinental mantle rocks and underline the Alboran orogenic system (Betics in Spain and Rif in Morocco) across the Gibraltar Arc. The complex slab deformation during 30 Ma of roll-back has shaped the surface geology (Lonergan & White, 1997; Royden, 1993) with coexistence of orocline orogenic system

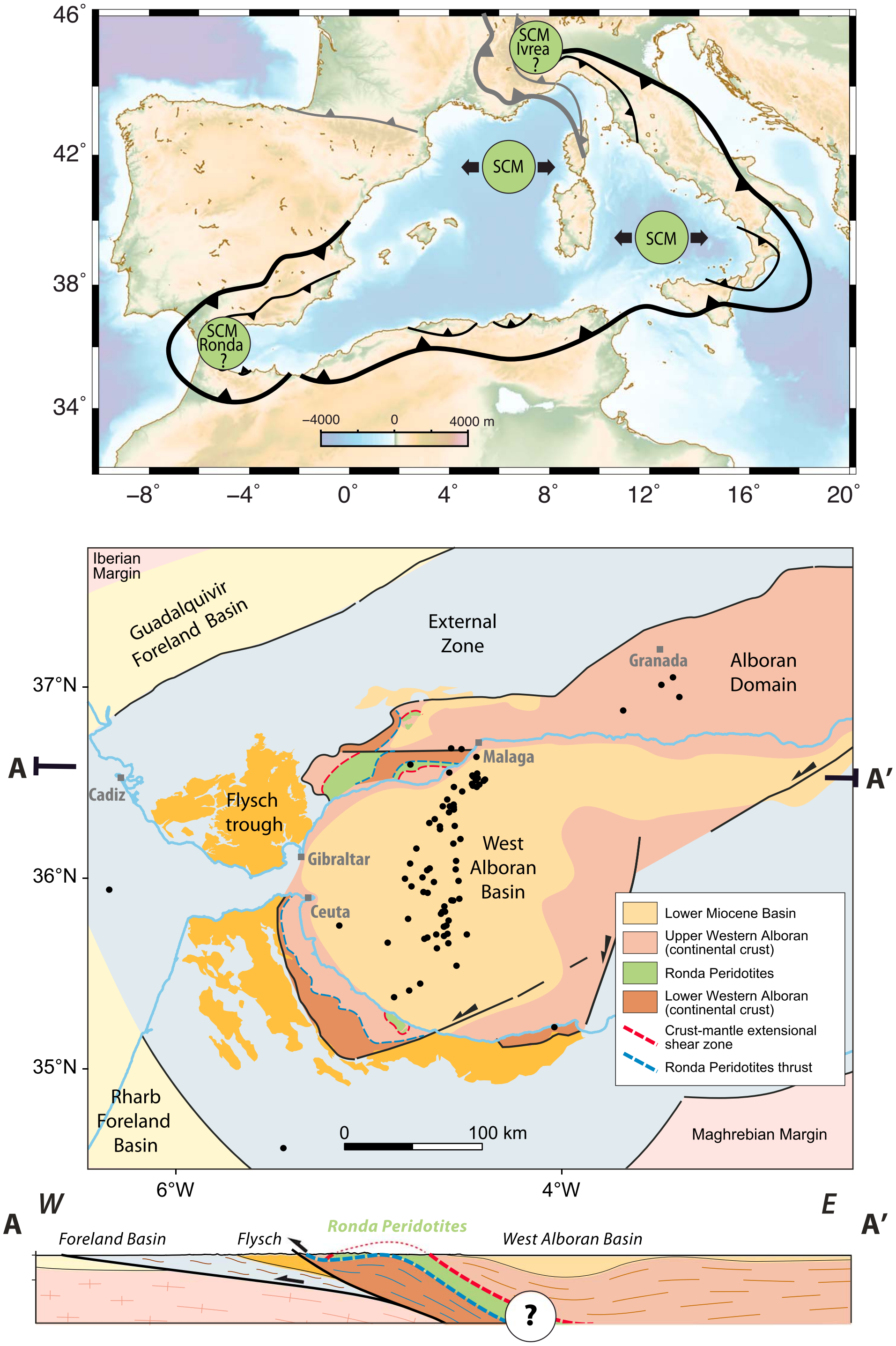

Figure 1. Occurrences of subcontinental mantle in Western and Central Mediterranean system with focus on the world largest exposure in the Alboran domain. (top) Simplified tectonic map of the western Mediterranean with location of subcontinental mantle (SCM) exhumation. (middle) Tectonic map of Ronda subcontinental mantle rocks (modified from Gueydan & Frasca, 2017), overlying hyperstretched continental crust (with crust-mantle extensional shear zone underlined in red), and underlying continental margin with high-temperature metamorphic sole underlined in blue. The green color indicates subcontinental mantle major outcrops, with three bodies in Spain (Sierra Bermeja to the West, Sierra Alpujata to the East and Carratraca to the North) and two bodies in Morocco (Ceuta serpentinitic sliver and Beni Bousera). The black dots indicate earthquakes between 30 and 100 km depth (NEIC catalog, http://earthquake.usgs.gov/regional/neic/). (bottom) E-W cross section with structures constrained for the first 5 km by field data (modified from Frasca et al., 2015). Sierra Bermeja peridotite body is thin and flat lying (West), while Sierra Alpujata body (East) is around 10 km thick and steeply dipping to the east.

(Betic-Rif) and deep sedimentary basin (Alboran Basin with locally more than 8 km of Miocene sedimentation; Figure 1). Slab tearing along African and Iberian continental margins is the primary mechanism that controls the formation of such arcuate system by the amplification of the trench curvature during slab roll-back (Spakman & Wortel, 2004). The polyphase deformation history of Alboran rocks (Variscan, Tethyan, and Alpine deformation stages, see review and related references in Gueydan et al., 2015) and the overall reset of medium to low temperature ages during lower Miocene (Esteban et al., 2004) led to contrasting explanations of the relationships between Alboran slab evolution and the peridotites emplacement (see review in Précigout et al., 2013, for Ronda and Gueydan et al., 2015, for Beni Bousera and in Platt et al., 2013).

A robust characterization of the lithospheric-scale geometry of the Western Alboran would be a first-order constraint on the tectonic process responsible for large subcontinental mantle emplacement. The western Alboran subcontinental mantle bodies (Ronda and Beni Bousera peridotites) are tectonic nappes within the metamorphic Alboran continental crust that were thrust on top of the Iberian/Moroccan passive margin (Figure 1; Frasca et al., 2015; Platt et al., 2013). Large Bouguer gravity anomalies highlight the Ronda and Beni Bousera peridodites along the Gibraltar Arc (Torné et al., 1992). Previous gravimetric modeling suggests that the Ronda peridotites are intracrustal features and are therefore not rooted inside the Alboran lithosphere mantle (Torné et al., 1992). This implies that the thrusting process is restricted to crustal level and may be earlier in time; that is, the Ronda peridotites are a tectonic sliver inside the crust. In contrast, Mazzoli and Martín-Algarra (2011) proposed, based on geological arguments on the Ronda peridotites thrust footwall, that the Ronda mantle is rooted at depth within the Alboran mantle. In addition, recent tomographic studies, based on local earthquakes, suggest that the Ronda peridotites are rooted at the base of the Alboran crust (El Moudnib et al., 2015), likely implying a lithosphere-scale thrusting event.

The objective of the present study is to quantify the depth extent of the Ronda peridotites, based on the combination of gravimetric and tomographic data, and hence to propose a new tectonic model for the emplacement of large volumes of subcontinental mantle in orogenic systems. Using a combination of geological and geophysical data, we show that continental margin obduction, that is, thrusting of a hyper-stretched continental lithosphere onto a continent (Iberia and Morocco), is the primary tectonic process that drove the emplacement of subcontinental mantle rocks and has affected the entire Alboran domain along the Gibraltar arc.

2. Geological Setting

2.1. The Western Alboran Domain

The Betic-Rif system is an orocline orogenic system divided in two main zones. First, the external zone consists in a nonmetamorphosed Mesozoic and Tertiary sedimentary cover on top of the Iberian/Maghrebian basement (Figure 1). Second, the internal zone, also called the Alboran Domain (Figure 1), is characterized by metamorphic rocks with variable metamorphic grades and ages and is structurally composed by a nappe pile of three tectonic units, which are, from bottom to top, the Nevado-Filabride (cropping out only in the Eastern Betics), the Alpujarrides, and the Malaguide (see Didon et al., 1973). A tertiary high-pressure event is recorded in the Nevado Filabrides, with varying ages ranging from Eocene to Mid-Miocene, implying contrasting geodynamical implications (see review in Platt et al., 2013). The Malaguide unit is nonmetamorphosed. In the western Alboran, the Alpujarides/Sebtides units have registered two main metamorphic events (Variscan and Alpine) leading to a diversity of tectonic scenarios to explain their deformation (see a well constrained example in Sánchez-Navas et al., 2017, and a broader discussion in Gueydan et al., 2015). The Ronda peridotites (s.l.) are outcropping inside the Alpujarides (Sebtides in Morocco), with three bodies in Spain (Sierra Bermeja to the West, Sierra Alpujata to the East, and Carratraca to the North) and two bodies in Morocco (Ceuta serpentinitic sliver and Beni Bousera). All these major peridotites bodies are connected with smaller serpentinite bodies, suggesting an original continuity between the peridotites outcrops on the two sides of the Gibraltar arc. The polyphase metamorphism and deformation history of the Alpujarides/Sebtides leads to several tectonic scenarios for the Ronda peridotites exhumation and crustal emplacement.

Along the Gibraltar arc, the “*Flysch Trough*” (Figure. 1) lies structurally on top of the External zone and is mainly composed of Cretaceous to Miocene deep marine clastic sediments. Sedimentation ends in the

Lower Miocene, marking the onset of the main shortening event in the Flysch Trough (Luján et al., 2006). Lower Miocene-Quaternary foreland sediments delineate the northern and southern terminations of the Betic-Rif arcuate belt: the Guadalquivir Basin in the Betics and Rharb Basin in the Rif (Figure 1).

2.2. A Variety of Geodynamic Scenarios

The tectonic origin of the Betic-Rif belt remains a matter of debate. Several geodynamical scenarios are proposed to explain the arcuate geometry of the Alboran system.

Andrieux et al. (1971) proposed the indentation of an exotic microplate in the Iberian and Maghrebian margin, accommodated by strike-slip shearing along the lateral boundaries of the rigid indenter. However, extension is widespread in the Alboran Domain (García-Dueñas et al., 1992) and can be explained by gravitational collapse of a previous mountain belt (Platt & Vissers, 1989), possibly driven by delamination of the lithosphere mantle (García-Dueñas et al., 1992).

The imaging of an east dipping slab beneath Gibraltar (*G*utscher et al., 2002; Wortel & Spakman, 2000; Spakman & Wortel, 2004) has demonstrated that subduction with slab roll-back is the main mechanism that has shaped the Western Mediterranean system. Subduction slab roll-back can also explain both the arcuate evolution of the Betic-Rif external zones and the extensional structures in the internal zones (Lonergan & White, 1997; Royden, 1993). Furthermore, the spatial distribution of the different types of volcanism (Duggen et al., 2004) and the transition along the Betics from marine to continental sedimentation (Iribarren et al., 2009) also suggest a subduction rollback origin for the mountain belt and its metamorphic units. The amount of slab rollback and the direction of trench migration is still a matter of controversy, with three main geodynamical scenarios (see review in Chertova et al., 2014). (1) An initial northwest dipping subduction along the west-central Mediterranean (from Gibraltar or southeast of Iberia to Corsica) initiated in Oligocene and rolled back first to the south and then to the west (Faccenna et al., 2004; Jolivet et al., 2006), (2) a short N-S trending subduction zone located south of the Baleares islands rolled back westward during the upper Miocene (Frizon de Lamotte et al., 2009; Rosenbaum & Lister, 2004; Spakman & Wortel, 2004; Van Hinsbergen et al., 2014), and (3) an initial subduction zone dipping to the S-SE under the African margin (Alpine type) that rolled back first northward and progressively to the NW (Vergés & Fernández, 2012).

2.3. The Ronda Peridotites

The western Alboran subcontinental mantle bodies (Ronda and Beni Bousera peridotites) are tectonic nappes within the metamorphic Alboran continental crust that were thrust on top of the Iberian/Moroccan passive margin (Figure 1; Frasca et al., 2015; Platt et al., 2013). The overlying crustal rocks correspond to a strongly thinned continental crust, less than 5 km thick now, which has recorded a continuous decompression locally coeval with a temperature increase (Platt et al., 2013). The peridotites have also registered a strong decompression from mantle depths (garnet-peridotite facies) to low pressure (Spinel and even Plagioclase peridotites facies, (Garrido et al., 2011)). Consistent foliations and shear criteria in both overlying deep crust and mantle and a strain gradient from mantle to crust indicate the existence of a kilometer scale crust-mantle extensional shear zone (Afiri et al., 2011; Précigout et al., 2013) that accommodates lithosphere thinning. The Western Alboran peridotites and their overlying continental crust (hereafter called Upper Western Alboran, Figure 1) are therefore a complete strongly thinned lithosphere section, less than 10 km thick. The crustal thickness above the peridotites has been locally reduced to less than 50 m, testifying of hyperstretching during Oligo-Miocene times (Frasca et al., 2016). Consistently, partial melting occurs at the end of the extensional deformation of the peridotites (Marchesi et al., 2012), locally leading to gabbros intrusion (Frasca et al., 2016; Hidas et al., 2015). Michard et al. (2002) and Tubía et al. (2009) already suggested a continental margin affinity for the Ronda peridotites and their crustal envelopes. The base of the hyperstretched continental lithosphere nappe is the Ronda peridotites thrust, marked by a metamorphic sole with a strong thermal gradient up to migmatitic gneiss in the underlying crustal rocks (Tubía et al., 1997). The crustal units below the Ronda Peridotite Thrust (Blanca, Ojen, Guadaiza, and Nieves units [Tubía & Cuevas, 1986; Tubía & Gil Ibarguchi, 1991; Esteban et al., 2008, Martín-Algarra, 1987]) are called Lower Western Alboran (Frasca et al., 2015). The upper 5-10 km of the Alboran crust is therefore relatively well constrained by several geological studies, as synthetized in the cross section of Figure 1: thrusting of the Upper Western Alboran thinned continental lithosphere onto the Lower Western Alboran crust. Although shortening directions are varying from NW-SE to N-S (Frasca et al., 2015; Mazzoli & Martín-Algarra, 2014;

Tubía et al., 2013), shortening is found to be coeval with E-W dextral strike slip corridors (Torcal to the North and Coin in the internal zone of the Betics; see Frasca et al., 2015), demonstrating a E-W direction of displacement during the main thrusting events at around 20 Ma. We use therefore an E-W cross section (called hereafter the Ronda profile) to document first the geometry of the geological units (Figure 2) and in what follows the depth extent of the Ronda peridotites.

Tubía et al. (2009) and Michard et al. (2002) proposed, mainly on the basis of stratigraphic correlations between sedimentary units in the Betics and Rif, that the continental margin whence the Ronda Peridotites are derived is of Jurassic ages. Radiochronological ages show two clusters of ages (Varsican and Alpine, see Rossetti et al., 2013, and review in Frasca et al., 2017). In situ U/Pb ages inside sheared migmatite suggest an age for lithosphere thinning of late Oligocene to early Miocene (Frasca et al., 2017). Variscan ages reported in the granulite overlying the peridotites suggest however a polyphased deformation and metamorphic history of the continental crust above the peridotites, leading to such a variety of interpretation. A wealth of high-temperature ages at approximately 20 Ma in leucogranites dykes associated with the "hot" Ronda peridotite thrust constrain a Lower Miocene age for the final crustal emplacement of the peridotites (Esteban et al., 2004, and see synthesis in Frasca et al., 2017). In addition, the metamorphic and tectonic study of the Nieves sedimentary unit in the footwall of the Ronda peridotite thrust provides independent constraints to a hot emplacement of the Ronda peridotites after the Aquitanian (metamorphosed sediments of Aquitanian ages below the peridotites; Martín-Algarra, 1987; Mazzoli et al., 2013). A fast switch from extension (between 30 and 21 Ma) to thrusting (at 21 Ma) has therefore been proposed to explain the thrusting of the Ronda peridotites onto the Iberian/Moroccan margin (Álvarez-valero et al., 2014; Frasca et al., 2017).

Note that very different mechanisms and ages for mantle rock exhumation are proposed (see review and references in Frasca et al., 2015): mantle core complex (ii) extrusion of a mantle wedge during transpression along a subducting slab, detachment faulting during extensional collapse of the Betic-Rif chain, and the inversion of a thinned back-arc lithosphere during slab rollback. The ages of exhumation of the subcontinental mantle are also strongly variable from Paleozoic to Mesozoic and Oligo-Miocene.

From this variety of models and hypotheses, we can synthetize the polyphase deformation history as follows: (1) Variscan time: high-temperature metamorphism in the crustal envelope of the peridotites (with no record in the peridotites), most probably related to extensional collapse of the Variscan orogen, and (2) Jurassic times: Tethyan rifting, recorded in the Ronda peridotites *(*Tubía et al., 2009*),* with two opposite scenarios. Scenario 1: Peridotites were unroofed to surface level (similar to the Alpine ophiolites and the ophiolites embedded in Cretaceous flysch in Morocco; Michard et al., 2002; Van Hinsbergen et al., 2014). Scenario 2: Peridotites were only unroofed from diamond stability field to garnet stability field (from 100 to 70 km, see discussion in Garrido et al., 2011). This Jurassic time rifting events also explains the stratigraphic structuration of the entire Alboran domain. (3) Oligo-Miocene times: If peridotites were unroofed at surface level (scenario 1), they are just passively involved as tectonic nappes in the formation of the Betic-Rif orogenic system driven by slab roll back (Van Hinsbergen et al., 2014). If peridotites were still at great depths (scenario 2), back-arc rifting leads to the final unroofing (from 70 to 0 km) immediately followed by thrusting (Frasca et al., 2017).

The present study does not wish to add further geological or geochronological data but instead to provide geophysical constraints (gravimetry and local tomography) to the depth extent of the Ronda peridotites. This will ultimately allow proposing a new tectonic scenario for the Ronda peridotite exhumation and final crustal emplacement and hence can be used to better constrain the geodynamical model of the region.

3. Gravimetric Data and Models

In order to better characterize the depth extent of the Ronda peridotites, new gravimetric data were acquired in southern Spain (black triangle, Figure 2a). Gravity measurements were collected at 67 new stations using a Scintrex CG5 relative gravimeter. The overall survey techniques and processing (Gabalda et al., 2003) are described below. The mean distance between gravity stations is about 3 km. The location of the gravity network is complementary with existing data available at the International Gravimetric Bureau (IGB, grey points, Figure 2a). A base station was setup in the central part of the network and measured at least once a day to correct the drift of the relative gravimeter (approximately 0.03

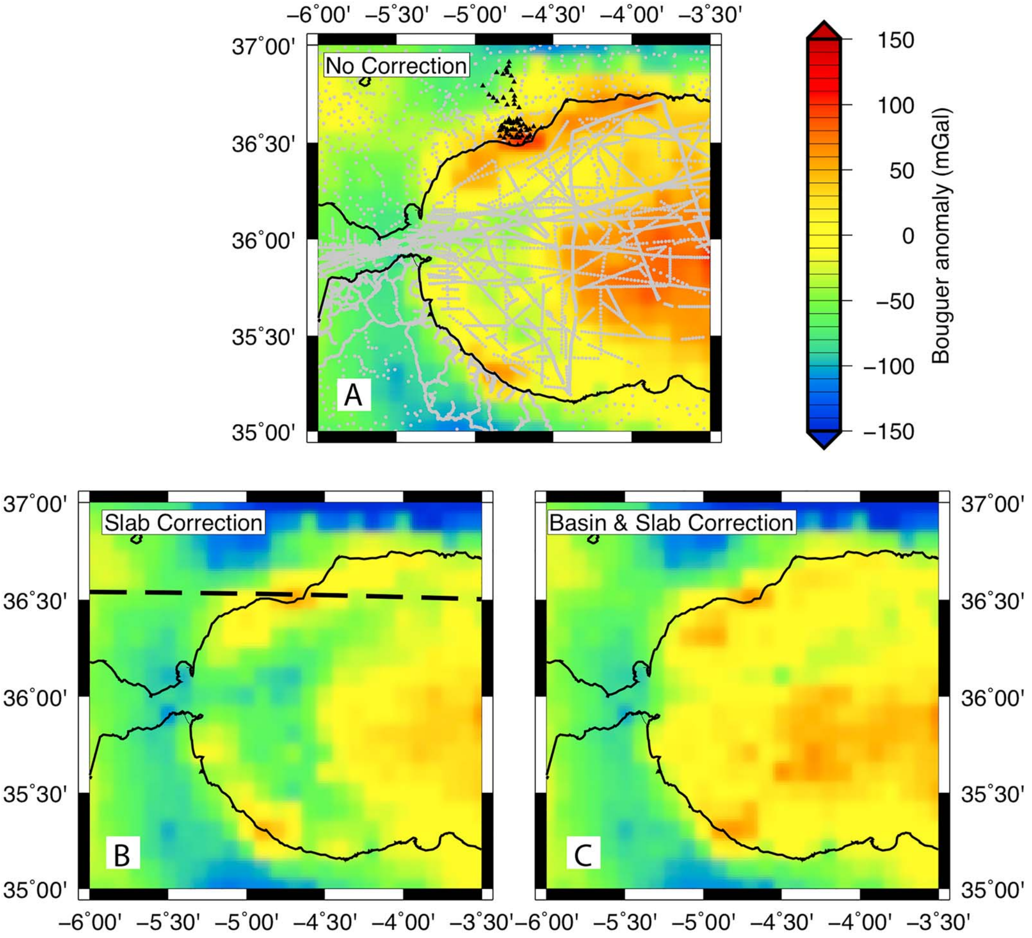

Figure 2. Gravimetric data in the Western Alboran domain. (a) New Bouguer gravimetric data collected in the Western Betics (triangles) together with Bouguer gravimetric data from the International Gravimetric Bureau (dots). (b) Bouguer anomalies corrected from the Alboran slab effect (Villaseñor et al., 2015). (c) Bouguer anomalies corrected from the Alboran slab effect (Villaseñor et al., 2015) and the sedimentary basins (mainly Western Alboran basin, located in Figure 1 (Iribarren et al., 2009))

mGal/days). The precision of the gravity reading depends on weather conditions but is better than 0.1 mGal. The gravity data anomaly is tied to an absolute gravity point in Malaga measured in 1993 (IGB data). The heights (above ellipsoid) of the gravity stations were estimated from 15-min GPS measurements (double frequency) processed using Precise Point Positioning. Repeatability of the GPS height is better than 1 m at the base station measured every day. Bouguer anomalies are calculated with a density of 2,670 kg/m^3 for the terrain correction (Wang & Geller, 2003) based on the SRTM (Shuttle radar Topography Mission: http://www2.jpl.nasa.gov/srtm/index.html) topography data. The comparison of the new data with IGB data within a distance of less than 1 km shows a mean bias smaller than 1 mGal and a standard deviation of 3 mGal.

The complete Bouguer anomaly data set, shown in Figure 2a, comprises our new acquired data (black triangles) and the existing IGB data (grey dots) previously used in Torné et al. (1992) study. Two first-order corrections are performed. First, a correction for the gravity anomaly associated with the underlying Alboran slab is computed based on the *P* wave velocity model (including slab position) imaged by recent seismic tomography (Villaseñor et al., 2015). Conversions from *P* wave velocity to density anomaly are based on empirical calibrations (Christensen & Mooney, 1995) for ultramafic rocks (dunites). The slab density anomalies are computed from 100- to 600-km depth and result in a correction of about +30-55 mGal over our study area, with a slight eastward trend (Figure 2a versus 2b). Second, a correction for the gravity anomaly associated with the West Alboran, Gharb, and Guadalquivir sedimentary basins is applied using compiled basins thickness models (Iribarren et al., 2009). Sediment density is assumed constant (2,600 kg/m^3). This correction results in an increase of the corrected Bouguer anomaly by about 15-50 mGal over the three basins, with the largest effect associated with the approximately 5- to 8-km thick West Alboran basin (Figure 2b versus 2c). Both corrections emphasize the short wavelength signature (50-100 km) of the Ronda and Beni Bousera peridotites, with a quasi-continuous anomaly curved along the Gibraltar Arc.

In this study, we first model in 2-D the Bouguer gravity anomalies (only corrected for the slab effect, shown in Figure 2b with the corresponding profile in Figure 3a) along the primary Ronda profile (described in section 4). This allows us to propose an alternative geometry for the Ronda peridotites depth extension (Torné et al., 1992). Second, we invert in a 3-D scheme the Bouguer gravity anomalies (corrected for both slab and basin effects, shown in Figure 2c) for the whole Alboran region (section 5). This permits to take into account the 3-D geometry of the structures and to retrieve the extension of Ronda peridotites through the crust along the Gibraltar Arc. The Ronda profile analysis corresponds to a 2-D direct model of the slab-corrected Bouguer anomaly. Contrary to previous gravity modeling, which arbitrary removed deepest bodies based on regional trend of Bouguer anomaly (Torné et al., 1992), we calculate our slab correction on recent tomographic model (Villaseñor et al., 2015). Then, guided by new local tomography data (El Moudnib et al., 2015, and Figure 3c), we test the validity of a peridotite continuous body with a simple 1- × 1-km grid model, for which the upper 5 km are constrained by the geological cross section (Figure 1). The rest of the crust and upper mantle is tuned to fit the combined long and short wavelength components of the gravity profile. The reference densities are 2,800 and 3,300 kg/m^3 for crust and mantle, respectively. Sediments and peridotite bodies in the crust are modeled with densities of 2,450 and 3,200 kg/m^3, respectively (Torné et al., 1992). We tested three different dipping angles for the peridotite body (20, 26, and 35°; Figure S1 and Text S1 in the supporting information).

In a second step, we perform a 3-D analysis over the whole region using a nonlinear inversion (Tiberi et al., 2003) of the slab- and basin-corrected Bouguer anomaly. This allows us to focus on the lateral and 3-D extent of the peridotites body around the Gibraltar Arc without long wavelength artifact from other major bodies. The inversion retrieves the density contrasts within cells of 10- × 10- × 10-km size over a 45-km-thick volume. A priori information is included as heterogeneous standard deviation distribution for the model parameters in order to take into account the information obtained with the former 2-D models (e.g., Widiwijayanti et al., 2004, for details). Initial a priori model is homogeneous with a zero density contrast for all layers, and we laterally extend the density model by approximately 100 km to overcome boundary effects. The resulting root-mean-square (RMS) decrease is 80%, with a final value of 10 mGal.

4. 2-D Crustal and Lithosphere Structure

The Bouguer gravimetric anomalies, corrected for the steeply dipping Alboran Slab effect (Figure 2b), show two main features along the E-W profile parallel to the geological cross section (Figure 3). (1) A landward (east to west) trend of decreasing Bouguer anomaly from about 0 to -70 mGal (see Figure 2b for a similar pattern around the entire Alboran domain). This long-wavelength trend (300-400 km) is likely due to variations in crustal thickness from thin continental crust in the Alboran basin (with the associated sedimentary basin; Iribarren et al., 2009) to thick crust in the Iberian margin, as indicated by receiver functions (Mancilla et al., 2015) and surface wave tomography (Levander et al., 2014). (2) A short wavelength positive Bouguer anomaly up to ~50 mGal, southeast of Malaga, is related to the large Ronda peridotite body (Torné et al., 1992). The very sharp gradient on the west side of this positive anomaly is well constrained by our newly acquired data (black triangles in Figure 2a) and likely indicates an asymmetric and steeply dipping peridotite body.

In our direct model, we account for crustal thickness variations, the sedimentary basins, and the local high-density peridotite body. The long wavelength anomalies are best modeled by a landward (westward) increase in crustal thickness from ~30 to ~40 km (Figure 3b) combined with an ~5-km-thick sedimentary basin tapering out ~15 km east of the shoreline (beginning of the Malaga basin; Iribarren et al., 2009). A homogeneous simple peridotite body steeply eastward dipping and rooted in the Alboran mantle can perfectly fit the Ronda short wavelength positive anomaly (Figure 3b). We estimate the dipping angle by testing other geometries. A steeper angle overestimates the Bouguer anomaly high, while a lower

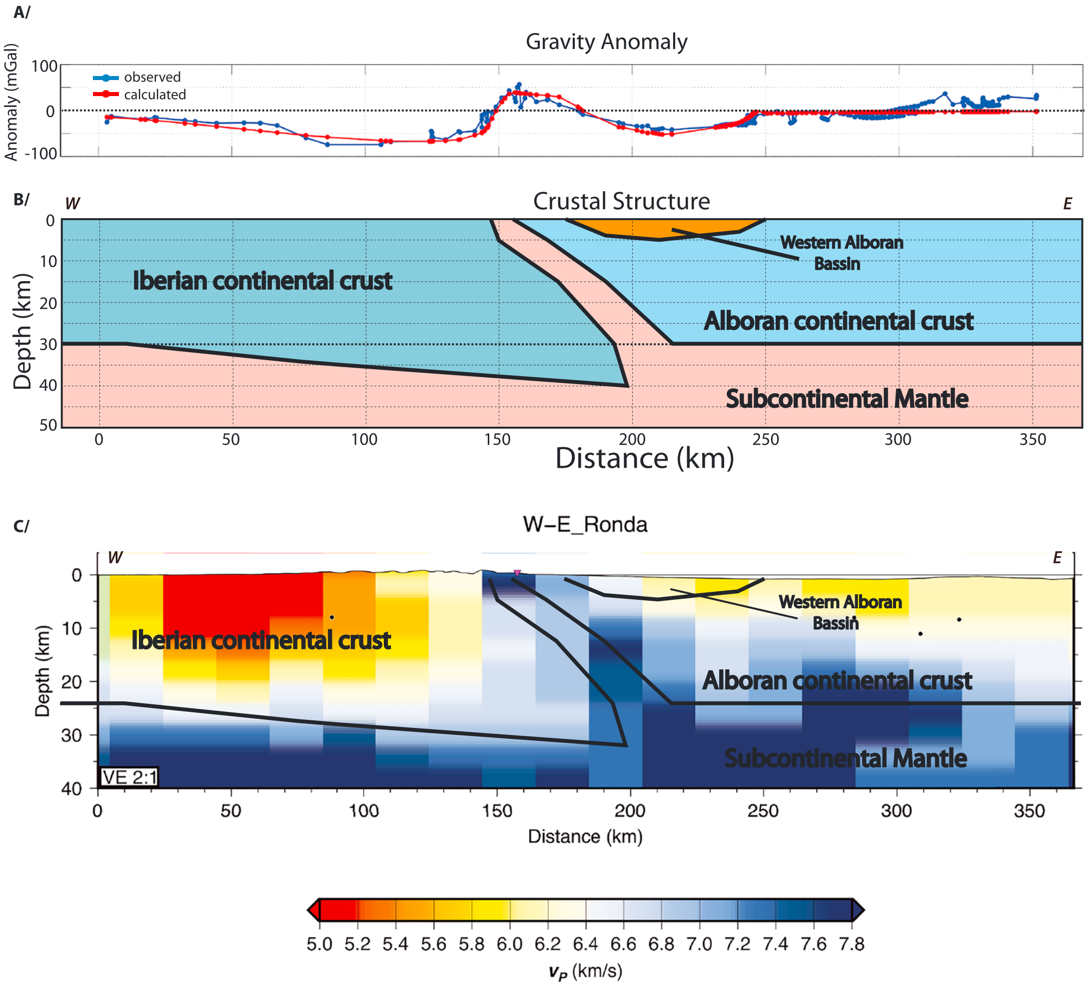

Figure 3. 2-D direct gravimetric modeling along the Ronda profile. (a) E-W 120-km-long gravimetric cross section corrected from the Alboran slab effect (see location on Figure 2). (b) Density body structure to model the gravity anomaly profile. (c) E-W local earthquake tomographic cross section (same location as (a)), derived from El Moudnib et al. (2015). Note the vertical exaggeration by a factor of 2 in both (b) and (c).

value counteracts too much the basin effect east of Ronda peridotites (Figure S1). We cannot rule out alternative and more complex density models, but our results show that the gravity anomalies are consistent with a 20-km-thick deep-rooted peridotite body, dipping 26-30° eastward. This geometry is supported by a recent tomographic study, which shows up a high Vp body rooted at depth (El Moudnib et al., 2015). The 2-D geometry inferred by this seismic analysis is in good agreement with our direct modeling of gravimetric data (Figure 3b versus 3c) and supports the rooting of the Ronda peridotites body within the Alboran mantle.

On these bases, we suggest that at the lithosphere scale the Ronda peridotites correspond, for the western outcrop (e.g., Sierra Bermeja; Figure 1), to a thin and flat lying body and, for the eastern outcrop (e.g., Sierra Alpujata, Figure 1), to a 10-km-thick steeply dipping body rooted in the Alboran mantle, both thrusted on top of a continental domain (Figure 4). Seismicity distribution displays at lithosphere scale the boundary between the Alboran domain and the Iberian margin. The clustering of earthquakes at depth between 40 and 90 km along a steeply dipping slab supports the hypothesis of a downgoing oceanic plate attached to the Iberian continental margin (Mancilla et al., 2015; Villaseñor et al., 2015). The gravity-based modeled Moho at 40-km depth to the West is therefore the Iberian (foreland) Moho, while the Alboran Moho is located at 30-km depth to the East (Figure 4). This lithosphere-scale cross section, constrained by geological and geophysical data, shows that a hyperstretched continental lithosphere is thrust onto a continental crust, a feature that can be defined as *continental margin obduction*.

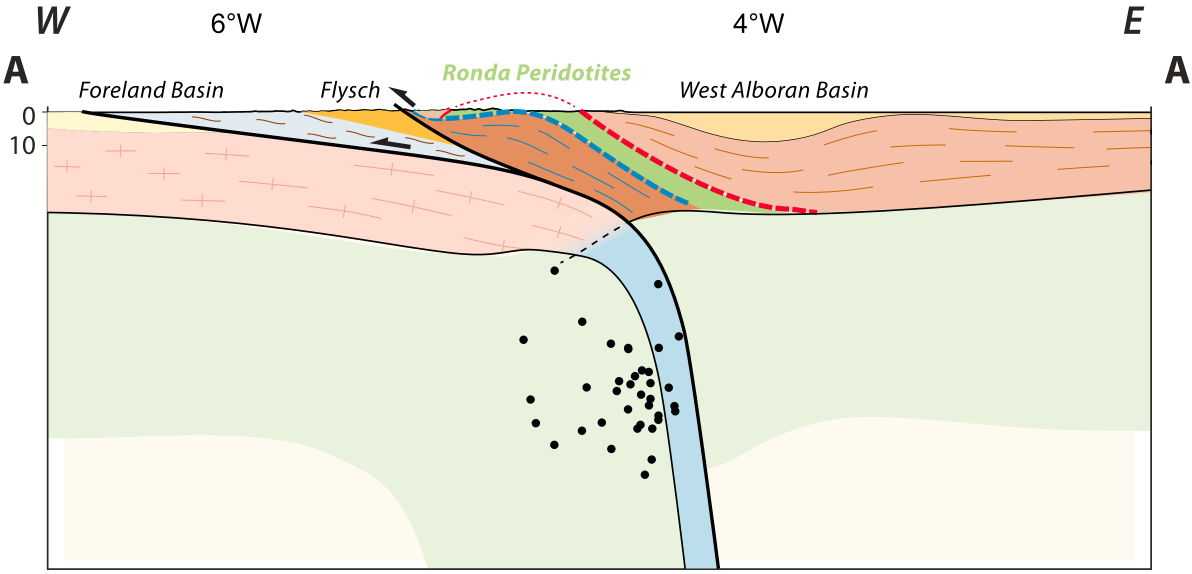

Figure 4. Lithosphere scale cross-section along the Ronda profile, constrained from the geological cross-section (Figure 1), the direct gravimetric modeling (Figure 3b), tomographic imaging (Figure 3c) and the earthquake distribution (black dots from NEIC catalog, http://earthquake.usgs.gov/regional/neic/).

5. 3-D Structures

The 2-D profile analysis in southern Spain is obviously limited by the complex, noncylindrical, geometry of the Alboran domain (Figures 1 and 2 for the noncylindrical shape of the Bouguer anomaly). In order to test the applicability of the 2-D model and the spatial distribution of the crustal-scale peridotites body, we compare the 3-D density structure obtained from our gravity data inversion (section 4) with the 3-D P wave velocity model of the region derived from local earthquake tomography (Villaseñor et al., 2015). Figure 5 shows three sections corresponding to layers at 0- to 10-, 10- to 20-, and 20- to 40-km depths in both models. The density model does not show any effect from overcorrecting or undercorrecting the sediment basins, a posteriori validation of the corrections made in section 3. In the 30- to 40-km depth range, an overall westward trend from high- to low-density anomalies (Figure 5c) and fast- to slow-velocity anomalies (Figure 5f) is observed that is coherent with a mix of crustal and upper mantle signature for the west Alboran Sea, juxtaposed to the almost solely crustal signature on land. As for the 2-D Ronda profile, this long wavelength (300-400 km) signal marks the general thickening of the crust in a westward and radial pattern away from the West Alboran Sea.

For the shallower depth range (0-10 km), the density and velocity anomalies also show a good, first-order correlation. In particular, both data sets illustrate the presence of a high-density, high-velocity body wrapping the coastline of the Gibraltar Arc curvature (Figures 5a and 5d). This structure extends over the entire domain from southern Spain to northern Morocco (except for the velocity data that present a deficient resolution for the northern Morocco coast). On the basis of its location, short wavelength signature, density, and velocity anomaly amplitudes, we associate this structure with the regional extension of the peridotites bodies that outcrop in the Ronda, Ceuta, and Beni Bousera regions (Figure 1). Because of the low resolution of both density and velocity models, details of the spatial variation in the peridotites bodies cannot be estimated. However, the maximum density signal amplitude correlates well with the two major outcrops (Ronda and Beni Bousera, Figure 5a), suggesting that the size of the peridotites bodies decreases both eastward and toward the Gibraltar Strait.

For the depths between 10 and 20 km, the peridotite bodies are well imaged by the local earthquake tomography (Figure 5e), supporting their extent at depth. Note, however, that our 3-D gravimetric inversion (Figure 5b) does not constrain well the depth extent of the peridotites bodies because the inversion procedure forces the short-wavelength density anomaly to be localized in the upper part of the crust.

In addition, in the supporting information we present additional evidence for the deep extent of the high-velocity body associated with the surface expression of the Ronda and Beni Bousera peridotites

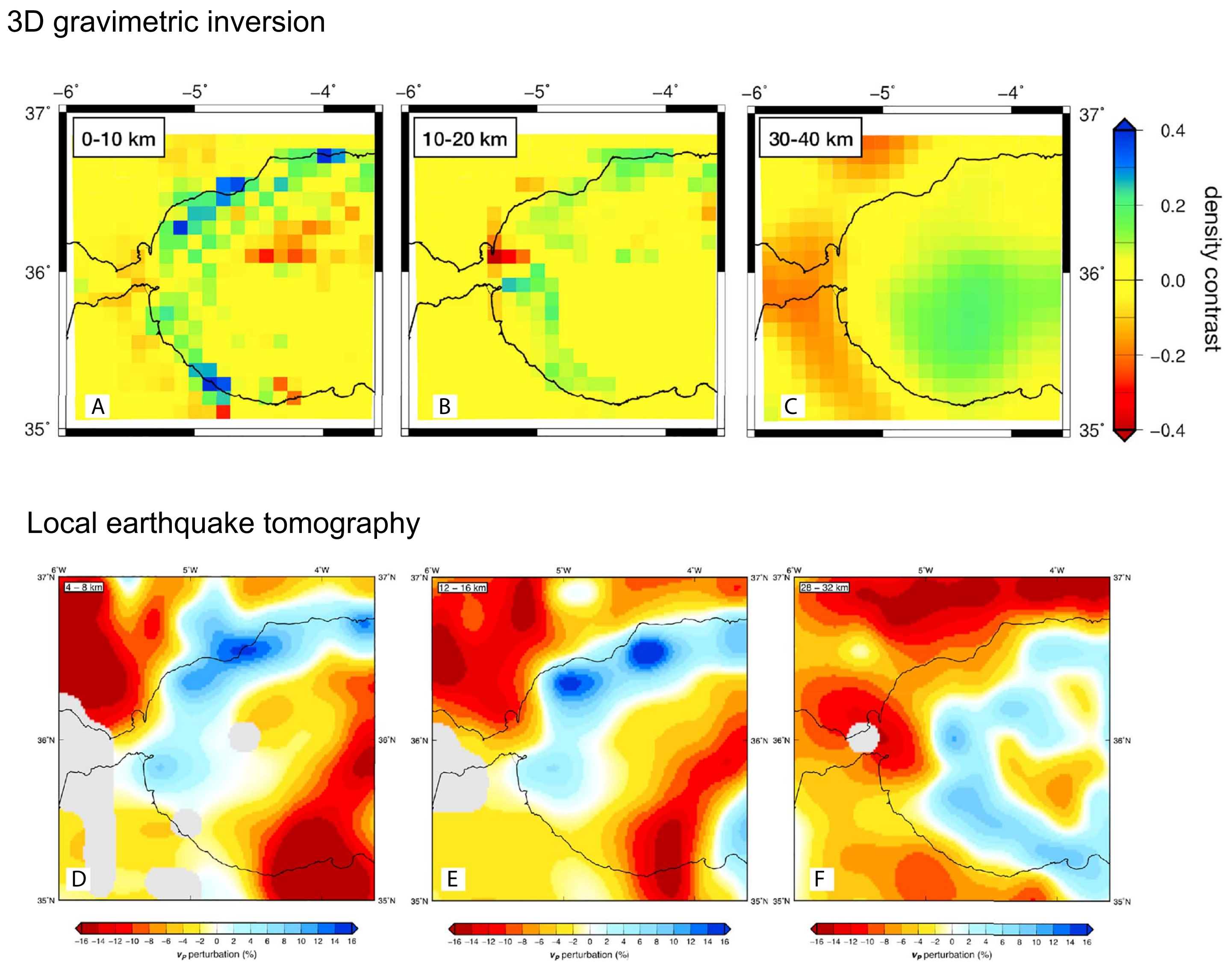

Figure 5. Comparison between 3-D gravimetric inversion and local earthquake tomographic models. (a–c) 3-D inversion of the gravimetric data (presented in Figure 2c) for respectively 0- to 10-, 10- to 20-, and 30- to 40-km depths. (d–f) Local earthquake tomographic images (from the tomographic model presented in El Moudnib et al., 2015) for respectively 4- to 8-, 12- to 16-, and 28- to 32-km depths.

(Figures S2 to S10 and Text S2; Díaz et al., 2009; El Moudnib et al., 2015; Palomeras et al., 2017; Silveira et al., 2013; Villaseñor et al., 2007). This evidence comes from ambient noise tomography, a methodology that uses cross correlations of long recordings of seismic ambient noise to obtain Green's functions of the medium that can be used as input for surface wave tomography (e.g., Shapiro et al., 2005).

On these bases, we propose that the 2-D lithospheric scale cross section defined for the Ronda profile (section 4) applies to the entire Western Alboran domain, which is thus characterized by obduction of the continental margin (e.g., hyperstretched lithosphere with exhumed subcontinental mantle) on the Iberian continent to the north and African continent to the south.

6. Discussion and Conclusion

The 2-D and 3-D modeling of gravimetric data (with newly acquired data) allow us to constrain the geometry of the Ronda peridotite at depth. A simple body steeply dipping eastward and rooted in the Alboran mantle fits the short wavelength gravimetric anomaly associated with the Ronda peridotites. The 3-D gravity

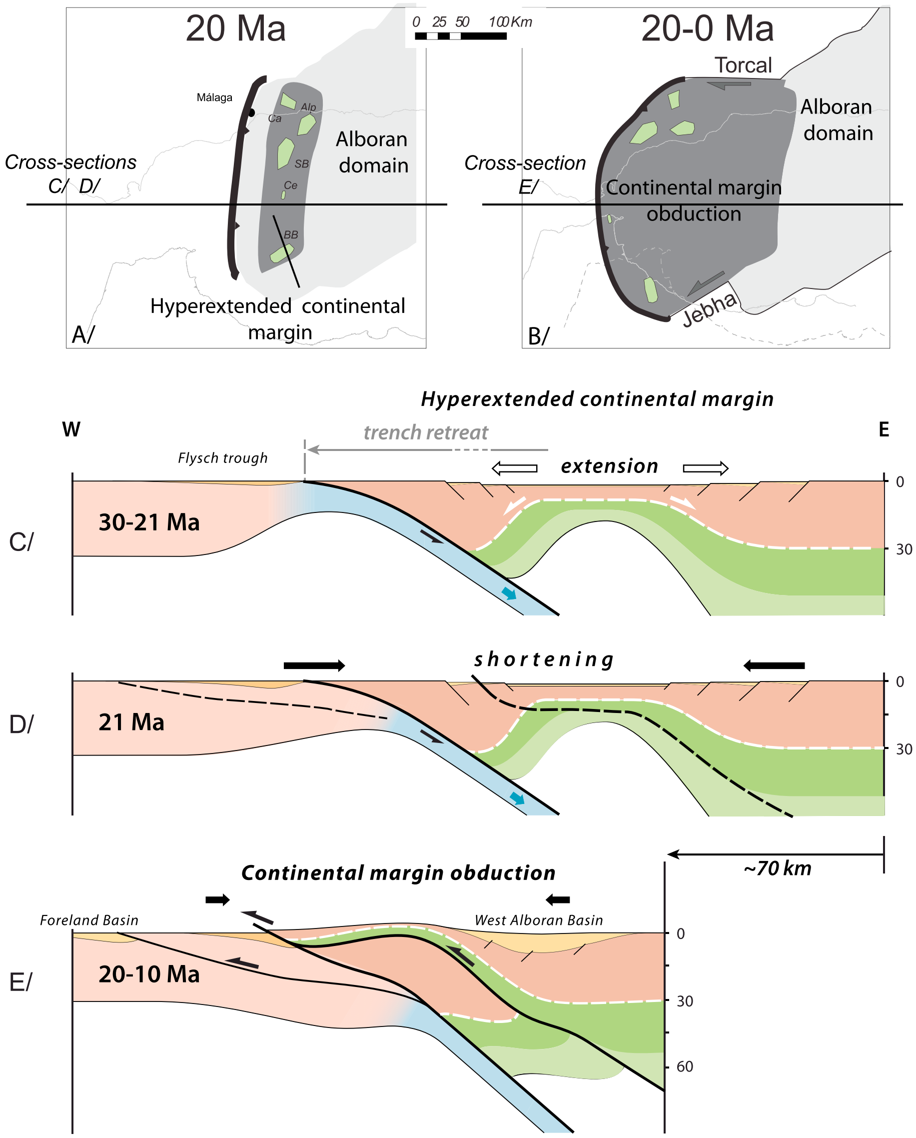

Figure 6. Schematic description of continental margin obduction process. (a) Restored geometry at 20 Ma of the Alboran domain after back-rotation of the peridotite bodies (modified from Gueydan & Frasca, 2017). (b) Present-day tectonic map of the western Alboran with the main peridotite bodies in green, and major strike-slip corridors (Torcal in the Betics and Jebha in the Rif) accommodating the displacement during thrusting and westward/southwestward motion (modified from Gueydan and Frasca (2017)). (c–e) Lithosphere scale cross sections (located in Figure 6a and 6b) representing the three successive steps of the continental margin obduction: (c) back-arc hyperstretching of the continental lithosphere, (d) rift-inversion triggered by the onset of subduction of the Iberian continental margin, and (e) complete underthrusting of the cold fore-arc and arc domain below the hot hyper stretched continental margin nappe, with thinned crust and subcontinental mantle. Foreland basin deposition (Iribarren et al., 2009) during the continental obduction is underlined by orange colors.

modeling combined with local tomographic data further shows that the rooting of the peridotite bodies inside the Alboran mantle occurs along the entire Gibraltar arc. Based on geological data and geological cross-section models, Mazzoli and Martín-Algarra (2011) proposed that the Ronda peridotites are rooted inside the Alboran mantle in Spain. Compared to their analysis, the novelty of our study is to quantitatively constrain, through geophysical data and modeling, that such rooting is a robust feature and is not limited to the Ronda system but occurs along the entire Gibraltar arc. Furthermore, our inferred lithosphere-scale structure shows a hyperstretched continental lithosphere that is thrust onto a continental crust, a major feature that we define as *continental margin obduction*.

In the western Mediterranean, we propose that continental margin obduction occurs when a switch from extension to compression is triggered in the upper plate of the subduction zone. Such a switch happened when the Iberian/Moroccan continent entered into the subduction zone at around 20 Ma (onset of shortening recorded in the western Alboran; see Platt et al., 2013, and Frasca et al., 2015, for a synthesis). Using the initial position of the hyperextended rift, prior to obduction, defined by Gueydan and Frasca (2017), Figure 6 presents the continental margin obduction in three main steps as follows:

1. The subduction of an oceanic slab, affected by a westward rollback, leads to the back-arc extension, extreme thinning of the upper continental plate, and subsequent exhumation of the subcontinental mantle in extensional setting (30-21 Ma; Figure 6a).
2. The entering of a buoyant continental domain modifies the subduction dynamics and results in shortening in the weakest part of the upper plate, the hyperstretched continental margin (21 Ma, Figure 6b). This leads to the initiation of the Ronda peridotites thrust. The presence of a thick continental domain in Iberia and Africa is now confirmed by receiver function, tomography, and the present gravimetric data that show continental crust as thick as 30-40 km around the Gibraltar arc (Levander et al., 2014; Mancilla et al., 2015). A change in the upper plate kinematics may also trigger the onset of thrusting in the former extended domain. In the Western Alboran domain, the change in direction of Nubia/Eurasia motion at 21 Ma (Vissers & & Meijer, 2012) from N-S to NW-SE may also contribute to such shortening in the upper plate.
3. The ongoing shortening in the upper plate results in rapid underthrusting of the western part of the rifted continental margin below the inverted rift, that is, a complete continental margin obduction (20-10 Ma, Figure 6c). Note that the arc and fore-arc domains are therefore subducted beneath the obducted continental margin.

The compilation of geochronological data in the Western Alboran domain (western Betics and Rif) shows the absence of medium to low temperature ages older than 20 Ma in the thrust footwall (see discussion and references in Frasca et al., 2017), suggesting a reset of medium- to low-temperature ages by heating at approximately 21 Ma followed by a general and fast cooling (Esteban et al., 2004). Our tectonic model implies the thrusting of a hot hyperstretched continental lithosphere on the fore-arc that leads to the formation of a high-temperature metamorphic sole below the peridotites (Hot Ronda Peridotites thrust; Tubía et al., 1997) and therefore provides a regional explanation for the heating at 21 Ma in the Western Alboran region. The subsequent subduction of the cold fore-arc leads to a fast cooling of the Upper Western Alboran nappes (peridotites and the overlying crustal envelope) in less than 4 Ma (see discussion in Frasca et al., 2017), providing also an explanation for the fast cooling reported in the Western Alboran domain.

The heating and subsequent fast cooling is also an indirect argument for an Oligo-Miocene rifting immediately followed by rift inversion at 20-21 Ma. A Jurassic rifting (Michard et al., 2002; Tubía et al., 2009; Van Hinsbergen et al., 2014; Vergés & Fernández, 2012) and a later inversion during Alpine history cannot explain the high-temperature metamorphism during Miocene time. A possible source for this high-temperature metamorphism can be an asthenospheric upwelling (Rossetti et al., 2013), which cannot however explain why the high-temperature metamorphism is restricted to the Western Alboran region.

Continental margin obduction at 21 Ma can moreover provide a tectonic explanation for the formation of the Western Alboran basin. Our study shows that a steeply dipping peridotites body from the surface to the Moho (approximately 30 km; Figures 4 and 6) characterizes the Alboran region. The fast cooling of this steeply dipping mantle slab implies a fast thermal subsidence (McKenzie, 1978). The western Alboran basin is likely located above the steeply dipping mantle slab inside the crust, in which a very important subsidence rate is registered since 20 Ma without any significant normal faults (Iribarren et al., 2009; Watts et al., 1993). Note however that the subsidence recorded in the western Alboran basin is much larger than that predicted by isostasy and thermal subsidence, implying other processes such as slab pull and delamination (Baratin et al., 2016).

This progressive evolution from subduction to continental margin obduction is also traced by a variation in magmatic/volcanic production with a transition from tholeitic basalts to acid dykes (Duggen et al., 2004). Note also that the arc volcanism is registered in the Alboran domain only since approximately 20 Ma

(Duggen et al., 2004), leading to hypothesize that roll-back started only at that period of time (Frizon de Lamotte et al., 2009). However, magmatic products like tholeitic dykes and gabbroic intrusion inside the hyperstretched Western Alboran lithosphere suggest ongoing active roll-back upper plate extension since Oligocene time (Hidas et al., 2015). The subduction of the volcanic arc and the entire fore-arc during the continental margin obduction can explain the absence of outcrop of arc volcanism older than 20 Ma.

We can integrate the impact of continental margin obduction in the numerous and debated geodynamical models for the Western Mediterranean. In particular, the amount of slab rollback and the direction of trench migration are matters of controversy (see summary in Chertova et al., 2014, and our introduction). Our findings fit well with a NW dipping subduction restricted to the Baleares-Sardinia-Corsica margin (Chertova et al., 2014, and references therein; Van Hinsbergen et al., 2014; Spakman et al., 2018). Furthermore, the present study adds important new constraints on position and timing of the tectonic context at ~20 Myr in the Western Alboran that is differently reconstructed (much further east) in Van Hinsbergen et al. (2014). The reconstructed orientation and position of the extended continental margin at 20 Myr (prior to continental margin obduction, Figure 6a) agree well with the numerically modeled slab position at ~20 Myr after a 10 Myr phase of very rapid slab rollback starting at the Baleares margin, as recently modeled in Spakman et al. (2018). In contrast with Faccenna et al. (2004) and Jolivet et al. (2006) that predict limited amount of roll-back in this NW dipping subduction scenario, the very rapid slab roll back between 30 and 20 Ma (Spakman et al., 2018) is necessary to trigger upper plate extension and hyperextension.

More generally, this regional example allows us to identify the main features of the continental margin obduction at the surface: (1) the thrusting of an hyperstretched continental lithosphere (e.g., high-grade continental crust and subcontinental mantle, previously exhumed in a hot back-arc setting) onto a continental domain; (2) the formation of a high-temperature metamorphic sole in the underlying continental crust rocks; (3) heating followed by fast regional cooling of the obducted domain (e.g.; reset of most ages); (4) subduction and hence disappearance of the volcanic arc and fore-arc domain of the former extending upper plate; and (5) formation of a highly subsiding basin on top of the obducted continental margin.

Continental margin obduction may be a key tectonic process to explain the exhumation and emplacement of subcontinental mantle rocks and associated overlying deep continental crustal rocks. In the Alps, the Ivrea Body, which is associated with a large positive Bouguer gravimetric anomaly, may be a marker for the continental margin obduction of the Adriatic hyper-stretched domain (Adriatic mantle and associated Ivrea granulitic deep crust) at the onset of subduction/collision of the European Margin in early Oligocene (Rosenbaum & Lister, 2005). Continental margin obduction may also explain (1) the rapid and intense subsidence of the Po plain basin, which started in early Oligocene (Handy et al., 2010), and (2) the absence of preserved volcanic arc in the Alps. In the Pyrenees, recent tomographic images show the rooting at depth of the subcontinental mantle erratically cropping out at the surface (Wang et al., 2016), suggesting also a continental margin obduction process. Note that in the Pyrenean case, the hyperstretching does not occur in back-arc setting but at plate boundary before inversion (Vissers & Meijer, 2012). In the South-East Pacific, the recent discovery of the youngest granulitic deep crust and subcontinental mantle could be associated with continental margin obduction in the northern part of the Banda system (Pownall et al., 2014), also possibly triggered by lateral variation in slab buoyancy (Spakman & Hall, 2010). More generally, continental obduction is a proxy for former extreme thinning of the continental upper plate driven by slab rollback, and a marker of the onset of continental collision, that is, the entering of a continental margin into the subduction zone or a change in plate kinematics.

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