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Research paper

Constraints on the geodynamic evolution of the Africa–Iberia plate margin across the Gibraltar Strait from seismic tomography

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ABSTRACT

Geophysical studies point to a complex tectonic and geodynamic evolution of the Alboran Basin and Gulf of Cadiz. Tomographic images show strong seismic waves velocity contrasts in the upper mantle. The high velocity anomaly beneath the Alboran Sea recovered by a number of studies is now a well established feature. Several geodynamic reconstructions have been proposed also on the base of these images. We present and elaborate on results coming from a recent tomography study which concentrates on both the Alboran and the adjacent Atlantic region. These new results, while they confirm the existence of the fast anomaly below the Alboran region, also show interesting features of the lithosphere-asthenosphere system below the Atlantic. A high velocity body is imaged roughly below the Horseshoe Abyssal plain down to sub-lithospheric depths. This feature suggests either a possible initiation or relic subduction. Pronounced low velocity anomalies pervade the upper mantle below the Atlantic region and separate the lithospheres of the two regions. We also notice a strong change of the upper mantle velocity structure going from south to north across the Gorringe Bank. This variation in structure could be related to the different evolution in the opening of the central and northern Atlantic oceans.

1. Introduction

The geodynamic evolution of the Gulf of Cadiz/Alboran Basin region is the result of the complex interaction between central and northern Atlantic oceanic domains, and the African and Eurasian plates (Fig. 1). Observations on magnetic anomalies and seismic data suggest that the central and northern Atlantic oceans opened at different times, although the precise age of the early oceanic crust is still debated (e.g., Labails et al., 2010; Bronner et al., 2011; Sibuet et al., 2012). Spreading occurred in early Jurassic in the central Atlantic and in early Cretaceous in the northern Atlantic. In the Iberian margin of North Atlantic mantle exhumation has been inferred to play a major role in the early opening stage (Bronner et al., 2011), whereas magnetic anomalies in the central Atlantic indicate that accretion is markedly asymmetric, with more oceanic crust produced on the American side (Labails et al., 2010; Sibuet et al., 2012). Interestingly, this last observation is connected to the occurrence, on the African side, of the central Atlantic magmatic province (Labails et al., 2010). The Gibraltar-Newfoundland Fracture Zone (GNFZ) is the northern limit of the central Atlantic, and is also the zone of transfer of spreading into the Alpine Tethyan seaway in Jurassic times. In the western Tethyan region convergence between Eurasia (Iberia) and Africa plates started by Eocene, leading to consumption of the plate margins and to the present geological setting (Platt et al., 2013 and references therein). At present the convergence between the two plates is at a rate of ~5 mm/yr (Stich et al., 2006; Serpelloni et al., 2007). The Africa-Eurasia plate boundary is clearly defined from the Gloria fault to the Gorringe Bank (McKenzie, 1972; Srivastava et al., 1990; Zitellini et al., 2009). From the Gorringe Bank proceeding to the east, across the Strait of Gibraltar, the boundary is diffuse (McKenzie, 1972; Sartori et al., 1994; Serpelloni et al., 2007) with different locations having been proposed for it. A narrow band of deformation (SWIM Fault Zone), is considered as a precursor to the formation of a new transcurrent plate boundary between Iberia and Africa (Zitellini et al., 2009). The end result of this complex geodynamic

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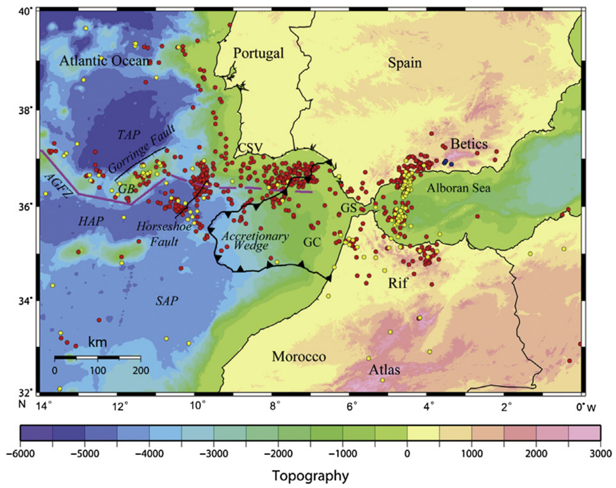

Figure 1. Map of the study region with the main structural features and geographical names. Colored circles represent subcrustal seismicity at different depth intervals (red circles, 35–70 km; yellow circles, 70–300 km; blue circles, >300 km). Hypocentral locations are from http://www.02.ign.es/ign/layoutIn/sismoFormularioCatalogo.do (Instituto Geográfico Nacional, Spain). GS = Gibraltar Strait; CSV = Cape St. Vincent; GC = Gulf of Cadiz; GB = Gorringe Bank; SAP = Seine Abyssal Plain; HAP = Horseshoe Abyssal Plain; TAP = Tagus Abyssal Plain; AGFZ = Azores-Gibraltar Fracture Zone. Magenta thick curve is the Eurasia–Africa plate boundary (Grange et al., 2010). Black thick curve with triangles is the external limit of the Gulf of Cadiz accretionary wedge (redrawn from Zitellini et al., 2009).

evolution is a strong crustal and mantle scale heterogeneity. This heterogeneity is particularly evident in our restricted study area (Fig. 1).

East of the Gibraltar Strait, the wide amount of geological and geophysical data led to the proposal of two broad groups of models for the geodynamic evolution of the Alboran region: (1) The collision of Europe and Africa led to lithospheric thickening during the Paleogene. The thickened continental lithosphere was later (~25 Ma) detached by convective removal (Platt and Vissers, 1989) or by delamination (Seber et al., 1996; Calvert et al., 2000). The increased gravitational potential led to the collapse of this thickened orogen, causing extension of the Alboran basin and uplift around the margin. (2) The subduction of negatively buoyant oceanic lithosphere caused slab rollback and extension within the Alboran Basin in the Miocene (Royden, 1993; Lonergan and White, 1997; Bijwaard and Spakman, 2000; Gutscher et al., 2002); the break-off of the slab has also been proposed (Blanco and Spakman, 1993; Zeck, 1996).

West of the Gibraltar Strait, in the Atlantic side, geophysical data show: (1) a large-scale low velocity anomaly seen in global tomography images west of Africa below the central Atlantic (e.g., Simmons et al., 2012); (2) the distribution of heterogeneous volcanism of varying age along western, southwestern Iberia and the Gulf of Cadiz (e.g., Duggen et al., 2004; Merle et al., 2006); (3) low heat flow anomalies in the Gulf of Cadiz (Polyak et al., 1996; Grevemeyer et al., 2009); (4) a very strong gravimetric high at the Gorringe Bank (Purdy, 1975), and (5) a very heterogeneous bathymetry with seamounts and abyssal plains in a restricted area such as the Gulf of Cadiz (e.g., Zitellini et al., 2009).

An open question is if and how the subduction process in the Alboran side (east of the Gibraltar Strait) has extended to the Atlantic side (west of the Gibraltar Strait). Some of the models for the Alboran also include the Gulf of Cadiz (e.g., Royden, 1993), but they are not clearly supported. In spite of the numerous clues, our knowledge of the mantle is limited by the lack of seismic tomography models in the Atlantic region at the appropriate scale, as most of the previous higher resolution studies have concentrated on the Alboran due to scarce data coverage in the Atlantic region (e.g., Bezada et al., 2013; Palomeras et al., 2014).

Recently, a first image at upper mantle scale of both the Alboran and the Atlantic regions has been produced by Monna et al. (2013) using OBS (Ocean Bottom Seismometer) teleseismic data recorded in the Gulf of Cadiz in the framework of the NEAREST project (http://nearest.bo.ismar.cnr.it). In the present study, starting from this model (hereafter quoted as model WMGC-OBS), we identify and discuss some features that can be important for the geodynamic reconstruction of the area.

2. Geological setting

Within the Africa–Eurasia convergence the Iberia plate shows complex kinematics, as evident from Atlantic sea-floor magnetic anomalies. According to previous studies (Srivastava et al., 1990), Iberia was part of Africa from late Cretaceous to early Oligocene, whereas from late Oligocene to present it became part of Europe, following the Pyrenean collision. Recent reviews of the magnetic anomalies suggest a possible alternative (Vissers and Meijer, 2012), which allows for some 50–70 km convergence between Africa and Iberia for the late Cretaceous–middle Eocene time span. Altogether, the N–S convergence between Africa and Iberia is in the order of 200–250 km, a figure that can hardly account for the westward arc propagation of the Betic-Rif fold-and-thrust belt and the width and shape of the east-dipping subducted slab imaged by high-resolution seismic tomography (e.g., Bezada et al., 2013; Palomeras et al., 2014). In fact, several tectonic models imply a substantial westward subduction/rollback in order to account for the geological and tomographic evidence (e.g., Gutscher et al., 2002; Rosenbaum et al., 2002; Faccenna et al., 2004).

The complex geodynamic evolution described in section 1 is well represented by the heterogeneous geological setting which is synthetically depicted in Fig. 2. Outwards thrusting in the external Betics and external Rif is ca. coeval to the extension in the Alboran basin, from 20 to 18 Ma (Platt and Vissers, 1989; Platt et al., 2013). The units involved belong to the continental margins of Iberia and North Africa, and are facing an oceanic region to the south and north, respectively. It is implicitly considered to be the same ocean, i.e., Alpine Tethys, connected to the central Atlantic. However, although the water masses of the central Atlantic and Alpine Tethys were certainly connected, the paleogeography of the Gibraltar-Alboran seaway, and the nature of the underlying crust in particular, are still not properly constrained.

The extensional tectonics that affected the internal domains consists of two major events and is closely related to volcanic activity (e.g., Platt et al., 2013). The early extensional event (early–middle Miocene) is related to the collapse of the Alboran Domain and to the exhumation of the Alpujarride units. Large vertical-axis rotations, documented by paleomagnetic studies, make it difficult to infer the direction of extension. The later event (middle–late Miocene) is characterized by SW-directed extension and basin formation in the internal Betics.

The Alboran Sea basin formed in the Neogene as a result of this extensional tectonics, and is currently floored by thinned continental crust, 13–20 km thick (Watts et al., 1993). Moreover, thermal models for metamorphic units from the floor of the Alboran Basin are consistent with post-collisional rapid exhumation and associated heating (e.g., Platt et al., 2013).

Magmatic products cover a ca. 200 km-wide belt that extends from the eastern Rif to the eastern Betics, crossing the Alboran Sea, with NNE–SSW direction. Volcanic activity spans from early Miocene to Pleistocene and presents mainly an orogenic magmatic affinity. Only in the eastern part of the magmatic belt, and particularly in the