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Research paper

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

S. Monna [a,*], A. Argnani [b], G.B. Cimini [a], F. Frugoni [a], C. Montuori [a]

[a] *Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy*
[b] *Istituto di Scienze Marine – Consiglio Nazionale delle Ricerche, Bologna, Italy*

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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.

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## 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

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* Corresponding author. Tel.: +39 (0) 651860404.
*E-mail address:* stephen.monna@ingv.it (S. Monna).

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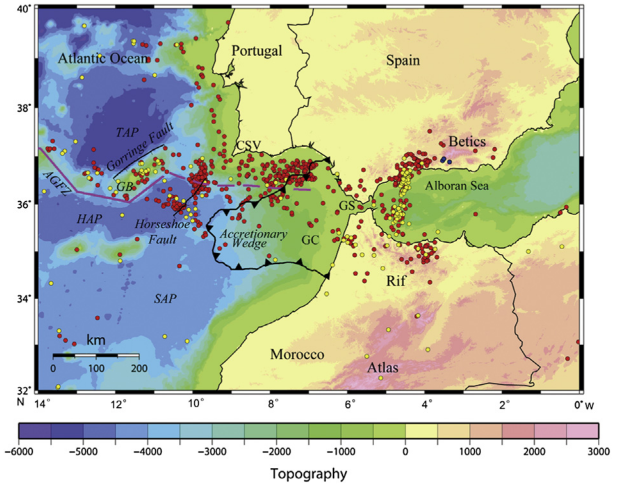

**Figure 1.** Map of the study region with the main structural features and geographical names. Colored circles represent subcrustal seismicity at different depth intervals (red circles, 35–70 km; yellow circles, 70–300 km; blue circles, >300 km). Hypocentral locations are from http://www.02.ign.es/ign/layoutIn/sismoFormularioCatalogo.do (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).

transcurrent plate boundary between Iberia and Africa (Zitellini et al., 2009). The end result of this complex geodynamic 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

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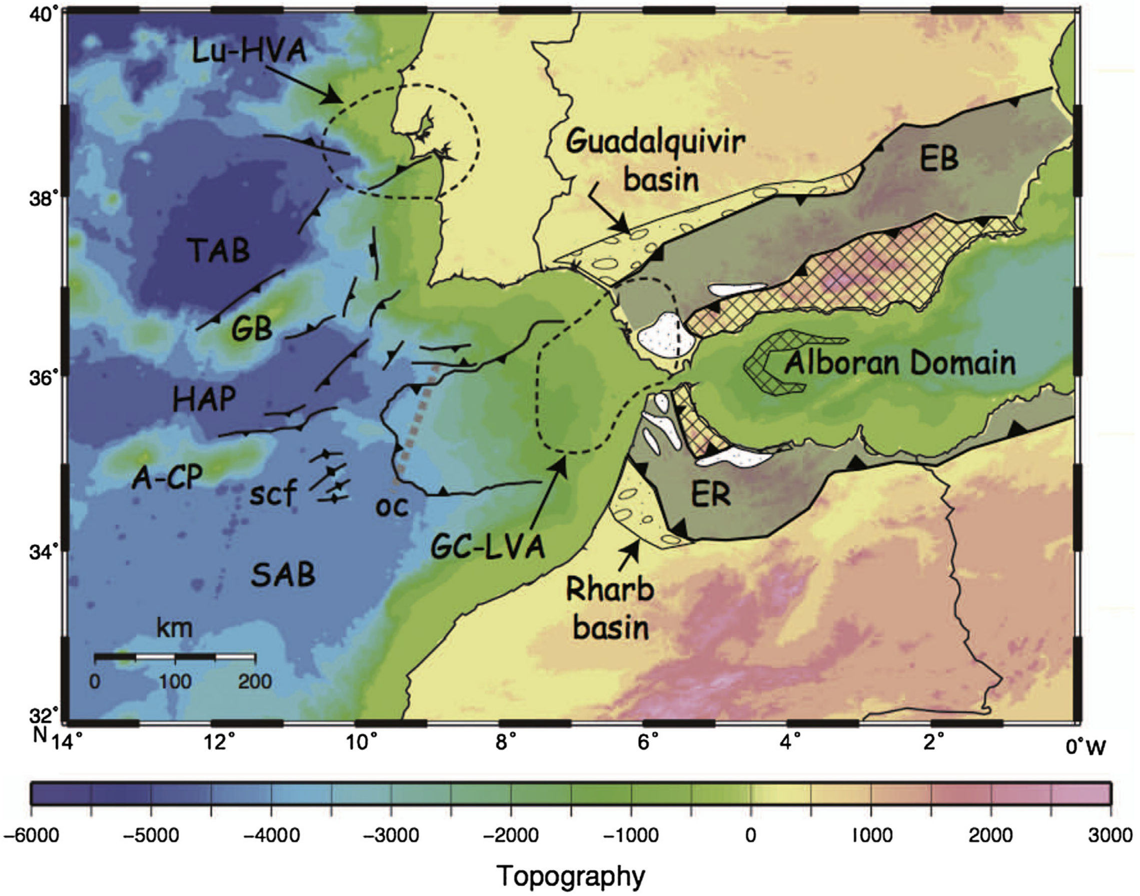

**Figure 2.** Simplified geological map of the study area (after Gutscher et al., 2012; Duarte et al., 2013; Platt et al., 2013). The Alboran domain is indicated by cross hatched pattern. The External Betics (EB in gray pattern) includes the Subbetic and Prebetic, and the External Rif (ER in gray pattern) includes the Intrarif and Mesorif. The white field with dotted pattern represents the Flysch belt. The gray dashed line indicates the extent of oceanic crust (oc) inferred from refraction seismic (Sallarès et al., 2011). The approximate location of the Lu-HVA (at about 400 km depth) and of the GC-LVA (100–200 km depth) is also indicated. A-CP = Ampere-Coral Patch seamounts. TAP, GB, HAP, and SAP are as in Fig. 1.

NE Betics, volcanics of anorogenic affinity are present, including lamproites (e.g., Wilson and Bianchini, 1999). In general, the older volcanic terms are orogenic, and are followed by anorogenic volcanics. Geochemical and geochronological data show that this transition from post-collisional subduction-related to intraplate-type magmatism occurred between 6.3 and 4.8 Ma (Duggen et al., 2005). This change in magmatic character has been related to either removal of lithospheric root (Turner et al., 1999) or westward slab rollback (Duggen et al., 2004). Such magmatic evolution recalls that of the northern Tyrrhenian-Tuscany volcanic province, where the occurrence of continental delamination has been inferred (e.g., Serri et al., 1993; Argnani, 2002). The Alboran region is characterized by the pronounced arcuate shape of the Betics and Rif fold-and-thrust belts, which mostly originated in the Miocene at the expense of the external units, during the westward migration of the internal units (Alboran domain). Paleomagnetic data from the Rif and western Betics indicate that most of the rotation and arc formation was accomplished by the early Pliocene (e.g., Platzman et al., 1993; Krijgsman and Garces, 2004; Cifelli et al., 2008).

The SW Iberian margin, which faces the Cadiz Gulf, has been extensively investigated through seismic reflection and refraction surveys and high-resolution swath bathymetry acquisitions (e.g., Zitellini et al., 2009; Gutscher et al., 2012). The margin originated during the break up of Pangea and the opening of the central Atlantic Ocean in Triassic–Jurassic. The continental crust of SW Iberia has been thinned and stretched, as shown by tilted fault blocks along the margin (e.g., Tortella et al., 1997). Recent seismic refraction experiments have shown the occurrence of oceanic crust, of presumably Jurassic age in the western part of the Gulf of Cadiz (Sallarès et al., 2011). This data has been used to infer the occurrence of a continuous oceanic subduction that goes from the Atlantic to beneath the Alboran basin (Gutscher et al., 2012), an inference that has also strong implications for Jurassic palaeogeography (e.g., Frizon de Lamotte et al., 2011). As shown later, our data brings a potentially significant contribution to this last issue.

The presence of thick oceanic lithosphere of late Jurassic–early Cretaceous age is also inferred from the depth of seismicity (down to 60 km; Geissler et al., 2010) in the eastern part of the Horseshoe Abyssal Plain. This deep oceanic basin is bounded to the NW by a large topographic feature known as Gorringe Bank (Fig. 1). Peridotites, gabbros and other oceanic floor rocks have been dredged and drilled from this 200 km long and very shallow bank, which has been interpreted as a thrust of oceanic lithosphere (e.g., Mauffret et al., 1989; Hayward et al., 1999 and references therein). The large Tagus Abyssal Plain is located north of the Gorringe Bank and represents the oceanic portion of the Iberia continental margin, with a transition to continental crust which is inferred to occur in the eastern half of the deep sea plain (Pinheiro et al., 1992). An alternative view, implying that the basin is floored by exhumed mantle rocks, has been recently proposed (Bronner et al., 2011). However, this point is still debated (e.g., Tucholke and Sibuet, 2012).

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A remarkably large accretionary prism extends for about 300 km into the Atlantic Ocean, off the Gibraltar Strait (e.g., Zitellini et al., 2009), representing the outermost deformation of the Gibraltar Arc. Although it is difficult to assess whether this accretionary prism is currently active or not, this information is critical in establishing whether subduction is still active under the Gibraltar Arc. Some authors proposed that the sedimentary prism was mostly emplaced gravitationally before the end of Miocene, with little or no deformation occurring since, as in several places late Miocene sediments onlap the prism without being deformed (e.g., Sartori et al., 1994; Zitellini et al., 2009). Other authors argued that several hints, including Pliocene–Quaternary sediments found above the prism and showing undulating folds, suggest that the prism is still actively accreting (e.g., Gutscher et al., 2012). Far from being just an academic exercise, these alternative interpretations lead to different possible locations of the great 1755 Lisbon earthquake ($M_w$ 8.5–8.7; Stich et al., 2007 and references therein). In fact, the first group of authors points to a fault located in the area of the Gorringe Bank, whereas the second group supports a seismogenic source at the Gibraltar Arc subduction interface.

## 3. Seismic tomography models

A number of tomographic studies have been performed in the last decade to image the deep seismic velocity structure of the area. A “bigger-picture” approach that includes both the Atlantic and the Alboran regions would greatly benefit our understanding of the evolution of this area and, more generally, of the western Mediterranean. Although global scale tomography works cover both regions, they do not have the capability to resolve the finer details. On the other hand, in spite of the increase in available data, the great majority of the higher resolution (regional scale) tomography models do not image the mantle below the Atlantic region west of the Gibraltar Strait due to a lack of station coverage at sea. The recent tomographic model WMGC-OBS (Monna et al., 2013) overcomes this limitation thanks to broadband marine data from sensors deployed in the Cadiz Gulf. Figs. 3–5 show a series of slices extracted from the 3D model. Fig. 3 displays the velocity structure on horizontal layers sampled at depth intervals of 100 km. Fig. 4 shows three vertical slices which help in reconstructing the geometry of the anomalous bodies. Fig. 5 shows an oblique vertical slice across the Gorringe Bank.

The main features in WMGC-OBS are:

(1) A high velocity body with slab-like shape under the Alboran Sea area (Al-HVA).
(2) A high-velocity body under the Horseshoe Abyssal Plain in the Atlantic region (HAP-HVA).
(3) A diffuse low velocity anomaly (EAt-LVA) present in the Eastern Atlantic region south of the Gloria fault, down to the mantle transition zone.
(4) A prominent low velocity anomaly below the Gulf of Cadiz (GC-LVA, part of EAt-LVA) which separates the two high-velocity bodies found under the Alboran (Al-HVA) and Atlantic regions (HAP-HVA) (See also Fig. 2).
(5) A deep (>180 km down to the transition zone) high velocity anomaly (Lu-HVA) in the northern Atlantic, below the Lusitanian sedimentary basin off-shore central-north Portugal (See also Fig. 2).

Regional studies show a high-velocity body under the Alboran Sea, which has been interpreted as a continuous subducting slab (Gutscher et al., 2002; Piromallo and Morelli, 2003), as a broken-off slab (Blanco and Spakman, 1993), and as lithosphere which has undergone delamination (Calvert et al., 2000). This high-velocity structure has been imaged down to mantle depths since the first tomographic studies (Blanco and Spakman, 1993; Bijwaard and Spakman, 2000; Calvert et al., 2000). The geometry of this structure has been better defined by more recent works thanks to improved station coverage and data quality (e.g., Piromallo and Morelli, 2003). Very recent high-resolution studies (Bezada et al., 2013; Palomeras et al., 2014) confirm the presence a slab-shaped high velocity body, seen from the surface down to the bottom of the transition zone, and interpret it as a slab composed of subducted Alboran mantle lithosphere and the surrounding Alpine Tethys ocean lithosphere. The shape and position of Al-HVA (Fig. 3; Fig. 4, cross-sections AA′, CC′) are in agreement with the most recent regional models previously mentioned, in spite of some minor differences.

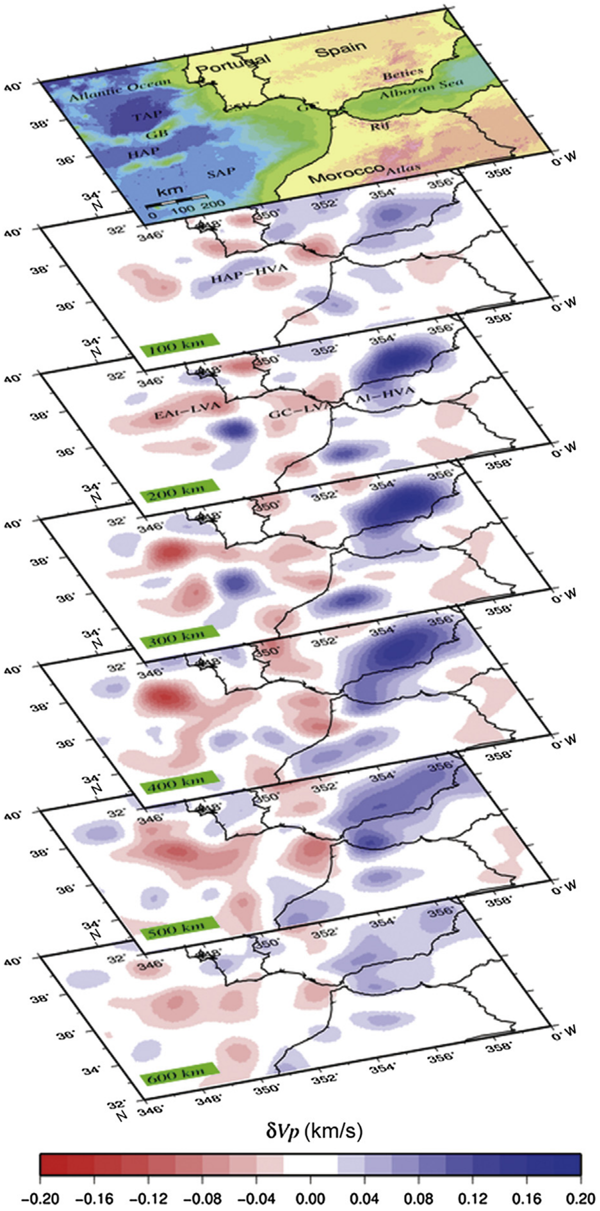

**Figure 3.** Perspective view showing a series of horizontal slices extracted from the WMGC-OBS velocity model at depth interval of 100 km. Blue colored areas indicate high velocity anomalies, as in the Betic-Alboran region (Al-HVA) and in the Atlantic SW Portugal (HAP-HVA). Red colored areas are zones of low velocity anomalies for the eastern Atlantic (EAt-LVA) and the Gulf of Cadiz (GC-LVA).

Lateral heterogeneity in the upper mantle beneath western Mediterranean and adjacent Atlantic region is also imaged by global travel time tomography (Bijwaard and Spakman, 2000; Montelli et al., 2004; Li et al., 2008; Simmons et al., 2012, among many others). These tomographic models are designed to image large-scale seismic structure in the whole mantle for the primary purpose of understanding the convective processes within the Earth's interior (Grand et al., 1997). The recent global-scale P wave velocity model LLNL-G3Dv3 developed by Simmons et al. (2012), which takes advantage of a more complex representation of the Earth's stratification (relative to a purely spherical model) and uses a multiscale inversion approach (called PMTI) to capture also the fine details (where data are sufficient), reveals interesting features in the lithosphere-asthenosphere system of the study region. The most relevant aspects of model LLNL-G3Dv3 that can be compared to the features of model WMGC-OBS, are: the pronounced high velocity anomaly, as large as +2.5% (with respect to the mean velocity of 8.1 km/s), imaged from the Moho to at least 115 km depth in the Atlantic region southwest Portugal, and the large-scale low velocity anomaly (−1.0%) between the Atlantic Ridge and northwest Africa, which extends from 265 km down to the lower mantle (see Fig. 9, Simmons et al., 2012). The fast structure at 115 km depth corresponds well to our HAP-HVA below the Horseshoe Abyssal Plain (Fig. 4, cross-sections AA′, BB′, and Fig. 5), suggesting that it is a reliable upper mantle structure. The northerly portion of the large-scale low velocity anomaly in the central Atlantic is also captured by the WMGC-OBS model southwest of the western Iberian margin. The low velocity volume EAt-LVA in our study area is characterized by a larger velocity contrast (∼−2%) with respect to the broad LLNL-G3Dv3 low velocity anomaly.

## 4. Discussion

Seismic tomography gives us a snapshot of the current velocity heterogeneity which can help us answer some open problems regarding the geodynamic evolution of this area. One of the key questions concerns the present relation between the Atlantic and Alboran regions. Recent studies based on extensive deployment of temporary land seismic arrays, both on the Iberian Peninsula and North Africa (Topo-Iberia, http://www.ictja.csic.es/gt/rc/LSD/PRJ/indexTOPOIBERIA.html; PICASSO, https://earth.usc.edu/research/picasso/home), are able to focus with high resolution on the Alboran region. The shape of the high velocity body below the Alboran region has been well imaged in a recent paper (Bezada et al., 2013) where the slab appears disconnected (torn off) from the Iberian plate under the Betics. The Al-HVA of our model is consistent with the Alboran slab imaged by these high resolution studies, pointing to a former oceanic domain now entirely subducted. These land-based studies, however, do not give information on the transition towards the Atlantic region. Model WMGC-OBS is a first attempt to image this transition at upper-mantle scale based on the integration of marine (OBS) and land data. A major result evident from the model is that there is not a continuity between the fast structures imaged in the two regions. In fact, the high-velocity body (Al-HVA) under the Alboran Sea area is interrupted at its western side by a pronounced low-velocity anomaly (GC-LVA; Figs. 2 and 4, cross-section AA′). Fig. 6 is a 3D rendition of the high (A) and low (B) upper mantle velocity heterogeneity. These plots suggest a more articulate reconstruction than one based on eastward subduction underneath the Alboran of a single oceanic slab connected to the Atlantic domain (e.g., Royden, 1993; Gutscher et al., 2002).

What more can we say about the Atlantic region? HAP-HVA is imaged in an area roughly underlying the Horseshoe Abyssal Plain, where the plate boundary passes from a linear transform to a diffuse convergent margin, and where the occurrence of Jurassic oceanic lithosphere is inferred (Hayward et al., 1999; Zitellini et al., 2009; Geissler et al., 2010). The thickness of HAP-HVA (∼80–150 km in cross sections AA′–BB′; Fig. 4) does agree with values proposed in literature for old (∼140 Ma) oceanic lithosphere (McKenzie et al., 2005; Conrad and Lithgow-Bertelloni, 2006). The presence of oceanic crust, of presumably Jurassic age, has also been supported by a seismic refraction profile in the Gulf of Cadiz (Sallarès et al., 2011). The HAP-HVA is interrupted to the east by the well resolved GC-LVA seen in model WMGC-OBS.

The position and geometry of HAP-HVA, dipping in the southeast direction within the upper mantle, suggest the presence of subducted lithosphere (Fig. 5). The Gorringe Bank has been identified by Gurnis et al. (2004), from geodynamic modeling based on geophysical and geological information, as an incipient margin that could develop into a subduction zone. In this view the Gorringe Bank is an *early stage system* undergoing a *forced* style of subduction driven by compression. The shortening accommodated across the Gorringe Bank and adjacent structures has been estimated to range from ∼50 km (Hayward et al., 1999) to a minimum of 20 km (Jiménez-Munt et al., 2010) on the basis of flexural isostatic models.

In spite of possible vertical smearing of the velocity anomalies, our images show a continuous, narrow and steep slab which reaches at least 350 km depth, suggesting a developed subduction process well beyond the *early stage*. The occurrence of a thickened oceanic lithosphere which has accommodated the shortening caused by Africa–Iberia convergence (Jiménez-Munt et al., 2011), does not seem appropriate to explain the HAP-HVA given the depth extent of the high velocity body. In fact, assuming a 120 km thick oceanic lithosphere, the subducted slab is about 250 km long, suggesting that Africa–Iberia convergence has been accommodated in this structure since some millions of years. Future seismological investigations with larger instrumental coverage of this area need to be carried out for a better definition of the geometry of the subducted slab.

Subduction initiation in this area may be due to the convergence component rather than foundering of a negatively buoyant lithosphere, as no evidence of extensional tectonics has been reported in the upper plate of the Horseshoe Abyssal Plain, where compressional earthquake focal mechanisms are found (e.g., Stich et al., 2007). Furthermore, our tomographic results indicate that subduction is limited to the Gorringe Bank structure and it may be related to a lateral change from strike slip to transpression along the Gloria fault (Serpelloni et al., 2007).

The tomographic evidence of limited subduction underneath the Horseshoe Abyssal Plain, physically separated by the larger Alboran slab (Al-HVA), points to a different scenario with respect to those proposed by Duarte et al. (2013) for the active tectonics of the region: the Gibraltar subduction is mostly inactive, as suggested by geodetic data which show small to none differential motion across the Gibraltar Strait (Stich et al., 2006; Serpelloni et al., 2007). On the other hand, Africa–Iberia convergence is active and it is accommodated by significant shortening in the Gorringe Bank-Horseshoe region (Jiménez-Munt et al., 2011).

Interestingly, most of the subcrustal seismicity located in this area is included in HAP-HVA (Fig. 5). Furthermore, two recent strong earthquakes have been located below the Horseshoe abyssal Plain (Fukao, 1973; Stich et al., 2007) and are found at the top of the descending lithosphere (Fig. 5). Our tomographic results support the interpretation that the Gorringe Bank-Horseshoe region could be the possible source area of the great 1755 Lisbon tsunamigenic earthquake, as suggested by other authors (e.g., Stich et al., 2007 and references therein), and contrast with the hypothesis of a source located at the subduction interface underneath the Gibraltar Arc (e.g., Gutscher et al., 2012 and references therein).

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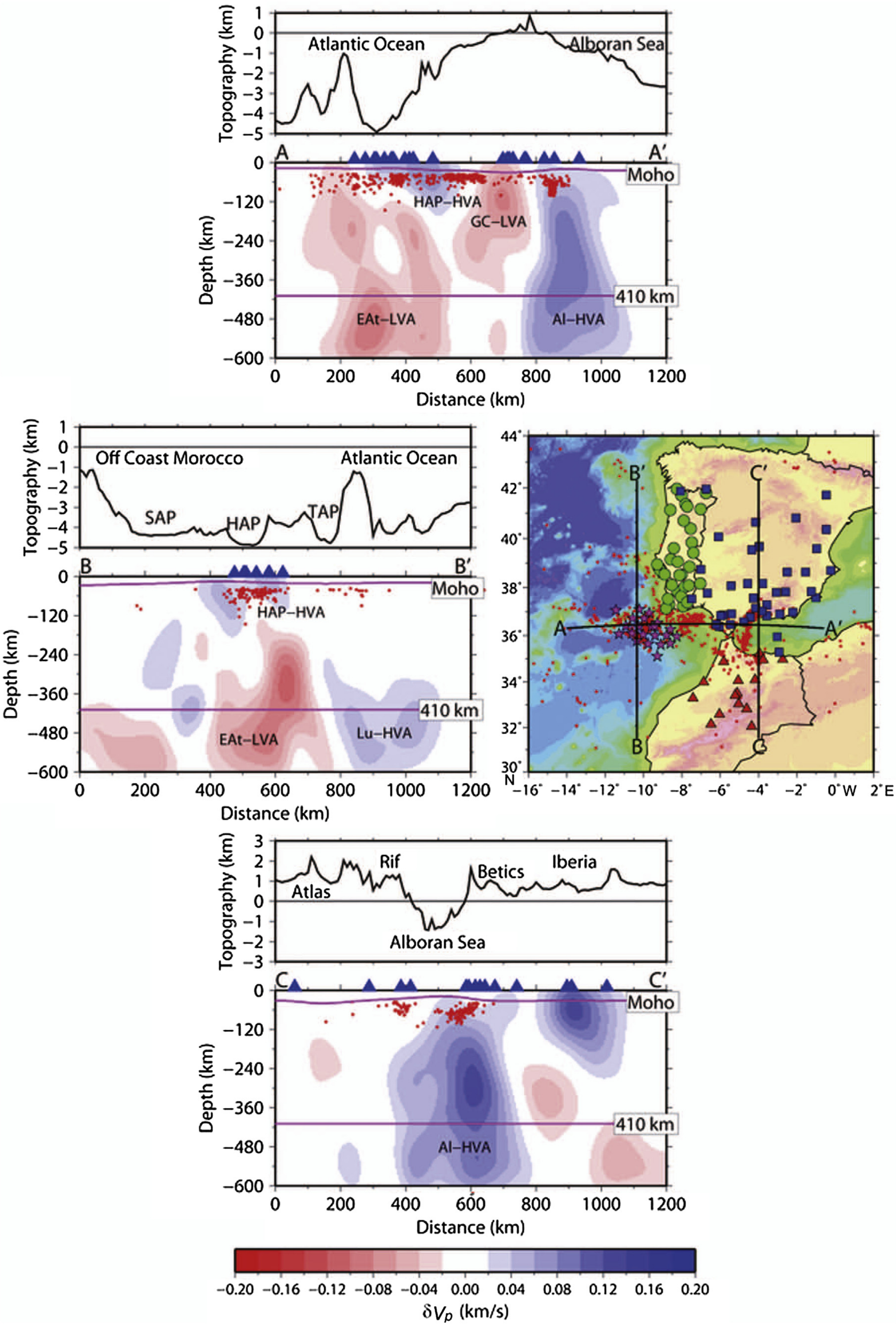

**Figure 4.** Vertical slices displaying the velocity anomalies of model WMGC-OBS along a west to east profile crossing the Gibraltar Arc (AA′), and along two south to north profiles crossing the Atlantic Ocean (BB′) and the Alboran Sea (CC′). SAP, HAP, and TAP as in Fig. 1. Blue triangles and red dots indicate the seismic stations and the subcrustal seismicity located within a 100 km wide zone centered on the profile. In profile CC′, hypocenters deeper than 600 km represent the deep events below the Granada region. In the geographic map, colored symbols indicate seismic stations of the Portuguese (green circles), Spanish (blue squares), Moroccan (red triangles), and NEAREST-OBS (magenta stars) networks used in the tomography. Topography/bathymetric profiles are from the Global-Integrated-Topo/Bathymetry Grid (GINA) (Lindquist et al., 2004). Moho topography is from the European Moho depth map (Grad et al., 2009).

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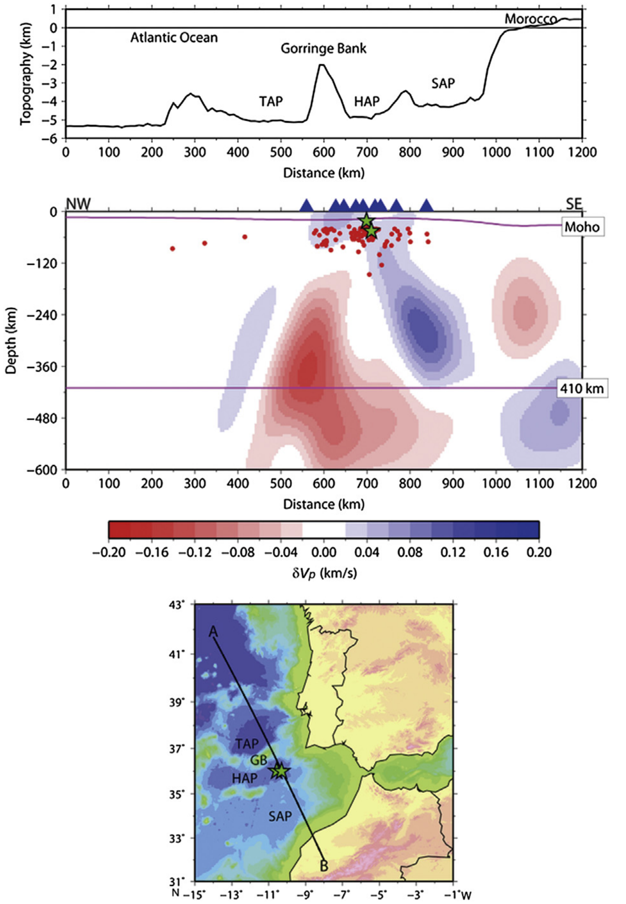

**Figure 5.** Vertical slice crossing the Gorringe Bank and adjacent abyssal plains from NW to SE. The image shows a slab-like high velocity anomaly dipping southeastward down to the top of transition zone. Red dots as in Fig. 4. The green stars indicate the locations of the February 28th 1969, $M_w$ 7.8, and February 12th, 2007, $M_w$ 6.0, Horseshoe earthquakes. Hypocentral depths are about 22 km (Fukao, 1973) and 45 km (Stich et al., 2007), respectively.

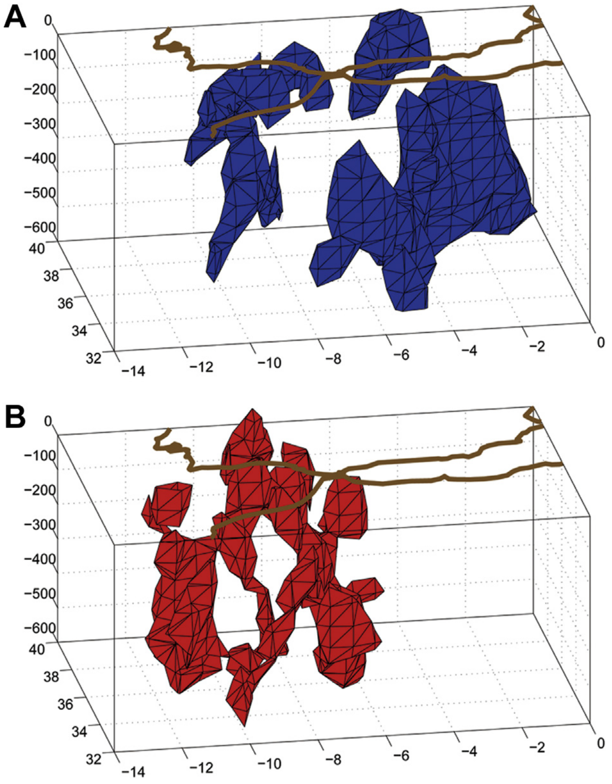

**Figure 6.** Three-dimensional perspective view (azimuth 200°, elevation 30°) of the high velocity (A) and low velocity (B) isosurfaces extracted from the 3D model. Isosurfaces are drawn at ±0.07 km/s velocity perturbations relative to the reference values. Note the complex morphology of the Alboran subduction zone moving along the pronounced arcuate shape of the Betics and Rif mountain belts. West of Gibraltar Strait, the 3-D visualization shows well-developed slow structures which interrupt the lateral continuity with the Atlantic high velocity anomaly.

Another important feature seen in the Atlantic region is EAt-LVA, the diffuse low velocity anomaly found at sub-lithospheric depths below the Atlantic region (down to 600 km depth; Figs. 3 and 4, cross-sections AA′–BB′ and Fig. 6B), which is the northern part of a larger low velocity anomaly imaged in global models (Simmons et al., 2012). The low values of EAt-LVA could be associated to a hot upper mantle. In fact, although other important factors, such as the phase (i.e., the presence or absence of partial melt) and composition (lithology, mineralogy and chemistry), should be considered (Anderson, 2007), at these depths temperature can play a first order role in determining lateral seismic velocity heterogeneity (e.g., Ranalli, 1996). This global low velocity anomaly has been explained as a sheet-like region of upper-mantle upwelling linked to the Eastern Atlantic Magmatic Province (Hoernle et al., 1995), or as part of the Azores-Canary-Cape Verde mantle plume extending into the lower mantle (Montelli et al., 2004). It has also been inferred that the Mid Atlantic Ridge (MAR) decoupled from the hotspots represented by this wide low velocity anomaly after 70 million years ago (Anderson et al., 1992). In this case the low velocity anomaly, of which our EAt-LVA is part, could represent a previous location of the MAR (a “ghost” ridge).

This global anomaly also corresponds to the passive continental margin of Morocco, where extensive lava emissions took place during the opening of the central Atlantic Ocean (190 Ma), and originated seaward dipping reflectors (Menzies et al., 2002). This magmatism is part of the vast central Atlantic magmatic province (Knight et al., 2004). Magmatic activity continued through Cretaceous to present, leading to the onset of alkaline magmatism along a N–NE trend in the eastern Atlantic margin and Europe (Oyarzun et al., 1997). In fact, isotopic and geochemical studies indicate that a long-lived thermal anomaly is the most plausible explanation for the alkaline magmatism of western Portugal and the adjacent Atlantic region (Merle et al., 2006; Martins et al., 2009; Miranda et al., 2009; Grange et al., 2010).

It is noteworthy that EAt-LVA is mostly confined in its northern part by the prolongation of the Gloria transform (Fig. 1 and Fig. 4-BB′; see also Simmons et al., 2012). The position of the main part of EAt-LVA can be explained by the early opening stage of the central Atlantic Ocean. The edge of EAt-LVA is to a limited extent present as a strong anomaly below the Gorringe Bank and the Tagus Abyssal Plain (Figs. 3 and 5), which could be the result of a late expansion of the EAt-LVA following the initial stage of opening of the northern Atlantic Ocean (Sibuet et al., 2012). This strong sub-lithospheric mantle anomaly underlies the lithospheric density anomaly observed below Gorringe Bank/Tagus Abyssal Plain and interpreted as serpentinized mantle (Jiménez-Munt et al., 2010; Salláres et al., 2013).

The low velocity anomaly below the Gulf of Cadiz, GC-LVA extends from the top of the model down to about 300 km, interrupting to the west the continuity of the Alboran subducted slab. Given its areal extent, this low velocity anomaly may likely represent a fragment of thinned continental lithosphere which originated during the Mesozoic opening of the central Atlantic and Alpine Tethys (Dewey et al., 1989; Rosenbaum et al., 2002; Vissers and Meijer, 2012). This piece of continental lithosphere may indicate that the Tethyan margin between Africa and Iberia was a continental transform that linked the oceanic crust of the Horseshoe and Seine Abyssal plains to the oceanic Alpine Tethys. The most relevant implication for this paleogeographic interpretation is that this buoyant continental lithosphere may have caused the extinction of the westward rollback of the Alpine Tethys oceanic lithosphere, while entering subduction. This interpretation agrees with paleomagnetic data that show that oroclinal bending ended in early Pliocene or earlier (e.g., Platt et al., 2003, Cifelli et al., 2008) and also with the present day GPS velocity filed, which shows that the Betics and Rif units in the Gibraltar Strait are currently moving together with the African region located north of the Atlas (e.g., Serpelloni et al., 2007).

Finally, in the resolved part of our model below the European plate we find a deep high velocity anomaly, Lu-HVA (Figs. 2 and 4, profile BB′) which resides in the mesosphere (400–650 km depth), the region where slabs may accumulate (Anderson et al., 1992). This high velocity body is located below the Variscan belt of Portugal. The Variscan orogeny took place from about 350 to 300 Ma (e.g., Matte, 2001), contributing to the assembly of Pangea. The high velocity body could therefore represent a relic subducted slab. Similar relics of Variscan subduction are interpreted to occur underneath the Paris Basin, where a high velocity anomaly is present in the upper mantle (Averbuch and Piromallo, 2012). Pre-Variscan palaeoreconstructions suggest that western Iberia had a different evolution with respect to NW Africa, (e.g., Frizon de Lamotte et al., 2013). Interestingly, the transform zone (GNFZ) that separated the Variscan belt of Europe from the Appalachian-Mauritanian belt is inferred to run more or less along the present day Gloria Fault. This long-term evolution may have originated mantle heterogeneity that varies north and south of the Gloria Fault. The subsequent impinging of the eastern Atlantic magmatic activity may have also overprinted any pre-existing mantle features on the African plate.

## 5. Conclusions

The tomographic images of the upper mantle below the southwestern Iberian margin-Alboran region presented in this study can help us better understand the lithosphere-asthenosphere system across the Gibraltar Strait. Two clear high velocity anomalies of oceanic nature have been imaged in the Atlantic (HAP-HVA) and Alboran (Al-HVA) regions. The passage from the Atlantic to the Alboran is characterized by the pronounced low velocity anomaly GC-LVA which separates the high velocity lithospheres (HAP-HVA and Al-HVA), thus excluding the existence of a single slab subducting from the Cadiz Gulf under the Alboran region. Velocity contrasts between the fast/slow structures are 3 to 5%. In our interpretation GC-LVA represents a thinned continental lithosphere which separated the Alboran and Atlantic oceanic domains.

The geometry of HAP-HVA below the Horseshoe abyssal plain, is consistent with the presence of a limited subduction zone (of ca. 250 km) underlying the Horseshoe Abyssal Plain, driven by plate convergence. This evidence suggests that compression in the region comprising the Gorringe Bank-Horseshoe Abyssal Plain possibly started earlier than expected on the basis lithospheric thickening only.

A diffuse volume of low velocity, EAt-LVA, extends from northwest Africa to southwest Iberia and from the surface down to the bottom of our model. This EAt-LVA is mostly confined in its northern part by the prolongation of the Gloria transform, and it may have originated in the Jurassic, during the opening of the central Atlantic Ocean.

In this study we presented and discussed new images extracted from the tomographic model WMGC-OBS. Our model clarifies some aspects and at the same time opens new questions on the upper mantle structure and on the plate-tectonic evolution of this area. We hope that this new information will prompt further discussion and reinterpretation of the wide amount of acquired geophysical and geological data.

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