Mantle dynamics beneath the Gibraltar Arc (western Mediterranean) from shear-wave splitting measurements on a dense seismic array

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[1] Controversial evolutionary models have been proposed for the Gibraltar Arc system, a complex interaction zone between the Eurasia and African plates. Here we derive new mantle anisotropic constraints from SKS splitting measurements on a dense network of about 90 broad-band stations deployed over South Iberia and North Morocco. The inferred fast polarization directions (FPD) clearly show a spectacular rotation along the arc following the curvature of the Rif-Betic chain, while stations located at the South and South-East edges show distinct patterns. These results support geodynamical processes invoking a fast retreating slab rather than convective-removal and delamination models. The FPD variations along the Gibraltar arc can be explained by fossil anisotropy acquired during the Western Mediterranean Eocene subduction, while changes to the South and South-East of the Rif-Betic chain could be the imprint of a flow episode around an Alboran high velocity slab during its Miocene fragmentation from the Algerian slab. **Citation:** Diaz, J., J. Gallart, A. Villaseñor, F. Mancilla, A. Pazos, D. Córdoba, J. A. Pulgar, P. Ibarra, and M. Harnafi (2010), Mantle dynamics beneath the Gibraltar Arc (western Mediterranean) from shear-wave splitting measurements on a dense seismic array, *Geophys. Res. Lett.*, *37*, L18304, doi:10.1029/2010GL044201.

1. Introduction

[2] The Iberia-Maghreb region, located at the Western edge of the Mediterranean Sea is a region of complex tectonic deformation resulting from the interaction between the African and Eurasian plates (Figure 1). Paleozoic outcrops cover the western part of Iberia, forming three different units of the Iberian Massif: the South-Portuguese, the Ossa-Morena and the Central Iberian Zones, accreted in Carboniferous times and geologically stable for the last 300 Ma [*Gibbons and Moreno*, 2002]. East- and Southwards, the so-called Gibraltar Arc System [*Platt and Vissers*, 1989] represents the southernmost area affected by the Alpine orogeny and comprises three different domains: the internal zone (Rif-Betic chain), formed mainly by metamorphic units, the external domain (Maghebides, Atlas, external Rif, external Betics), formed by piled-up slices of the sedimentary cover of the paleo margin and the extensional back-arc domain (Alboran basin). The limit between Iberian and African plates is not well constrained from the Gulf of Cadiz to the Algerian coast [*Vernant et al.*, 2010]. The contact appears as a diffuse transpressive band of active deformation with significant seismicity at intermediate and deep levels. Geological, geophysical and geochemical data have provided evidences of coeval extensional tectonics in the Alboran region during convergence between Africa and Eurasia [*Dewey*, 1988; *Comas et al.*, 1999]. The area was affected by a N-S convergence since 35 Ma [*Platt and Vissers*, 1989], followed by a roughly EW oriented extensional episode from 27 to 7 Ma [*Watts et al.*, 1993] and slow oblique convergence (5–6 mm/y), oriented approximately NNW-SSE, from 7 Ma to present.

[3] Different, often incompatible, geodynamical models have been proposed to explain the extensional features in the Alboran region, from processes including a continental scale thermal mantle source driving rifting from the Rhine Graben into the westernmost Mediterranean [*Hoernle et al.*, 1995] to models suggesting regional scale recycling of the lithosphere by delamination [*Seber et al.*, 1996], slab break-off [*Zeck*, 1996], convective removal [*Platt and Vissers*, 1989] or the presence of active eastward subduction of oceanic crust [*Gutscher et al.*, 2002]. Nowadays, many authors favor models relating the Alboran extension to the evolutionary sequence of the Western Mediterranean Subduction Zone (WMSZ) [*Lonergan and White*, 1997; *Faccenna et al.*, 2004; *Jolivet et al.*, 2008]. These models explain the origin of the tight Gibraltar and Calabrian arcs as the result of the segmentation of the WMSZ and the fast retreat of the subsequent narrow slabs.

[4] The knowledge of the seismic anisotropy pattern, as derived from the splitting of SKS waves, has been regarded as a way to extend geodynamics to the upper mantle levels [*Silver*, 1996] and therefore could provide significant clues to discern between the proposed geodynamical models. Nowadays it has been widely accepted that the primary origin of the observed anisotropy is related to the lattice preferred orientation (LPO]) of the minerals that form the lithosphere and/or the uppermost asthenosphere [*Babuska and Cara*, 1991]. However, different hypotheses have been considered to explain the geodynamical processes responsible of this LPO [*Savage*, 1999], the most controversial point being to

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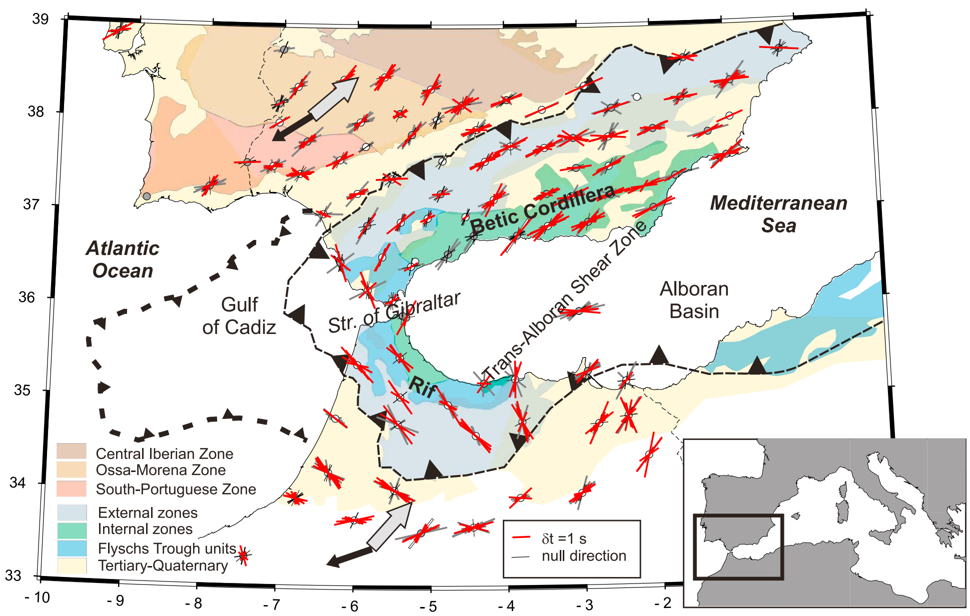

Figure 1. Anisotropic parameters retrieved from our dataset overprinting a simplified tectonic map of the region. Bars are oriented along the FPD and its length is proportional to the measured δt. Red bars are for "good" quality measurements while gray bars stand for "fair" results. Null measurements are represented by thin black lines oriented along the backazimuth. Absolute plate motion vectors in the no-net rotation frame and the fixed hotspot frame are show by gray wide and black thin arrows.

discern if the observed anisotropy corresponds to the signature of an ancient tectonic episode that has remained "frozen-in" in the lithosphere or to a present-day flow pattern affecting the asthenospheric levels. In this contribution we use the new dataset collected during the multidisciplinary Topo-Iberia project to investigate the anisotropic properties of this area. This project includes the installation of the IberArray broad-band (BB) seismic network (Figure S1 of the auxiliary material), aiming to sample the whole Iberian Peninsula and Northern Morocco in a scaled version of Earthscope project [*Díaz et al.*, 2009].[1] The first footprint of this network, covering northern Morocco (20 stations) and southern Iberia (35 stations) started progressively during summer 2007 and has been fully operational for more than 18 months. Additional nodes of the array are covered by permanent stations of different networks, resulting in a database with the continuous waveforms for more than 90 BB stations. (see Figure S1 and Table S1).

2. Shear-Wave Splitting Analysis

[5] Until few years ago, very scarce data regarding the presence of anisotropy in the Southern part of the Iberian Peninsula were available [*Díaz et al.*, 1996, 1998; *Calvert et al.*, 2000; *Serrano et al.*, 2005]. The installation during the last decade of new BB stations in the Betics and Rif areas provided first evidences on the rotation of the anisotropy pattern parallel to the Gibraltar arc [*Buontempo et al.*, 2008], even if only a couple of sites in N Morocco could be inspected. The much denser network managed in the Topo-Iberia project should therefore significantly improve the knowledge of the anisotropic features of the area, with special emphasis in the Moroccan part. Up to 59 events with epicentral distances between 90° and 130° and magnitudes greater than 6.0, recorded in a total of 92 BB stations [55 IberArray and 37 permanent ones] during the year 2008, have been investigated and reported here (Figure S2). We have used the usual quality criteria in anisotropic studies, based firstly in a good signal-to-noise ratio allowing a clear phase identification and secondly, in the linearization of the particle motion and the retrieval of the backazimuthal direction once the anisotropic effect has been corrected. This has lead to a total of 792 non-null and 228 null measurements during 2008, with 11 valid measurements per station on average. To inspect this large amount of data we have benefited of the SplitLab software [*Wüstefeld et al.*, 2008], that provides a useful tool to measure the splitting parameters and manage the resulting database.

[6] Figure 1 depicts the obtained results, overprinting a geological sketch of the area. The more relevant feature is the observation of a spectacular rotation of the measured FPD along the Gibraltar arc, following the curvature of the Rif-Betic chain (see details at Figure S3 and Table S2). At the internal and external units of the Gibraltar arc, FPD directions mimic its orientation, shifting from N60°E at the northern Betic domain, to close to N-S around the Strait of Gibraltar and N50°W at the Moroccan side of the arc. For most stations, the anisotropic parameters retrieved from the inspected events are rather consistent, providing a significant mean value of the FPD and δt. However, some degree of azimuthal dependence is observed, probably related to the presence of two anisotropic layers. This is particularly true for stations at the southern edge of the Iberian Peninsula and the NE part of Morocco, where the SKS arrivals are often unclear, and both a significant number of null measurements and marked azimuthal scattering are inferred.

[1] Auxiliary materials are available in the HTML. doi:10.1029/2010GL044201.

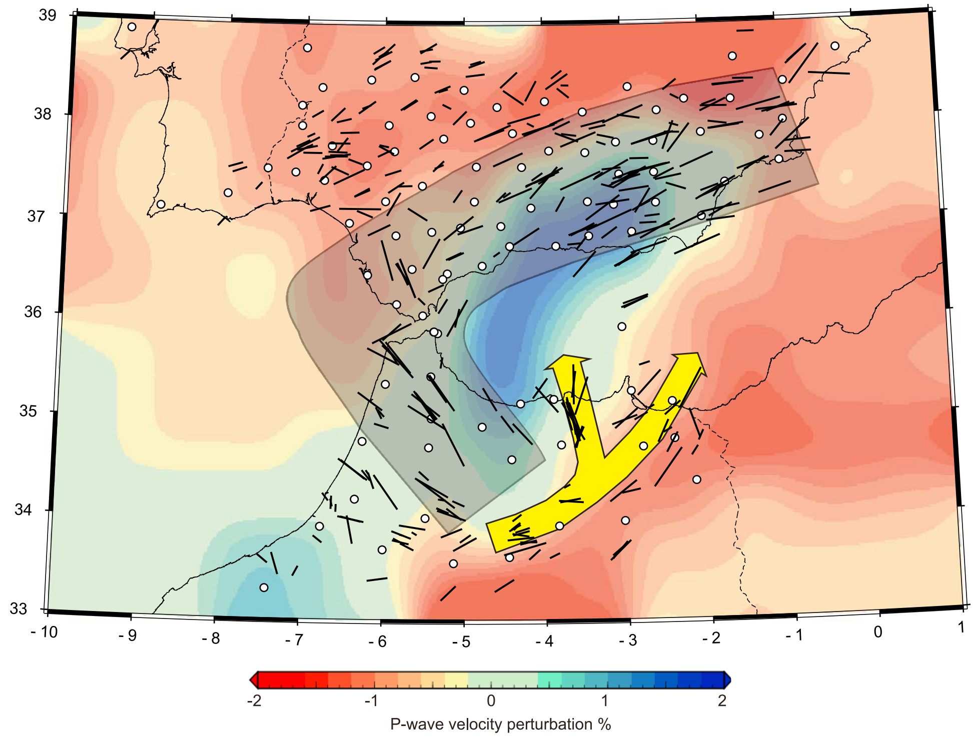

Figure 2. FPD for the best quality measurements shifted to their 200 km depth piercing point, represented over the same depth layer of the P-wave global tomographic model of *Bijwaard et al.* [1998], updated by *Villaseñor et al.* [2003]. Gray band show the region where FPD clearly follow the Gibraltar Arc geometry. Yellow arrow depicts the flow episode in the mantle responsible for the anisotropic pattern.

[7] A clear change in FPD is observed between the stations located in the internal Rif zone and those in the external and foreland units. Beneath the Mediterranean coast of Morocco, close to the Alhoceima region (approx. 4°W), the abrupt change in FPD is coincident with the southern limit of the Trans-Alboran Shear Zone (TASZ), a band of strike-slip faults oriented roughly NE-SW associated with Neogene volcanism [*Bousquet*, 1979] and clearly delineated by superficial (d< 10 km) seismicity [*Stich et al.*, 2006]. A clear change is also observed for the stations in the southern part of the array, already at the foreland units of the Moroccan meseta. In the western part of this region, near the Atlantic coast, the FPD are oriented close to EW, while further East the direction changes to NE/SW near 3° W and reach N-S directions in the NE part of Morocco. The permanent station placed at Alboran Island shows a FPD oriented N80E, clearly different from nearby stations in northern Morocco.

[8] In the Variscan domain of the Iberian Massif the FPD are oriented between N30°E and N60°E, and the southernmost stations, located in the African foreland, show also a similar fast axis. It must be noted that those FPD are not far from the absolute plate motion (APM) direction in the no-net rotation frame, oriented close to N50°E (around N240°E if the HS3-Nuvel1A fixed hotpot frame is considered) (UNAVCO, http://sps.unavco.org/crustal_motion/dxdt/model). Therefore, the FPD beneath the Variscan units of South Iberia could be related to asthenospheric dynamic flow, even if the slow plate velocities (about 2 cm/year) do not favor this hypothesis.

[9] Considering the whole array, an average value of 1.3 s is derived for the δt shift parameter. Both at the NW and Southern edges of the study area, δt values significantly smaller, around 1.0s are obtained, depicting a smaller degree of anisotropy.

[10] It is well-known that the anisotropic parameters retrieved using different methods can differ significantly if seismic noise is present [*Vecsey et al.*, 2008]. As a further constraint to our dataset, we have performed the analysis of each individual measurement using two methods: maximization of the correlation between the two quasi-shear waves and minimization of the energy of the transverse component. Only those measurements with differences between both methods less that 20° in the FPD and 0.5s in δt have been finally retained (Figure 2 and Table S2). This procedure reduces the number of measurements to about 40%, but the main features derived do not change significantly.

3. Discussion and Conclusions

[11] The Northeastern part of Morocco, where we identify an abrupt change in the anisotropic parameters, correlates not only with the limit of tectonic units in surface (Figure 1) but also with significant variations reported in many different geophysical parameters, such as seismicity maps [*Buforn et al.*, 1995; *Stich et al.*, 2006], lithosphere-asthenosphere boundary (LAB) models derived from elevation and geoid anomaly data [*Fullea et al.*, 2007], Bouguer anomaly maps [*Fullea et al.*, 2008], heat flow [*Soto et al.*, 2008] or stress indicators [*Olaiz et al.*, 2009], suggesting that this region, close to 4°W in northern Morocco, acts as a major lithospheric boundary. GPS studies show a significant southward differential motion of the Rif-Alboran-Betics block with

respect to the African plate and suggest a deep dynamical process controlling the deformation at surface [*Stich et al.*, 2006; *Vernant et al.*, 2010]. At deep levels, the region marks the southern limit of the high velocity slab observed in tomographic models down to about 600 km [*Bijwaard et al.*, 1998]. The geometry of this high velocity body has been interpreted as a "spoon-shaped" slab of lithospheric material tearing in the mantle [*Spakman and Wortel*, 2004] and the presence of this steeply dipping slab has also been invoked by *Bokelmann and Maufroy* [2007] to explain differences in the dispersion properties of body waves recorded from different backazimuths. Our results evidence a good correlation between the arcuate geometry of the slab at 200 km depth and the changes in the FPD measurements once projected to its piercing point at the same depth (Figure 2).

[12] As previously pointed out by *Buontempo et al.* [2008], FPD results derived from SKS splitting are nearly coincident with those from Pn data beneath the Betic Chain. The new data allow confirming this point but also show that both parameters clearly differ in Northern Morocco [*Serrano et al.*, 2005; *Calvert et al.*, 2000]. Stretching directions deduced from lower crustal material [*Jolivet et al.*, 2009] are subparallel to FPD beneath the Betics and Rif but, again, clearly differ beneath NE Morocco. Both results suggest that significant coupling between crust and deeper levels of the upper mantle can exist beneath the Gibraltar arc but not beneath NE Morocco. In the Calabrian arc, related also to the Neogene extension of the western Mediterranean, FPD inferred from SKS anisotropic measurements display a clear rotation along the arc and has been interpreted as the result of toroidal flow in the mantle due to slab rollback [*Civello and Margheriti*, 2004]. In our case, the abrupt change in FPD beneath the Alhoceimas region and the clearly asymmetric anisotropic pattern does not support toroidal flow around the slab, but the results may be interpreted in terms of simple mantle flow coming from the S-SW, that may be induced by the westward rollback of the slab.

[13] Geodynamical models implying asthenospheric upwelling (delamination, convective removal of the lower lithosphere, slab break-off) seem hardly compatible with our results. This point, already suggested by *Buontempo et al.* [2008], is confirmed now from the analysis of a more representative data set. Anisotropic models for mantle plumes show that the expected FPD distribution would be approximately radial [*Walker et al.*, 2005], while the FPD along the Gibraltar Arc show a tangential, arc-parallel distribution.

[14] The anisotropic pattern imaged by our data supports models involving a westward retreating slab to explain the geodynamics of the Gibraltar Arc System. The FPD pattern beneath NE Morocco, clearly different from the result beneath the Rif, is related to the imprint of a mantle flow episode, probably during the segmentation of the Alboran and Algerian slabs [*Faccenna et al.*, 2004] in Early Miocene times. Alternatively, this flow can be interpreted as a present-day feature related to the slab rollback and perhaps facilitated by the lithospheric thinning beneath the Atlas belt [*Missenard et al.*, 2006]. We attribute the arc parallel FPD rotation beneath the Rif-Betic ranges to a trench-parallel anisotropy acquired in the subducting slab while the WMSZ was active, that has remained frozen-in at lithospheric levels since then and was later on deformed during the rollback arc emplacement of the Gibraltar Arc. Results suggesting that the lithosphere is significantly thickened beneath the Rif-Betic ranges [*Fullea et al.*, 2007] are consistent with this hypothesis of frozen-in anisotropy in this area, also supported by the agreement between SKS, Pn and stretching results over this area [*Serrano et al.*, 2005; *Jolivet et al.*, 2009]. Therefore, the mantle beneath the Gibraltar Arc preserves the imprint of the main processes having affected the Western Mediterranean, namely, the compressive regime associated to the subduction of Africa beneath Eurasia and the subsequent extension related to the roll-back arc emplacement of the Gibraltar Arc System. The present-day convergence between Africa and Eurasia appears to be too small to overprint this pattern.

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