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Seismic Anisotropy from the Variscan Core of Iberia to the Western African Craton: New Constrains on Upper Mantle Flow at Regional Scales.

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Abstract

The regional mantle flow beneath the westernmost Mediterranean basin and its transition to the Atlantic domain is addressed by inspecting the anisotropic properties of the mantle. More than 100 new sites, from the Variscan core of Iberia to the northern rim of the Western African Craton, are now investigated using the data provided by different temporary and permanent broad-band seismic arrays. Our main objective is to provide a larger regional framework to the results recently presented along the Gibraltar Arc in order to check the validity of the different geodynamic interpretations proposed so far.

The significant variations in the retrieved anisotropic parameters suggest that different processes must be invoked to explain the origin of the observed anisotropy. Beneath the Variscan units of the Central Iberian Massif the new results show a moderate amount of anisotropy with fast polarization directions (FPD) oriented close to E-W. Those results can only be explained in terms of global mantle flow if models accounting for contributions from surface plate motion, net lithosphere rotation and density variations are taken into consideration. One of the major results presented is the significant number of good quality data without evidence of anisotropy ("nulls") observed beneath permanent stations in southern Portugal. Those "nulls" can be explained by the presence of a predominantly vertical mantle flow associated to large variations in the lithospheric thickness. Beneath the Gibraltar Arc the FPD show a spectacular rotation, evidenced by the results presented by Diaz et al. (2010) and Miller et al. (2013). Those results are reviewed here taking also into consideration the geodynamic modeling presented recently by Alpert et al. (2013) and other geophysical and geodetic results. Further South, the analysis of new broad-band stations installed in the

Moroccan Meseta and the High Atlas show a small degree on anisotropy and a large number of “null” events, pointing again to the presence of vertical flow in the mantle.

The results favor an asthenospheric origin related to present-day mantle flow for the anisotropy observed from the Variscan core of Iberia to the northern rim of the West African Craton. This flow is deflected around the high velocity slab beneath the Gibraltar Arc and seems affected locally by vertical flow associated to edge-driven convective cells. The presence of significant backazimuthal variations in the anisotropic parameters retrieved from single events suggests that a second order contribution from an anisotropic layer within the lithosphere may also exist.

The origin of the upper mantle anisotropy has been classically related to the strain-induced lattice preferred orientation (LPO) of the mantle minerals, in particular of olivine (e.g., Nicolas and Christensen, 1987). Anisotropy thus provides one of the best tools to investigate deformation in the upper mantle, in a way extending structural geology. In tectonically active areas, fast polarization directions (FPD) are expected to mark the direction of flow. In zones without present-day large-scale tectonic activity, LPO results from strain from the last significant tectonic episode preserved in the subcrustal lithosphere or from dynamic flow in the asthenosphere. Therefore, even if it involves some ambiguity, the knowledge of the anisotropic properties can provide new clues on the geodynamic processes beneath the investigated area.

2 Data acquisition and processing

Until the last decade, very scarce data regarding the presence of anisotropy in the southern part of the Iberian Peninsula were available (Díaz et al., 1996, Díaz et al., 1998, Calvert et al, 2000, Serrano et al., 2005). The installation of new permanent and semi-permanent broad-band stations in the Betics area allowed a first regional reconnaissance of its anisotropic properties (Buontempo et al, 2008), documenting geographical variations in the anisotropic parameters, even if only a few sites in N Morocco could be studied. Later on, with the installation of the much denser TopoIberia network, the knowledge of the anisotropic features beneath the Gibraltar Arc was significantly improved (Díaz et al. 2010). The contribution of the PICASSO network has recently increased the data density along a North-South transect and has allowed the first numerical flow modeling beneath the area (Miller et al., 2013, Alpert et al., 2013).

In this contribution, we expand the previously published data with new measurements coming from seismic stations installed over a wider geographic region. From North to South, we have used the data provided by the second TopoIberia-Iberarray deployment, covering the central part of the Iberian Peninsula, additional TopoIberia stations installed over the Moroccan Meseta and the High Atlas, and the temporary deployment carried out by the Univ. of Munster and the Univ. of Bristol in the framework of the Comitac project that covers the western High Atlas and the Anti-Atlas domain. We also had access to the data from two short-

1 Introduction

The Western Mediterranean area has a complex geodynamic evolution the main points of which are still under debate and that result in a zone with clear extensional features in the framework of a compressional regime related to the present-day collision between Nubia and Eurasia. Moving further west, the Atlantic margin, and in particular the Gulf of Cadiz, show also a great degree of complexity; with a poorly defined plate boundary, the presence of historic large magnitude seismicity and a sustained amount of small to moderate seismicity at subcrustal depths. An appropriate way to try to discern between the different geodynamic hypotheses proposed is the acquisition and interpretation of larger amounts of geophysical data, even if this often leads to more complex images than those proposed by theoretical modeling. During the last years, large scale projects such as TopoIberia (Díaz et al., 2009) and PICASSO have been designed with this objective. Up to now, the main focus has been centered in the Gibraltar Arc System (Platt and Vissers, 1989) which has been investigated by magnetotelluric profiles (Anahnah et al., 2011; Ruiz-Constán et al., 2012), local and teleseismic tomography (Villaseñor et al., 2011, El Moudnib et al, 2012; Bezada et al, 2013), surface wave tomography (Palomeras et al., 2012), crustal structure derived from receiver function analysis (Mancilla et al., 2012; Thurner et al., 2012) and wide-angle reflection/refraction profiles (Gallart et al., 2012) or mantle anisotropy (Díaz et al. 2010, Miller et al., 2013, Alpert et al., 2013).

The main objective in this contribution is to present and analyze the new anisotropic parameters obtained from shear-wave splitting data beneath a large area including, North to South, from the Variscan Central Iberian Massif of Iberia to the northern rim of the West African Craton and, East to West, from the Algerian basin to the Atlantic domain. Those new results provide a wider framework to the anisotropic results presented recently in the Gibraltar arc by Diaz et al 2010 and Miller et al. (2013) and allow reviewing the geodynamic modeling presented by Alpert et al. (2013) as it allows a better understanding of the interactions of the Gibraltar Arc with the surrounding, more stable regions. To achieve this purpose, we have gathered data from different permanent and temporary broad-band networks installed over the investigated region, including some over the marine areas covered by short term ocean bottom seismometer (OBS) deployments. The final data set allows the calculation of anisotropic parameters over a large number of stations and facilitates the geodynamic interpretation of the results.

term broad-band OBS deployments in the Alboran Sea and Gulf of Cadiz installed by Geomar as part of the Topomed project. Finally, we have gathered data from the permanent networks in Spain, Portugal and Morocco (Figure 1). This has resulted in a dataset comprising 106 stations to be added to the 92 sites investigated previously by Díaz et al., (2010) and the 81 sites, mostly along a dense profile oriented N-S, presented by Miller et al (2013).

The different deployments are not completely coincident in time. Time intervals of about 12 to 18 months have been inspected for each station within a time interval between summer 2009 and the end of 2011 (Supplemental Table 1). The OBS were deployed firstly in the Alboran Sea for 4 months and later in the Gulf of Cadiz during 6 months. This rather short time interval, together with the intrinsic problems in recording seismic signals at long periods undersea (noise, coupling, sensor orientation), made it possible to retain only some anisotropic measurements at each instrument. All the events with magnitude greater than 6.0-6.2 and epicentral distances ranging between 90º and 130º have been inspected and up to 130 events have finally provided useful anisotropic measurements. Due to the dominant period of the inspected SKS waves, it is difficult to get accurate measurements of very small delay times. As a general rule, only the events with delay times greater than 0.4s are classified as anisotropic.

To inspect this large amount of data we have benefited from the SplitLab software (Wüstefeld et al., 2006), that provides a useful tool to measure the splitting parameters and manage the resulting database. Most of the results have been obtained using the method based on the search for a maximum correlation between the two quasi-shear waves (Figure 2), as it is less sensitive to possible misorientations of the seismometer horizontal components than the methods based on the minimization of the transverse component energy (Tian et al., 2011). In a few particular cases we preferred to retain the result from this last method as it provided a more realistic adjustment. We have used the usual quality criteria in anisotropic studies, based firstly on a good signal-to-noise ratio allowing clear phase identifications and, secondly, in the linearization of the particle motion and the retrieval of the backazimuthal direction once the anisotropic effect has been corrected. According to those criteria, events were classified into three categories (good, fair, poor) and only those in the firsts two classes were further used. Measurements providing small delay times relative to the dominant period of the SKS waves, (around 6-8 s) are interpreted as “nulls”, that is, as not showing evidence of anisotropy. However, in the presence of noise some of those “nulls” can simply correspond to unstable measurements. To avoid this misinterpretation we have only retained as "nulls" the good measurements providing delay times smaller than 0.25s and we have discarded the measurements with delay times between 0.25 and 0.4 s. This resulted in a total of 981 non-null and 404 null measurements. For most of the stations we have retained 10 to 20 observations, with a mean value of 16.2 valid measurements per station. Supplemental Table 1 shows the mean FPD and delay time for each analyzed station as well as the corresponding standard deviation. The individual results are presented in the Supplemental Table 2 and displayed in Figure 3. We have checked the stability of the results by retaining only those cases for which the difference between the results from the maximum correlation and transverse energy minimization methods does not exceed 20º for FPD and 0.3s for δt. Even if the amount of individual measurements decreases a 40% under those restrictive conditions, the general anisotropic pattern remains nearly unchanged (see Supplemental Table 2).

3 Results

The investigated area encompasses very different tectonic units, from the Variscan units of Central Iberia to the West African Craton (WAC). We will summarize our results, presented in Figure 3, for each different unit.

To the North, the central and western part of Iberia corresponds to the Variscan Central Iberian Massif (CIM), which has remained tectonically stable for the last 300 Ma, since the end of the Hercynian orogeny (Gibbons and Moreno, 2002). The anisotropic parameters retrieved over this area are quite uniform, with FPDs oriented close to E-W and a moderate degree of anisotropy, with δt values around 1.0 s. The eastern part of central Iberia is dominated by Meso-Tertiary zones reworked by the Alpine orogeny. The anisotropic parameters remain similar to those reported for the CIM, even if the amount of anisotropy seems to increase slightly. The easternmost area is dominated by the extension associated to the opening of the Valencia Trough in Neogene time, as a result of the clockwise rotation of the Balearic block (Dewey et al., 1989). The FPD obtained at the Balearic Islands also show a dominant E-W trend beneath the western islands, but with a significant shift to ESE-WNW beneath the easternmost island of Menorca.

Further South, the western part of the investigated area still corresponds to the Variscan Massif, in this case formed by the South-Portuguese and the Ossa-Morena units, both accreted to the Central Iberian Massif in Carboniferous times and geologically stable for the last 300 Ma (Gibbons and Moreno, 2002). The most relevant observation derived from the analysis of permanent stations in southern Portugal is the presence of a large number of events with clear SKS arrivals without any evidence of anisotropy, commonly identified as “nulls”. For the rest of the cases, the FPD inferred from individual events show large variations, even if a dominant NE-SW direction can be identified. The delay times are small, in the 0.5-0.8s range. As will be discussed later on, those facts suggest a geodynamic complexity which is not directly related to the surface geology.

The eastern part of South Iberia and the northern part of Morocco are formed by the so-called Gibraltar Arc System (Platt and Vissers, 1989). This system has classically been divided in three domains; the internal zone formed mainly by metamorphic units, the external zone, formed mainly by piled-up slices of the sedimentary cover of the paleo margin and the Alboran basin, which corresponds to the extensional back-arc domain. The results over this zone have already been presented and discussed in Díaz et al. (2010) and have been confirmed recently by Miller et al. (2013) using a denser deployment focused along a N-S profile. The main feature observed is the spectacular rotation of the FPD along the Gibraltar arc following the curvature of the Rif-Betic chain, from roughly N65ºE beneath the Betics to close to N65ºW beneath the Rif chain. Additionally, a clear change is observed between the internal Rif and the external and foreland units. New data from the OBSs deployed in the Alboran Sea, even if limited in number and quality, show a small degree of anisotropy, with FPD oriented mostly E-W and quite consistent with previous results in the permanent station located at the Alboran Island.

The Gulf of Cadiz lies at the eastern termination of the Azores-Gibraltar fracture zone and has also a complex structure, including a change from extensional tectonics in the West to mostly compressional in the East, the transition from oceanic to continental crust (Sallarès et al., 2012) and the presence of significant seismicity around 70 km depth (Buforn et al., 2004). OBSs located in the western part of the gulf show a North-South component in the inferred FPDs, while in the central zone the FPDs are closer to E-W. However, few measurements are available and thus those results must be taken with caution.

Northern Morocco can be divided into three main tectonic domains; the Rif Chain, the Meseta-Atlasic domain and the Anti-Atlas domain, corresponding to the northern limit of the WAC (Michard et al., 2008). The Meseta-Atlansic domain is formed in turn by the Moroccan Meseta, the High Atlas and the Middle Atlas. Díaz et al., (2010) show a clear change in FPD between the Rif and the northern part of the Middle Atlas. Miller et al., (2013), confirmed this point and extended the available anisotropic measurements further South along a profile crossing the Atlas, getting small δt (0.6 – 0.9 s) and FPD oriented ENE-WSW. The new data presented here show similar results for sites in the central part of the Moroccan Meseta as well as in the central and western sections of the High Atlas. Further South, the northern rim of the WAC, the Anti-Atlas domain, is explored using the data provided by the Comitac network, also used by Miller et al. (2013). Most of the stations show a small degree of anisotropy (0.5 - 0.8 s) and FPD not far from E-W. It is important to note that, as already described for SW Portugal, there is a large number of high quality events without evidence for anisotropy (”nulls”) beneath the western part of the High Atlas and Anti-Atlas units.

4 Geodynamic interpretation

In order to progress from the observation of anisotropy on seismic data to their interpretation in geodynamic terms, three steps are needed. Firstly, we need to identify the effect of anisotropy in the data. In this contribution we used one of the most robust effects of seismic propagation trough an anisotropic medium, the birefringence or splitting of the SKS shear-waves. This phenomenon has been widely investigated and the techniques to identify it have now become routinely used.

As a second step, we need to explain the process that originates the observed anisotropy. Even if Fichtner et al. (2013) have suggested that the observed seismic anisotropy can often be explained by purely isotropic layering, it remains widely accepted that anisotropy in the mantle is related to the lattice preferred orientation (LPO) of the minerals, in particular olivine, which is the major constituent of the upper mantle (Nicolas and Christensen, 1987). LPO patterns in peridotites measured in laboratory show that in most of the cases, the fast propagation axes align with the direction of maximum shear, allowing relating anisotropy and strain. However, factors such as temperature, melt fraction or presence of water result in changes in the olivine fabric and its relationship with deformation (Long and Becker, 2010). Other mechanisms, such as the presence of melt pockets or the preferred orientation of cracks in the upper crust can also play a significant role in the origin of the anisotropy (Savage, 1999).

Finally, the last step is to discuss the tectonic process responsible for the deformation. One good candidate, in particular for tectonically active areas, is the existence of a present-day asthenospheric flow that dynamically produces the observed LPO. In a classical interpretation (Vinnik et al., 1989), the passive motion of the lithosphere over the asthenospheric mantle will result in FPD oriented parallel to the absolute plate motion. At a global scale, the anisotropic parameters inferred from SKS and surface waves have been used to derive new mantle flow models taking into consideration not only the surface plate motions but also the effect of lateral heterogeneity in viscosity, which induce net lithosphere rotation, and the presence of density-driven flow (Becker, 2008, Kreemer, 2009, Conrad and Behn, 2010). Alternatively, the origin of the observed anisotropy can be related to the last tectonic event affecting the region, whose strain would have been preserved, “frozen-in”, in the subcrustal lithosphere. This mechanism has often been invoked to explain anisotropic observations in passive areas. Under this hypothesis, the FPD are expected to be parallel to major structures, such as plate boundaries or mountains belts. It is important to note that the major limitation of the shear-wave splitting measurements is its lack of vertical resolution, as we can only measure the integrated effect of anisotropy along the raypath. We know that the contribution of the crust is limited to few tens of second and it is widely accepted that most of the anisotropy comes from the upper mantle, even if it remains unclear whether anisotropy is confined to the upper 200 km or continues through the transition zone (Savage, 1999). Therefore, SKS measurements cannot identify if the main source of anisotropy lies in the lithosphere or the asthenosphere and hence discriminate between the above hypotheses. However, with the availability of large amounts of anisotropic observations worldwide, it seems clear that, in particular for continental areas, the anisotropy is a complex phenomenon that probably involves contributions both at lithospheric and asthenospheric levels.

Beneath central Iberia, the retrieved FPD are rather uniform, oriented close to E-W and with δt around 1.0 s. This orientation is difficult to interpret in terms of “frozen-in” anisotropy related to a Variscan deformation preserved in the lithosphere, as the retrieved FPD clearly differ from the surface expression of the Variscan orogeny, with tectonic lineaments oriented close to NW-SE in the southern part of Iberia and shifting smoothly to N-S in NW Iberia following the arcuate Variscan belt (Matte, 1991). Global plate tectonic models assuming no net rotation, determined solely from the relative motions between plates, give an absolute plate motion (APM) vector oriented close to NE (N50ºE) beneath Iberia. Models obtained within a hot spot based reference frame, and thus assuming net rotation of the tectonic plates, result in a nearly opposite direction, close to WSW (N238ºE). In both cases the speed is low, around 20 mm/year (http://www.unavco.org/community_science/science-support/crustal_motion/dxdt/model.html). Neither of those directions is parallel to the FPD observed beneath Central Iberia, as would be expected if the anisotropy was due to present-day mantle flow. However, a viscous mantle flow model presented by Conrad and Behn (2010) taking into consideration the contributions to global flow of plate tectonics, mantle density heterogeneity and net lithosphere rotation results in a flow field at upper mantle depths (200-400 km) oriented E-W beneath central Iberia, which is compatible with our splitting measurements (Figure 4a). This model is also consistent with the previous splitting measurements in northern Iberia (Supplementary Figure 1), showing N-E oriented FPD (Díaz et al., 2006) as well as the results beneath the Pyrenees, where the FPD is oriented ESE-WNW (Barruol et al., 1998).

Results beneath the Balearic Islands also show E-W FPD beneath the western islands, but the results shift to ESE-WNW beneath the easternmost island of Menorca. This FPD change could be related to the differential rotation affecting the Balearic Islands and the Corsica-Sardinia block in Late Oligocene-Early Miocene times. Barruol et al. (2004) interpreted the FPD variations observed in SE France and Corsica as an evidence of mantle flow preserved in the deep lithosphere since the end of the Cenozoic extensive episode. However, more information on the anisotropic parameters beneath the eastern termination of the Pyrenees and Sardinia is needed to properly discuss the origin of anisotropy in this region.

Díaz et al. (2010) suggested that the spectacular rotation of the FPD along the Gibraltar Arc may be the outcome of two processes; an active mantle flow around the high velocity slab beneath the Gibraltar Arc imaged by tomography and a lithospheric contribution acquired during the Western Mediterranean subduction in Eocene times. However, new results from both teleseismic and Pn tomographic studies do not seem to support the last point. Bezada et al. (2013) and Villaseñor et al. (2011), using new data from the TopoIberia and Picasso experiments, have produced new teleseismic 3D tomographic images that clearly refine the previous ones. A high velocity slab is identified beneath the Alboran Sea and the eastern Betics down to at least 600 km. Below 100 km, this slab is almost vertical and has an arcuate geometry following the arc from the eastern Betics to the Rif. Above this depth, the anomaly can hardly be identified beneath the Betics, while it is clearly observed to the East of the Strait of Gibraltar, where it seems to be connected to the surface. This geometry supports the presence, already pointed out by Spakman and Wortel (2004), of slab tearing beneath the eastern Betics, which has also been proposed by Garcia-Castellanos and Villaseñor (2011), based on uplift rates in the Betics and the Rif. Pérouse et al. (2010) proposed a dynamic modeling of the western Mediterranean to account for GPS observations in which the slab is detached beneath the Betics but remains coupled beneath the Rif. The Pn tomography results presented by Díaz et al. (2013) show a large low velocity anomaly at the uppermost mantle beneath the eastern Betics which can be related to hot materials filling the zone where the slab is detached. Therefore, it seems now difficult to explain the anisotropy parameters observed along the arc as corresponding to a vertically coherent anisotropy acquired during the formation of the Gibraltar arc and preserved in the lithosphere, in particular if we note that eastern Betics is one of the zones with maximum observed delay times. It seems more plausible to explain the observations of Díaz et al. (2010), as well as the additional data presented by Miller et al. (2013), as the result of asthenospheric flow deflected around the fast velocity slab, located east of the Strait of Gibraltar (Figure 4b). The detachment of the slab beneath the Eastern Betics justifies the presence of the hot material at subcrustal levels, which can contribute to the strong anisotropic signature observed beneath this area (Figure 4c). Even if very different models have been proposed to explain the tectonic evolution of the Gibraltar Arc (Andrieux et al., 1971, Platt and Vissers, 1989, Faccenna et al., 2004, Gutscher et al, 2002, Carminati et al., 2012, Vergés and Fernandez 2012), there is now an overall agreement to explain the Betic-Rif orogen as a consequence of the Ligurian-Tethys subduction and a west or northwest oriented slab roll-back. Different analog and numerical models have shown that roll-back can result in arcuate FPD variations (Facenna and Capitanio, 2013), and this mechanism has been proposed to explain the FPD rotation along the Calabrian Arc (Baccheschi et al., 2011). Even if the anisotropic pattern retrieved in our case is similar, results from different fields, from structural geology to volcanism or geodesy strongly argue against an ongoing rollback process in the Gibraltar Arc (Platt et al., 2013). Alpert et al. (2013) presented a geodynamic flow model in which the observed anisotropy pattern could be explained without invoking this slab rollback. However, large slab density contrast and viscosity values are needed to induce the flow deflection around the slab and the observed FPD beneath the southernmost Spain or at the Alhuceimas region (aprox 35ºN, 3ºW) are only partially reproduced. Therefore we interpret that the observed anisotropy pattern as depicting present-day mantle flow around a fixed Gibraltar slab. The scarce anisotropic measurements obtained from the OBSs deployed in the western section of the Alboran Sea show a small, roughly E-W oriented FPD which do not seem to follow the general arcuate trend observed onland. However, further OBS deployments are needed to assess this point, as the available results are not robust enough to be conclusive.

Away from the Gibraltar Arc, the FPD observed beneath southern Iberia, shifting from NE-SW in the West to ENE-WSW in the eastern part, can also result from mantle flow deflected around the fast velocity slab. Note that stations located further North, discussed previously, show a clearly different E-W trend. Stations in the transitional area (37-38ºN, west of 4ºW) have a clear NE-SW mean FPD but show significant backazimuthal variability, interpreted as an image of complexity and depicting the limit of the area affected by flow around the slab. At northern Morocco, FPD evidences a rather symmetrical image, depicting a NW-SE oriented mantle flow beneath the Rif and the Gharb basin. The abrupt change in FPD in northern coast of Morocco at about 3ºW (Alhuceimas region) has been interpreted as indicating the flow around the southward edge of the slab (Díaz et al., 2010). Note that the northern edge of the slab does not result in a similar change in FPD.

The new anisotropic measurements beneath SW Portugal show a quite different anisotropic pattern, with small amount of anisotropy and a large percentage of "nulls". Under the classical hypothesis, "nulls" are only expected for those SKS waves with backazimuths coincident with the fast or slow directions of anisotropy, oriented orthogonally. The presence of nulls over a large backazimuthal range, mixed with evidences of anisotropy for other events, suggest that a more complex anisotropy pattern does exist beneath this area. It has been proposed by different authors (Long et al., 2010, Wagner at al., 2012), that the presence of a significant number of nulls can be explained by a poorly organized asthenospheric flow or, more probably, by the presence of a predominantly vertical flow. Models based on potential fields (Fullea et al., 2010, Jiménez-Munt et al., 2011) have evidenced a large variation, exceeding 100 km, in lithospheric thickness between SW Portugal and the Gulf of Cadiz. While in southern Portugal the lithospheric thickness is estimated in 100-110 km, beneath the central part of the Gulf it can reach 200 km. Such variation may activate small-scale convective cells and thus vertical flow in the upper asthenosphere, resulting in small indications of anisotropy. The OBSs in the Gulf of Cadiz show a complex pattern, with the westernmost one displaying a North-South FPD, while the rest of the instruments have grossly EW oriented FPDs, similar to what is observed in the Alboran Sea. Few measurements are available and hence those results must be taken with caution; however, such anomalous variations can be related to the presence of vertical flow beneath SW Portugal, which would result in a complex anisotropy pattern.

Stations in the Moroccan Meseta, the western High Atlas and the Anti-Atlas show similar results, with small values of δt, significant differences in the FPD derived from individual events and a large amount of nulls for a broad range of backazimuths. Lithospheric models presented by Fullea et al., 2010, show a thinned lithosphere beneath the Middle and High Atlas, with a difference of 50-75 km with respect to the Gulf of Cadiz. The presence of a vertical offset of the lithosphere-asthenosphere interface at the flanks of the High-Atlas has been recently documented by Miller and Becker (2013). Missenard et al., (2011) have independently proposed the presence of edge-driven convective cells beneath the Atlas to account for volcanologic observations. The significant step in lithospheric thickness could justify the presence of such small scale vertical convective cells, which in turn allow explaining the large observed number of nulls. Miller et al. (2013) reported relatively large delays beneath the axis of the northern part of the High Atlas and proposed that it may be related to plume material channeled along the sub-lithospheric corridor from the Canary Islands hotspot previously suggested by Duggen et al., (2009). The new stations analyzed in the central part of the High Atlas show mean δt values close to 1.0 s, similar to the values obtained in the Middle Atlas, but only a small amount of anisotropy is observed beneath the western High Atlas and in the Moroccan Meseta, with FPD showing a general ENE-WSW FPDs orientation, δt values clearly below 1.0s and a large number of nulls. This seems inconsistent with the hypothesis of a sub-lithospheric corridor, which should be present not only beneath the western High Atlas but all along its path from the Canary Islands. We prefer to interpret the anisotropic observations for the stations in the Anti-Atlas domain in terms of vertical flow in the mantle, associated to the very significant change in the elastic thickness beneath the northern rim of the WAC identified by Pérez-Gussinyé et al. (2009).

5 Conclusions

The knowledge of the anisotropic parameters beneath the Western Mediterranean region, from the Western African Craton to the Variscan core of Iberia is significantly improved by the new anisotropic measurements gathered at more than 100 new sites, including permanent broad-band stations, the regularly spaced TopoIberia-Ibearray seismic network and additional temporary networks deployed over the area. Those new results provide an enlarged view of the regional geodynamic setting and allow a review of the previously proposed geodynamic models.

The anisotropic parameters here presented can be globally related to the LPO of mantle minerals generated by mantle flow at asthenospheric depths, even if different processes must be invoked to explain the observations (Figure 5). Beneath central Iberia, an area quite stable tectonically, the anisotropic parameters are rather uniform and cannot be related to the deformation inherited from the Variscan orogeny, the last large-scale tectonic event affecting the zone. The E-W oriented FPD seems compatible with the Conrad and Behn (2010) mantle flow model, which is computed from a combination of mantle flow fields driven by relative plate motions, mantle density heterogeneity and net lithosphere rotation. On the contrary, those FPD are not consistent with classical mantle flow models using NNR nor hotspot framed models to prescribe surface boundary conditions, as those used in Alpert et al. (2013). Further South, the data presented by Díaz et al. (2010), Miller et al. (2013) and Alpert et al. (2013) are discussed together taking into consideration recent results coming from teleseismic and Pn tomography, uplift rates or GPS measured relative displacements, which suggest that most of the observed anisotropy is probably due to mantle flow at different levels of the mantle. The arcuate variation of the FPDs following the Gibraltar Arc results from the mantle deflection around the fast velocity slab extending down to 600 km. Large delays are observed beneath the eastern Betics, in an area where tearing has been proposed and where Pn tomography shows the presence of hot materials, suggesting that uppermost mantle materials can contribute to the observed anisotropy. The small degree of anisotropy and the large number of observations without evidences of anisotropy beneath SW Iberia, the High Atlas and the northern rim of the West African Craton suggest the presence of vertical mantle flow associated to edge-driven convective cells triggered by large variations of the lithospheric thickness. It is important to note that many of the investigated stations show significant backazimuthal variations in the anisotropic parameters retrieved from single events. The analysis of those variations is beyond the objectives of this contribution, but previous work has shown that they can often be explained by the presence of multiple anisotropic layers, suggesting that lithospheric and asthenospheric contributions may coexist, at least beneath some regions.

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Figure Captions

Figure 1: Topographic/bathymetric map of the investigated area. Blue dots show the location of TopoIberia stations with previously published anisotropic parameters. Red dots are for TopoIberia stations contributing to this work. Yellow dots account for permanent broad-band stations here analyzed. Black dots show the positions of temporary networks deployed as part of the Comitac project (High Atlas and Anti-Atlas) as well as the OBS deployed in the Alboran Sea and Gulf of Cadiz. Black diamonds show the PICASSO project stations, analyzed in terms of anisotropy by Miller et al. 2013.

Figure 2: Example of the splitting parameters obtained using the SplitLab software. a) Example of a good quality non-null measurement at station E054, located in eastern Iberia. b) Example of a fair quality event at station E053, also located in easterm Iberia. c) Example of "null" measurement at station M211, located in the Anti-Atlas domain.

Figure 3: Anisotropic parameters retrieved from our dataset overprinting a simplified tectonic map of the region. The results are presented in the projected location of the piercing point at a depth of 200 km. Bars are oriented along the FPD and their length is proportional to the measured δt. Red bars are for "good" quality measurements while orange bars stand for "fair" results. Null measurements are represented by thin black lines oriented along the backazimuth.

Figure 4: Sketch of the different processes invoked to explain the observed anisotropic parameters. Red lines account for the mean FPDs presented in this study and in Diaz et al 2010. Blue lines show the FPDs calculated by Miller et al. 2013. Black lines are for the LPO direction derived from the Conrad and Behn (2010) global mantle flow model. a) Beneath central Iberia, the inferred FPD are in agreement with the proposed mantle flow, while they are not consistent with the APM in the no-net rotation and the fixed hotspot reference frames (Dark and light green arrows, respectively). b) The high velocity slab anomaly (blue shadowed area) imaged by seismic tomography beneath SW Iberia (Bezada et al. 2013) acts as a keel at upper mantle depths, deflecting the mantle flow around it (yellow arrows). c) Above 100 km the slab seems detached beneath the eastern Betics, allowing the presence of hot material at sublithospheric depths which can contribute to the total observed anisotropy. d) SW Iberia, the Morocco Meseta, western High Atlas and Anti-Atlas (brown contoured

areas) show small amount of anisotropy and large number of “nulls”. The color scale shows the percentage of nulls measurements for each station.

Figure 5: Cartoon depicting the main mantle flow pattern derived from the interpretation of our data. Green arrows account for the general direction of LPO deduced from the Conrad and Behn (2010) model. The blue body represents the fast velocity slab imaged by tomography, with dashed lines indicating 100 km depth intervals. Yellow arrows show the proposed mantle flow around the slab. Orange arrows represent the proposed small-scale vertical flow associated to changes in lithospheric thickness beneath SW Iberia and the western High Atlas and Anti-Atlas domains.

Supplemental Table Captions

Suppl. Figure 1: Extended regional view of the available FPD data. Red lines account for the mean FPDs presented in this study and in Diaz et al 2010. Blue lines show the previously published FPDs as compiled in the Géosciences Montpellier's SplitLab Shear-wave splitting database (Wüstefeld et al., 2009). Black lines are for the LPO direction derived from the Conrad and Behn (2010) global mantle flow model

Suppl. Table 1: Geographical coordinates, mean fast polarization direction (FPD), standard deviation FPD, mean δt, standard deviation δt , number of “null”, number of total valid observations and time period analyzed for each of the investigated stations

Suppl. Table 2: Individual FPD and δt determinations for the stations not previously investigated. Event identifier, station code, station longitude, station latitude, backazimuth, quality factor (g for good, f fo fair), FPD and δt derived from the rotation-correlation (RC) method, FPD and δt from the minimum energy method (ME) and preferred method.

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***Highlights (for review)**

Anisotropy beneath Iberia and N Morocco related to mantle flow in the asthenosphere.
FPDs consistent with global mantle flow models outside the Gibraltar Arc.
The fast velocity slab beneath the Gibraltar Arc deflects mantle flow around it.
Possible presence of edge-driven convective cells beneath the High Atlas and SW Portugal.

Figure 1
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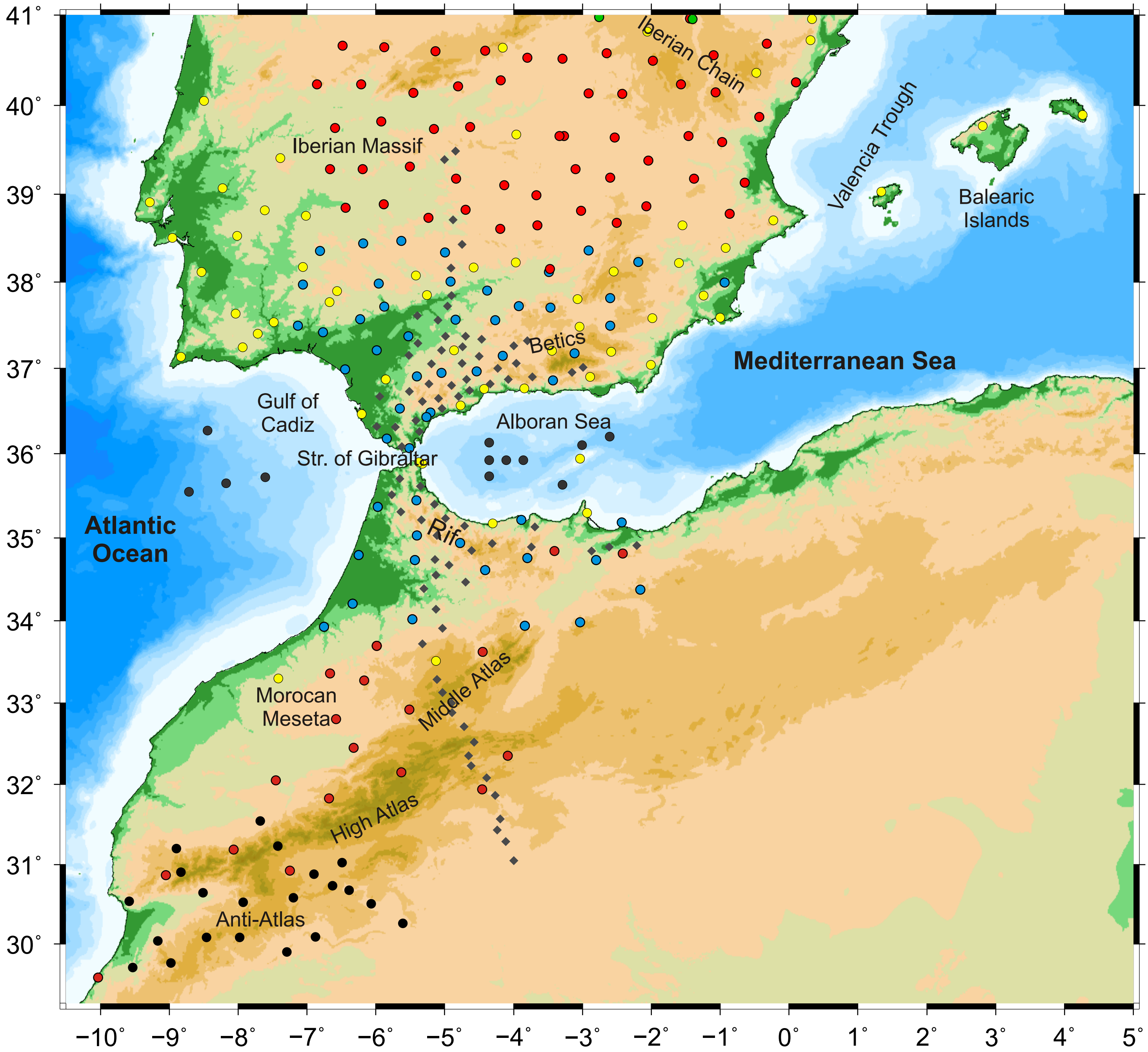

Figure 1

Figure 2

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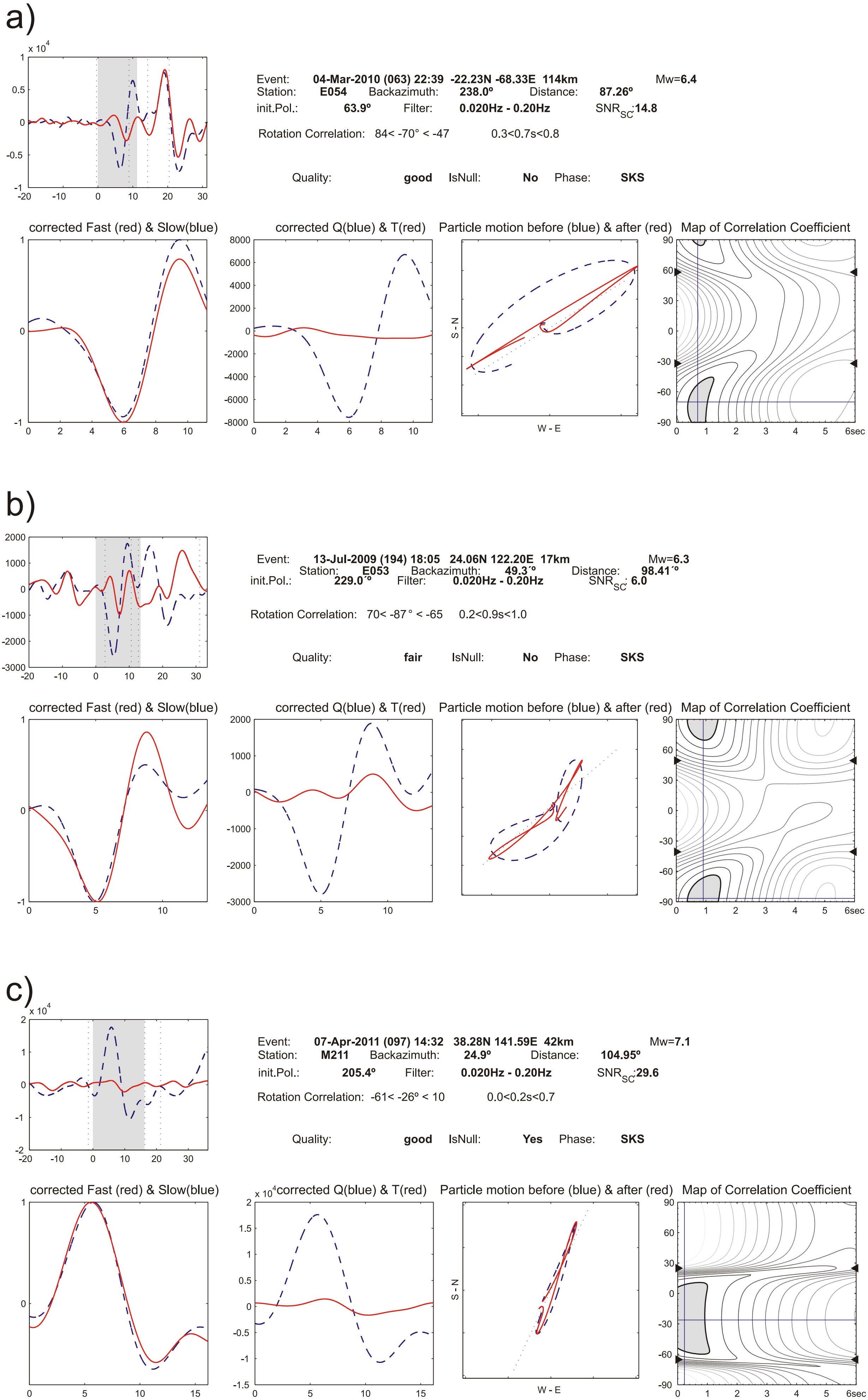

Figure 2

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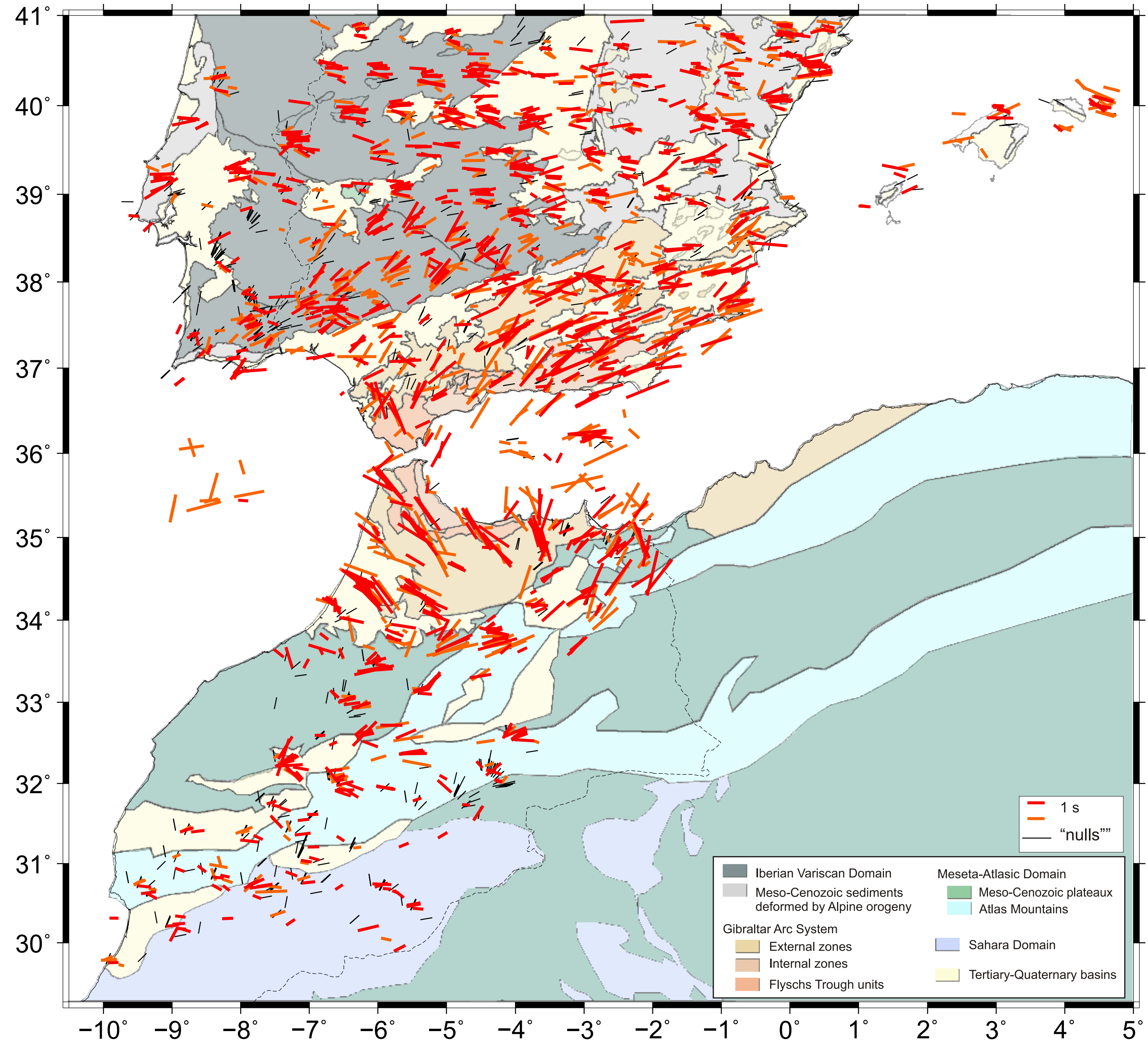

Figure 3

Figure 4

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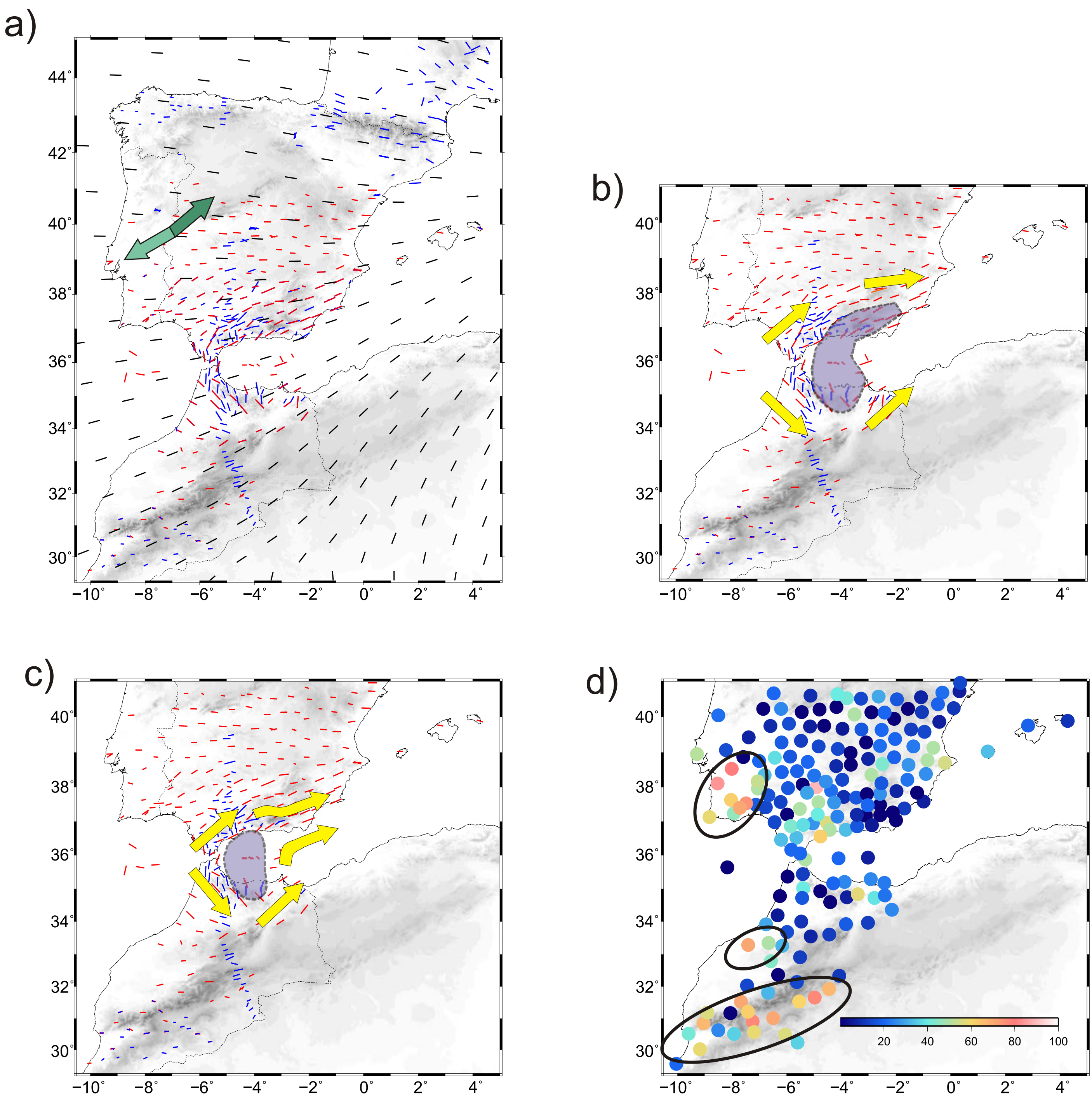

Figure 4

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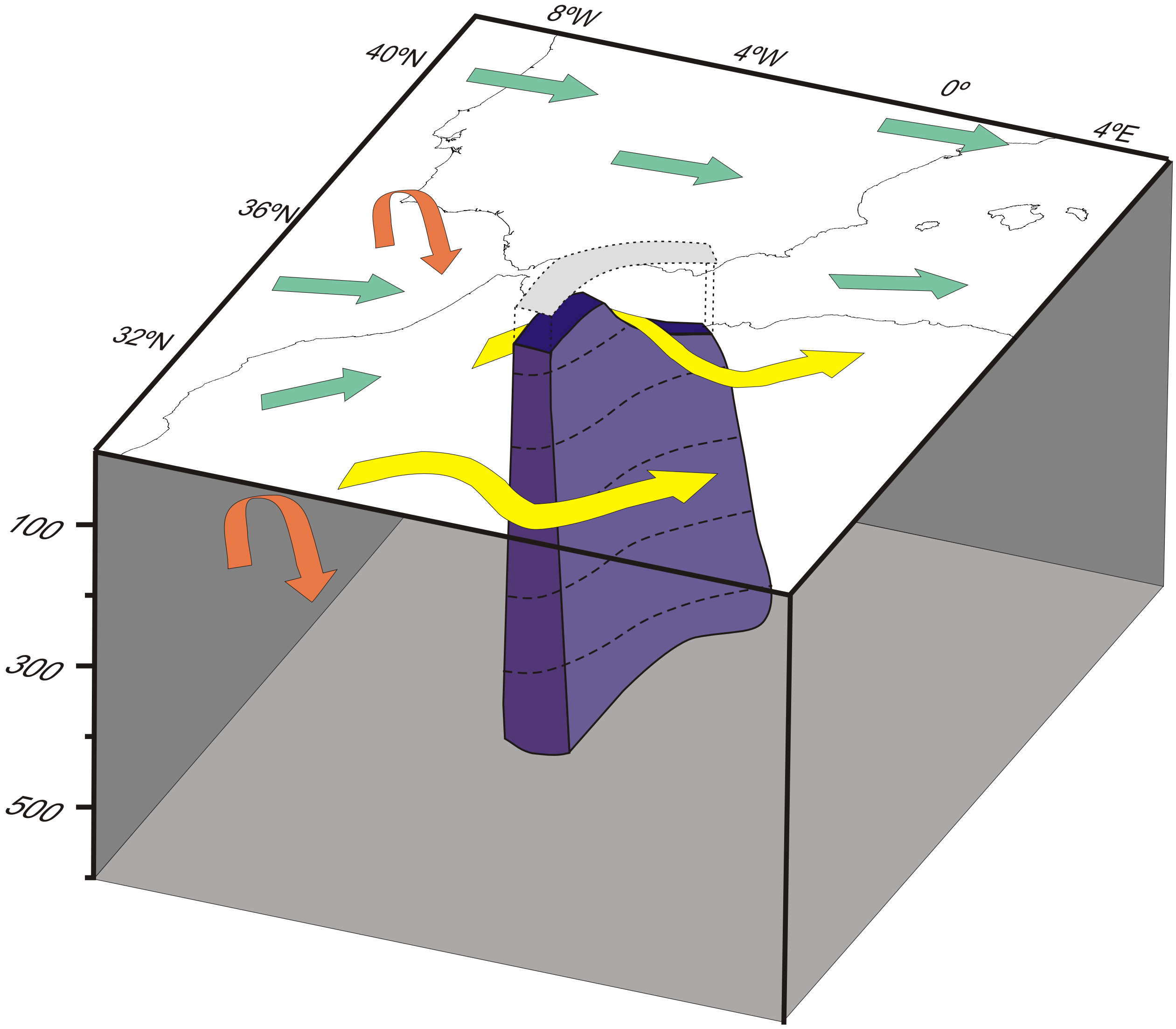

Figure 5