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From the Bay of Biscay to the High Atlas: Completing the anisotropic characterization of the upper mantle beneath the westernmost Mediterranean region

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ABSTRACT

The knowledge of the anisotropic properties beneath the Iberian Peninsula and Northern Morocco has been dramatically improved since late 2007 with the analysis of the data provided by the dense TopoIberia broad-band seismic network, the increasing number of permanent stations operating in Morocco, Portugal and Spain, and the contribution of smaller scale/higher resolution experiments. Results from the two first TopoIberia deployments have evidenced a spectacular rotation of the fast polarization direction (FPD) along the Gibraltar Arc, interpreted as an evidence of mantle flow deflected around the high velocity slab beneath the Alboran Sea, and a rather uniform N100°E FPD beneath the central Iberian Variscan Massif, consistent with global mantle flow models taking into account contributions of surface plate motion, density variations and net lithosphere rotation. The results from the last Iberarray deployment presented here, covering the northern part of the Iberian Peninsula, also show a rather uniform FPD orientation close to N100°E, thus confirming the previous interpretation globally relating the anisotropic parameters to the LPO of mantle minerals generated by mantle flow at asthenospheric depths. However, the degree of anisotropy varies significantly, from delay time values of around 0.5 s beneath NW Iberia to values reaching 2.0 s in its NE corner. The anisotropic parameters retrieved from single events providing high quality data also show significant differences for stations located in the Variscan units of NW Iberia, suggesting that the region includes multiple anisotropic layers or complex anisotropy systems. These results allow to complete the map of the anisotropic properties of the westernmost Mediterranean region, which can now be considered as one of best constrained regions worldwide, with more than 300 sites investigated over an area extending from the Bay of Biscay to the Sahara platform.

1. Introduction

The investigation on the anisotropic properties of the uppermost mantle is one of the best approaches to better understand the geodynamic processes affecting this depth range. 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) developed in response to tectonic flow. Even if the relationship between deformation and anisotropy properties is not straightforward, in tectonically active areas (mid-ocean ridges, rifts, subduction zones) fast polarization directions (FPDs) are expected to mark the direction of mantle flow, while in zones without present-day large-scale tectonic activity, FPD can be related to the strain from the last significant tectonic episode preserved in the subcrustal lithosphere, to dynamic flow in the asthenosphere or to the combined effect of both mechanisms (Savage, 1999; Silver, 1996; Vauchez et al., 2012).

Uppermost mantle anisotropy can be explored using different seismic methodologies, including surface wave scattering, Pn tomography, P wave travel-time azimuthal variation and shear-wave splitting, the latter being widely accepted as the most fructiferous approach. When traveling across an anisotropic medium, a shear wave will split in two waves orthogonally polarized and traveling with different velocities, which will arrive to the seismic station separated by a certain time delay. As this delay is smaller than the period of the teleseismic shear-waves, the polarization of these waves is not linear but shows a characteristic ellipticity. SKS waves, which travel as compressional waves through the external core and are converted again to shear waves in the core mantle boundary (CMB) grossly beneath the station

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are widely used to investigate anisotropy, as their waypaths assure that any anisotropic effect detected must be generated near vertically beneath the receiver station, hence providing a good lateral resolution. On the contrary, the method does not provide direct constrains on the vertical position of the anisotropic zone. During the last decades a large amount of contributions have analyzed SKS splitting in many tectonic settings, from the oldest cratons to active subduction zones (e.g., Long, 2013; Vinnik et al., 2012). As SKS waves have typical periods of 5–10 s, they lay in the middle of the microseismic peak, the zone of the seismic spectra with the largest background noise, mostly related to the interaction of oceanic waves. This makes difficult to get clear SKS arrivals, even for large magnitude events. Additionally, SKS waves need to be isolated from other phases traveling with similar apparent velocities, thus limiting the distance range of useful events to 85°–120°. The first contributions in the 1980s and 1990s (Silver and Chan, 1988; Vinnik et al., 1989) were based in the data from the scarce number of permanent broad band stations deployed worldwide. With the availability of an increasing number of portable broad-band seismometers, experiments focused on anisotropy started to be carried out at local scale using dense deployments recording data during weeks to months. Those studies have been typically focused in relatively small areas or devoted to study larger regions by means of high density linear profiles crossing their main structures. The EarthScope project, started in 2005 in the United States, marked the beginning of a new era in seismic exploration, as it involved the deployment of an homogeneous network of broad-band stations covering the contiguous USA with a regular grid of about 70 km × 70 km. Regarding anisotropic studies, the EarthScope project allowed to obtain very detailed results, including, for example, the observation of toroidal flow around the Juan de Fuca plate (Zandt and Humphreys, 2008). The Iberarray seismic network, integrated in the large-scale TopoIberia project (Díaz et al., 2009), has allowed deploying a similar network in Iberia and northern Morocco. Using more than 70 broad-band instruments and three different deployments, and integrating the permanent stations in the area, the experiment provided a final database holding more than 300 sites, forming a 60 km × 60 km grid and covering a region of approximately 600.000 km^2. Therefore, the TopoIberia network is one of the first examples of high density regional scale seismic experiment providing information on large scale regions with unprecedented detail.

The anisotropic analysis of the first TopoIberia deployments, covering North Morocco and the Southern and central part of the Iberian Peninsula, have already been published by Díaz et al. (2010) and Diaz and Gallart (2014). The objective of this contribution is twofold; firstly, we will present the anisotropic results derived from the data recorded during the last TopoIberia deployment, covering the northern part of Iberia, from the Mediterranean Sea to the Atlantic passive margin (Fig. 1). Secondly, the results from the three deployments will be summarized in order to get, for the first time, a comprehensive image of the anisotropic properties of the westernmost Mediterranean region. In order to complete this image, we present also the anisotropic parameters derived from the analysis of broadband seismic stations in Portugal, including permanent sites and the stations deployed in the framework of the WILAS project, an independent experiment designed to complete the Iberia coverage provided by TopoIberia (see Custodio et al., 2014 for details). The retrieval of the anisotropic properties of this large area allows to further constraining the geodynamic interpretation of the region.

2. Tectonic setting of northern Iberia

The northern part of the Iberian Peninsula has been affected by two large compressional episodes, the Variscan and Alpine orogenies, separated by a period of significant extensional deformation in the Mesozoic.

The Variscan orogeny started with the closure of the Rheic Ocean and the collision between Laurentia-Baltica-Avalonia and the continental margin of Gondwana during the Carboniferous, giving rise to the building of the Pangea supercontinent (Matte, 1991). The western part of northern Iberia is represented by the Variscan Iberian Massif, one of the best-exposed sections of the Variscan belt in Europe, formed mainly by granitoids and metasediments of Precambrian/Paleozoic ages that remained tectonically stable (although locally affected by the western termination of the Alpine orogeny) for the last 300 Ma (Gibbons and Moreno, 2002). The geological trends of the Variscan orogen in North-Iberia show an overall E-verging structure, later complicated by the development of the Ibero-Armorican Arc (or Cantabrian Orocline) in the latest Carboniferous (Gutiérrez Alonso et al., 2012). This massif shows a well-established zonation, based on structural, metamorphic and paleogeographic differences (Farias et al., 1987; Julivert et al., 1972). The Cantabrian Zone is the most external unit and represents the thin-skinned foreland fold-and-thrust belt (Pérez-Estaún et al., 1988, 1994). To the west, the transition to the hinterland zones is represented by the West Asturian-Leonese Zone (WALZ), with westward-increasing metamorphism and internal deformation (Martínez Catalán et al., 1990). Finally, the most internal part of the orogen is located in the western end of northern Iberia and is divided into the Central Iberian Zone (CIZ) and the Galicia-Tras-os-

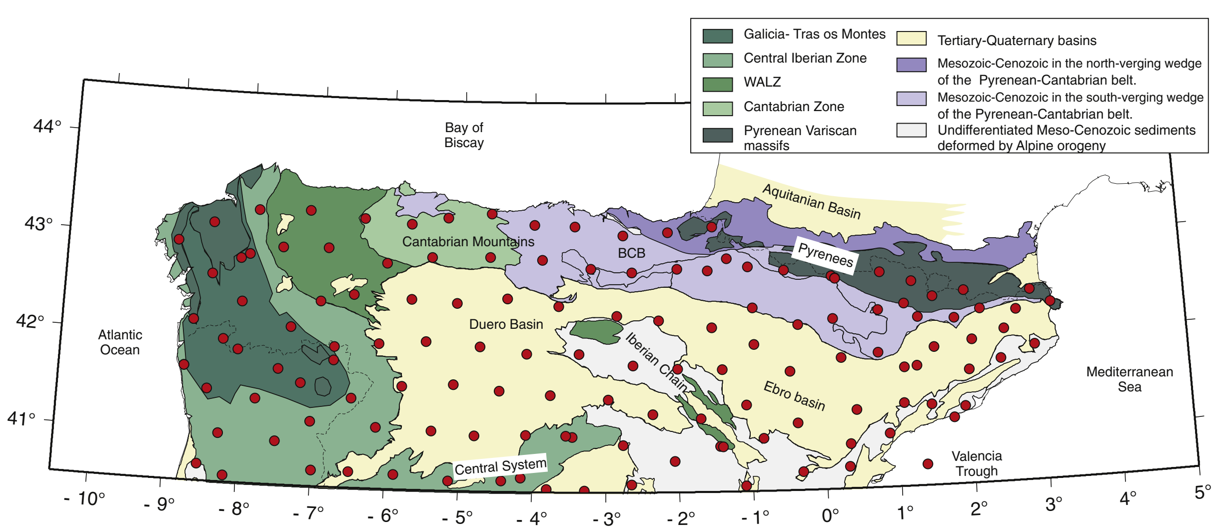

Fig. 1. Simplified geological map of north Iberia showing the locations of the investigated stations, including TopoIberia and WILAS deployments and permanent sites.