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Insights into the lithospheric architecture of Iberia and Morocco from teleseismic body-wave attenuation

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ABSTRACT

The long and often complicated tectonic history of continental lithosphere results in lateral strength heterogeneities which in turn affect the style and localization of deformation. In this study, we produce a model for the attenuation structure of Iberia and northern Morocco using a waveform-matching approach on P-wave data from teleseismic deep-focus earthquakes. We find that attenuation is correlated with zones of intraplate deformation and seismicity, but do not find a consistent relationship between attenuation and recent volcanism. The main features of our model are low to moderate Δt^* in the undeformed Tertiary basins of Spain and high Δt^* in areas deformed by the Alpine orogeny. Additionally, low Δt^* is found in areas where the Alboran slab is thought to be attached to the Iberian and African lithosphere, and high Δt^* where it has detached. These features are robust with respect to inversion parameters, and are consistent with independent data. Very mild backazimuthal dependence of the measurements and comparison with previous results suggest that the source of the attenuation is sub-crustal. In line with other recent studies, the range of Δt^* we observe is much larger than can be expected from lithospheric thickness or temperature variations.

1. Introduction

An accumulated history of magmatism, faulting, and metasomatism creates continental lithosphere of heterogeneous and evolving strength. This strength heterogeneity, in turn, influences the location and style of deformation in response to tectonic stresses; both at geologic time scales through mountain building and rifting, and at human time scales through seismicity. The geology of Iberia and Morocco records several cycles of shortening and extension in the last 300 Ma, providing an environment in which the effect of evolving strength heterogeneities on deformation can be studied.

Seismic methods provide a means to image the regional scale structure and infer strength variations associated with the irregularly distributed deformation of the latest (and ongoing) phase of contraction. Coordinated deployments of large, temporary seismograph networks in Spain and Morocco over the last decade provide abundant, high-quality data for such investigations. In this study we focus on seismic attenuation, which provides information on the architecture of the lithosphere, and the processes controlling its strength, that is independent from that gained from seismic velocity and anisotropy. We use a time-domain waveform-matching method of analysis on teleseismic deep-focus earthquakes. Attenuation structure is found to be closely related to tectonic features, and is consistent with independent observations from a local deep-focus event. Our results are discussed in terms of their relationship to tectonic deformation, seismicity, volcanism, and lithospheric delamination.

2. Tectonic background

The rugged physiography of the Iberian Peninsula and northern Morocco is primarily the product of the Late Paleozoic Variscan and Late Cretaceous Alpine orogenies (e.g., de Vicente and Vegas, 2009; Rosenbaum et al., 2002). Consequently, Iberian geology is often divided into a western Variscan domain and an eastern Alpine domain (e.g., Gibbons and Moreno, 2002), although some Spanish Variscan structures were reactivated during the Alpine orogeny. While this division is not as commonly used to describe Moroccan geology, we adopt it here to highlight the similarities of tectonic structures north and south of the western Mediterranean (Fig. 1).

The Variscan orogeny resulted from Gondwana–Laurasia collision during the assembly of Pangea (Matte, 1986, 2001), and is comprised of several distinct zones with characteristic deformation styles and tectonic origin (Fig. 1). The highly arcuate boundaries between these zones are a result of oroclinal bending during late-

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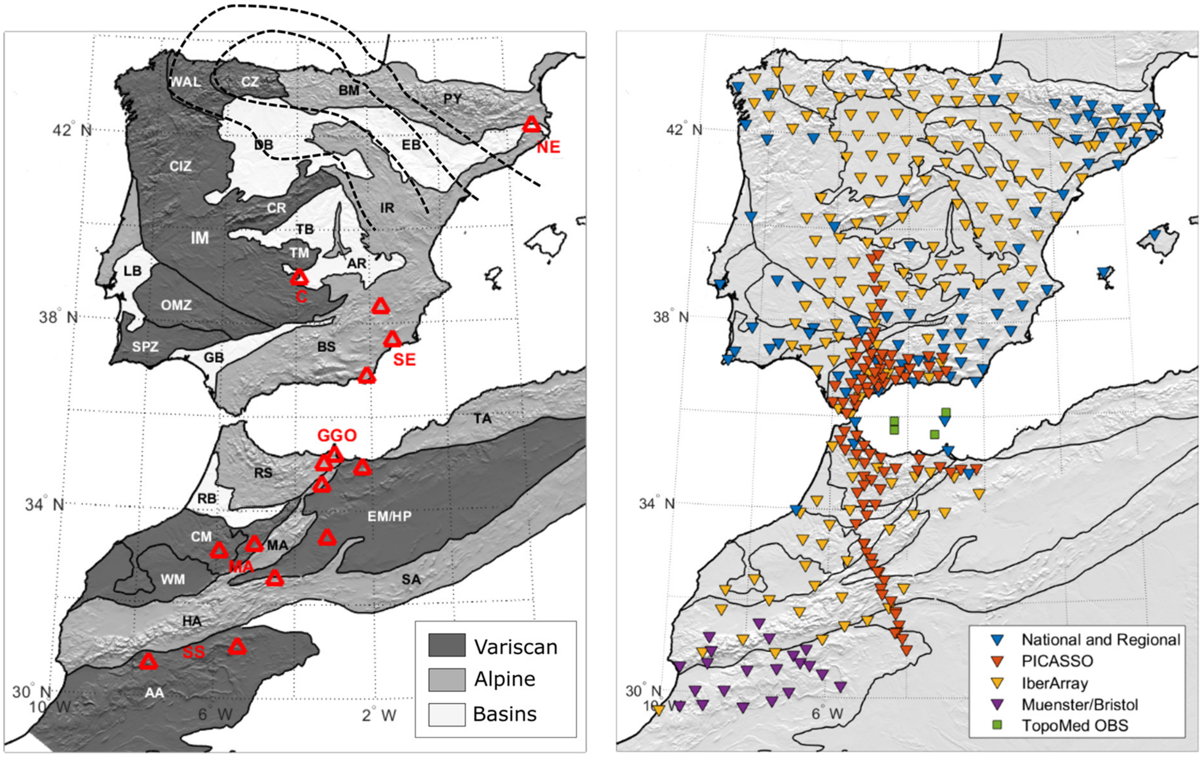

Fig. 1. Left: Simplified map of tectonic provinces in Iberia and Morocco, after Piqué and Michard (1989), Michard et al. (2008), and Vergés and Fernàndez (2006). PY – Eastern and Central Pyrenees; BM – Basque Mountains; CZ – Cantabrian Zone; WAL – Western Asturian–Leonese zone; CIZ – Central Iberian Zone; IM – Iberian Massif; CR – Central Ranges; TM – Toledo Mountains; LB – Lower Tajo Basin; OMZ – Osa Morena Zone; SPZ – South Portuguese Zone; GB – Guadalquivir Basin; DB – Duero Basin; TB – Tajo Basin; AR – Altomira Range; BS – Betics System; IR – Iberian Ranges; EB – Ebro Basin; RS – Rif System; RB – Rharb (Gharb) Basin; TA – Tell Atlas; EM/HP – Eastern Meseta/High Plateau; MA – Middle Atlas; HA – High Atlas; SA – Saharan Atlas; CM – Central Massif; WM – Western Meseta; AA – Anti Atlas. Volcanic features are indicated by red open triangles. NE – Northeast Volcanic Province; C – Calatrava Volcanic Province; SE – Southeast Volcanic Province; GGO – Guilliz–Gourougou–Oujda Volcanic Province; MA – Middle Atlas Volcanic Province; SS – Siroua–Sahro volcanic Province. Right: Location of the seismic stations used in this study. Stations are color-coded according to their network affiliation, as indicated in the figure. Outlines of tectonic provinces as in the left panel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

stage collision (Ibero-Armorican Arc, Gutiérrez-Alonso et al., 2012; Pérez-Estaún et al., 1988; Weil et al., 2010), and may extend further east in the subsurface (Martínez Catalán et al., 2007). In Morocco, the Variscan orogeny emplaced the exotic terranes of the Eastern and Western Mesetas (Hoepffner et al., 2005).

The Mesozoic breakup of Pangea and opening of the neo-Tethys and Atlantic oceans created rift basins around and within Iberia (Salas and Casas, 1993; Vergés and Fernàndez, 2006), as well as in Morocco (e.g., Laville et al., 2004). Starting in the Late Cretaceous, the compressive Alpine orogeny began as Africa and Europe converged slowly, with Iberia caught in the middle (Dewey et al., 1989; Rosenbaum et al., 2002). Northward motion of Iberia resulted in Iberian accretion to Europe, uplift of the Pyrenees Mountains, and inversion of the Mesozoic rifts. The NW–SE trending Iberian Range, is an example of rift inversion (Guimerà et al., 2004; van Wees and Stephenson, 1995), while Variscan structures farther west were also reactivated producing the NE–SW trending Central Ranges and the Toledo Mountains (de Bruijne and Andriessen, 2002; de Vicente and Vegas, 2009). As in Spain, Mesozoic rifts were inverted in Morocco during the Alpine Orogeny, forming the High and Middle Atlas Mountains (Frizon de Lamotte et al., 2008, and references therein; Teixell et al., 2003).

In southern Spain and northern Morocco, the Alpine orogeny is represented by the Betic and Rif uplifts respectively. These mountain belts record the interaction of southern Iberia and northwestern Africa with subduction and rollback of the intervening lithosphere (Bezada et al., 2013; Bonnin et al., 2014; Lonergan and White, 1997; Royden, 1993; Spakman and Wortel, 2004; Villaseñor et al., 2015). The retreating slab seems to have partially removed some of the sub-continental mantle lithosphere beneath the margins, particularly in southern Spain, and this appears to be an ongoing process (Levander et al., 2014; Mancilla et al., 2013; Palomeras et al., 2014; Thurner et al., 2014).

In addition to the Variscan and Alpine deformed structures, the third major component of the Iberian microplate is a series of relatively undeformed Tertiary basins. The Ebro Basin represents the southern foreland basin of the Pyrenees. The Duero Basin in northern Spain is a broad and high plateau surrounded by Alpine mountain ranges. South of the Duero, the Tajo Basin is also bound by Alpine compressional structures. Unlike the Ebro or the Duero basins, Alpine compressional structures (Altomira Range) actually occur within the Tajo Basin (Fig. 1).

Limited Cenozoic volcanism occurred both in Spain and northern Morocco (Fig. 1). In Spain, there are three main volcanic fields: The Northeast Volcanic Province and the Calatrava Volcanic Province (the latter in central Spain) are comprised of alkaline basalts (Cebriá et al., 2000; e.g. Cebriá and López-Ruiz, 1995), whereas the Southeast Volcanic Province displays more diverse petrology that exhibits the signature of subduction (Duggen et al., 2005). In Morocco, Spain's Southeast Volcanic Province is mirrored by the Guelliz–Gourougou–Oujda volcanic field (Duggen et al., 2005), while alkaline basalt volcanism with an intraplate affinity occurred in the Middle Atlas and the Siroua and Sahro Volcanic fields at the northern edge of the Anti-Atlas (Duggen et al., 2009; Lustrino and Wilson, 2007).

3. Data and method

The most widely used approach for estimating body wave attenuation is the spectral ratio method (Teng, 1968), in which the