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Imaging Canary Island hotspot material beneath the lithosphere of Morocco and southern Spain

Meghan S. Miller [a,*], Leland J. O'Driscoll [a], Amber J. Butcher [a,1], Christine Thomas [b]

[a] University of Southern California, Department of Earth Sciences, Los Angeles, CA 90089, USA
[b] Institute of Geophysics, Westfalische Wilhelms-Universitat Münster, Correnssstraße 24, D-48149 Münster, Germany

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ABSTRACT

The westernmost Mediterranean has developed into its present day tectonic configuration as a result of complex interactions between late stage subduction of the Neo-Tethys Ocean, continental collision of Africa and Eurasia, and the Canary Island mantle plume. This study utilizes S receiver functions (SRFs) from over 360 broadband seismic stations to seismically image the lithosphere and uppermost mantle from southern Spain through Morocco and the Canary Islands. The lithospheric thickness ranges from ∼65 km beneath the Atlas Mountains and the active volcanic islands to over ∼210 km beneath the cratonic lithosphere in southern Morocco. The common conversion point (CCP) volume of the SRFs indicates that thinned lithosphere extends from beneath the Canary Islands offshore southwestern Morocco, to beneath the continental lithosphere of the Atlas Mountains, and then thickens abruptly at the West African craton. Beneath thin lithosphere between the Canary hot spot and southern Spain, including below the Atlas Mountains and the Alboran Sea, there are distinct pockets of low velocity material, as inferred from high amplitude positive, sub-lithospheric conversions in the SRFs. These regions of low seismic velocity at the base of the lithosphere extend beneath the areas of Pliocene–Quaternary magmatism, which has been linked to a Canary hotspot source via geochemical signatures. However, we find that this volume of low velocity material is discontinuous along strike and occurs only in areas of recent volcanism and where asthenospheric mantle flow is identified with shear wave splitting analyses. We propose that the low velocity structure beneath the lithosphere is material flowing sub-horizontally northeastwards beneath Morocco from the tilted Canary Island plume, and the small, localized volcanoes are the result of small-scale upwellings from this material.

1. Introduction

The tectonics of Northwest Africa have largely been dominated by late stage convergence of Africa with Eurasia during the Cenozoic. The last piece of Mesozoic oceanic lithosphere from the Tethys Ocean is being consumed across the Mediterranean, forming a series of arcuate shaped subduction zones (Royden, 1993; Rosenbaum et al., 2002; Faccenna et al., 2004; Govers and Wortel, 2005). The tightly curved Gibraltar arc is one of these fragments, occupying the westernmost Mediterranean, bounded by the Rif Mountains along the southern cusp and the Betic Mountains along the northern cusp. These interior units of the Gibraltar arc are part of a larger domain where the plate boundary between Africa and Iberia is distributed as a wide zone of deformation (e.g. Koulali et al., 2011). This arcuate region of rapidly uplifting topography in the Rif and Betics has fueled competing hypotheses of lithospheric-scale modification: mechanical delamination associated with adjacent slab rollback or convective-removal due to density contrasts induced by thickening or a combination of both mechanisms (e.g. Duggen et al., 2005; Platt et al., 2013; Levander et al., 2014), but all are based upon the premise that the tectonics are controlled by the collision of Africa with Eurasia.

The lithosphere of northern and central Morocco is actively deforming over a 300–400 km wide belt that is bounded to the north by the Rif Mountains. The southern extent of the deformation zone is the High Atlas Mountains, a NE trending intercontinental mountain belt that formed by reactivation of Triassic–Jurassic aged rift structures that were inverted during the Cenozoic convergence of Africa with Eurasia (e.g. Brede et al., 1992; Gomez et al., 2000; Pique et al., 2002; Arboleya et al., 2004; Missenard et al., 2006). The high elevations of the Atlas are superimposed on a broad topographic swell that consists of the west

* Corresponding author.
E-mail address: msmiller@usc.edu (M.S. Miller).
1 Present address: California State Polytechnic University, Department of Geological Sciences, Pomona, CA 91768, USA.

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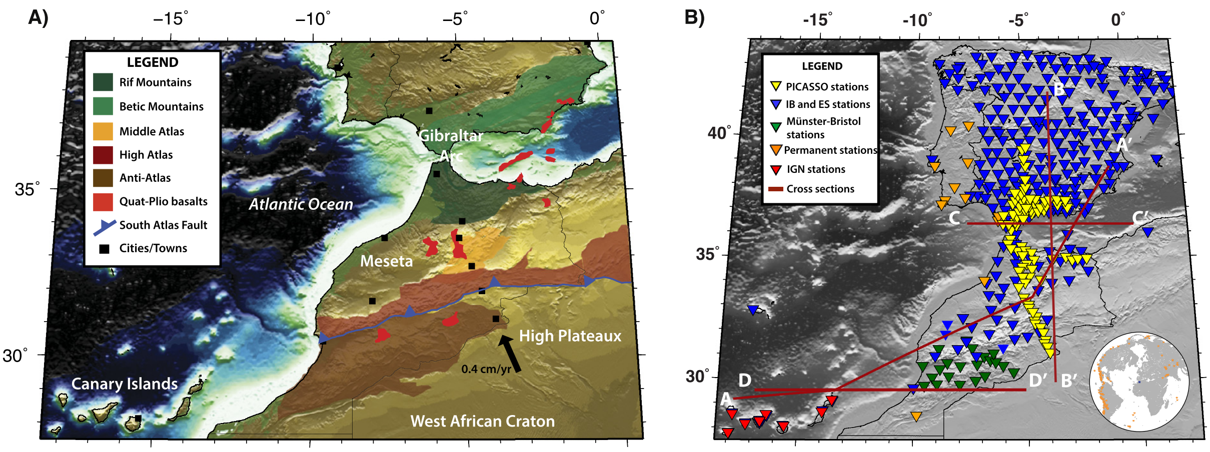

Fig. 1. A) Generalized map of the study region with plate convergence from Rosenbaum et al. (2002) shown with a black vector, and the political boundaries are indicated with thin black lines. B) Map of the broadband stations distribution, where the yellow triangles are the PICASSO stations, the blue triangles are IberArray stations, and the green triangles are from the Bristol–Münster array. The locations of the cross-sections and fence diagrams for Figs. 3–6 are shown with dark red lines. The globe inset shows the 180 earthquakes (in orange) used in the analysis.

Moroccan Meseta, the eastern High Plateau, and the Anti-Atlas Mountains in the southwest – none of which have undergone recent significant deformation (Fig. 1A).

Much of the knowledge of crustal and lithospheric structure of northwestern Africa, until recently, had been obtained by geophysical modeling based on gravity, heat flow measurements, and seismic refraction experiments (Teixell et al., 2003, 2005; Ayarza et al., 2005, 2014; Zeyen et al., 2005; Missenard et al., 2006; Fullea et al., 2010; Jimenez-Munt et al., 2011). These studies found a large range in lithospheric thicknesses across Morocco, with the thickest regions beneath the West African craton at ∼180 km and thinnest lithosphere beneath the Atlas Mountains (∼65 km). P-wave and surface wave tomography studies have also shown a thin lithosphere and a shallow low velocity zone beneath the Atlas (Seber et al., 1996; Calvert et al., 2000; Bezada et al., 2014; Bonnin et al., 2014; Levander et al., 2014; Palomeras et al., 2014). Recent regional receiver function studies have also found that the lithosphere is thin beneath the westernmost Atlas and Anti-Atlas (Spieker et al., 2014), the central Atlas (Miller and Becker, 2014), and the eastern Rif (Dündar et al., 2011; Mancilla et al., 2012; Thurner et al., 2014).

An intriguing linear trend through northern Morocco towards southeastern Spain hosts Pliocene to Quaternary volcanism (see red polygons, Fig. 1A) (Hoernle et al., 1995; Duggen et al., 2004, 2009 and references therein). This post-collisional magmatism in the region can generally be categorized into two groups: (1) alkali basalts that have geochemical similarities to intra-plate volcanics – possibly associated with plume-contaminated sub-lithospheric mantle, and (2) calc-alkaline, near the Mediterranean coast in both the Rif and the Betics that are linked to subduction beneath the Alboran (e.g. Duggen et al., 2005; Bosch et al., 2014). This unusual linear trend of anorogenic Cenozoic magmatism, along with the thinned lithosphere beneath Morocco and uplifted topography, has been described by Frizon de Lamotte et al. (2009) as the “Moroccan Hot Line”. The thinning of the lithosphere and correlation with Cenozoic volcanism is suggested to be attributed to edge-driven convection (Ramdani, 1998; Missenard and Cadoux, 2012; Kaislaniemi and van Hunen, 2014), delamination of the root of the Atlas Mountains (Ramdani, 1998; Bezada et al., 2014; Levander et al., 2014), or linked to the Canary Island hotspot (Hoernle et al., 1995; Oyarzun et al., 1997; Anguita and Hernan, 2000; Zeyen et al., 2005; Duggen et al., 2009; Miller and Becker, 2014; Mériaux et al., 2015).

The Canary Islands are an intra-plate island chain that is located ∼100 km off the Atlantic coast of Morocco that are built upon Jurassic-age oceanic lithosphere (Fig. 1A). The seven major islands are part of a ∼600 km long chain of volcanoes that have been active since the early Miocene (Schmincke, 1982). The age of the volcanoes decrease from east to west, which has been interpreted as being from a hot spot origin (e.g. Morgan, 1972). The Canary Islands have been extensively studied yet the crustal, lithospheric, and uppermost mantle structure is still debated. However, recent seismic studies are consistent with a deep mantle source, revealing a thin crust, a low velocity layer just beneath the lithosphere (e.g. van der Meijde et al., 2003; Lodge et al., 2012; Martinez-Arevalo et al., 2013; Bonnin et al., 2014), and a depressed 410 km discontinuity (Saki et al., 2015).

Here, we present seismological evidence from S receiver functions (SRFs) to show that thinned continental lithosphere extends across the inferred “Moroccan Hot Line” beneath the Atlas Mountains. Along this corridor a large volume of low seismic velocity material has pooled beneath the lithosphere, as inferred from high amplitude positive, sub-lithospheric conversions that extend from the Atlas, across the Alboran and into the southern Iberia Peninsula. This low velocity feature is coincident with the areas of Pliocene–Quaternary magmatism, which are consistent with a Canary hotspot source, not as a clearly defined sub-horizontal, sub-lithospheric channel, but as a discontinuous structure along strike of low velocity material that is inferred to be hot and perhaps melt bearing.

2. Data and methods

Data were collected at 360 broadband stations deployed in the westernmost Mediterranean and the Canary Islands between 2007 and May 2013. The 102 XB network stations (in yellow triangles in Fig. 1B) were part of the NSF-funded PICASSO experiment that extended between central Morocco and central Spain. The twenty-one 3D and ZI network stations (in green in Fig. 1B) were deployed by the University of Münster and the University of Bristol, respectively (Spieker et al., 2014). One hundred thirty-four stations (shown in blue in Fig. 1B) were part of the TopoIberia–Iberarray experiment that extends across the Iberian Peninsula to southern Morocco. The rest are a combination of permanent stations, including the extensive ES network, and deployments with broadband data available from the IRIS DMC.

Over 160 Mw 6.0+ earthquakes between 55–85 degrees away from the broadband stations were analyzed to produce ∼5300 individual S receiver functions (Fig. 1B inset). The data for these final ∼5300 SRFs were selected by first hand-editing the seismograms