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# The Canary Islands hot spot: New insights from 3D coupled geophysical–petrological modelling of the lithosphere and uppermost mantle

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ABSTRACT

The Canary archipelago (NW Atlantic African margin) is one of the best studied volcanic chains in the world yet its structure and geodynamic evolution are still under considerable debate. Oceanic island volcanoes typically form over hot spots due to upwelling of plume material followed by decompression melting and melt migration up to the surface. Here, the 3D lithospheric-uppermost mantle thermochemical structure beneath the Canary Islands is studied using an integrated and self-consistent geophysical–petrological approach exploiting the wealth of available data after decades of geophysical and petrological studies plus recent satellite data. A precise knowledge of the present-day thermal and compositional mantle structure beneath the Canary Islands is a key element to understand the geodynamic evolution of the area and, on a global scale, the thermal state of the Earth's mantle beneath hot spots. Our results suggest a likely chemically depleted and mechanically strong lithosphere showing no significant thinning with respect to the surrounding oceanic and continental domains ($110 \pm 20$ km thick). Models without a positive temperature anomaly in the sub-lithosphere (characterized by mantle $T_{\mathrm{pot}} = 1335\,^{\circ}\mathrm{C}$) fail to reproduce the observed sub-lithospheric seismic anomaly over the Canary Islands. A thermal sub-lithospheric anomaly of $+100\,^{\circ}\mathrm{C}$ (mantle potential temperature of $1435\,^{\circ}\mathrm{C}$) with respect to ambient mantle beneath the Canaries is able to explain both observed seismic tomography anomalies and measured geophysical and geodetic data. Such a sub-lithospheric thermal anomaly requires a dynamic contribution of 150–400 m to the static topography to match the present-day observed elevation in the Canary Islands and associated swell.

## 1. Introduction

Oceanic hot spots are generally related to deep thermal anomalies of $+(100\text{–}300)\,^{\circ}\mathrm{C}$ with respect to ambient mantle temperatures regardless of possible additional bulk chemical changes or volatile enrichment (e.g., Herzberg and Asimow, 2008; White, 2010). Oceanic island volcanoes typically form over hot spots due to upwelling of plume material followed by decompression melting and melt migration up to the surface. The Canary Islands (NW Atlantic African margin) are one of the best studied volcanic chains in the world yet some aspects of its structure and geodynamic evolution are still controversial (e.g., Anguita and Hernán, 2000). The Canary archipelago shows some specific characteristics with respect to other mid oceanic volcanic chains classically explained by the mantle plume hypothesis (e.g., Hawaii): (i) lack of a prominent bathymetric swell (e.g., Watts, 1994); (ii) long term and irregular volcanic evolution of >20 Ma and, perhaps 70–80 Ma in Fuerteventura (Le Bas et al., 1986); (iii) low melt production rates (Hoernle and Schmincke, 1993) and multiple cycles of volcanic activity. Alternative hypotheses on the origin of the Canary Islands excluding a mantle plume (see Anguita and Hernán, 2000 for an overview and references) are a propagating fracture connecting the archipelago and African Atlas Mountains, compression-related tectonic uplift, and local rifting in the Islands. Interaction between a plume and small-scale edge driven convection has also been suggested (e.g., Geldmacher et al., 2005). Most of the proposed geodynamic scenarios integrate as a key element the existence of a deep thermal sub-lithospheric anomaly (i.e., mantle plume/broad thermal anomaly) and its interaction with old and slowly moving Jurassic oceanic lithosphere close to the north Atlantic African passive margin. In this work we analyze the lithospheric-uppermost mantle thermochemical structure beneath the Canary Islands using

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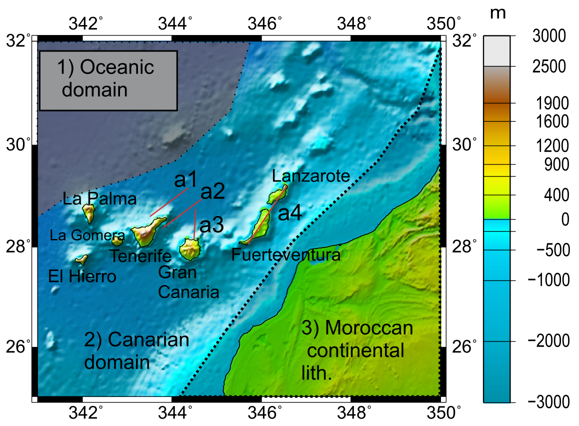

**Fig. 1.** Elevation map (Smith and Sandwell, 1994; Smith and Sandwell, 1997) of the study area. Red lines show the location of published seismic lines used to constrain the crustal structure (see Appendix A). a1 and a2: CD82-P11 and CD82-P12 respectively (Watts et al., 1997; Dañobeitia and Canales, 2000). a3: M24-P1 (Ye et al., 1999). a4: Banda et al. (1981); Dañobeitia and Canales (2000). Lithospheric mantle compositional domains (black dotted lines) based on crustal tectonics, and petrological and geophysical considerations are shown (see text for further details). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

an integrated geophysical–petrological approach, "LitMod" (Afonso et al., 2008; Fullea et al., 2009), able to reduce the uncertainties associated with the modelling of different data sets separately, avoid inconsistencies, and exploit the different sensitivities of geophysical observables. The wealth of available data after decades of geophysical and petrological studies (gravity and geoid anomalies, elevation, seismic and mantle xenoliths) is exploited here, along with recently released satellite data (GOCE gravity gradients), to constrain the present-day thermal and compositional 3D structure of the lithosphere/uppermost mantle beneath the Canary Islands as a fundamental element to understand its geodynamic evolution and, on a global scale, the thermal state of the Earth's mantle beneath hot spots.

## 2. Geological setting

The Canary archipelago, limited to the west and east by magnetic anomalies M25 and S1 (Verhoef et al., 1991; Roest et al., 1992), lies on Jurassic (150–170 Ma) oceanic lithosphere adjacent to the NW African passive margin (Fig. 1). This margin hosts a 3000-km-long volcanic belt that includes a considerable number of seamounts and volcanic islands. The seven major islands in the Canary archipelago exhibit a long volcanic history (70–80 Ma) and hence multiple oceanic volcanic islands stages (i.e., seamount, shield, erosional) are well represented. The volcanic activity in the Canary archipelago shows East–West age progression with the oldest exposed volcanic rocks in Fuerteventura (20 Ma, up to 70–80 Ma according to Le Bas et al., 1986) and the youngest (<4 Ma) in the western islands (La Palma and El Hierro). The eastern islands, Fuerteventura and Lanzarote, are parallel to the NW African margin and show a rather flat topography (max elevation of 807 and 607 m respectively) characteristic of its erosional stage. These two islands along with the conception Bank, north of Lanzarote, define the East Canary Ridge (Ancochea et al., 2004 and references therein). The central islands, Gran Canaria, La Gomera and Tenerife, exhibit an E–W trend. Tenerife and Gran Canaria are in the post-shield stage with rejuvenated volcanism which is absent in La Gomera (erosional stage, no volcanism in the last 2–3 Ma). The young western islands, La Palma and El Hierro, align along an N–S trend and are currently at a rather juvenile shield stage (Ancochea et al., 2004 and references therein). The most recent eruptive process took place offshore, October 2011–March 2012, near the southern shoreline of El Hierro (González et al., 2013).

## 3. Geophysical and petrological setting

Geophysical studies in the Canary archipelago at a crustal scale include wide-angle deep seismic experiments (e.g. Banda et al., 1981; Ye et al., 1999; Dañobeitia and Canales, 2000; see locations in Fig. 1), seismic tomography (Krastel and Schmincke, 2002; García-Yeguas et al., 2012) and receiver functions (Lodge et al., 2012; Martinez-Arevalo et al., 2013), magnetotellurics (Pous et al., 2002), gravity modeling (e.g., Ranero et al., 1995; Montesinos et al., 2006; Camacho et al., 2009, 2011), and elastic thickness estimates (e.g. Watts, 1994; Watts et al., 1997; Dañobeitia et al., 1994; Canales and Dañobeitia, 1998).

### 3.1. Crustal seismic structure

The Canary Islands were formed over Jurassic oceanic crust, characterized by a thickness of 5–7 km (Banda et al., 1981), which progressively thickens towards the Atlantic Moroccan passive margin to 27–35 km (Contrucci et al., 2004; Klingelhoefer et al., 2009; Spieker et al., 2014). The seismic structure beneath the central islands is defined by a volcanic edifice ($V_p = 5.5$–$6$ km/s) of variable thickness underlain by a 6–7-km-thick lower crust ($V_p = 6.6$–$7.3$ km/s) (Ye et al., 1999; Dañobeitia and Canales, 2000). In the eastern islands the upper crust ($V_p = 6$–$6.7$ km/s) is 5–8 km thick and the lower crust is absent (Dañobeitia and Canales, 2000 and references therein). Furthermore, under the central and eastern islands a 7–12-km-thick layer defined by P-wave velocities (7.4–8 km/s), higher than those of typical lower crust but lower that the average Jurassic oceanic uppermost mantle velocities in the neighborhood of the islands (8 km/s), has been interpreted as a magmatic underplating (Dañobeitia and Canales, 2000; Freundt and Schmincke, 1995; Lodge et al., 2012) (see Appendix A for more details).

### 3.2. Lithosphere and uppermost mantle structure and composition

Lithospheric-uppermost mantle scale studies in the Canary Islands are relatively scarce. Based on 2D seismic reflection and gravity data, Ranero et al. (1995) modelled a moderate lithospheric thinning from a lithosphere–asthenosphere-boundary (LAB) depth of 100 km west of the Canaries in the Jurassic oceanic lithosphere to about 80 km in the western islands (La Palma and El Hierro). These authors argued that the topographic swell associated with the archipelago could not be explained by crustal variations and that deep density anomalies were required instead. Neumann et al. (1995) estimated a lithosphere thickness of only 27 km under Lanzarote based on petrological constraints, and suggested thermal erosion as a possible explanation.

A recent seismic tomography model based on multimode inversion of surface- and S-wave forms in Europe shows a low velocity anomaly area centered in the central islands and affecting the whole Canarian domain at lithospheric (50–110 km) and sublithospheric depths (150–260 km) (Legendre et al., 2012). Earlier body-wave seismic tomography models have also identified a deep and broad low velocity zone in the mantle beneath the Canary Islands (Hoernle et al., 1995). A recent multiple-frequency P-wave velocity tomography model also shows a negative velocity anomaly underlying the Canary Islands in the lithosphere and upper mantle (Bonnin et al., 2014). The negative anomaly in Bonnin et al. (2014) seismic model seems to be restricted to the western islands in the lithosphere, progressively shifting north-westwards of La Palma in the mantle transition zone (their Fig. 6). However, the extent to which this W–E mantle velocity pattern in the upper mantle is a