Check for updates

Geophysical Research Letters

RESEARCH LETTER
10.1029/2021GL092874

Key Points:

- The Canary and Madeira hotspots are underlain by distinct upwellings sourced from the lower-mantle Central-East Atlantic Anomaly (CEAA)
- A "vote" analysis of 34 tomography models shows that the CEAA extends vertically from the African LLSVP up to the topmost lower mantle
- The plumelets seem at different stages of evolution and rise sporadically from mantle material accumulated below the 660-km discontinuity

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:
C. Civiero,
cciviero@cp.dias.ie

Citation:
Civiero, C., Custódio, S., Neres, M., Schlaphorst, D., Mata, J., & Silveira, G. (2021). The role of the seismically slow Central-East Atlantic Anomaly in the genesis of the Canary and Madeira volcanic provinces. *Geophysical Research Letters*, *48*, e2021GL092874. https://doi.org/10.1029/2021GL092874

Received 6 FEB 2021
Accepted 28 MAY 2021

© 2021. American Geophysical Union. All Rights Reserved.

The Role of the Seismically Slow Central-East Atlantic Anomaly in the Genesis of the Canary and Madeira Volcanic Provinces

Chiara Civiero[1], Susana Custódio[2], Marta Neres[2,3], David Schlaphorst[2], João Mata[2], and Graça Silveira[2,4]

[1]Dublin Institute for Advanced Studies (DIAS), Dublin, Ireland, [2]Instituto Dom Luiz (IDL), Faculdade de Ciências, Universidade de Lisboa, Lisbon, Portugal, [3]Instituto Português do Mar e da Atmosfera (IPMA), Lisbon, Portugal, [4]Instituto Superior de Engenharia de Lisboa, Lisbon, Portugal

Abstract The Canary and Madeira provinces in the Central-East Atlantic Ocean are characterized by an irregular spatio-temporal distribution of volcanism along the hotspot tracks, and several alternative scenarios have been suggested to explain it. Here, we combine results from seismic tomography, shear-wave splitting and gravity along with plate reconstruction constraints to investigate the mantle structure and dynamics beneath those provinces. We find that the Central-East Atlantic Anomaly (CEAA), which rises from the core-mantle boundary and stalls in the topmost lower mantle, is the deep source of distinct upper-mantle upwellings beneath the region. The upwellings detach intermittently from the top of the CEAA and appear to be at different evolutionary stages. We argue that the accumulation of plume material in the topmost lower mantle can play a key role in governing the first-order spatio-temporal irregularities in the distribution of hotspot volcanism.

Plain Language Summary The Canary and Madeira provinces, located in the Central-East Atlantic Ocean, show lineaments of volcanic islands and seamounts, known as hotspot tracks, which differ from most other tracks for their irregular distribution. These lineaments cannot be easily explained by the African plate movement over a fixed, narrow plume of hot mantle material rising from the deep Earth and alternative mechanisms may be required. Here, we integrate observations from seismology and gravity to demonstrate that some first-order spatio-temporal irregularities of volcanism in both provinces are due to small-scale upper-mantle plumes ("plumelets"), which sporadically rise from the top of a wide lower-mantle low-velocity structure, here named "Central-East Atlantic Anomaly" (CEAA). The CEAA extends vertically from the base of the African large low-shear-velocity province (LLSVP), a structure in the lowermost mantle situated under Africa and adjacent oceans and characterized by low-shear seismic velocities. According to the interpretation of global and regional tomography models, the CEAA material stalls in the topmost lower mantle, between ~700 and 1,200 km depth, intermittently generating plumelets under the Central-East Atlantic. Plate reconstructions from Cenozoic to present confirm that the CEAA is underlying these and other volcanic provinces (e.g., Western Iberia and NW Morocco) since at least 90 Ma.

1. Introduction

Intraplate volcanism occurs throughout the globe, yet it remains a poorly understood phenomenon. Most intraplate volcanism in oceanic settings forms linear, age-progressive chains, which have been attributed to lithospheric plates moving over narrow, fixed plumes rising from the base of the lower mantle (Morgan, 1972). In addition to such "classic", primary plumes, several studies recognize the existence of secondary plumes originating from the bottom of the mantle transition zone (MTZ) (e.g., Cao et al., 2011; Courtillot et al., 2003; Davaille & Vatteville, 2005) and shallower asthenospheric upwellings forming in response to tensile stresses in the lithosphere (Anderson, 2000; Foulger & Natland, 2003) or density inversions between the lithosphere and the asthenosphere (Ballmer et al., 2015; Belay et al., 2019; Conrad et al., 2011; Manjón-Cabeza Córdoba & Ballmer, 2020; Raddick et al., 2002).

Since the Late Cretaceous, the Central Atlantic Ocean has been the locus of widespread volcanism (Merle et al., 2019). On its eastern side, the adjacent Canary and Madeira provinces consist of two roughly

19448007, 2021, 13, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021GL092874, Wiley Online Library on [30/12/2022]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

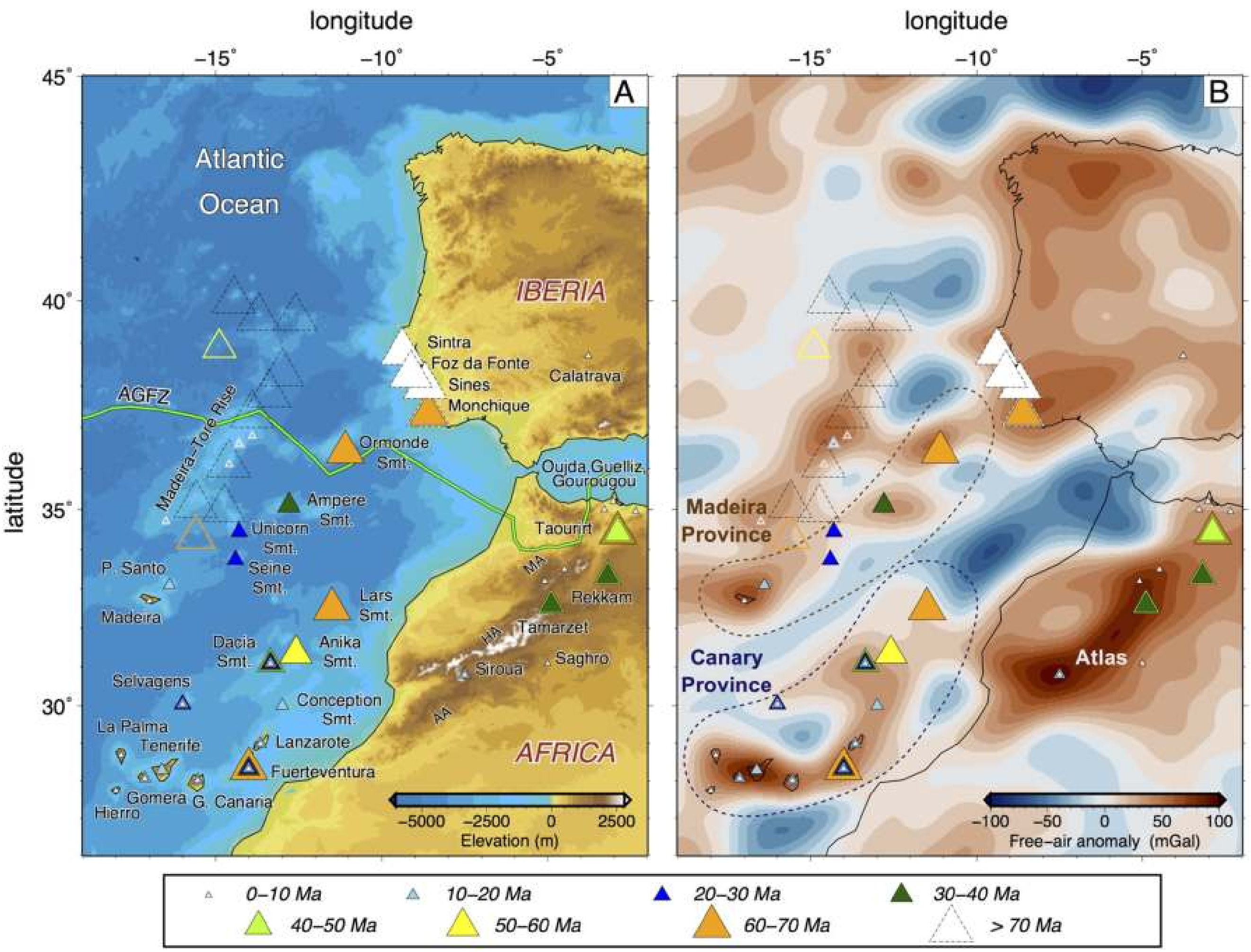

Figure 1. (a) Topography of Western Iberia, Northwestern Africa and bathymetry of Central-East Atlantic. Triangles of different sizes and colors show the locations and ages (from Cretaceous to present) of basaltic volcanism. The empty triangles mark the Madeira-Tore Rise volcanism, which is not discussed in this work. For more information see Table ST1. AA: Anti Atlas; HA: High Atlas; MA: Middle Atlas. AGFZ: Azores–Gibraltar Fracture Zone (Bird, 2003). (b) Satellite-derived long-wavelength (300-km filtered) free-air gravity anomaly (Sandwell et al., 2014). The dashed curve areas indicate the Canary and Madeira provinces.

700-km-long chains of intraplate volcanoes (Mjelde et al., 2010) (Figure 1). Madeira is considered the current location of the >70 Ma old Madeira hotspot, which built the Porto Santo island, the Seine, Ampère, and Ormond seamounts and, likely, the onshore Monchique massif in Southern Portugal (Geldmacher & Hoernle, 2000). El Hierro is believed to mark the present location of the Canary hotspot, which started at Lars seamount ~65 Ma and formed the Anika, Dacia, and Conception seamounts, as well as the Selvagens, Lanzarote, Fuerteventura, Gran Canaria, Tenerife, Gomera, and La Palma islands (Geldmacher et al., 2005). Geochronology of magmatic rocks from both provinces confirms a general progression of increasing volcanism age to the northeast consistent with the direction of the African plate with respect to a fixed (hotspot) mantle (Geldmacher et al., 2005). However, the "classic" plume model cannot easily explain the varying distances and irregular age relations between some individual volcanic complexes along the hotspot tracks.

So far, the lack of consensus on the origin of the Canary and Madeira volcanic provinces arises mainly from an inconclusive knowledge of the structure at depth. Global tomography images detect distinct low-velocity anomalies in the upper mantle beneath the Azores, Cape Verde, and the Canaries, which merge in the lower mantle (Montelli et al., 2006; Zhao, 2007). However, due to the insufficient resolution of global tomography, the structure of these upwellings, in particular, their upper to the lower mantle connection, is still unclear.

19448007, 2021, 13, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021GL092874, Wiley Online Library on [30/12/2022]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Consequently, there is no comprehensive geodynamic model that explains the occurrence of intraplate volcanism in the Central-East Atlantic Ocean.

Here, we combine seismological and gravity observations with constraints from plate reconstructions to explore the whole-mantle structure below the Central-East Atlantic region and, ultimately, advance a mechanism driving this intraplate volcanism. By integrating these multi-disciplinary data, we suggest that secondary, intermittent pulses of hot mantle material detached from a broad lower-mantle plume stalling below the MTZ. This plume has been proposed to be one of the internal instabilities of the African large low-shear-velocity province (LLSVP; e.g., Cottaar & Lekic, 2016; Davaille & Romanowicz, 2020; French & Romanowicz, 2015), but its morphology and role in governing surface volcanism have been poorly investigated. Our study introduces the specific term "Central-East Atlantic Anomaly" (CEAA) to define this lower-mantle instability and, more importantly, a new conceptual model that improves our understanding of the geodynamic evolution of the region.

2. Upper-Mantle Seismic Structure With Constraints From Gravity

The IBEM-P18 and IBEM-S19 regional velocity models (Civiero et al., 2018, 2019), obtained by inversion of P- and S-wave teleseismic delay-times respectively (see Supporting Text T1 for details), show differently shaped low-velocity anomalies in the upper mantle below the Madeira and Canary Islands as well as the Atlas Mountains (Figure 2). The anomalies below the western Canary Islands and the Atlas Mountains continue downwards through the MTZ. The low-velocity body below Madeira (better imaged with P-waves) shows a blob-like morphology and extends only down to ~300 km depth. Another weaker, less resolved, low-velocity anomaly is observed below the eastern Canary Islands. The upper-mantle structure beneath the study area is partially identified in the previous body-wave tomography of Bodin et al. (2012) and shows much more complexity than the large-scale low-velocity anomaly detected by global models (e.g., Hoernle et al., 1995; Montelli et al., 2006; Simmons et al., 2012).

Extensive resolution tests (Civiero et al., 2018, 2019, Figures S1 and S2) show that both models can resolve the upper-mantle structure at a relatively short wavelength (~100–200 km) despite some along-raypath smearing. However, the data coverage, and consequently the resolution, decreases gradually moving northwards from Madeira; therefore, we do not exclude that the Madeira blob-like anomaly can extend deeper, especially if its structure is thinner than the maximum wavelength that can be recovered (see Supporting Text T1 for further details).

Taken together, these observations allow us to identify three main mantle features: (1) the Canary upwelling (~150–200 km diameter), centered beneath El Hierro and La Palma islands, with a long tail throughout the upper mantle, (2) the blob-type Madeira upwelling (~100 km wide), apparently disconnected from the MTZ, and (3) the sub-vertical low-velocity "wall" below the Atlas Mountains, down to the base of the MTZ.

New teleseismic shear-wave splitting analyses (Schlaphorst et al., 2021) show a complex, radial orientation of the fast polarization directions in the Canaries and Madeira, which differs remarkably from the regional anisotropic pattern observed in Iberia and NW Morocco (Buontempo et al., 2008; Díaz et al., 2010, 2015; Miller et al., 2013) (Figure 2b). As shown by Walker et al. (2005), this pattern would indicate that the mantle flow is perturbed by the presence of rising upwellings beneath the islands. Also, previous studies (e.g., Deuss, 2007; Saki et al., 2015; Spieker et al., 2014) suggest an overall thinned MTZ beneath the Canaries indicating that it is likely crossed by material hotter than the ambient mantle (Figure S6, Table ST2). A slightly thinned or close-to-average MTZ thickness is also found below Madeira by global studies (e.g., Deuss, 2009; Houser et al., 2008; Lawrence & Shearer, 2008).

The signature of hotspots can often be seen in the Earth's gravity field (Tapley et al., 2005). The Canary and Madeira archipelagos as well as the Atlas region coincide with remarkable topographic and gravity anomalies (Figure 1 and S3–S5). The Canary and Madeira's topographic highs have >30 mGal positive long-wavelength free-air anomalies, which are stronger in amplitude where remarkable upper-mantle low-velocity seismic velocities are imaged, that is, around western Canaries (~80–90 mGal) and Madeira (~70 mGal) (Figure 1b). Moreover, both oceanic provinces are associated with high geoid anomalies that follow the orientation of the tracks and reach a maximum of 8–10 m below the inferred hotspots, and local positive (>240

19448007, 2021, 13, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021GL092874, Wiley Online Library on [30/12/2022]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

10.1029/2021GL092874

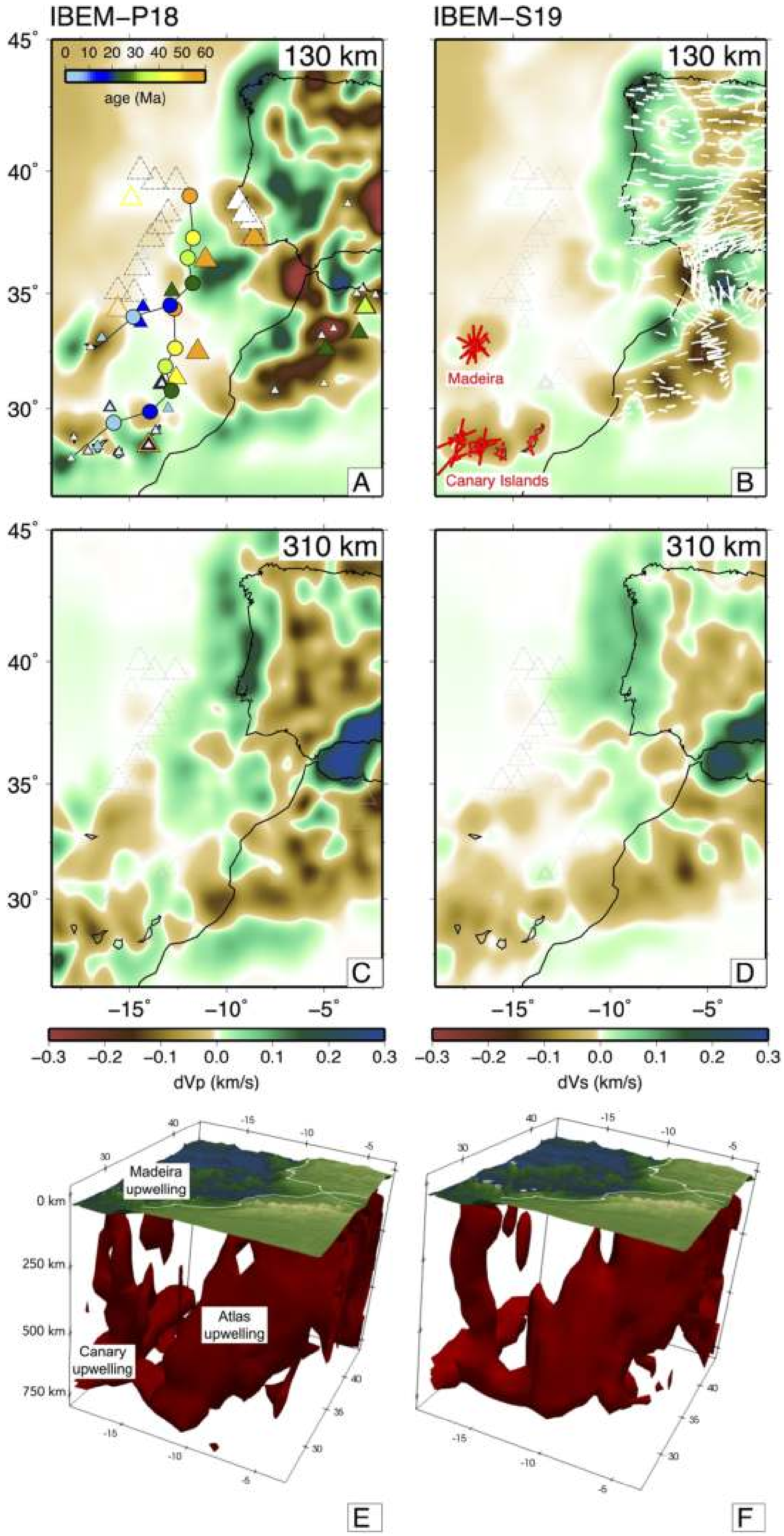

Figure 2

19448007, 2021, 13, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021GL092874, Wiley Online Library on [30/12/2022]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

19448007, 2021, 13, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021GL092874, Wiley Online Library on [30/12/2022]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

mGal) Bouguer anomalies (Figures S4 and S5, Text T2). In the Atlas, the locus of a broad topographic swell, we observe stronger positive free-air (~90 mGal; Figure 1) and geoid anomalies (~8–14 m, Figure S4) in line with the very low velocities imaged in the upper mantle and the volcanism at the surface. The Bouguer anomaly here is negative (~−100–200 mGal, Figure S5c); however, as suggested by Fullea et al. (2007, 2008) one would expect it to be even more negative to compensate the elevated topography (see Text T2 for more details).

The correspondence of strong gravity anomalies with areas of low seismic velocities imaged by the regional tomography supports the existence of deep-seated processes centered under the Canary and Madeira islands as well as the Atlas Mountains. These can be explained as hot, low-density plume-like upwellings, which feed the volcanism in the region and shape the surface topography.

3. "Vote" Analysis of the Lower Mantle

The resolving power of the regional tomography drastically decreases below ~800-km depth. Published whole-mantle tomography models provide complementary evidence on the deep mantle structure. We investigate the continuity of the low-velocity anomalies in the lower mantle with the "SubMachine" tool (Hosseini et al., 2018), which stacks together different P- and S-wave velocity models illustrating the prevalent velocity variations in the mantle (Figure 3). However, due to the different characteristics of each tomography model (resolution, regularization, etc.), small-scale structure in the region is likely to be filtered out, either because the features are too fine or because they are not consistently resolved in the same locations (Cottaar & Lekic, 2016; Davaille & Romanowicz, 2020). Also, we need to keep in mind that the uniformity of the "vote" images should not be interpreted as a homogenous structure within the cluster domain, but only as an agreement in classification across models (see Supporting Text T3).

The vote maps in Figure 3 (and Figures S7 and S8, where we use different thresholds and data types) show the most robust long-wavelength low-velocity anomalies in the lower mantle. The overall pattern of the seismically slow region highlights the agreement across models on the extent of the African LLSVP in the lowermost mantle (Figure 3c), which has been proposed to have been stable during the past 300 Ma (Torsvik et al., 2008, 2014) due to its thermochemical nature (Garnero & McNamara, 2008). Its morphology, as constrained in this study, is relatively consistent with that obtained by other analyses of global tomographic models (Cottaar & Lekic, 2016), studies of shear-wave waveforms (Lynner & Long, 2014; Wen et al., 2001), and mantle-flow predictions (Flament et al., 2017).

At shallower lower-mantle depths (~1,200–1,800 km; Figures 3a–3b), a persistent low-velocity region with a diameter >1,500 km is observed below southern Africa and the Eastern Atlantic. Beneath our study area, a large dome-like low-velocity anomaly, the CEAA, extends upward from the base of the LLSVP. Cross-sections AB and CD (Figure 3) show that after a lateral thinning at ~1,800 km depth, this anomaly broadens again between ~1,200 and 700 km depth, suggesting that a thick "layer" of hot material is stalled below the MTZ (Figure S9).

4. Plate Motion Reconstructions

Tomographic imaging provides a current snapshot of the 3D structure of the mantle. If coupled with plate reconstructions, it may shed new light on the evolution of the region through time. Assuming that the CEAA is stationary (Torsvik et al., 2014), we reconstruct its location back through time relative to the moving lithosphere, from the Late Cretaceous to present (Figures 3f–3i). Before 60 Ma, the CEAA underlay Iberia, Morocco, and the NE Atlantic (Figure S10). In SW Iberia, significant volcanism with ages ranging from 94 to 69 Ma occurred in the regions of Lisbon, Sines, and Monchique (Miranda et al., 2009). Such

Figure 2. (a, c) Slices at 130-km and 310-km depth of the IBEM-P18 model. Predicted hotspot tracks (0–60 Ma) of the Madeira and Canary upwellings and volcanism are plotted on top. The tracks are calculated with the software GPlates (Boyden et al., 2011) using the rotation frame of Torsvik et al. (2019). (b, d) Slices at 130-km and 310-km depth of the IBEM-S19 model. All the available SKS-splitting measurements (bars) in Iberia and Morocco are shown in white (Buontempo et al., 2008; Díaz et al., 2010, 2015; Miller et al., 2013). The recent measurements in the Canaries and Madeira (Schlaphorst et al., 2021) are indicated in red. (e, f) 3D low-velocity structure shown as velocity anomaly isosurfaces (at −0.04 km/s for IBEM-P18 and -0.03 km/s for IBEM-P18).

10.1029/2021GL092874

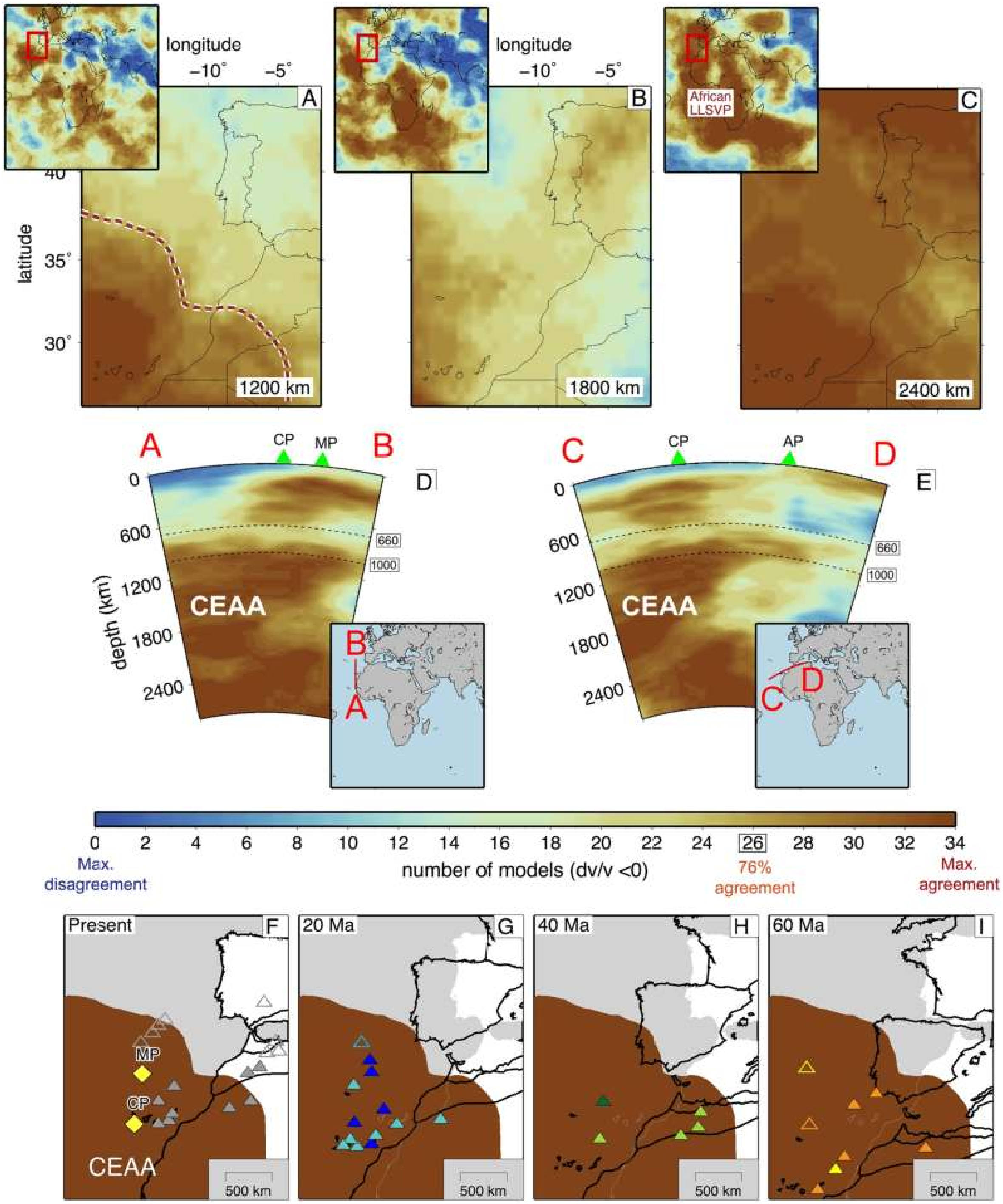

Figure 3. (a–e). Low-velocity vote maps and cross-sections based on 34 global tomographic models. For details on the models see Supporting Text T3 and Tables ST3–ST4. The dashed contour in panel a corresponds to a 26-vote count (76% agreement) and is used to approximately delimit the CEAA in panels f–i. The green triangles in panels d–e indicate the position of the Canary upwelling (CP), Madeira upwelling (MP), and Atlas upwelling (AP). (f–i) GPlates-based plate reconstruction of the Central-East Atlantic and adjacent regions from 60 Ma to present. The triangles show the volcanism generated approximately at each time frame of the reconstruction, colored according to the age code in Figure 1. The empty triangles indicate volcanism that is not originated from the CEAA (Rif-Betics) or not discussed in this study (Madeira-Tore Rise). The locations of the Canary and Madeira hotspots are indicated in panel f with two yellow diamonds.

19448007, 2021, 13, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021GL092874, Wiley Online Library on [30/12/2022]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

10.1029/2021GL092874

volcanism has been associated with the continuation of the Madeira hotspot track on the Eurasian plate (Geldmacher et al., 2000) or, alternatively, to another fixed mantle plume below the moving Iberian plate (Grange et al., 2010). From ∼60 to ∼20 Ma, the CEAA lay beneath all the Moroccan centers of volcanic activity occurring in this period (e.g., Missenard & Cadoux, 2012a, 2012b) and also beneath the Madeira and Canary provinces where the volcanism had already started (Geldmacher et al., 2005) (Figures 3g–3i). At present, with the exception of Rif-Betics volcanism associated with mantle flow around the Gibraltar slab (Civiero et al., 2020; Levander et al., 2014; Palomeras et al., 2017), the areas encompassing the reconstructed paleo-positions of volcanism either overlay or are very close to the border of the CEAA in the lower mantle (Figure 3f). The Madeira-Tore Rise also falls partly within the area of the CEAA, but its origin is highly debated (see Merle et al., 2019) and beyond the scope of this study.

Volcanism roughly reflects the predicted hotspot tracks caused by the NE motion of the African plate but their spatio-temporal distribution is non-linear (Figure 2a). These poorly-defined tracks are underlain by distinct upper-mantle plumes–or "plumelets" – rising from below the MTZ, which are smaller in size (≤200 km) compared to other plumes on Earth (e.g., Hawaii: ∼300–400 km; Wolfe et al., 2011). The lower-mantle source feeding these plumelets seems to be the CEAA. This instability develops from the base of the African LLSVP and stalls below the 660-km depth seismic discontinuity, and possibly deeper, at ∼1,000-km depth, where another mantle discontinuity has been recently detected by seismic studies (French & Romanowicz, 2015; Jenkins et al., 2017) and viscosity inversions (Rudolph et al., 2015).

5. Discussion

The origin of the Central-East Atlantic volcanism from the Upper Cretaceous onwards has often been associated with that of the Euro-Mediterranean region based on their geochemical affinities (e.g., Wilson & Downes, 2006; Lustrino & Wilson, 2007a, 2007b) and has been mainly attributed to: (i) a passive rise of the shallow mantle (Anguita & Hernán, 2000; Lustrino & Wilson, 2007a, 2007b); or (ii) a deep plume and/or shallower upper-mantle plumes and blobs (Hoernle & Schmincke, 1993; Hoernle et al., 1995 ; Long et al., 2020; Mata et al., 1998; Merle et al., 2019; Piromallo et al., 2008; Saki et al., 2015). However, clear evidence of such upwellings has been hampered by poor knowledge of the seismic mantle structure beneath this region.

The regional tomographic models IBEM-P18 and IBEM-S19 (Figure 2) image a low-velocity conduit below the western Canaries extending down to ∼700 km depth (and a weaker, less-defined low-velocity anomaly beneath the eastern archipelago, whose size is below the resolving power of our tomography). Beneath Madeira, a blob-like low-velocity anomaly is only observed down to asthenospheric depths. Together with notable positive long-wavelength gravity anomalies (Figures 1b, S3 and S4) and large variations in the fast shear-wave polarization directions (Figure 2b), these low-velocity anomalies are consistent with the presence of focused, differently shaped upper-mantle upwellings.

The Canary plumelet appears rooted in the lower-mantle CEAA, whereas the Madeira plumelet seems detached from it. Kumagai et al. (2008) and more recently Civiero et al. (2019) demonstrated that the dynamics of mantle plumes are strongly time-dependent. In line with this view, we propose that these two plumelets may be at different stages of evolution with the Madeira upwelling in a relatively later stage of development, already untailed from its source or, alternatively, with a thin tail (not resolved by our tomography). Both interpretations would explain the very low buoyancy flux (King & Adam, 2014) and eruption rates in Madeira (∼20–150 km^3/Ma) compared to those of the Canaries (∼2,000–10,000 km^3/Ma) (Geldmacher et al., 2000).

In Morocco, the Atlas Mountains are underlain by an SW-NE-oriented wall-like low-velocity zone, which has been previously interpreted as hot mantle material channeled from the Canary plume through a sub-lithospheric corridor (Duggen et al., 2009; Mériaux et al., 2015). However, according to our model, the sub-Atlas low-velocity anomaly is connected to the Canary conduit only beneath the MTZ (Figure 2). This implies that both the Canary and Atlas low-velocity anomalies are distinct upper-mantle upwellings, both sourced from the CEAA (Civiero et al., 2018, 2019). The computed free-air, geoid, and Bouguer anomalies (Figure 1, S4 and S5 respectively) support this interpretation. The deflection of the instabilities north-eastwards beneath Morocco is likely due to the mantle flow induced by the sinking Alboran slab beneath the Gibraltar arc (Civiero et al., 2018; Mériaux et al., 2016; Miller et al., 2015). Also, the small-amplitude splitting

19448007, 2021, 13, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021GL092874, Wiley Online Library on [30/12/2022]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

measurements (<~1 s) in the western Atlas and near the Atlantic coast (Figure 2b) do not corroborate the hypothesis of a continuous sub-lithospheric channel from the Canaries rather implying a deeper connection between the Canary and Atlas plumelets.

Whole-mantle seismic tomography (e.g., French & Romanowicz, 2014, 2015) shows that the African LLSVP contains a bundle of well-separated, low-velocity domes, which extend to different lower-mantle depths. For example, the East-African Anomaly rises up to MTZ depths tilting northeastwards; the toe of the African Anomaly instead does not reach such shallow depths, but stalls in the lowermost mantle (Cottaar & Lekic, 2016). The development of distinct instabilities from the African LLSVP is in line with fluid-mechanics experiments (Davaille et al., 2005; Kumagai et al., 2007; Davaille & Limare, 2015) displaying morphologies congruent with those shown in our study. In particular, Davaille et al. (2005) suggested that the African LLSVP consists of nine thermochemical instabilities at different stages of development. The CEAA can then be considered as one of these plumes that extends vertically from the base of the LLSVP and pools between the base of the MTZ and mid-mantle depths. However, the coarse resolution (~500–1,000 km length scale) of the global models and the apparent uniformity of the structure shown by the vote images do not allow us to distinguish its internal fine structure; therefore, we cannot rule out that such plume may instead represent clusters of smaller-scale upwellings that originate large regions of hot material beneath the MTZ by merging their heads (Boschi et al., 2007; Schubert et al., 2004).

Numerical simulations of thermochemical plumes (e.g., Cserepes & Yuen, 2000; Farnetani & Samuel, 2005; Tosi & Yuen, 2011) show that if the head of a plume contains a deep-mantle dense component (e.g., old subducted basaltic crust) the rising head material can accumulate below the 660- and 1,000-km depth discontinuities, acting as initial barriers for vertical flow. This has been confirmed by several seismic studies, which demonstrate that compositional heterogeneity could pond and divert around these discontinuities likely due to a density (and viscosity) contrast (French & Romanowicz, 2015; Jenkins et al., 2017; Rickers et al., 2013; Rudolph et al., 2015; Vinnik et al., 2010). The ascending light components give rise to differently shaped plumelets that originate from the unstable hot material accumulated below (Davaille, 1999; Liu & Leng, 2020; Ogawa, 2007; Rudolph et al., 2015). Our results suggest that the CEAA is the main source of the upper-mantle upwellings that generate the Madeira and Canary (and Atlas) volcanic provinces. Each of these volcanic provinces results from secondary, distinct plume pulses, which detach sporadically from a single, considerably wider plume anchored at the bottom of the mantle, after being hampered by mantle interfaces (Figure 4, S9). Some of the locally spawned structures, if sufficiently small in size, may be transported relatively far away by horizontal upper-mantle flow (van Keken & Gable, 1995) giving origin to the numerous, dispersed occurrences of volcanism observed in the Central-East Atlantic. This is in line with a recent geochemical study proposing that plume material feeds also isolated, off-track seamounts in the Canary Basin (Long et al., 2020). This scenario may also explain some first-order irregularities in the distribution of the volcanism along the hotspot tracks, such as large and varying age differences and distances between volcanic complexes. However, complementary mechanisms as variations of the lithospheric structure (Arana & Ortiz, 1991; Blanco-Montenegro et al., 2018; D'Oriano et al., 2010), edge-driven convection (King, 2007; Manjón-Cabeza Córdoba & Ballmer, 2020; Schmincke, 1982) and/or others may also play a role in the location, magma genesis, and evolution for some islands and seamounts that our model cannot account for.

The CEAA may further source other Atlantic hotspots within the Macaronesia region, such as the Azores and Cape Verde (Figure 4), as suggested by PP and SS precursors analysis (Saki et al., 2015), laboratory experiments (Davaille et al., 2005), and mantle-flow modeling (Forte et al., 2010). Moreover, the irregular nature of the South Atlantic hotspot tracks (e.g., Tristan-Gough, Meteor, Shona, and Bouvet) (Hoernle et al., 2016; Homrighausen et al., 2020) may be explained by a similar model, where secondary plumes locally emitted from a lower-mantle upwelling rooted in the southwestern domain of the African LLSVP would sustain irregular hotspot volcanism.

This model offers a challenge for seismologists to improve the resolution of the mantle structure in the Central Atlantic, namely by collecting new seismic data from ocean-bottom seismometers around the islands. Also, future geodynamic studies should explore whether alternative plume models can naturally explain varied behaviors and morphologies of upper-mantle upwellings using different buoyancy and viscosity contrasts.

19448007, 2021, 13, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021GL092874, Wiley Online Library on [30/12/2022]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

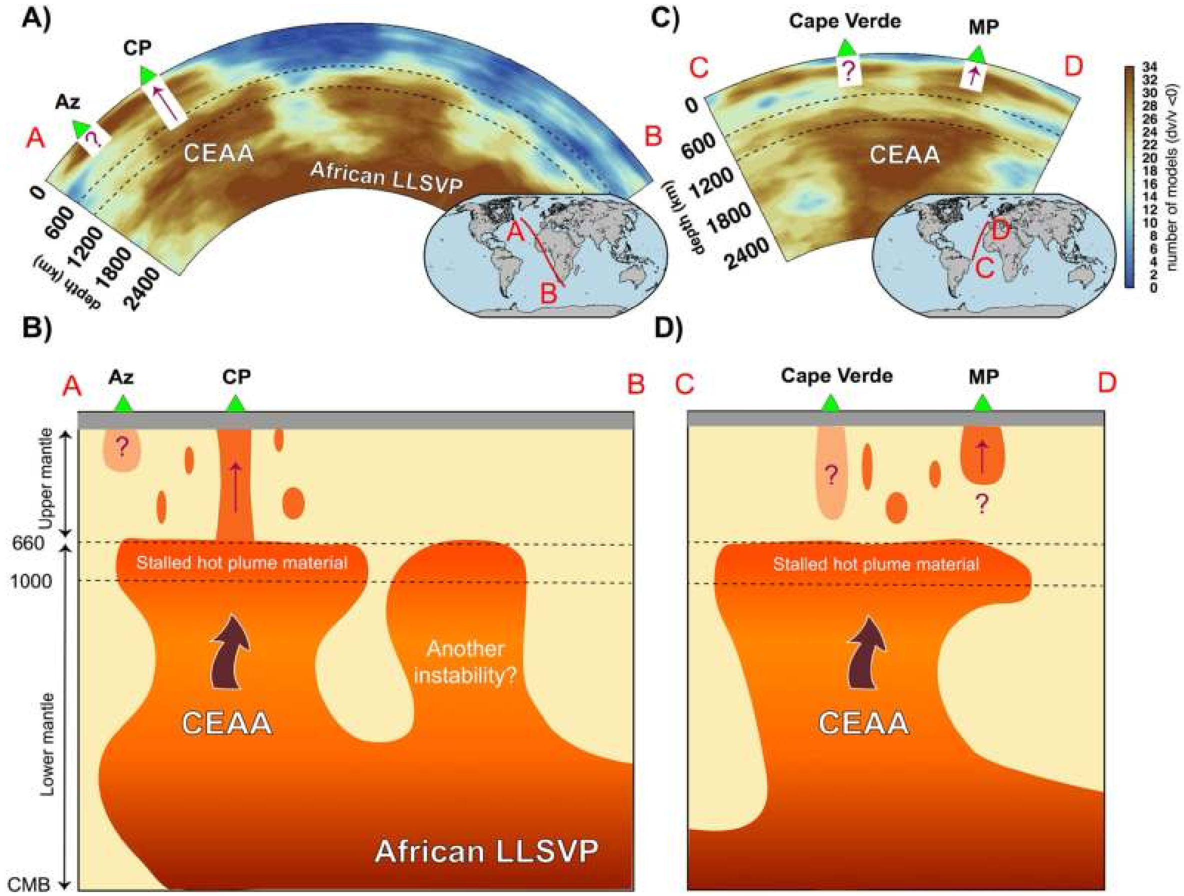

Figure 4. (a) Vote cross-section through the Canaries (CP) and Azores (Az). (b) Interpretative model of the mantle structure imaged. The red question mark indicates the upwelling below the Azores imaged as a low-velocity pond down to ~250 km without a tail (Silveira et al., 2006). (c) "Vote" cross-section through Madeira (MP) and Cape Verde islands. (d) Interpretative model of the mantle structure imaged. The red question mark below Cape Verde indicates the upwelling imaged as a low-velocity columnar anomaly down to ~500 km (Liu & Zhao, 2014). CMB: core-mantle boundary.

6. Conclusions

The multi-disciplinary approach used in this study finds that a broad plume, the CEAA, deeply rooted in the African LLSVP, extends vertically upwards to the uppermost lower mantle below the Central-East Atlantic and originates upper-mantle plumelets at various times and locations since at least 90 Ma. At present, differently evolved upwellings may exist below the volcanic Canary and Madeira islands, with the Madeira hotspot possibly fed by a later-stage plumelet.

Acknowledgments
The authors thank A. Manjón-Cabeza Córdoba, S. King, and the editor D. Sun for their thoughtful comments that helped to improve the manuscript. This work is a contribution to several projects SIGHT (PTDC/CTA-GEF/30264/2017), SPIDER (PTDC/GEOFIQ/2590/2014), RESTLESS (PTDC/CTA-GEF/6674/2020), LISA (PTDC/CTA-GEF/1666/2020), and UIDB/50019/2020-IDL from the Fundação para a Ciência e a Tecnologia. Additional funds were provided by the Science Foundation Ireland, the Geological Survey of Ireland, and the Marine Institute (Grants 13/CDA/2192 and 16/IA/4598).

Data Availability Statement

The IBEM-P18 and IBEM-S19 models are available online from the IRIS Earth Model Collaboration (https://ds.iris.edu/ds/products/emc-earthmodels/). The models for the vote analysis were downloaded from www.earth.ox.ac.uk/~smachine. The original free-air data were downloaded from https://topex.ucsd.edu.

References

Ahijado, A., Casillas, R., & Hernández-Pacheco, A. (2001). The dyke swarms of the Amanay Massif, Fuerteventura, Canary Islands (Spain). *Journal of Asian Earth Sciences*, *19*(3), 333–345. https://doi.org/10.1016/S1367-9120(99)00066-8

Amaru, M. L. (2007). Global travel time tomography with 3-D reference models. *Geologica Ultraiectina*, *274*, 174.

Ancochea, E., Brändle, J. L., Huertas, M. J., Hernán, F., & Herrera, R. (2008). Dike-swarms, key to the reconstruction of major volcanic edifices: The basic dikes of La Gomera (Canary Islands). *Journal of Volcanology and Geothermal Research*, *173*(3–4), 207–216. https://doi.org/10.1016/j.jvolgeores.2008.01.020

19448007, 2021, 13, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021GL092874, Wiley Online Library on [30/12/2022]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Anderson, D. L. (2000). The thermal state of the upper mantle; No role for mantle plumes. *Geophysical Research Letters*, *27*(22), 3623–3626. https://doi.org/10.1029/2000GL011533

Anguita, F., & Hernán, F. (2000). The Canary Islands origin: A unifying model. *Journal of Volcanology and Geothermal Research*, *103*, 1–26. https://doi.org/10.1016/S0377-0273(00)00195-5

Arana, V., & Ortiz, R. (1991). *The Canary Islands: Tectonics, Magmatism and Geodynamic Framework*. In Kampun. Magmatism in Extensional structural settings. Springer. https://doi.org/10.1007/978-3-642-73966-8_9

Auer, L., Boschi, L., Becker, T. W., Nissen-Meyer, T., & Giardini, D. (2014). Savani: A variable resolution whole-mantle model of anisotropic shear velocity variations based on multiple data sets. *Journal of Geophysical Research: Solid Earth*, *119*(4), 3006–3034. https://doi.org/10.1002/2013JB010773

Ayarza, P., Carbonell, R., Teixell, A., Palomeras, I., Marti, D., Kchikach, A., et al. (2014). Crustal thickness and velocity structure across the Moroccan Atlas from long offset wide-angle reflection seismic data: The SIMA experiment. *Geochemistry, Geophysics, Geosystems*, *15*, 1698–1717. https://doi.org/10.1002/2013GC005164

Ballmer, M. D., van Keken, P. E., & Ito, G. (2015). *Hotspots, large Igneous provinces, and Melting anomalies. Treatise on Geophysics* (2nd ed, Vol. 7). Elsevier B.V. https://doi.org/10.1016/B978-0-444-53802-4.00133-0

Balogh, K., Ahijado, A., Casillas, R., & Fernández, C. (1999). Contributions to the chronology of the Basal Complex of Fuerteventura, Canary Islands. *Journal of Volcanology and Geothermal Research*, *90*(1–2), 81–101. https://doi.org/10.1016/S0377-0273(99)00008-6

Belay, I. G., Tanaka, R., Kitagawa, H., Kobayashi, K., & Nakamura, E. (2019). Origin of ocean island basalts in the West African passive margin without mantle plume involvement. *Nature Communications*, *10*(1), 1–12. https://doi.org/10.1038/s41467-019-10832-7

Bernard-Griffiths, J., Gruau, G., Cornen, G., Azambre, B., & Macé, J. (1997). Continental lithospheric contribution to alkaline magmatism: Isotopic (Nd, Sr, Pb) and geochemical (REE) evidence from serra de monchique and mount ormonde complexes. *Journal of Petrology*, *38*(1), 115–132. https://doi.org/10.1093/petroj/38.1.115

Berrahma, M., & Delaloye, M. (1989). Données géochronologiques nouvelles sur le massif volcanique du Siroua (Anti-Atlas, maroc). *Journal of African Earth Sciences*, *9*(3–4), 651–656. https://doi.org/10.1016/0899-5362(89)90049-3

Berrahma, M., Delaloye, M., Faure-Muret, A., & Rachdi, H. E. N. (1993). Premières données géochronologiques sur le volcanisme alcalin du Jbel Saghro, Anti-Atlas, Maroc. *Journal of African Earth Sciences*, *17*(3), 333–341. https://doi.org/10.1016/0899-5362(93)90077-4

Bird, P. (2003). An updated digital model of plate boundaries. *Geochemistry Geophysics Geosystems*, *4*(3). https://doi.org/10.1029/2001GC000252

Blanco-Montenegro, I., Montesinos, F. G., & Arnoso, J. (2018). Aeromagnetic anomalies reveal the link between magmatism and tectonics during the early formation of the Canary Islands. *Scientific Reports*, *8*(1), 1–14. https://doi.org/10.1038/s41598-017-18813-w

Bodin, T., Salmon, M., Kennett, B. L. N., & Sambridge, M. (2012). Probabilistic surface reconstruction from multiple data sets: An example for the Australian Moho. *Journal of Geophysical Research: Solid Earth: Solid Earth*, *117*(10), 1–13. https://doi.org/10.1029/2012JB009547

Bonatto, L., Schimmel, M., Gallart, J., & Morales, J. (2013). Studying the 410-km and 660-km discontinuities beneath spain and morocco through detection of p-to-s conversions. *Geophysical Journal International*, *194*(2), 920–935. https://doi.org/10.1093/gji/ggt129

Bonatto, L., Schimmel, M., Gallart, J., & Morales, J. (2015). The upper-mantle transition zone beneath the Ibero-Maghrebian region as seen by teleseismic Pds phases. *Tectonophysics*, *663*, 212–224. https://doi.org/10.1016/j.tecto.2015.02.002

Bosch, D., Maury, R. C., Azzouzi, El M., Bollinger, C., Bellon, H., & Verdoux, P. (2014). Lithospheric origin for Neogene-Quaternary Middle Atlas lavas (Morocco): Clues from trace elements and Sr-Nd-Pb-Hf isotopes. *Lithos*, *205*, 247–265. https://doi.org/10.1016/j.lithos.2014.07.009

Boschi, L., Becker, T. W., & Steinberger, B. (2007). Mantle plumes: Dynamic models and seismic images. *Geochemistry, Geophysics, Geosystems*, *8*(10), 1–n. https://doi.org/10.1029/2007GC001733

Bowin, C., & Thompson, G. (1984). Residual geoid anomalies in Atlantic Ocean basin' relationship to mantle plumes. *Journal of Geophysical Research: Solid Earth*, *89*, 9905–9918.

Boyden, J. A, Muller, R. D., Gurnis, M., V. H. I. R. J, Vatson, & Cannon, J. S. (2011). Next-generation plate-tectonice reconstructions using GPlated. Geoinformatics: Cyberinfrastructure for the Solid Earth Sciences (pp. 95–113). Cambridge.

Buontempo, L., Bokelmann, G. H. R., Barruol, G., & Morales, J. (2008). Seismic anisotropy beneath southern Iberia from SKS splitting. *Earth and Planetary Science Letters*, *273*(3–4), 237–250. https://doi.org/10.1016/j.epsl.2008.06.024

Burdick, S., van der Hilst, R. D., Vernon, F. L., Martynov, V., Cox, T., Eakins, J., et al. (2012). Model Update March 2011: Upper mantle heterogeneity beneath North America from traveltime tomography with global and USArray transportable array data. *Seismological*, *83*(1), 23–28. https://doi.org/10.1785/gssrl

Burdick, S., Vernon, F. L., Martynov, V., Eakins, J., Cox, T., Tytell, J., et al. (2017). Model update May 2016: Upper-mantle heterogeneity beneath North America from travel-time tomography with global and US array data. *Seismological Research Letters*, *88*(2), 319–325. https://doi.org/10.1785/0220160186

Cao, Q., Van der Hilst, R. D., Hoop, D. M. V., & Shim, S. H. (2011). Seismic imaging of transition zone discontinuities suggests hot mantle west of Hawaii. *Science*, *332*(6033), 1068–1071. https://doi.org/10.1126/science.1202731

Carbó, A., Muñoz-Martín, A., Llanes, P., & Álvarez, J. (2003). Gravity analysis offshore the Canary Islands from a systematic survey. *Marine Geophysical Research*, *24*(1–2), 113–127. https://doi.org/10.1007/s11001-004-1336-2

Carracedo, J. C., Rodríguez Badiola, E., Guillou, H., Paterne, M., Scaillet, S., Pérez Torrado, F. J., et al. (2007). Eruptive and structural history of Teide Volcano and rift zones of Tenerife, Canary Islands. *Bulletin of the Geological Society of America*, *119*(9–10), 1027–1051. https://doi.org/10.1130/B26087.1

Carracedo, J. C., Rodrigues Badiola, E., & Soler, V. (1992). The 1730–1736 Eruption of Lanzarote, Canary Islands. *Journal of Volcanology and Geothermal Research*, *53*, 239–250. https://doi.org/10.1007/978-94-017-8628-7

Chang, S., Ferreira, A. M. G., Ritsema, J., Heijst, H. J., & Woodhouse, J. H. (2015). Joint inversion for global isotropic and radially anisotropic mantle structure including crustal thickness perturbations *Journal of Geophysical Research: Solid Earth*, *120*, 4278–4300. https://doi.org/10.1002/2014JB011824

Civiero, C., Armitage, J. J., Goes, S., & Hammond, J. O. S. (2019). The seismic signature of upper-mantle plumes: Application to the Northern East African Rift. *Geochemistry, Geophysics, Geosystems*, *20*, 6106–6122. https://doi.org/10.1029/2019GC008636

Civiero, C., Custódio, S., Duarte, J. C., Mendes, V. B., & Faccenna, C. (2020). Dynamics of the Gibraltar arc system: A complex interaction between plate convergence, slab pull, and mantle flow. *Journal of Geophysical Research: Solid Earth*, *125*(7), 1–23. https://doi.org/10.1029/2019JB018873

Civiero, C., Custódio, S., Rawlinson, N., Strak, V., Silveira, G., Arroucau, P., & Corela, C. (2019). Thermal nature of mantle upwellings below the Ibero-Western Maghreb region inferred from teleseismic tomography. *Journal of Geophysical Research: Solid Earth*, *124*(2), 1781–1801. https://doi.org/10.1029/2018JB016531

19448007, 2021, 13, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021GL092874, Wiley Online Library on [30/12/2022]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Civiero, C., Strak, V., Custódio, S., Silveira, G., Rawlinson, N., Arroucau, P., & Corela, C. (2018). A common deep source for upper-mantle upwellings below the Ibero-western Maghreb region from teleseismic P-wave travel-time tomography. *Earth and Planetary Science Letters*, *499*, 157–172. https://doi.org/10.1016/J.EPSL10.1016/j.epsl.2018.07.024

Conrad, C. P., Bianco, T. A., Smith, E. I., & Wessel, P. (2011). Patterns of intraplate volcanism controlled by asthenospheric shear. *Nature Geoscience*, *4*(5), 317–321. https://doi.org/10.1038/ngeo1111

Cottaar, S., & Lekic, V. (2016). Morphology of seismically slow lower-mantle structures. *Geophysical Journal International*, *207*(2), 1122–1136. https://doi.org/10.1093/gji/ggw324

Courtillot, V., Davaille, A., Besse, J., & Stock, J. (2003). Three distinct types of hotspots in the Earth's mantle. *Earth and Planetary Science Letters*, *205*(3–4), 295–308. https://doi.org/10.1016/S0012-821X(02)01048-8

Cserepes, L., & Yuen, D. A. (2000). On the possibility of a second kind of mantle plume. *Earth and Planetary Science Letters*, *183*(1–2), 61–71. https://doi.org/10.1016/S0012-821X(00)00265-X

Davaille, A. (1999). Simultaneous generation of hotspots and superwells by convetion in a heterogeneous planetary mantle. *Nature*, *402*(6763), 756–760. https://doi.org/10.1038/45461

Davaille, A., & Limare, A. (2015). *Laboratory studies of mantle convection. Treatise on Geophysics, 2^nd^ Edn*. Elsevier, Oxford.

Davaille, A., & Romanowicz, B. (2020). Deflating the LLSVPs: Bundles of mantle thermochemical plumes rather than thick stagnant "piles." *Tectonics*, *39*(10), 1–21. https://doi.org/10.1029/2020tc006265

Davaille, A., Stutzmann, E., Silveira, G., Besse, J., & Courtillot, V. (2005). Convective patterns under the Indo-Atlantic « box ». *Earth and Planetary Science Letters*, *239*(3–4), 233–252. https://doi.org/10.1016/j.epsl.2005.07.024

Davaille, A., & Vatteville, J. (2005). On the transient nature of mantle plumes. *Geophysical Research Letters*, *32*, a–n. https://doi.org/10.1029/2005GL023029

Deuss, A. (2007). Seismic observations of transition-zone discontinuities beneath hotspot locations. *Special Paper 430: Plates, Plumes and Planetary Processes*, 121–136. https://doi.org/10.1130/2007.2430(07)

Deuss, A. (2009). Global observations of mantle discontinuities using SS and PP precursors. *Surveys in Geophysics*, *30*(4–5), 301–326. https://doi.org/10.1007/s10712-009-9078-y

Díaz, J., Gallart, J., Morais, I., Silveira, G., Pedreira, D., Pulgar, J. A., et al. (2015). From the Bay of Biscay to the High Atlas: Completing the anisotropic characterization of the upper mantle beneath the westernmost Mediterranean region. *Tectonophysics*, *663*, 192–202. https://doi.org/10.1016/j.tecto.2015.03.007

Díaz, J., Gallart, J., Villaseñor, A., Mancilla, F., Pazos, A., Córdoba, D., et al. (2010). Mantle dynamics beneath the Gibraltar Are (western Mediterranean) from shear-wave splitting measurements on a dense seismic array. *Geophysical Research Letters*, *37*(18), 1–5. https://doi.org/10.1029/2010GL044201

D'Oriano, F., Angeletti, L., Capotondi, L., Laurenzi, M. A., López Correa, M., Taviani, M., et al. (2010). Coral Patch and Ormonde seamounts as a product of the Madeira hotspot, Eastern Atlantic Ocean. *Terra Nova*, *22*(6), 494–500. https://doi.org/10.1111/j.1365-3121.2010.00973.x10.1111/ter.2009.22.issue-1

Duggen, S., Hoernle, K. A., Hauff, F., Klügel, A., Bouabdellah, M., & Thirlwall, M. F. (2009). Flow of Canary mantle plume material through a subcontinental lithospheric corridor beneath Africa to the Mediterranean. *Geology*, *37*(3), 283–286. https://doi.org/10.1130/G25426A.1

Durand, S., Debayle, E., Ricard, Y., & Lambotte, S. (2016). Seismic evidence for a change in the large-scale tomographic pattern across the D′′ layer. *Geophysical Research Letters*, *43*(15), 7928–7936. https://doi.org/10.1002/2016GL069650

Durand, S., Debayle, E., Ricard, Y., Zaroli, C., & Lambotte, S. (2017). Confirmation of a change in the global shear velocity pattern at around 1000km depth. *Geophysical Journal International*, *211*(3), 1628–1639. https://doi.org/10.1093/gji/ggx405

El Azzouzi, E., El, M., Mohammed, A., Universit, M., Occidentale, B., Universit, B., & Occidentale, B. (2010). Petrology and K-Ar chronology of the Neogene-Quaternary Middle Atlas basaltic province, Morocco. *Bulletin de La Société Géologique de France*. https://doi.org/10.2113/gssgfbull.181.3.243

Farnetani, C. G., & Samuel, H. (2005). Beyond the thermal plume paradigm. *Geophysical Research Letters*, *32*(7), 1–4. https://doi.org/10.1029/2005GL022360

Flament, N., Williams, S., Müller, R. D., Gurnis, M., & Bower, D. J. (2017). Origin and evolution of the deep thermochemical structure beneath Eurasia. *Nature Communications*, *8*. https://doi.org/10.1038/ncomms14164

Flanagan, M. P., & Shearer, P. M. (1998). Global mapping of topography on transition zone velocity discontinuities by stacking SS precursors. *Journal of Geophysical Research: Solid Earth*, *103*(97), 2673–2692.

Forte, A. M., Quéré, S., Moucha, R., Simmons, N. A., Grand, S. P., Mitrovica, J. X., & Rowley, D. B. (2010). Joint seismic-geodynamic-mineral physical modeling of African geodynamics: A reconciliation of deep-mantle convection with surface geophysical constraints. *Earth and Planetary Science Letters*, *295*(3–4), 329–341. https://doi.org/10.1016/j.epsl.2010.03.017

Foulger, G. R, & Natland, J. H. (2003). Is " Hotspot " Volcanism a Consequence of Plate Tectonics? (May), 300(5621), 921–923.

French, S. W., & Romanowicz, B. (2015). Broad plumes rooted at the base of the Earth's mantle beneath major hotspots. *Nature*, *525*(7567), 95–99. https://doi.org/10.1038/nature14876

French, S. W., & Romanowicz, B. A. (2014). Whole-mantle radially anisotropic shear velocity structure from spectral-element waveform tomography. *Geophysical Journal International*, *199*(3), 1303–1327. https://doi.org/10.1093/gji/ggu334

Fukao, Y., & Obayashi, M. (2013). Subducted slabs stagnant above, penetrating through, and trapped below the 660 km discontinuity. *Journal of Geophysical Research: Solid Earth*, *118*(11), 5920–5938. https://doi.org/10.1002/2013JB010466

Fullea, J., Fernàndez, M., Afonso, J. C., Vergés, J., & Zeyen, H. (2010). The structure and evolution of the lithosphere-asthenosphere boundary beneath the Atlantic-Mediterranean Transition Region. *Lithos*, *120*(1–2), 74–95. https://doi.org/10.1016/j.lithos.2010.03.003

Fullea, J., Fernàndez, M., & Zeyen, H. (2008). FA2BOUG-A FORTRAN 90 code to compute Bouguer gravity anomalies from gridded free-air anomalies: Application to the Atlantic-Mediterranean transition zone. *Computers & Geosciences*, *34*(12), 1665–1681. https://doi.org/10.1016/j.cageo.2008.02.018

Fullea, J., Fernàndez, M., Zeyen, H., & Vergés, J. (2007). A rapid method to map the crustal and lithospheric thickness using elevation, geoid anomaly and thermal analysis. Application to the Gibraltar Arc System, Atlas Mountains and adjacent zones. *Tectonophysics*, *430*(1–4), 97–117. https://doi.org/10.1016/j.tecto.2006.11.003

Garnero, E. J., & McNamara, A. K. (2008). Structure and dynamics of earth's lower mantle. *Science*, *320*(5876), 626–628. https://doi.org/10.1126/science.1148028

Geldmacher, J., & Hoernle, K. (2000). The 72 Ma geochemical evolution of the Madeira hotspot (eastern North Atlantic): Recycling of Paleozoic (≤500 Ma) oceanic lithosphere. *Earth and Planetary Science Letters*, *183*(1–2), 73–92. https://doi.org/10.1016/S0012-821X(00)00266-1

19448007, 2021, 13, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021GL092874, Wiley Online Library on [30/12/2022]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Geldmacher, J., Hoernle, K., Bogaard, P. V. D., Duggen, S., & Werner, R. (2005). New40Ar39Ar age and geochemical data from seamounts in the Canary and Madeira volcanic provinces: Support for the mantle plume hypothesis. *Earth and Planetary Science Letters*, *237*(1–2), 85–101. https://doi.org/10.1016/j.epsl.2005.04.037
Geldmacher, J., Hoernle, K., Hanan, B. B., Blichert-Toft, J., Hauff, F., Gill, J. B., & Schmincke, H. U. (2011). Hafnium isotopic variations in East Atlantic intraplate volcanism. *Contributions to Mineralogy and Petrology*, *162*(1), 21–36. https://doi.org/10.1007/s00410-010-0580-5
Geldmacher, J., Hoernle, K., Klügel, A., Van Den Bogaard, P., Wombacher, F., & Berning, B. (2006). Origin and geochemical evolution of the Madeira-Tore Rise (eastern North Atlantic) *Journal of Geophysical Research: Solid Earth*, *111*(9). https://doi.org/10.1029/2005JB003931
Geldmacher, J., Hoernle, K., Van Den Bogaard, P., Zankl, G., & Garbe-Schönberg, D. (2001). Earlier history of the ≥70-Ma-old Canary hotspot based on the temporal and geochemical evolution of the Selvagen Archipelago and neighboring seamounts in the Eastern North Atlantic. *Journal of Volcanology and Geothermal Research*, *111*(1–4), 55–87. https://doi.org/10.1016/S0377-0273(01)00220-7
Geldmacher, J., Van Den Bogaard, P., Hoernle, K., & Schmincke, H. U. (2000). The 40Ar/39Ar age dating of the Madeira Archipelago and hotspot track (eastern North Atlantic). *Geochemistry, Geophysics, Geosystems*, *1*, a–n. https://doi.org/10.1029/1999GC000018
Grand, S. P. (2002). Mantle shear-wave tomography and the fate of subducted slabs. *Philosophical Transactions of the Royal Society A: Mathematical, Physical & Engineering Sciences*, *360*(1800), 2475–2491. https://doi.org/10.1098/rsta.2002.1077
Grange, M., Scharer, U., Merle, R., Girardeau, J., & Cornen, G. (2010). Plume-lithosphere interaction during migration of cretaceous alkaline magmatism in SW Portugal: Evidence from U-Pb Ages and Pb-Sr-Hf isotopes. *Journal of Petrology*, *51*(5), 1143–1170. https://doi.org/10.1093/petrology/egq018
Gu, Y. J., An, Y., Sacchi, M., Schultz, R., & Ritsema, J. (2009). Mantle reflectivity structure beneath oceanic hotspots. *Geophysical Journal International*, *178*(3), 1456–1472. https://doi.org/10.1111/j.1365-246X.2009.04242.x
Gutiérrez, M., Casillas, R., Fernández, C., Balogh, K., Ahijado, A., Castillo, C., et al. (2006). The submarine volcanic succession of the basal complex of Fuerteventura, Canary Islands: A model of submarine growth and emergence of tectonic volcanic islands. *Bulletin of the Geological Society of America*, *118*(7–8), 785–804. https://doi.org/10.1130/B25821.1
Herrero-Hernández, A., López-Moro, F. J., Gallardo-Millán, J. L., Martín-Serrano, Á., & Gómez-Fernández, F. (2014). Volcanism–sedimentation interaction in the Campo de Calatrava Volcanic Field (Spain): A magnetostratigraphic and geochronological study. *International Journal of Earth Sciences*, *104*(1), 103–122. https://doi.org/10.1007/s00531-014-1053-2
Hoernle, K., & Schmincke, H. U. (1993). The role of partial melting in the 15-MA geochemical evolution of gran canaria: A blob model for the Canary hotspot. *Journal of Petrology*, *34*(3), 599–626. https://doi.org/10.1093/petrology/34.3.599
Hoernle, K., Schwindrofska, A., Werner, R., van den Bogaard, P., Hauff, F., Uenzelmann-Neben, G., & Garbe-Schönberg, D. (2016). Tectonic dissection and displacement of parts of Shona hotspot volcano 3500 km along the Agulhas-Falkland Fracture Zone. *Geology*, *44*(4), 263–266. https://doi.org/10.1130/G37582.1
Hoernle, K., & Tilton, G. (1991). Sr-Nd-Pb isotope data for Fuerteventura (Canary Islands) basal complex and subaerial volcanics: Applications to magma genesis and evolution. *Schweizerische Mineralogische Und Petrographische Mitteilungen*, *71*, 5–21. https://doi.org/10.5169/seals-54342
Hoernle, K., Zhang, Y.-S., & Graham, D. (1995). Seismic and geochemical evidence for large-scale mantle upwelling beneath the eastern Atlantic and western and central Europe. *Nature*, *374*, 34–39. https://doi.org/10.1038/374034a0
Homrighausen, S., Hoernle, K., Zhou, H., Geldmacher, J., Wartho, J. A., Hauff, F., et al. (2020). Paired EMI-HIMU hotspots in the South Atlantic-Starting plume heads trigger compositionally distinct secondary plumes? *Science Advances*, *6*(28), 1–10. https://doi.org/10.1126/sciadv.aba0282
Hosseini, K. (2016). Global multiple-frequency seismic tomography using teleseismic and core-diffracted body waves. Ludwig-Maximilians-Universität München. Retrieved from http://nbn-resolving.de/urn:nbn:de:bvb:19-195973
Hosseini, K., Matthews, K. J., Sigloch, K., Shephard, G. E., Domeier, M., & Tsekhmistrenko, M. (2018). SubMachine: Web-based tools for exploring seismic tomography and other models of earth's deep interior. *Geochemistry, Geophysics, Geosystems*, *19*(5), 1464–1483. https://doi.org/10.1029/2018GC007431
Hosseini, K., Sigloch, K., Tsekhmistrenko, M., Zaheri, A., Nissen-Meyer, T., & Igel, H. (2020). Global mantle structure from multifrequency tomography using P, PP and P-diffracted waves. *Geophysical Journal International*, *220*(1), 96–141. https://doi.org/10.1093/gji/ggz394
Houser, C., Masters, G., Flanagan, M., & Shearer, P. (2008). Determination and analysis of long-wavelength transition zone structure using SS precursors. *Geophysical Journal International*, *174*(1), 178–194. https://doi.org/10.1111/j.1365-246X.2008.03719.x
Houser, C., Masters, G., Shearer, P., & Laske, G. (2008). Shear and compressional velocity models of the mantle from cluster analysis of long-period waveforms. *Geophysical Journal International*, *174*(1), 195–212. https://doi.org/10.1111/j.1365-246X.2008.03763.x
Jenkins, J., Deuss, A., & Cottaar, S. (2017). Converted phases from sharp 1000 km depth mid-mantle heterogeneity beneath Western Europe. *Earth and Planetary Science Letters*, *459*, 196–207. https://doi.org/10.1016/j.epsl.2016.11.031
Kennett, B. L. N., Sambridge, M., & Williamson, P. R. (1988). Subspace methods for large inverse problems with multiple parameter classes. *Geophysical Journal International*, *94*, 237–247. https://doi.org/10.1111/j.1365-246X.1988.tb05898.x
King, S. D. (2007). Hotspots and edge-driven convection. *Geology*, *3*, 223–226. https://doi.org/10.1130/G23291A.1
King, S. D., & Adam, C. (2014). Hotspot swells revisited. *Physics of the Earth and Planetary Interiors*, *235*, 66–83. https://doi.org/10.1016/j.pepi.2014.07.006
Koelemeijer, P., Ritsema, J., Deuss, A., & van Heijst, H. J. (2016). SP12RTS: A degree-12 model of shear- and compressional-wave velocity for Earth's mantle. *Geophysical Journal International*, *204*(2), 1024–1039. https://doi.org/10.1093/gji/ggv481
Kool, de, M., Rawlinson, N., & Sambridge, M. (2006). A practical grid-based method for tracking multiple refraction and reflection phases in three-dimensional heterogeneous media. *Geophysical Journal International*, *167*(1), 253–270. https://doi.org/10.1111/j.1365-246X.2006.03078.x
Kumagai, I., Davaille, A., & Kurita, K. (2007). On the fate of thermally buoyant mantle plumes at density interfaces. *Earth and Planetary Science Letters*, *254*(1–2), 180–193. https://doi.org/10.1016/j.epsl.2006.11.029
Kumagai, I., Davaille, A., Kurita, K., & Stutzmann, E. (2008). Mantle plumes: Thin, fat, successful, or failing? Constraints to explain hot spot volcanism through time and space. *Geophysical Research Letters*, *35*(16), 1–5. https://doi.org/10.1029/2008GL035079
Lawrence, J. F., & Shearer, P. M. (2006). A global study of transition zone thickness using receiver functions. *Journal of Geophysical Research: Solid Earth*, *111*(6), 1–10. https://doi.org/10.1029/2005JB003973
Lawrence, J. F., & Shearer, P. M. (2008). Imaging mantle transition zone thickness with SdS - SS finite-frequency sensitivity kernels. *Geophysical Journal International*, *174*(1), 143–158. https://doi.org/10.1111/j.1365-246X.2007.03673.x
Lekić, V., & Romanowicz, B. (2011). Inferring upper-mantle structure by full waveform tomography with the spectral element method. *Geophysical Journal International*, *185*(2), 799–831. https://doi.org/10.1111/j.1365-246X.2011.04969.x

19448007, 2021, 13, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021GL092874, Wiley Online Library on [30/12/2022]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Levander, A., Bezada, M. J., Niu, F., Humphreys, E. D., Palomeras, I., Thurner, S. M., et al. (2014). Subduction-driven recycling of continental margin lithosphere. *Nature*, *515*(7526), 253–256. https://doi.org/10.1038/nature13878

Li, C, Van Der Hilst, R. D, Engdahl, E. R, & Burdick, S. (2008). A new global model for P wave speed variations in Earth's mantle *Geochemistry, Geophysics, Geosystems*, *9*(5). https://doi.org/10.1029/2007GC001806

Li, X., Kind, R., & Yuan, X. (2003). Seismic study of upper mantle and transition zone beneath hotspots. *Physics of the Earth and Planetary Interiors*, *136*(1–2), 79–92. https://doi.org/10.1016/S0031-9201(03)00021-9

Liu, H., & Leng, W. (2020). Plume -tree structure induced by low-viscosity layers in the upper mantle. *Geophysical Research Letters*, *47*(1), 1–10. https://doi.org/10.1029/2019GL086508

Liu, X., & Zhao, D. (2014). Seismic evidence for a mantle plume beneath the Cape Verde hotspot. *International Geology Review*, *56*(10), 1213–1225. https://doi.org/10.1080/00206814.2014.930720

Long, X., Geldmacher, J., Hoernle, K., Hauff, F., Wartho, J. A., & Garbe-Schönberg, C. D. (2020). Origin of isolated seamounts in the Canary Basin (East Atlantic): The role of plume material in the origin of seamounts not associated with hotspot tracks. *Terra Nova*, *32*(5), 390–398. https://doi.org/10.1111/ter.12468

Longpré, M. A., Chadwick, J. P., Wijbrans, J., & Iping, R. (2011). Age of the El Golfo debris avalanche, El Hierro (Canary Islands): New constraints from laser and furnace 40Ar/39Ar dating. *Journal of Volcanology and Geothermal Research*, *203*(1–2), 76–80. https://doi.org/10.1016/j.jvolgeores.2011.04.002

Lu, C., & Grand, S. P. (2016). The effect of subducting slabs in global shear wave tomography. *Geophysical Journal International*, *205*(2), 1074–1085. https://doi.org/10.1093/gji/ggw072

Lu, C., Grand, S. P., Lai, H., & Garnero, E. J. (2019). TX2019slab: A New P and S tomography model incorporating subducting slabs. *Journal of Geophysical Research: Solid Earth*, *124*(11), 11549–11567. https://doi.org/10.1029/2019JB017448

Lustrino, M., & Wilson, M. (2007a). The circum-Mediterranean anorogenic Cenozoic igneous province. *Earth-Science Reviews*, *81*(1–2), 1–65. https://doi.org/10.1016/j.earscirev.2006.09.002

Lustrino, M., & Wilson, M. (2007b). The circum-Mediterranean anorogenic Cenozoic igneous province. *Earth-Science Reviews*, *81*, 1–65. https://doi.org/10.1016/j.earscirev.2006.09.002

Lynner, C., & Long, M. D. (2014). Lowermost mantle anisotropy and deformation along the boundary of the African LLSVP. *Geophysical Research Letters*, *41*(10), 3447–3454. https://doi.org/10.1002/2014GL059875

Manjón-Cabeza Córdoba, A., & Ballmer, M. (2020). The role of edge-driven convection in the generation of volcanism I: A 2D systematic study. *Solid Earth Discussions*, 1–25. https://doi.org/10.5194/se-2020-120

Martinez-Arevalo, C., Mancillade, F. L., Helffrich, G., & Garcia, A. (2013). Seismic evidence of a regional sublithospheric low velocity layer beneath the Canary Islands. *Tectonophysics*, *608*, 586–599. https://doi.org/10.1016/j.tecto.2013.08.021

Mata, J., Kerrich, R., MacRae, N. D., & Wu, T. W. (1998). Elemental and isotopic (Sr, Nd, and Pb) characteristics of Madeira Island basalts: Evidence for a composite HIMU - EM I plume fertilizing lithosphere. *Canadian Journal of Earth Sciences*, *35*(9), 980–997. https://doi.org/10.1139/e98-046

Mériaux, C. A., Duarte, J. C., Duarte, S. S., Schellart, W. P., Chen, Z., Rosas, F., et al. (2015). Capture of the Canary mantle plume material by the Gibraltar arc mantle wedge during slab rollback. *Geophysical Journal International*, *201*(3), 1717–1721. https://doi.org/10.1093/gji/ggv120

Mériaux, C. A., Mériaux, A.-S., Schellart, W. P., Duarte, J. C., Duarte, S. S., & Chen, Z. (2016). Mantle plumes in the vicinity of subduction zones. *Earth and Planetary Science Letters*, *454*, 166–177. https://doi.org/10.1016/j.epsl.2016.09.001

Merle, R., Jourdan, F., & Girardeau, J. (2018). Geochronology of the Tore-Madeira Rise seamounts and surrounding areas: A review. *Australian Journal of Earth Sciences*, *65*(5), 591–605. https://doi.org/10.1080/08120099.2018.1471005

Merle, R., Schärer, U., Girardeau, J., & Cornen, G. (2006). Cretaceous seamounts along the continent-ocean transition of the Iberian margin: U-Pb ages and Pb-Sr-Hf isotopes. *Geochimica et Cosmochimica Acta*, *70*(19), 4950–4976. https://doi.org/10.1016/j.gca.2006.07.004

Merle, R. E., Jourdan, F., Chiaradia, M., Olierook, H. K. H., & Manatschal, G. (2019). Origin of widespread Cretaceous alkaline magmatism in the Central Atlantic: A single melting anomaly? *Lithos*, *342–343*, 480–498. https://doi.org/10.1016/j.lithos.2019.06.002

Miller, M. S, Allam, A. A, Becker, T. W, Leo, D. J. F, & Wookey, J. (2013). Constraints on the tectonic evolution of the westernmost Mediterranean and northwestern Africa from shear wave splitting analysis. *Earth and Planetary Science Letters*, *375*, 234–243. https://doi.org/10.1016/j.epsl.2013.05.036

Miller, M. S., Driscoll, L. J. O., Butcher, A. J., & Thomas, C. (2015). Imaging Canary Island hotspot material beneath the lithosphere of Morocco and southern Spain. *Earth and Planetary Science Letters*, *431*, 186–194. https://doi.org/10.1016/j.epsl.2015.09.026

Miranda, R., Valadares, V., Terrinha, P., Mata, J., Azevedodo, M. R., Gaspar, M., et al. (2009). Age constraints on the Late Cretaceous alkaline magmatism on the West Iberian Margin. *Cretaceous Research*, *30*(3), 575–586. https://doi.org/10.1016/j.cretres.2008.11.002

Missenard, Y., & Cadoux, A. (2012a). Can Moroccan Atlas lithospheric thinning and volcanism be induced by Edge-Driven Convection? *Terra Nova*, *24*(1), 27–33. https://doi.org/10.1111/j.1365-3121.2011.01033.x

Missenard, Y., & Cadoux, A. (2012b). Can Moroccan Atlas lithospheric thinning and volcanism be induced by Edge-Driven Convection. *Terra Nova*, *24*, 27–33. https://doi.org/10.1111/j.1365-3121.2011.01033.x

Mjelde, R., Wessel, P., & Müller, R. D. (2010). Global pulsations of intraplate magmatism through the Cenozoic. *Lithosphere*, *2*(5), 361–376. https://doi.org/10.1130/L107.1

Mokhtari, A., & Velde, D. (1988). Xenocrysts in Eocene Camptonites from Taourirt, Northern Morocco. *Mineralogical Magazine*, *52*(368), 587–601. https://doi.org/10.1180/minmag.1988.052.368.04

Montelli, R, Nolet, G, Dahlen, F. A., & Masters, G. (2006). A catalog of deep mantle plumes: New results from finitefrequency tomography *Geochemistry, Geophysics, Geosystems*, *7*(11). https://doi.org/10.1029/2006GC001248

Morgan, W. J. (1972). Deep mantle convection plumes and plate motions. *The American Association of Petroleum Geologists Bulletin*. https://doi.org/10.1306/819A3E50-16C5-11D7-8645000102C1865D

Moulik, P., & Ekström, G. (2014). An anisotropic shear velocity model of the Earth's mantle using normal modes, body waves, surface waves and long-period waveforms. *Geophysical Journal International*, *199*(3), 1713–1738. https://doi.org/10.1093/gji/ggu356

Obayashi, M., Yoshimitsu, J., Nolet, G., Fukao, Y., Shiobara, H., Sugioka, H., et al. (2013). Finite frequency whole mantle P wave tomography: Improvement of subducted slab images. *Geophysical Research Letters*, *40*(21), 5652–5657. https://doi.org/10.1002/2013GL057401

Ogawa, M. (2007). Superplumes, plates, and mantle magmatism in two-dimensional numerical models. *Journal of Geophysical Research: Solid Earth*, *112*(6), 1–16. https://doi.org/10.1029/2006JB004533

Oyarzun, R., Doblas, M., López-Ruiz, J., & Cebrá, J. M. (1997). Opening of the central Atlantic and asymmetric mantle upwelling phenomena : Implications for long-lived magmatism in western North Africa and Europe. *Geology*, 727–730.

19448007, 2021, 13, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021GL092874, Wiley Online Library on [30/12/2022]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Palomeras, I., Villaseñor, A., Thurner, S., Levander, A., Gallart, J., & Harnafi, M. (2017). Lithospheric structure of Iberia and Morocco using finite-frequency Rayleigh wave tomography from earthquakes and seismic ambient noise. *Geochemistry, Geophysics, Geosystems*, *18*, 1824–1840. https://doi.org/10.1002/2016GC006657

Palomeras, T. , S., Levander, A., Liu, K., Villaseñor, A., Carbonell, R., & Harnafi, M. (2014). Finite-frequency Rayleigh wave tomography of the western Mediterranean: Mapping its lithospheric structure. *Geochemistry, Geophysics, Geosystems*, *15*(1), 140–160. https://doi.org/10.1002/2013GC004861

Panning, M. P., Lekić, V., & Romanowicz, B. A. (2010). Importance of crustal corrections in the development of a new global model of radial anisotropy. *Journal of Geophysical Research: Solid Earth*, *115*(12), 1–18. https://doi.org/10.1029/2010JB007520

Piromallo, C., Gasperini, D., Macera, P., & Faccenna, C. (2008). A late Cretaceous contamination episode of the European – Mediterranean mantle. *Earth and Planetary Science Letters*, *268*, 15–27. https://doi.org/10.1016/j.epsl.2007.12.019

Rachdi, H., Berrahma, M., Delaloye, M., Faure-Muret, A., & Dahmani, M. (1997). Le volcanisme tertiaire du Rekkame (Maroc): Pétrologie, géochimie et géochronologie. *Journal of African Earth Sciences*, *24*(3), 259–269. https://doi.org/10.1016/S0899-5362(97)00042-0

Raddick, M. J., Parmentier, E. M., & Scheirer, D. S. (2002). Buoyant decompression melting: A possible mechanism for intraplate volcanism. *Journal of Geophysical Research: Solid Earth*, *107*(B10), 2228–2231. https://doi.org/10.1029/2001jb000617

Ramalho, R. S, Silveira, da, A. B, Fonseca, P. E, Madeira, J, Cosca, M., et al. (2015). The emergence of volcanic oceanic islands on a slow-moving plate: The example of Madeira Island, NE Atlantic. *Geochemistry, Geophysics, Geosystems*, *16*(1), 267–300. https://doi.org/10.1002/2014GC005684.Key

Rawlinson, N., & Kennett, B. L. N. (2004). Rapid estimation of relative and absolute delay times across a network by adaptive stacking. *Geophysical Journal International*, *157*(1), 332–340. https://doi.org/10.1111/j.1365-246X.2004.02188.x

Rawlinson, N., & Sambridge, M. (2004). Multiple reflection and transmission phases in complex layered media using a multistage fast marching method. *Geophysics*, *69*(11), 1338–1350. https://doi.org/10.1190/1.1801950

Rawlinson, N., & Urvoy, M. (2006). Simultaneous inversion of active and passive source datasets for 3-D seismic structure with application to Tasmania. *Geophysical Research Letters*, *33*(24), 1–5. https://doi.org/10.1029/2006GL028105

Rickers, F., Fichtner, A., & Trampert, J. (2013). The Iceland-Jan Mayen plume system and its impact on mantle dynamics in the North Atlantic region: Evidence from full-waveform inversion. *Earth and Planetary Science Letters*, *367*, 39–51. https://doi.org/10.1016/j.epsl.2013.02.022

Ritsema, J., Deuss, A., Van Heijst, H. J., & Woodhouse, J. H. (2011). S40RTS: A degree-40 shear-velocity model for the mantle from new Rayleigh wave dispersion, teleseismic traveltime and normal-mode splitting function measurements. *Geophysical Journal International*, *184*(3), 1223–1236. https://doi.org/10.1111/j.1365-246X.2010.04884.x

Ritsema, J., Van Heijst, H. J., & Woodhouse, J. H. (1999). Complex shear wave velocity structure imaged beneath Africa and Iceland. *Science*, *286*(5446), 1925–1931. https://doi.org/10.1126/science.286.5446.1925

Rock, N. M. S. (1982). The late Cretaceous alkaline igneous province in the Iberian Peninsula, and its tectonic significance. *Lithos*, *15*(2), 111–131. https://doi.org/10.1016/0024-4937(82)90004-4

Rudolph, M. L., Lekić, V., & Lithgow-Bertelloni, C. (2015). Viscosity jump in Earth's mid-mantle. *Science*, *350*(6266), 1349–1352. https://doi.org/10.1126/science.aad1929

Saki, M., Thomas, C., Nippress, S. E. J., & Lessing, S. (2015). Topography of upper mantle seismic discontinuities beneath the North Atlantic : The Azores, Canary and Cape Verde plumes. *Earth and Planetary Science Letters*, *409*, 193–202. https://doi.org/10.1016/j.epsl.2014.10.052

Sanchez, G., Merle, R., Hinschberger, F., Thinon, I., & Girardeau, J. (2019). Post-spreading deformation and associated magmatism along the Iberia-Morocco Atlantic margins: Insight from submarine volcanoes of the Tore-Madeira Rise. *Marine Geology*, *407*(June 2018), 76–93. https://doi.org/10.1016/j.margeo.2018.10.011

Sandwell, D. T., Müller, R. D., Smith, W. H. F., Garcia, E., & Francis, R. (2014). New global marine gravity model from CryoSat-2 and Jason-1 reveals buried tectonic structure. *Science*, *346*(6205), 65–67. https://doi.org/10.1126/science.1258213

Schlaphorst, D, Silveira, G, Mata, J, Krüger, F, & Dahm, T. (2021). Similarities between the Madeira and Canary hotspots revealed by seismic anisotropy from teleseismic and local shear-wave splitting with the SIGHT Project, 50019.

Schmincke, H. U. (1982). Volcanic and chemical evolution of the Canary Islands. *Geology of the Northwest African Continental Margin*, 273–306. https://doi.org/10.1007/978-3-642-68409-810.1007/978-3-642-68409-8_12

Schubert, G., Masters, G., Olson, P., & Tackley, P. (2004). Superplumes or plume clusters? *Physics of the Earth and Planetary Interiors*, *146*(1–2), 147–162. https://doi.org/10.1016/j.pepi.2003.09.025

Sethian, J. A. (1996). A fast marching level set method for monotonically advancing fronts. *Pnas*, *93*(4), 1591–1595. https://doi.org/10.1073/pnas.93.4.1591

Shephard, G. E., Matthews, K. J., Hosseini, K., & Domeier, M. (2017). On the consistency of seismically imaged lower mantle slabs. *Scientific Reports*, *7*(1), 1–17. https://doi.org/10.1038/s41598-017-11039-w

Silveira, G., Stutzmann, E., Davaille, A., Montagner, J., Mendes-Victor, L., & Sebai, A. (2006). Azores hotspot signature in the upper mantle. *Journal of Volcanology and Geothermal Research*, *156*, 23–34. https://doi.org/10.1016/j.jvolgeores.2006.03.022

Simmons, N. A., Forte, A. M., Boschi, L., & Grand, S. P. (2010). GyPSuM: A joint tomographic model of mantle density and seismic wave speeds. *Journal of Geophysical Research: Solid Earth*, *115*(12), 1–24. https://doi.org/10.1029/2010JB007631

Simmons, N. A., Myers, S. C., Johannesson, G., & Matzel, E. (2012). LLNL-G3Dv3: Global P wave tomography model for improved regional and teleseismic travel time prediction. *Journal of Geophysical Research: Solid Earth*, *117*(10), B10302. https://doi.org/10.1029/2012jb009525

Smith, R. B., Jordan, M., Steinberger, B., Puskas, C. M., Farrell, J., Waite, G. P., et al. (2009). Geodynamics of the Yellowstone hotspot and mantle plume: Seismic and GPS imaging, kinematics, and mantle flow. *Journal of Volcanology and Geothermal Research*, *188*(1–3), 26–56. https://doi.org/10.1016/j.jvolgeores.2009.08.020

Spieker, K, Wölbern, I, Thomas, C, Harnafi, M, & Moudnib, L. (2014). Crustal and upper-mantle structure beneath the western Atlas Mountains in SW Morocco derived from receiver functions. *Geophysical Journal International*, *198*(3), 1474–1485. https://doi.org/10.1093/gji/ggu216

Sun, S.-S. (1980). Lead isotopic study of young volcanic rocks from mid-ocean ridges, ocean islands and island arcs. *Philosophical Transactions of the Royal Society of London - Series A: Mathematical and Physical Sciences*, *297*(1431), 409–445. https://doi.org/10.1098/rsta.1980.0224

Tapley, B., Ries, J., Bettadpur, S., Chambers, D., Cheng, M., Condi, F., et al. (2005). GGM02-An improved Earth gravity field model from GRACE. *Journal of Geodesy*, *79*(8), 467–478. https://doi.org/10.1007/s00190-005-0480-z

19448007, 2021, 13, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021GL092874, Wiley Online Library on [30/12/2022]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Tavares Martins, L. (1999). Cretaceous alkaline magmatism in algarve Littiral (South Portugal): A Basanite-Lamprophyre Rock Siute. *Geolines*.

Teixell, A., Ayarza, P., Zeyen, H., Fernàndez, M., & Arboleya, M. L. (2005). Effects of mantle upwelling in a compressional setting: The Atlas Mountains of Morocco. *Terra Nova*, *17*(5), 456–461. https://doi.org/10.1111/j.1365-3121.2005.00633.x

Tesoniero, A., Auer, L., Boschi, L., & Cammarano, F. (2015). Hydration of marginal basins and compositional variations within the continental lithospheric mantle inferred from a new global model of shear and compressional velocity. *Journal of Geophysical Research B: Solid Earth*, *120*(11), 7789–7813. https://doi.org/10.1002/2015JB012026

Torsvik, T. H., Smethurst, M. A., Burke, K., & Steinberger, B. (2008). Long term stability in deep mantle structure: Evidence from the ∼ 300 Ma Skagerrak-Centered Large Igneous Province (the SCLIP). *Earth and Planetary Science Letters*, *267*(3–4), 444–452. https://doi.org/10.1016/j.epsl.2007.12.004

Torsvik, T. H., Steinberger, B., Shephard, G. E., Doubrovine, P. V., Gaina, C., Domeier, M., et al. (2019). Pacific-Panthalassic reconstructions: Overview, errata and the way forward. *Geochemistry, Geophysics, Geosystems*, *20*(7), 3659–3689. https://doi.org/10.1029/2019GC008402

Torsvik, T. H., Van Der Voo, R., Doubrovine, P. V., Burke, K., Steinberger, B., Ashwal, L. D., et al. (2014). Deep mantle structure as a reference frame for movements in and on the Earth. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(24), 8735–8740. https://doi.org/10.1073/pnas.1318135111

Tosi, N., & Yuen, D. A. (2011). Bent-shaped plumes and horizontal channel flow beneath the 660km discontinuity. *Earth and Planetary Science Letters*, *312*(3–4), 348–359. https://doi.org/10.1016/j.epsl.2011.10.015

Van Keken, P. E., & Gable, C. W. (1995). The interaction of a plume with a rheological boundary - A comparison between 2-dimensional and 3-dimensional models. *Journal of Geophysical Research-Solid Earth*, *100*(B10), 20291–20302. https://doi.org/10.1029/95jb01152

Vinnik, L. P., Oreshin, S. I., Speziale, S., & Weber, M. (2010). Mid-mantle layering from SKS receiver functions. *Geophysical Research Letters*, *37*(24), 1–n. https://doi.org/10.1029/2010GL045323

Wagner, C., Mokhtari, A., Deloule, E., & Chabaux, F. (2003). Carbonatite and alkaline magmatism in Taourirt (Morocco): Petrological, geochemical and Sr-Nd isotope characteristics. *Journal of Petrology*, *44*(5), 937–965. https://doi.org/10.1093/petrology/44.5.937

Walker, K. T., Bokelmann, G. H. R., Klemperer, S. L., & Nyblade, A. (2005). Shear wave splitting around hotspots: Evidence for upwelling-related mantle flow? *Special Paper of the Geological Society of America*, *388*(August 2009), 171–192. https://doi.org/10.1130/0-8137-2388-4.171

Wen, L., Silver, P., James, D., & Kuehnel, R. (2001). Seismic evidence for a thermo-chemical boundary at the base of the Earth's mantle. *Earth and Planetary Science Letters*, *189*(3–4), 141–153. https://doi.org/10.1016/S0012-821X(01)00365-X

Wessel, P., Luis, J. F., Uieda, L., Scharroo, R., Wobbe, F., Smith, W. H. F., & Tian, D. (2019). The generic mapping tools version 6. *Geochemistry, Geophysics, Geosystems*, *20*(11), 5556–5564. https://doi.org/10.1029/2019GC008515

Wilson, M., & Downes, H. (2006). Tertiary-quaternary intra-plate magmatism in Europe and its relationship to mantle dynamics. *Geological Society, London, Memoirs*, *32*(1), 147–166. https://doi.org/10.1144/GSL.MEM10.1144/gsl.mem.2006.032.01.09

Wolfe, C. J., Solomon, S. C., Laske, G., Collins, J. A., Detrick, R. S., Orcutt, J. A., et al. (2011). Mantle P-wave velocity structure beneath the Hawaiian hotspot. *Earth and Planetary Science Letters*, *303*(3–4), 267–280. https://doi.org/10.1016/j.epsl.2011.01.004

Zeyen, H., Ayarza, P., Fernàndez, M., & Rimi, A. (2005). Lithospheric structure under the western African-European plate boundary: A transect across the Atlas Mountains and the Gulf of Cadiz. *Tectonics*, *24*(2), 1–16. https://doi.org/10.1029/2004TC001639

Zhao, D. (2007). Seismic images under 60 hotspots: Search for mantle plumes. *Gondwana Research*, *12*(4), 335–355. https://doi.org/10.1016/j.gr.2007.03.001

19448007, 2021, 13, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021GL092874, Wiley Online Library on [30/12/2022]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License