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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.

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

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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

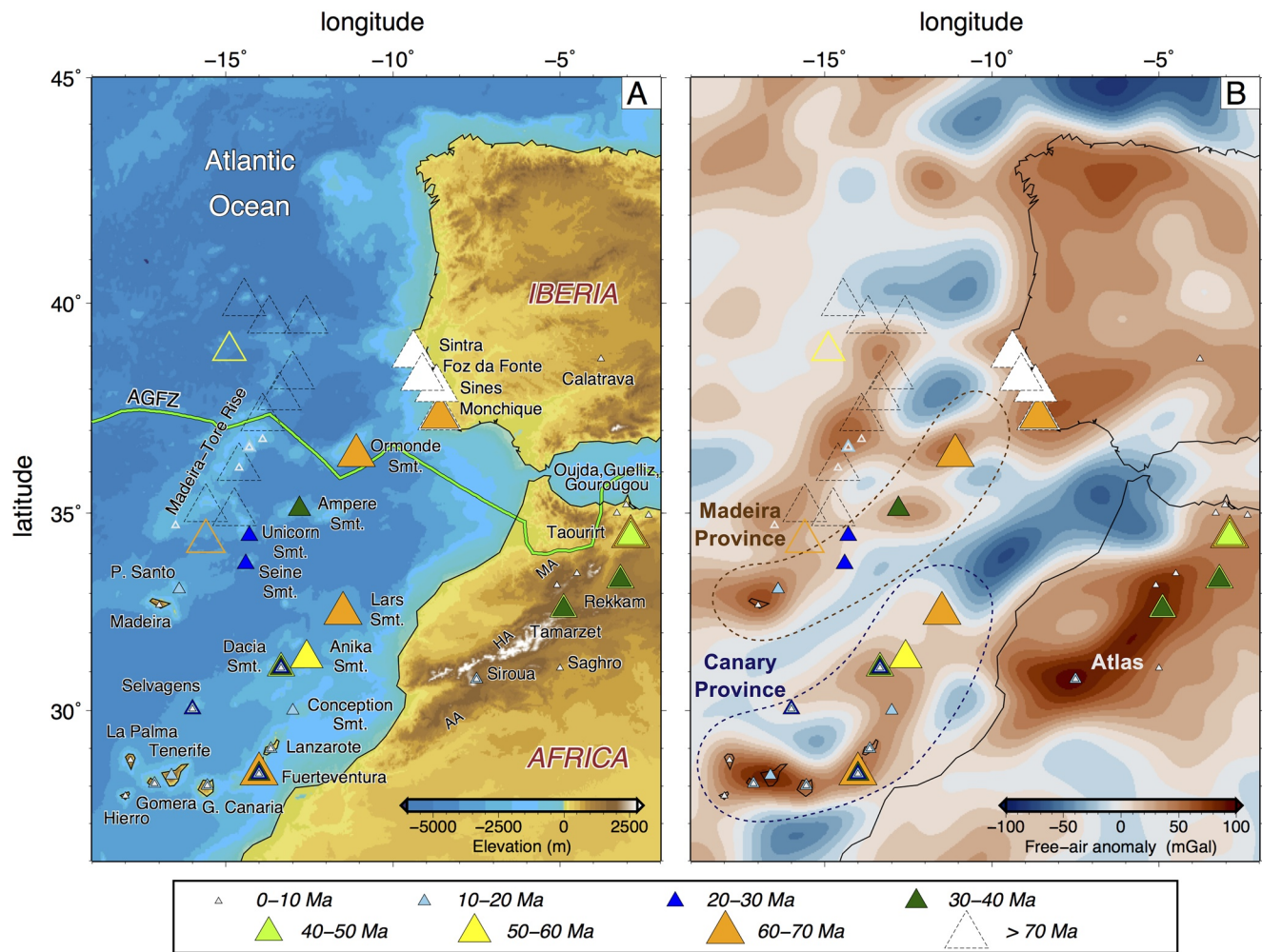


Figure 1. (a) Topography of Western Iberia, Northwestern Africa and bathymetry of Central-East Atlantic. Triangles of different sizes and colors show the locations and ages (from Cretaceous to present) of basaltic volcanism. The empty triangles mark the Madeira-Tore Rise volcanism, which is not discussed 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.

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

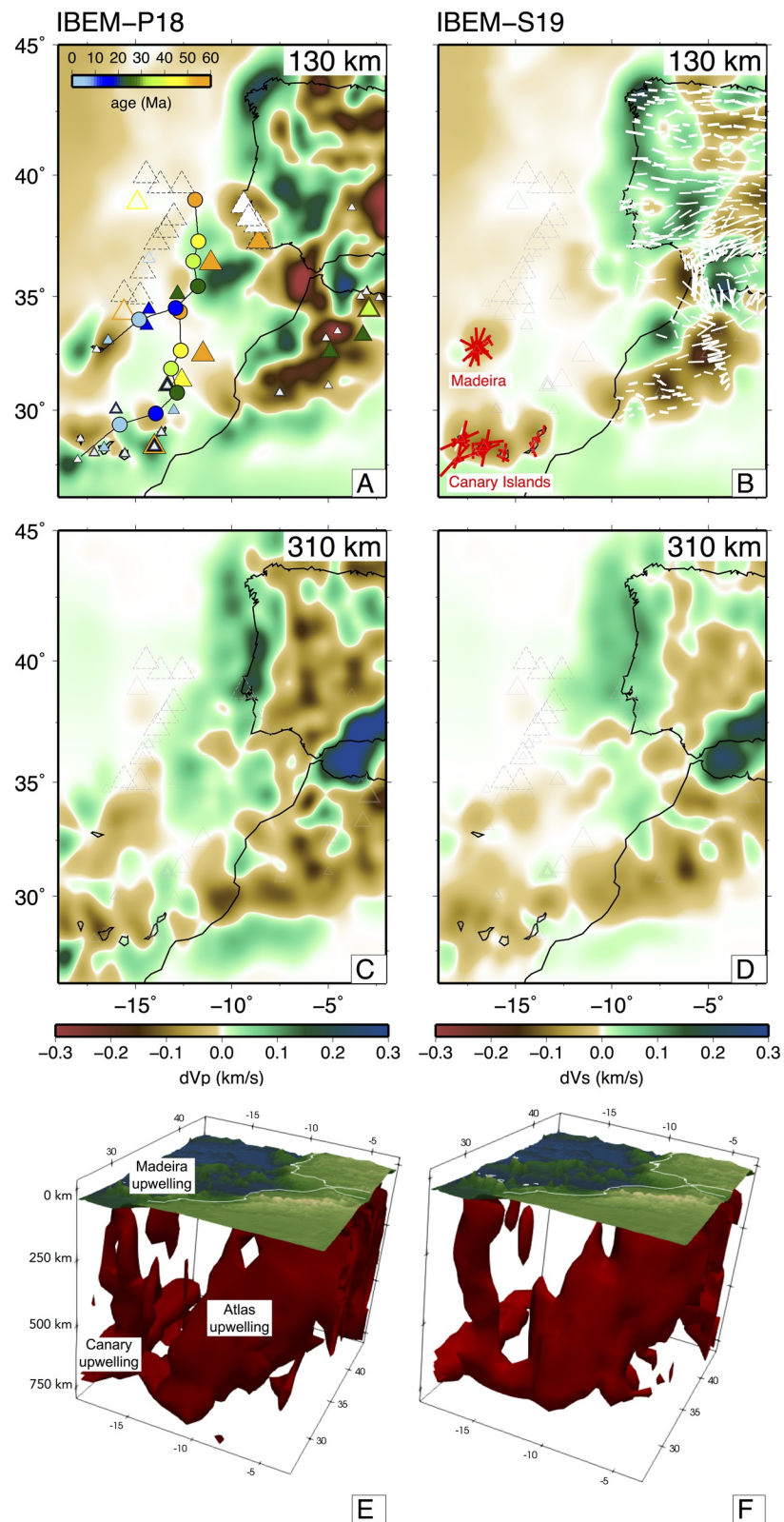


Figure 2

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 Fulla 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 ($\sim 1,200$ – $1,800$ 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 CEEA, extends upward from the base of the LLSVP. Cross-sections AB and CD (Figure 3) show that after a lateral thinning at $\sim 1,800$ km depth, this anomaly broadens again between $\sim 1,200$ 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 CEEA 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 CEEA 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-S19).

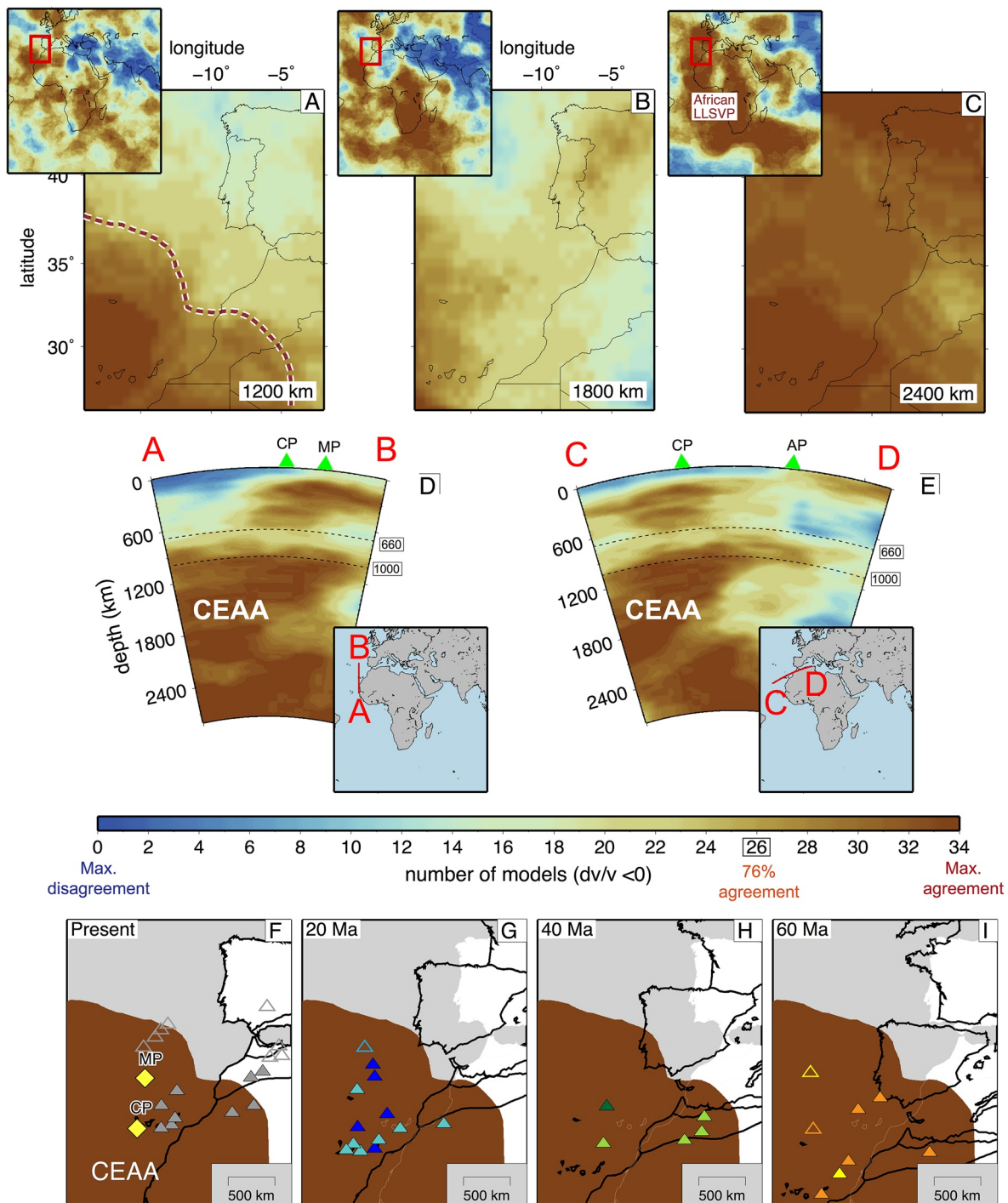


Figure 3. (a–e). Low-velocity vote maps and cross-sections based on 34 global tomographic models. For details on the models see Supporting Text T3 and Tables ST3–ST4. The dashed contour in panel a corresponds to a 26-vote count (76% agreement) and is used to approximately delimit the CEEA in panels f–i. 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 CEEA (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.

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 km³/Ma) compared to those of the Canaries (~2,000–10,000 km³/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

measurements ($< \sim 1$ 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 tomographic 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.

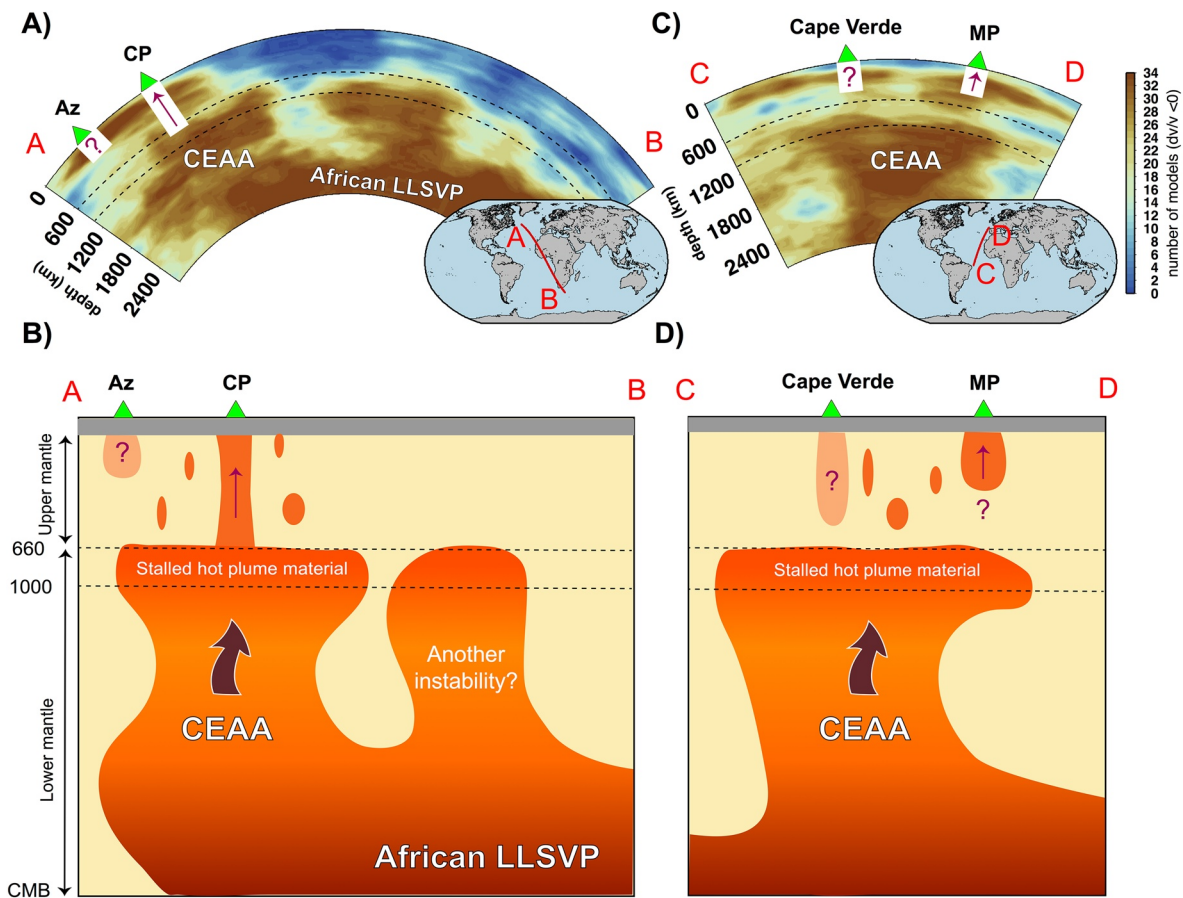


Figure 4. (a) Vote cross-section through the Canaries (CP) and Azores (Az). (b) Interpretative model of the mantle structure imaged. The red question mark indicates the upwelling below the Azores imaged as a low-velocity pond down to ~ 250 km without a tail (Silveira et al., 2006). (c) “Vote” cross-section 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.

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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>.

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