

Tracking a common mantle source: From southwest Iberia to the Madeira-Canarias Islands

Ricardo Pereira^{1,2,*}, Bruno Araújo², João C. Duarte², and João Mata²

¹GeoBioTec, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Quinta da Torre, 2829-516, Monte da Caparica, Portugal

²Instituto Dom Luiz (IDL), Faculdade de Ciências, Universidade de Lisboa, Campo Grande, 1749-016, Lisbon, Portugal

ABSTRACT

Paleogeographic reconstructions across the Central-East Atlantic Alkaline Province (CEAAP) reveal that a stationary super-plume, ponded at the mantle transition zone since the Late Cretaceous, is responsible for the irregular spatial-temporal distribution of magmatism across the mobile Iberian microplate and the northwest of the African plate. The mantle upwelling affecting the Southwest Iberian Margin (SWIM) (103–70 Ma) shows cogenetic paleogeographic affinities with subsequent magmatism in Morocco (57–45 Ma) and Madeira-Canarias (<32 Ma), resulting in episodic intra-plate magmatic activity both on oceanic and continental settings. The model indicates that the intermittent emission of plumelets resulted in the emplacement of distinct and correlative clusters of magmatism in each sector. Additionally, our results suggest that plumelet dragging may be responsible for the rejuvenated magmatism along the Canarias, Madeira, and Tore regions. On the Sahara Seamounts (142–75? Ma) and the Moroccan Atlas (<11 Ma), the combined paleogeographic reconstructions point to distinct magmatic sources, independent from the initial SWIM super-plume. Edge-driven convective models are not required to explain the conspicuous spatial-temporal distribution of magmatism across the continent-ocean domains of the CEAAP.


INTRODUCTION

The origin, upwelling processes, and impact of deep-seated mantle plumes feeding intra-plate magmatism have long been debated, with the spotlight predominantly directed toward oceanic hotspot volcanism (Wilson, 1965; Morgan, 1971; Koppers et al., 2021). However, for magmatism occurring on continental margins, conspicuous mantle sources and processes are less evident and often lead to the debate on which mechanisms can generate and/or sustain recurrent magmatism in discrete regions through time.

The rise of voluminous igneous material, often responsible for generating Large Igneous Provinces, is interpreted to have originated from the D'' layer, overlying the core-mantle boundary (e.g., Torsvik et al., 2014). Despite its

widespread distribution, magmatism of Large Igneous Provinces is characterized by short-lived activity (<5 m.y.), which contrasts with transient events originated from deep mantle upwelling with smaller spatial distribution but longer duration (30–200 m.y.) (Bryan and Ernst, 2008; Black et al., 2021). An example of the latter is the here-called the Central-East Atlantic Alkaline Province (CEAAP) (Fig. 1) formed since the Late Cretaceous, comprising the sectors of the Southwest Iberian Margin (SWIM), Morocco, Madeira, Canarias, Tore, and its associated seamounts. New geophysical evidence from offshore the SWIM has revealed new post-lithospheric breakup magmatic occurrences, including the Fontanelas Volcano and the Estremadura Spur Intrusion (e.g., Pereira et al., 2022) (Fig. 1), suggesting that crustal expression of mantle upwellings are more pervasive than anticipated, thus expanding the insights of Merle et al. (2019).

To explain intra-plate magmatism, different processes have been invoked, either through mantle plumes (e.g., Koppers et al., 2021), secondary plumes linked to a stacked superplume head (Courtillet et al., 2003; Civiero et al., 2021; Cloetingh et al., 2022), edge-driven convection (e.g., Missenard and Cadoux, 2012; Córdoba and Ballmer, 2022), or adiabatic decompression resulting from lithosphere stretching (Mata et al., 2015; Lu and Huisman, 2021) (Fig. S1 in the Supplemental Material¹). Most of these processes have been suggested to explain the magmatic occurrences at the CEAAP (e.g., Geldmacher et al., 2005; Missenard and Cadoux, 2012; Civiero et al., 2021; Córdoba and Ballmer, 2022). Although supported by robust geochemistry and geochronology studies (e.g., Bernard-Griffiths et al., 1997; Geldmacher et al., 2000; Merle et al., 2006; Miranda et al., 2009; Grange et al., 2010; Merle et al., 2009, 2018, 2019) (Fig. 1; Table S1), a conclusive spatial-temporal solution for the whole province has not been attained. Previous works have tried to define tracks (or trends) that could explain the geochemical affinities and their connection with a mantle source (Geldmacher et al., 2000; D'Oriano et al., 2010; Grange et al., 2010; Merle et al., 2009, 2018, 2019; Civiero et al., 2021). However, these studies have not fully resolved some conflicts of plate motion and magmatic manifestations, thus not facilitating the understanding of the likely mantle-sourced processes for the CEAAP. For example, the onshore Late Cretaceous magmatism on the SWIM was explained by a mantle plume impinged on a northeast-moving lithosphere (Grange et al., 2010), or invoking a deep lithospheric fault (Terriinha et al., 2018). For the Madeira and Canarias provinces, the role of mantle plumes has been

Ricardo Pereira  <https://orcid.org/0000-0003-4589-1145>
*rns.pereira@fct.unl.pt

¹Supplemental Material. (1) Detailed methodology used in this work; (2) a summary table with the magmatic occurrences within the Central-East Atlantic Alkaline Province, showing the geochronological data used in this work, along with its references; (3) supplemental figures that show the different paleogeographic reconstructions; and (4) a video showing the tectonic plates moving over a fixed mantle upwelling, from which the multiple magmatic manifestations were derived. Please visit <https://doi.org/10.1130/G52930.1> to access the supplemental material; contact editing@geosociety.org with any questions.

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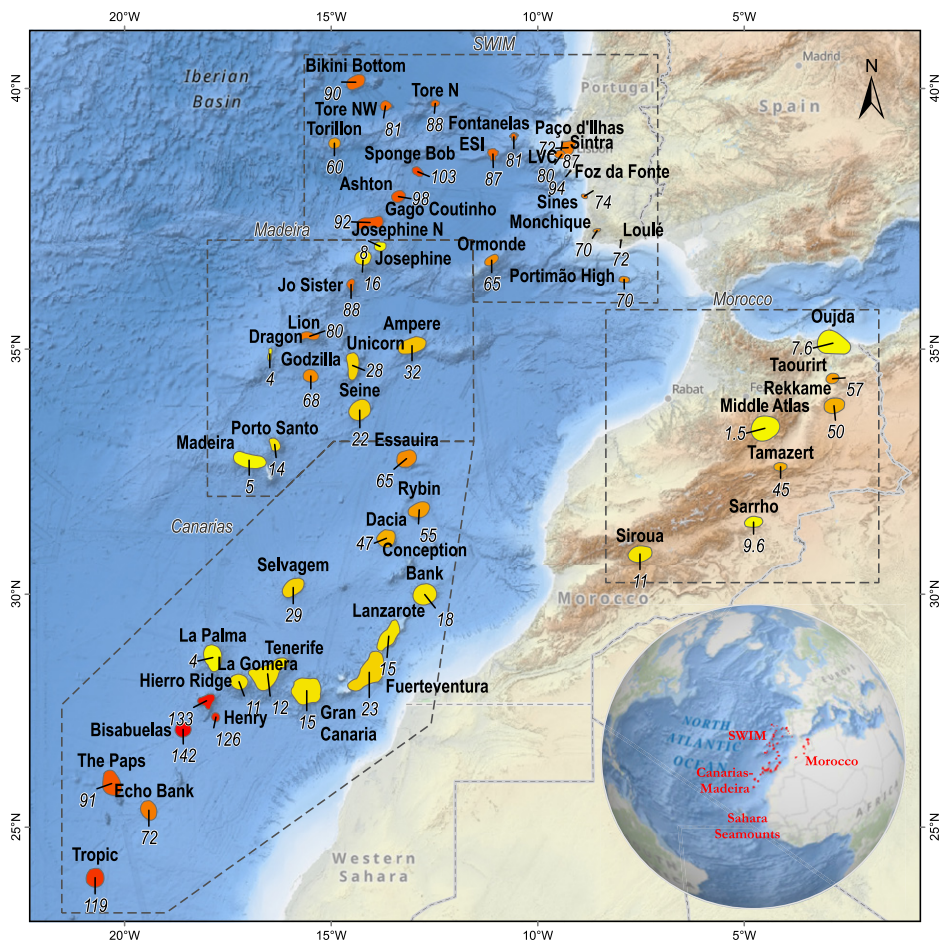


Figure 1. Location of the different regions analyzed in this work, with the magmatic occurrences throughout the Central-East Atlantic Alkaline Province since the Late Cretaceous to present day, colored by age (Ma; red—older, yellow—younger). ESI—Estremadura Spur Intrusion; LVC—Lisbon Volcanic Complex; SWIM—Southwest Iberian Margin.

suggested to create hotspot-like trails (e.g., Geldmacher et al., 2000), which contrasts with the invoked edge-driven convection models (e.g., Córdoba and Ballmer, 2022), or the unifying concept by Merle et al. (2019), which considered that these magmatic sub-provinces could be sourced from a single upper mantle source. An alternative explanation is therefore needed.

In this work, we apply plate reconstruction models to the CEAAP to analyze the timing and the mantle sources paleo-locations since the latest lower Cretaceous. We elucidate which processes can be responsible for the magmatic activity as the lithosphere has been drifting, namely for the diachronous magmatism on the SWIM and how it relates to the younger magmatic events in the Canarias, Madeira, and Morocco.

TRACKING MANTLE PLUMES

Based on the approximate age (Table S1; Fig. S2) and the present-day location of the magmatic occurrences across the CEAAP (Fig. 1), we investigate the crustal paleogeographic location of emplacement in relation to a stationary mantle reference (see Methods and Video 1 in the Supplemental Material). Their position was

reconstructed with GPlates software, assessing the effect of plate tectonics on the combined spatial-temporal relation, to investigate which process may have controlled magma ascent and emplacement. Our analysis reveals four distinct periods of magmatic activity (Fig. S3), which include: (A) The occurrences comprising the SWIM and continental Morocco (103–45 Ma); (B) the Canarias-Madeira cluster (<32 Ma); (C) the recent magmatism across the Moroccan Atlas (<11 Ma); and (D) the 142–72 Ma seamounts south of Canarias. Our model unveils the formation of discrete clusters that can be assigned to three stationary mantle sources, i.e., the Sahara Seamounts, the SWIM, and the Moroccan Atlas (Fig. 2).

Additionally, the motion path vectors for the individual magmatic occurrences were extracted from GPlates to assess their spatial and age affinity with itinerating tectonic plates (Fig. 3). Overall, these vectors reveal the general clockwise motion associated with the migration of the Iberian microplate and North African plate for the past 145 m.y. (Figs. S4 and S6–S8). The motion paths for the occurrences on the SWIM show that during the Late Cre-

taceous (ca. 103–70 Ma, from Sponge Bob to Monchique), the Iberian microplate has moved ~1200 km in a NNW direction above a fixed mantle reference (Figs. 3, S4, and S5A). From this period onward, the fixed upwelling location is progressively overlain by the northwestern African plate, materializing a shift in the direction of the continental lithosphere drift toward a dominant N-NE direction (Figs. 3 and S5B). For the period of 60–40 Ma, the African plate moves over the SWIM mantle source to form two independent upwelling clusters in continental Morocco (Taourirt, Rekkame, and Tamazert) and its offshore region (Dacia and Rybin), thus unrelated with the recent volcanism in the region (Figs. S4 and S5C).

On the Canarias region (Fig. 1), the magmatic occurrences show a large age distribution from Essaouira Seamount (65 Ma) to La Palma Island (<4 Ma) (Figs. 3 and S7). The modeled paleogeographic positions at the time of magmatism and its associated motion paths reveal a cluster of magmatic occurrences linking the mantle position of the older Lion, Tore NW, or Godzilla (80–67 Ma) with a correlative position of younger magmatism such as Selvagens, Tenerife, or La Gomera (29–11 Ma), suggesting a common origin from the same restricted mantle domain. The Madeira Island was considered the youngest magmatic occurrence of a plume-track, including the island of Porto Santo, the seamounts of Seine, Unicorn, Ampère, and Ormonde, and the onshore Monchique massif in southwest Iberia (Geldmacher et al., 2000, 2005). However, the paleogeographic position of Ormonde and Monchique at the time of its genesis is clearly distinct from that of the mentioned cluster, invalidating their incorporation on the Madeira track, but correlative with the geographic position of present-day Canarias archipelago (Fig. 3).

For the relatively recent middle Atlas occurrences (<11 Ma; e.g., Siroua, Sarrho, Oujda) the paleogeographic analysis could suggest an independent origin from the SWIM cluster. However, Civiero et al. (2021) have detected a sub-vertical low-velocity “wall” below the Atlas rooted in the same uppermost mantle anomaly as the SWIM cluster, suggesting some degree of parentage for the Paleogene volcanism (e.g., Benamrane et al., 2023). Our analysis reveals that the SWIM cluster is independent of those from the south Canarias (e.g., Bisabuelas, Hierro Ridge, Echo Bank), ultimately suggesting a link to the entire Sahara Seamounts and Cape Verde (<26 Ma; see Ramalho, 2011) (Figs. 2 and S8).

UNRAVELLING A COMMON AND ENDURING MANTLE SOURCE

The CEAAP is revealed as a post-rift intra-plate magmatic province formed since the latest Early Cretaceous, both on continental and oceanic crust. If stretching-related adiabatic decom-

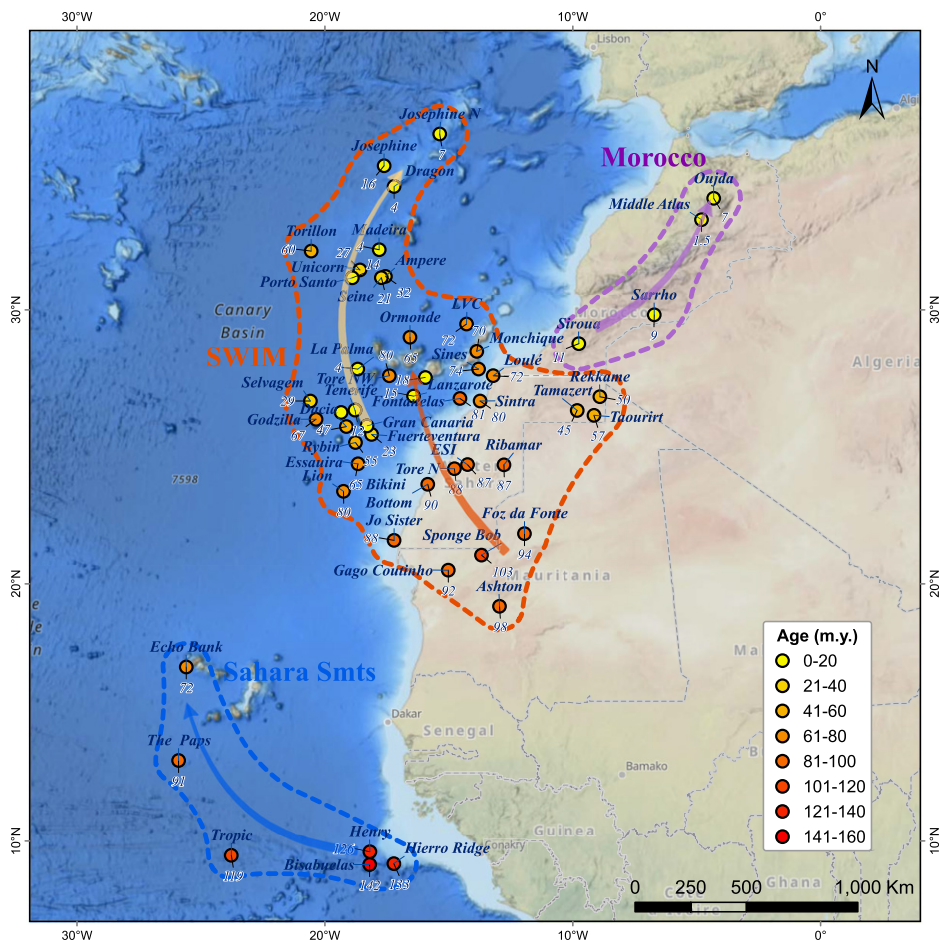


Figure 2. Time-reconstructed positions of mantle derived magmatism across the Central-East Atlantic Alkaline Province, projected on the present-day geographic map. Magmatic occurrences colored by emplacement age (red—older, yellow—younger). Outlines group the coeval magmatic occurrences, based on clustered ages of emplacement. Arrows indicate the apparent direction of rejuvenation of magmatism driven by the lithospheric drift over a stationary mantle plume. ESI—Estremadura Spur Intrusion; LVC—Lisbon Volcanic Complex; SWIM—Southwest Iberian Margin.

pression melting dominated the previous Iberian rifting phases (e.g., Mata et al., 2015), such a model cannot be applied to the Iberian post-rift occurrences or the entire CEAAP. Also, despite several plume tracks having been postulated for specific groups of occurrences (e.g., Geldmacher et al., 2005; Grange et al., 2010), the CEAAP, as a whole, does not present the typical age-distance correlation generated by the lithosphere drifting over a mantle plume (s.l.). For this province, our work proposes an origin at a common and stationary mantle domain, covering a widespread region ($\sim 1.4 \times 10^6$ km²) located between 20–30°N and 10–20°W, that has been active for a long period (>100 m.y.) (Fig. 2).

The occurrence of episodic mantle upwellings rooted on a large anomaly at the upper mantle was initially proposed by Merle et al. (2019) to explain this large magmatic province. However, recent seismic tomographic studies (Civiero et al., 2021; Bonatto et al., 2024) have not detected such “shallow” irregularity, but instead reveal a vast low-velocity anomaly

below the mantle transition zone, corresponding to the head of an enduring and stationary mantle plume. He isotope ratios for Canarias (³He/⁴He up to 9.7 times higher than the present-day atmosphere) are indicative of a time-integrated evolution under lower (U + Th)/³He ratios than the mid-ocean-ridge basalt sources (upper mantle), suggesting a lower mantle contribution (e.g., Day and Hilton, 2021). Moreover, the thinning of the mantle transition zone beneath Canarias and Madeira (Bonatto et al., 2024) suggests the upwelling of hot material from the lower mantle. This allows us to consider such a top-most lower mantle anomaly as the root for the upper-mantle intermittent secondary plumes (sensu Courtillot et al., 2003; Cloetingh et al., 2022). Fittingly, our model suggests the episodic release from this ponded material below the mantle transition zone of individual plumelets that can ascend to the surface, thus generating the diachronous and unevenly distributed magmatism on a wide region (Fig. 4). Our proposal is supported by recent numerical modeling of

low viscosity plume heads behavior, capable of producing multiple secondary plumes reaching the lithosphere at distinct times and locations (e.g., Li et al., 2023). Moreover, this process can be sustained for long periods (10–100s of m.y.) through the replenishment from a deep mantle source, providing long-term support of the ponded plume head, from which the emerging plumelets allow the rejuvenation of magmatism within a region (e.g., Torsvik et al., 2014; Davaille and Romanowicz, 2020).

The geochemistry analysis of the CEAAP is beyond the scope of this study. However, we note that two of its most prominent sub-provinces (Madeira and Canarias) are characterized by clearly distinct isotope signatures, but forming arrays converging to a similar composition (e.g., Geldmacher et al., 2005, 2011), thus suggesting a geochemically common mantle origin. The pervasive alkaline character of the CEAAP is here considered the result of low buoyancy fluxes (King and Adam, 2014) and of a thick lithosphere (continental or oceanic), limiting the percentage of partial melting. The former would be a major factor in of magmatism emplaced in regions of relatively thick oceanic and continental lithosphere (Fig. 1).

Our model indicates that on a regional scale, different pulses of the CEAAP mantle source were responsible for the different sub-clusters of magmatism identified since the latest lower Cretaceous. The first pulse (103–45 Ma) was responsible for clustered magmatism in Iberia and Morocco (Figs. 2, 3, and S5) and later rejuvenated on an overlapping region NW of the initial CEAAP super-plume, subsequently responsible for the diachronous and uneven distribution of magmatism on the Canarias and Madeira regions (<32 Ma). This evidence contributes to the debate on the migration of magmatism originated from a common uppermost lower mantle source, but distinct in age, such as that of the CEAAP and specifically the Madeira-Tore Rise (Grange et al., 2010; Merle et al., 2019). How this magmatism relates to the evidence of other alkaline occurrences on the Nova Scotia and Newfoundland conjugate margins (e.g., Merle et al., 2019) remains unclear. However, considering the tectonic drifting since the lithospheric breakup of the Atlantic Ocean, between the Morocco–Nova Scotia and West Iberia–Newfoundland conjugated margins, any pre-rift quasi-stationary mantle plumes would later generate discrete clusters of magmatic activity separated by seafloor spreading.

Despite their diverging ages and current location of magmatism (e.g., Canarias, Madeira), a northward rejuvenation of magmatism can be tracked within the inherited and wider SWIM cluster (Figs. 3 and S4–S7). The younger occurrences assigned to the Canarias and Madeira clusters corroborate that other processes may explain the relative rejuvenation of magmatism

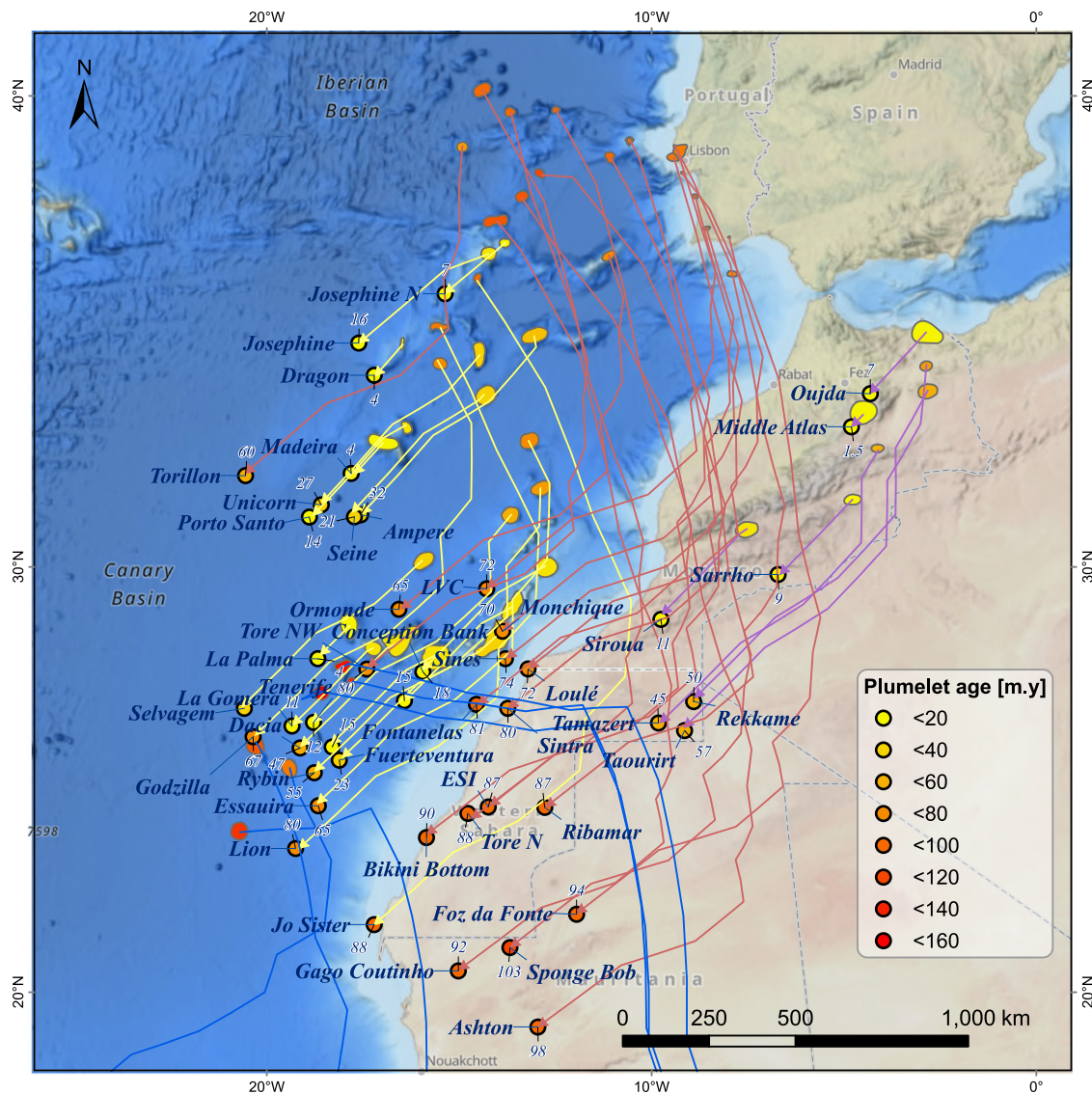


Figure 3. Motion paths tracing the paleo-locations of the magmatic occurrence at the Central-East Atlantic Alkaline Province (circles colored by age) and grouped by geographic province (Sahara Seamounts—blue; Southwest Iberia—orange; Canarias-Madeira—yellow; and the Moroccan Atlas—purple). ESI—Estremadura Spur Intrusion; LVC—Lisbon Volcanic Complex.

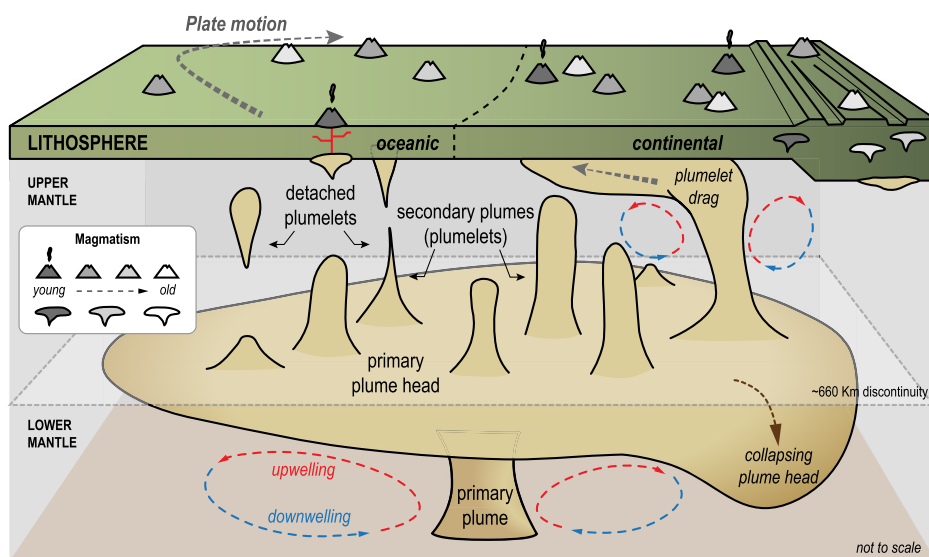


Figure 4. Model sketch for the proposed origin of the Central-East Atlantic Alkaline Province, involving a stationary mantle plume and associated plumelets, responsible for the diachronous and widespread magmatism on an itinerant lithosphere.

on a N-NE trend. Specifically, those derived from seismic tomography on the CEAAP (Civiero et al., 2021; Bonatto et al., 2024) that suggest the presence of a “tilted” thermochemical plume, an aspect that fits the modeled northward revival of magmatism in the region (Figs. 3, 4, S5, and S7). This explains the discrete and diachronous clusters of magmatism that can emerge at crustal levels, despite its apparently conflicting spatial-temporal distribution (Fig. 4).

CONCLUSIONS

Paleogeographic models integrating the spatial-temporal distribution of magmatism in the CEAAP can be traced toward distinct stationary thermochemical secondary plumelets active since the latest lower Cretaceous. A widespread stationary plume head at the top of the lower mantle is interpreted to be responsible for the episodic emission of plumelets, initially resulting in magmatism on the SWIM and Morocco (103–45 Ma), and later in the Canarias, Madeira,

and Tore regions (<32 Ma). Rejuvenated magmatism on the Canarias-Madeira-Tore regions suggests a progressive dragging of plumelets at the base of the lithosphere transition. The paleogeographic model also reveals that the SWIM super-plume is unrelated to magmatism at the Sahara Seamounts and Cape Verde, reinforcing the idea that multiple thermochemical upwelling sources may have controlled the magmatic activity across the central-eastern Atlantic. Our outcomes also suggest that edge-driven convection underneath a thinned continental lithosphere is not necessary to explain the intra-plate magmatism across the CEAAP.

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