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New $^{40}Ar/^{39}Ar$ age and geochemical data from seamounts in the Canary and Madeira volcanic provinces: Support for the mantle plume hypothesis

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Abstract

The role of mantle plumes in the formation of intraplate volcanic islands and seamount chains is being increasingly questioned. Particular examples are the abundant and somewhat irregularly distributed island and seamount volcanoes off the coast of northwest Africa. New $^{40}Ar/^{39}Ar$ ages and Sr–Nd–Pb isotope geochemistry of volcanic rocks from seamounts northeast of the Madeira Islands (Seine and Unicorn) and northeast of the Canary Islands (Dacia and Anika), however, provide support for the plume hypothesis. The oldest ages of shield stage volcanism from Canary and Madeira volcanic provinces confirm progressions of increasing age to the northeast. Average volcanic age progression of ~1.2 cm/a is consistent with rotation of the African plate at an angular velocity of ~$0.20° \pm 0.05$ /Ma around a common Euler pole at approximately 56° N, 45° W computed for the period of 0–35 Ma. A Euler pole at 35° N, 45° W is calculated for the time interval of 35–64 Ma. The isotope geochemistry further confirms that the Madeira and Canary provinces are derived from different sources, consistent with distinct plumes having formed each volcanic group. Conventional hotspot models, however, cannot easily explain the up to 40 m.y. long volcanic history at single volcanic centers, long gaps in volcanic activity, and the irregular distribution of islands and seamounts in the Canary province. A possible explanation could involve interaction of the Canary mantle plume with small-scale upper mantle processes such as edge-driven convection. Juxtaposition of plume and non-plume volcanism could also account for observed inconsistencies of the classical hotspot concept in other volcanic areas.

Keywords: Canary and Madeira islands; East Atlantic volcanism; African plate motion; hotspot; $^{40}Ar/^{39}Ar$ age dating; isotope geochemistry

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1. Introduction

Since the introduction of plate tectonics, linear chains of volcanic islands and seamounts (or hotspot tracks) within the ocean basins have generally been attributed to upwelling mantle plumes (e.g., [1,2]). Recently, however, a global debate has developed concerning whether or not mantle plumes exist (e.g., http://www.mantleplumes.org). It is being increasingly argued that intraplate or hotspot volcanism results primarily from shallow upper mantle processes, such as shallow convection processes (e.g., [3]) or melting along lithospheric fractures (e.g., [4]), rather than from deeply derived mantle plumes. The strongest argument in support of relatively stationary mantle plumes beneath the moving lithospheric plates is the age progression of volcanic centers yielding increasingly older ages in the direction of plate movement. Although general age progressions are confirmed for many hotspot tracks (e.g., Hawaii, Easter, Reunion), new $^{40}Ar/^{39}Ar$ investigations of some Pacific island chains seem to require other models (e.g., [5]). In general, variation of lithospheric structure and thickness can provide important factors that influence irregularities in volcanic chains.

Whereas hotspot tracks on the fast-moving plates in the Pacific realm are generally easy to recognize, broader, more irregular volcanic chains are formed on slow-moving plates for example in the Atlantic realm, making it difficult to detect age progressions [6]. The central East Atlantic off the coast of northwest Africa hosts a broad belt of late Mesozoic to recent volcanism extending from the Azores–Gibraltar Fracture Zone to the Sierra Leone Rise containing four island groups (Madeira, Selvagen, Canary and Cape Verde), large submarine rises (e.g., >500 km long Madeira–Tore Rise) and dozens of large seamount groups (see Fig. 1). Many diverse explanations have been proposed for the origin of East Atlantic volcanism, which can be grouped into plume and non-plume models. Plume models range from multiple small hotspots [6–9] or collections of blobs [10] to large-scale regional upwellings [11] and megaplumes [12]. Non-plume models include volcanism along propagating fractures [13] or lithospheric sutures [14] or as a result of diffuse upper mantle edge-driven convection [15,16].

One of the major goals of research cruise M51/1 (Sept.–Oct., 2001) was to sample the main submarine shield stage of volcanism on select guyots (former ocean island volcanoes) presently located northeast of the Madeira and Canary Islands (Fig. 1), in order to provide age and geochemical data to test further a possible plume origin for this intraplate volcanism. An additional goal was to gain a better understanding of the long-term volcanic history of individual seamount volcanoes. This study presents the first age and geochemical data from Seine and Unicorn Seamounts (northeast of Madeira) and Anika Seamount (northeast of the Canary Islands) and new data from samples dredged from the deeper slopes of Dacia seamount. The new data allow a critical examination of the plume hypothesis for these intraplate seamount volcanoes.

2. Geological and geochemical background

Volcanism in the study area can be grouped into two distinct geographic provinces using isotope geochemistry (Fig. 1): the Canary and the Madeira Volcanic Provinces [6]. The Madeira Province forms an ~700 km long by ~200 km wide chain of volcanoes, with a crude progression of increasing ages from southwest to northeast [9]: Madeira (0–>5 Ma), Porto Santo Island (11–14 Ma), Ampere Seamount (31 Ma), Ormonde Seamount (65–67 Ma) and possibly the Serra de Monchique (70–72 Ma) igneous complex in southern Portugal [9,17,18]. Whereas the beginning and the end of the proposed hotspot track are well defined, only a single age has been published from the central group of islands, which include Seine, Unicorn, Ampère and Coral Patch Seamounts.

In contrast to the Madeira Province, the Canary Province is twice as wide (~700 by ~400 km), volcano distribution is more random, individual volcanoes are active for much longer intervals and the spatial distribution and age variation of volcanoes are very complex (Fig. 1) [6]. A crude age progression has long been recognized in the Canary Islands (e.g., [19,20]). A propagating fracture model for the Canary Islands, however, fails to explain the origin of the seamounts NE of the Canaries [13]. Based on geophysical data, Holick et al. [8] proposed a Canary hotspot track starting at ~65 Ma near Lars Seamount, which would fit well with the age of 68 Ma obtained from a sample dredged from Lars Seamount [6]. Nevertheless, previously published ages within the interior of

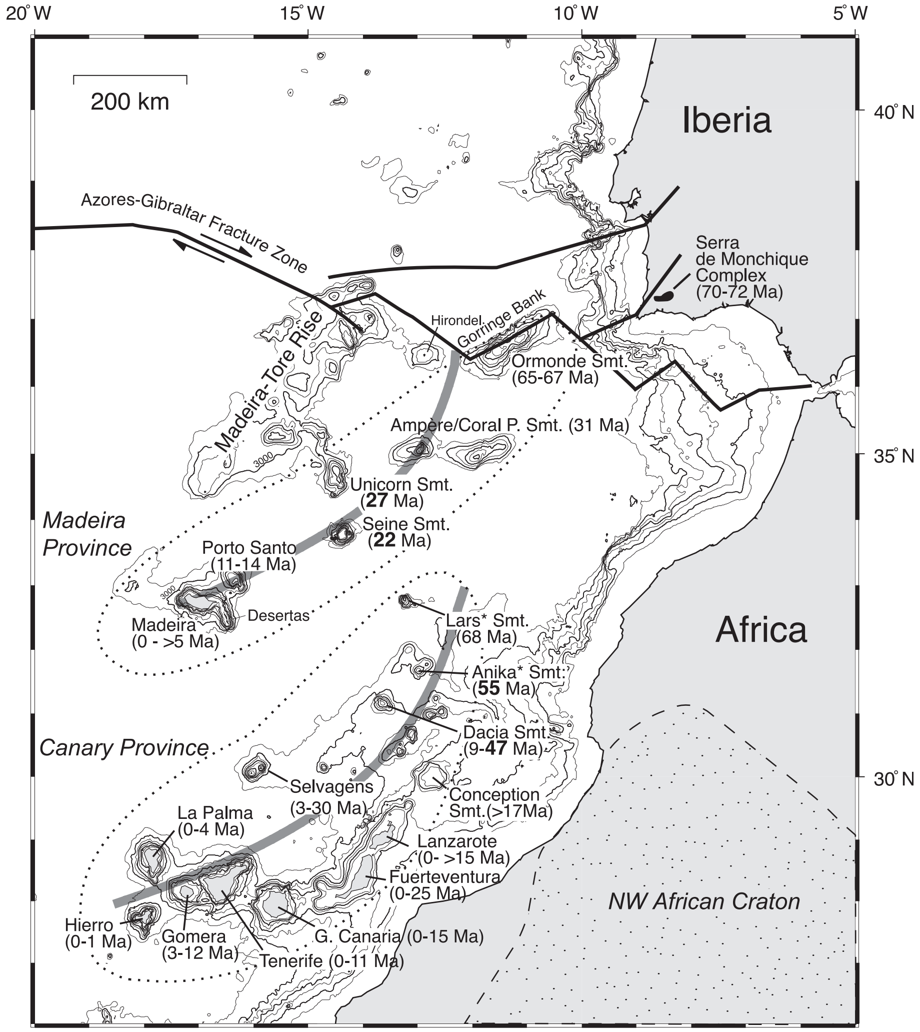


Fig. 1. Predicted bathymetric map of seamounts and islands in the central northeast Atlantic (only depth contours above 3500 m are shown for clarity) after [53]. Stippled lines mark geochemically defined Madeira and Canary volcanic provinces. Published radiometric ages for each volcanic center are given in Ma. New age data from this study are shown in bold. Thick gray lines mark center of possible hotspot tracks. Asterisks (*) mark working names for unnamed seamounts. Sources for age data are given in caption to Fig. 5. Locations of the Azores–Gibraltar Fracture Zone system and northwest African craton boundary after [54,55].

the province do not show a clear age progression (Fig. 1). For example, the only previously published age for Dacia Seamount, located in the northeast near Lars Seamount, was 9 Ma [6], although the age predicted from its location is ~50 Ma, challenging a possible hotspot-generated age progression.

As seen on the well-studied Canary Islands, volcanism on single islands can span long time periods. For example, volcanism on Fuerteventura covers at least 20 Ma [21] and on the Selvagen Islands, which form the pinnacles of a single large primarily submarine volcano, at least 27 Ma [6]. The evolution of the Canary and Selvagen volcanoes can be divided into two major stages: 1) voluminous primarily transitional tholeiitic to alkali basaltic shield stage lasting ~5–10 Ma, and 2) low-volume, generally more SiO_2-undersaturated late (post-erosional or rejuvenated) stage. Age determinations of late stage volcanic rocks only represent minimum ages for the formation of the shields of these volcanoes and thus cannot be used to determine the passage of the lithosphere over a relatively stationary sub-lithospheric magma source (hotspot). Therefore, only shield stage volcanism should be considered in evaluating if an age progression exists.

Detailed studies of the Canary and Selvagen Islands magmatic evolution have shown that the shield stage of volcanism is characterized by more radiogenic Pb isotopic compositions ($^{206}Pb/^{204}Pb \geq 19.4$) than the late stage volcanism ($^{206}Pb/^{204}Pb \leq 19.5$) (e.g., [6,22,23]). Consequently, the Pb isotopic composition of isolated rock samples dredged from submarine seamounts in the Canary region can in most cases be used to distinguish between the two stages. The $^{206}Pb/^{204}Pb$ ratios of previously obtained samples from Dacia are less than 19.5, indicating derivation of these samples from late stage volcanism [6]. Therefore 9 Ma must be taken as a minimum age for the Dacia volcano. If the hotspot model is applied to the Canary Volcanic Province, then it is implied that volcanism has occurred for at least 40 Ma at Dacia. Volcanism spanning 40 Ma at a single volcano, however, is difficult to accommodate with the hotspot concept even on the slow moving African plate.

3. Description of dredge sites and rocks samples

Volcanic rock samples from Unicorn, Seine, Dacia and Anika Seamount have been dredged during RV Meteor cruise M 51/1. Coordinates of dredge sites are given in Table 1. Unicorn and Seine seamounts are isolated, large (>50 km diameter) volcanic structures to the southeast of the Madeira–Tore Rise, rising from the seafloor at >4000 m depth up to less than a few hundred meters below sea level. The olivine-phyric, nephelinitic samples 423 DR-1 and -2 were dredged from the upper northwest flank of Unicorn at 1352 m water depths. Seine seamount is located about 75 km south of Unicorn and shows a guyot-like flat top at ~250 m water depth. Basanitic, olivine-phyric samples 426 DR-1, -2 and -3 were dredged from the northern flank of Seine seamount at water depths of 1300 m.

Hirondel seamount, located north of Ampère seamount (Fig. 1) was also sampled at two sites but no volcanic samples were recovered. Since primarily serpentinites were obtained, Hirondel is interpreted to represent a portion of lower oceanic crust or lithospheric mantle that was uplifted at the Azores–Gibraltar Fracture Zone as has also been proposed for most of the neighboring Gorringe Bank (e.g., [24,25]).

Dacia and Anika seamounts belong to a cluster of seamounts northeast of the Canary islands. Guyot-shaped Dacia seamount rises from 3000 m depths and has a flat top at 120 m below sea level, indicating that Dacia was once an island. Strongly silica-undersaturated nephelinitic samples 449 DR-1, 450 DR-1, 454 DR-1 and 455 DR-1 have been dredged from elongated ridges and deeper flanks of Dacia seamount between 1800 and 2650 m water depths. Anika seamount (working name), is located about 80 km north-

Table 1

Sample	Dredge sites	Type	Age [Ma]	2 Sigma	% ^{39}Ar Plateau	MSWD
Unicorn Smt.						
423 DR-1	34°47.41N 14°35.28W	matrix, step-heating plateau	27.4	2.4	85.7	0.7
Seine Smt.						
426 DR-1	33°52.07N 14°22.14W	matrix, step-heating plateau	21.7	0.2	55.3	1.2
Dacia Smt.						
449 DR-1	31°17.30N 13°44.62W	hbl (amph), single.-crystal. weight, mean ($n=9$)	46.3	0.6	–	2.76
450 DR-1	31°13.62N 13°45.05W	matrix, step-heating plateau	47.4	1.6	86.5	1.7
Anika Smt.						
456 DR-1	31°34.45N 12°59.06W	fsp single.-crystal. weight, mean ($n=20$)	55.3	0.2	–	1.9
456 DR-1	31°34.45N 12°59.06W	hbl (amph.) single.-crystal. weight, mean ($n=11$)	55.1	0.2	–	1.7

Abbreviations: fsp = feldspar, amph = amphibole (hornblende). MSWD = Mean squared weighted deviates.

east of Dacia. The benmoreitic sample 456 DR-1 containing alkali feldspar and hornblende phenocrysts was dredged from the deep southern flank of the seamount at water depths of 2700 m.

4. Results

A description of sample preparation methods and analytical techniques including reproducibility and accuracy compared to international standard material is given in the Appendix. Detailed results of step-heating and single-crystal $^{40}Ar/^{39}Ar$ analyzes are presented in Table 1. Age-temperature spectra and isotope correlation diagrams are shown in Fig. 2. Analyses of nephelinitic matrix chips from Unicorn Seamount (423 DR-1) yielded a plateau age of 27.4 (±2.4) Ma (all errors are two sigma). Matrix analyses of basanite sample 426 DR-1 from Seine Seamount gave an age of 21.7 (±0.2) Ma. The benmoreitic sample from 456 DR-1 from Anika seamount contains phenocrysts of amphibole (hornblende) and alkali feldspar dated at 55.1 (±0.2) and 55.3 (±0.2) Ma, respectively. The nephelinitic samples dredged from an elongated ridge on the deeper flanks of Dacia Seamount, yielded ages of 47.4 (±1.6) Ma (matrix, 450 DR-1), and 46.3 (±0.6) Ma (amphibole phenocrysts from 449 DR-1).

All samples have enriched incompatible element signatures (e.g., Ce/Yb = 61–96) and display typical ocean island basalt (OIB) trace element signatures with characteristic enrichment in Nb and Ta and depletions in Pb and Heavy Rare Earth Elements (Fig. 3).

There is no significant difference in trace element signatures between shield stage and late

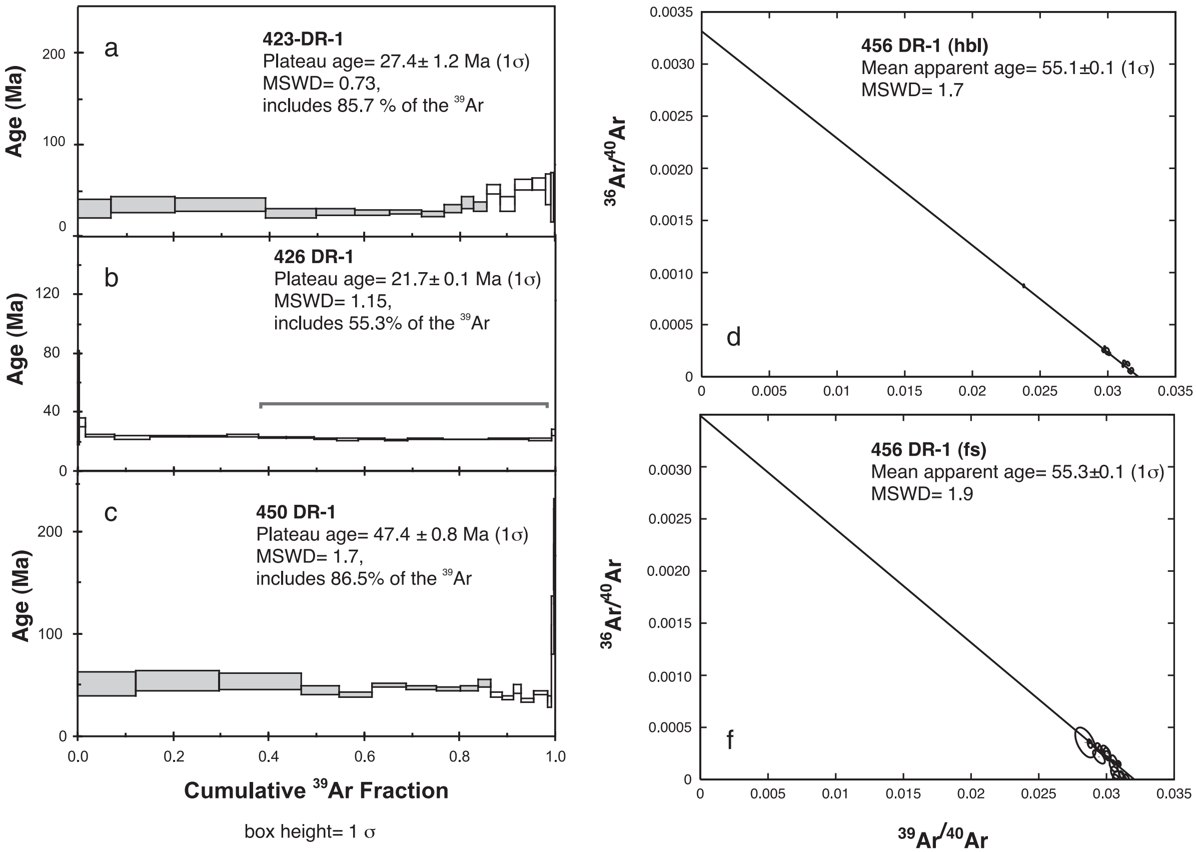


Fig. 2. Isotope correlation diagrams for Ar isotope compositions of phenocrysts and age–temperature spectra (step heating) for whole rock samples. Filled boxes in 2 a, b, c, indicate plateau steps included in the plateau age calculation (also indicated by horizontal bar in 2b). See Appendix for analytical details.

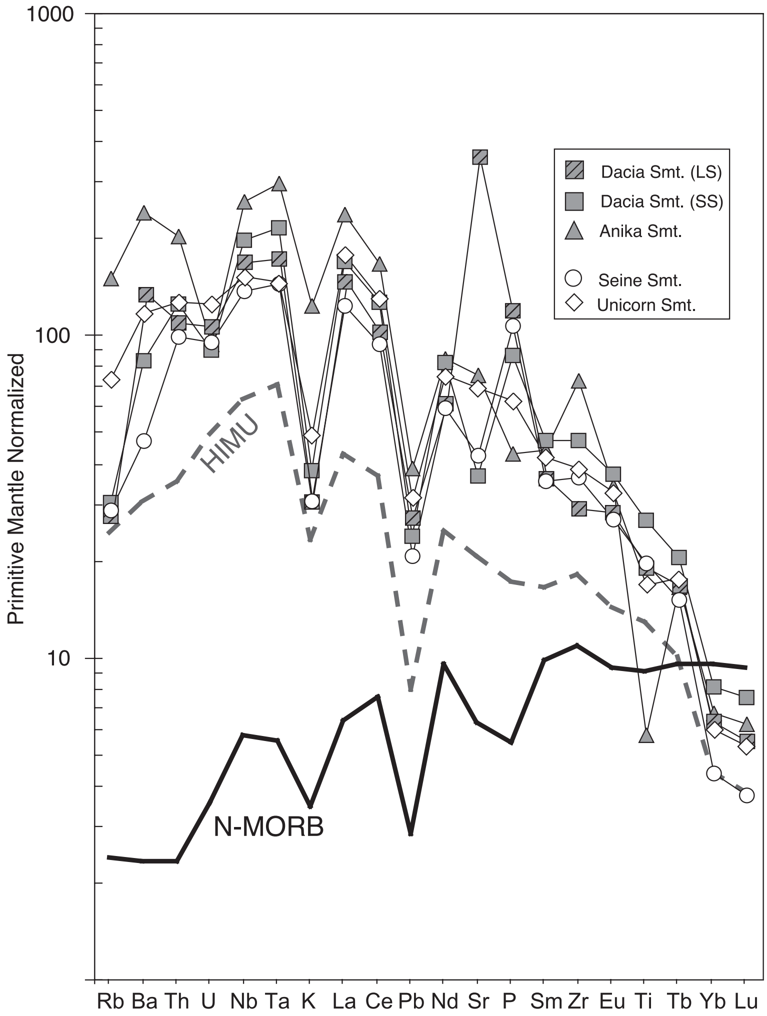


Fig. 3. Multi-element diagram of shield stage (SS) and one late stage (LS) lava from sampled seamounts in the Madeira and Canary volcanic provinces (normalized after [56]). Solid and stippled lines show compositions of average N-MORB from Hofmann [56] and HIMU ocean island basalt from Chaffey et al. [57], respectively.

stage lavas as demonstrated by samples 449 DR-1 and 455 DR-1 from Dacia seamount. The exceptional high Sr contents of late stage sample 455 DR-1 probably result from sea water alteration as also confirmed by its elevated Sr isotope composition (see below). The most evolved benmoreitic sample from Anika seamount shows the highest concentration in most incompatible elements and a marked depletion in Ti reflecting its evolved nature.

The Sr isotope data for one sample from Unicorn (423 DR-2) and two samples from Dacia (454 DR1, 455 DR1) have been affected by seawater alteration (Table 2) and therefore, Sr isotope ratios will not be considered further. Canary province samples from Dacia and Anika display systematically higher $^{207}Pb/^{204}Pb$ isotope ratios than the Madeira province samples from Unicorn and Seine seamounts for a given $^{206}Pb/^{204}Pb$ ratio and all samples plot on the $^{206}Pb/^{204}Pb$ vs $^{207}Pb/^{204}Pb$ isotope correlation diagram within the respective fields for Canary and Madeira provinces, respectively (Fig. 4). All data plot within the shield stage fields of both provinces except three younger samples from Dacia Seamount (e.g.,<9

Table 2

Sample	Name	Volc. stage	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{87}Sr/^{86}Sr$	$^{143}Nd/^{144}Nd$
423 DR-1	Unicorn Smt.	SS	19.208 (4)	15.523 (3)	39.000 (8)	0.703077 (3)	0.512962 (2)
423 DR-2	Unicorn Smt.	SS	19.304 (4)	15.529 (3)	39.324 (8)	0.703062 (5)	0.512956 (2)
426 DR-1	Seine Smt.	SS	19.439 (9)	15.542 (7)	39.528 (18)	0.703507 (3)	0.512879 (2)
426 DR-2	Seine Smt.	SS	19.896 (5)	15.585 (4)	40.646 (10)	0.703493 (7)	0.512871 (5)
426 DR-3	Seine Smt.	SS	19.762 (6)	15.561 (4)	40.279 (11)	0.703490 (2)	0.512880 (2)
449 DR-1	Dacia Smt.	SS	19.716 (3)	15.614 (2)	39.735 (5)	0.703154 (3)	0.512925 (3)
450 DR-1	Dacia Smt.	SS	19.602 (3)	15.612 (2)	39.590 (7)	0.703122 (3)	0.512925 (2)
454 DR-1	Dacia Smt.	LS	19.243 (2)	15.560 (2)	38.999 (4)	0.705977 (3)	0.512980 (3)
455 DR-1	Dacia Smt.	LS	19.278 (1)	15.554 (1)	38.992 (2)	0.707816 (2)	0.512948 (3)
DS 809-1[a]	Dacia Smt.	LS	19.420 (4)	15.567 (4)	39.175 (9)	0.703062 (5)	0.512946 (4)
456 DR-1	Anika Smt.	SS	19.705 (2)	15.589 (2)	39.643 (4)	0.703147 (4)	0.512926 (2)

[a] Data for DS 809-1 dated at 9 Ma from Geldmacher et al. [6]. SS = Shield Stage, LS = Late Stage.

Ma), which plot within the late stage field for the Canary province. The late stage fields for both provinces overlap the Atlantic mid-ocean-ridge basalt (MORB) field on isotope correlation diagrams, whereas the shield stage rocks display more enriched isotopic compositions characteristic of ocean island basalts (OIB's).

5. Discussion

5.1. Age progression of East Atlantic volcanism

The new age determinations from Seine and Unicorn seamount fill the hitherto existing analytical gap in the central part of the Madeira volcanic province

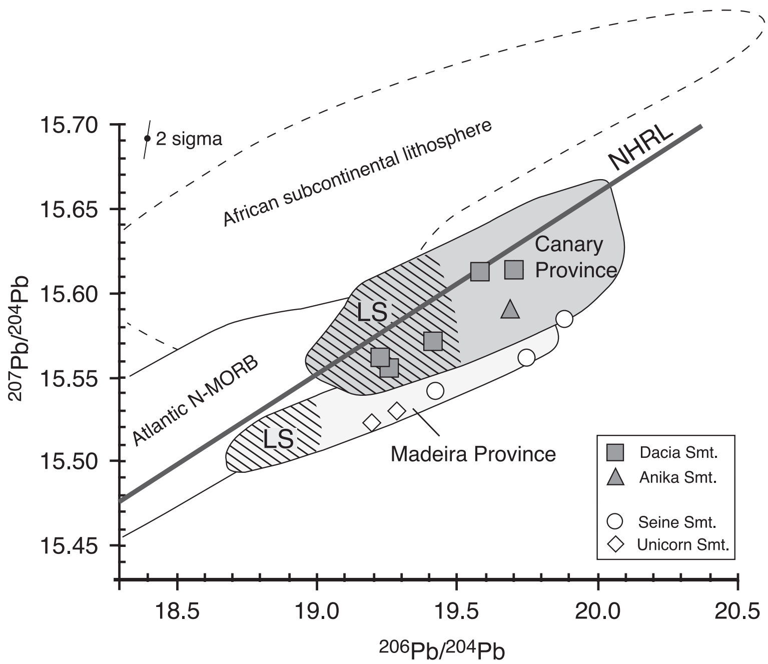


Fig. 4. Lead isotopic composition of Unicorn and Seine Seamounts overlap the field for the Madeira province [41], whereas Dacia and Anika Seamounts plot within the Canary province field [22, 23 and unpublished data]. Shaded areas (LS) mark compositions of late stage magmatism of the two provinces. NHRL = Northern Hemisphere Reference Line. Field for subcontinental African mantle comes from analyses of mantle-derived xenolites [58,59]. Atlantic N-MORB data (Mid-Atlantic Ridge) between 10° and 30° N from the literature.

(see Fig. 1). Ages of 22 Ma for Seine and 27 Ma for Unicorn rock samples are consistent with ages predicted from the fixed hotspot model (~25–30 Ma) [9] and therefore would support the idea of an age progressive Madeira hotspot track. The calculated average age progression of ~1.2 ± 0.2 cm/a for the entire 67 m.y. old chain (Fig. 5a) could reflect the slow movement of the African Plate over the Madeira hotspot. The 70–72 Ma old alkaline volcanism at Serra de Monchique in southern Portugal [18] has been proposed to be part of a possible Madeira hotspot track before it was ~200 km displaced through right lateral offset along the Azores–Gibraltar Fracture Zone [9] (Fig. 1). Since the Serra de Monchique complex is now situated on the European Plate, it is not considered in Fig. 5a.

If only the oldest shield stage volcanic rocks with $^{206}Pb/^{204}Pb > 19.5$ are considered from the Canary Volcanic Province, the new age data from Dacia and Anika also support a SW to NE age progression: Hierro (1 Ma), La Palma (4 Ma), Gomera (12 Ma), Tenerife (11 Ma), Gran Canaria (15 Ma), Fuerteventura (25 Ma), Selvagen (30 Ma), Dacia (47 Ma) and Anika (55 Ma) (Fig. 5b, see Fig. caption for references). Only late stage volcanic rocks have been hitherto found at the easternmost island of Lanzarote ($^{206}Pb/^{204}Pb = 19.12 - 19.57$, oldest age 15 Ma; [21]) and at the submarine Conception Bank ($^{206}Pb/^{204}Pb \leq 19.51$, 17 Ma; [6]).

A dated sample from Lars Seamount, located at the NE end of the volcanic province, yielded an age of 68 Ma, is also consistent with a SW to NE age progres-

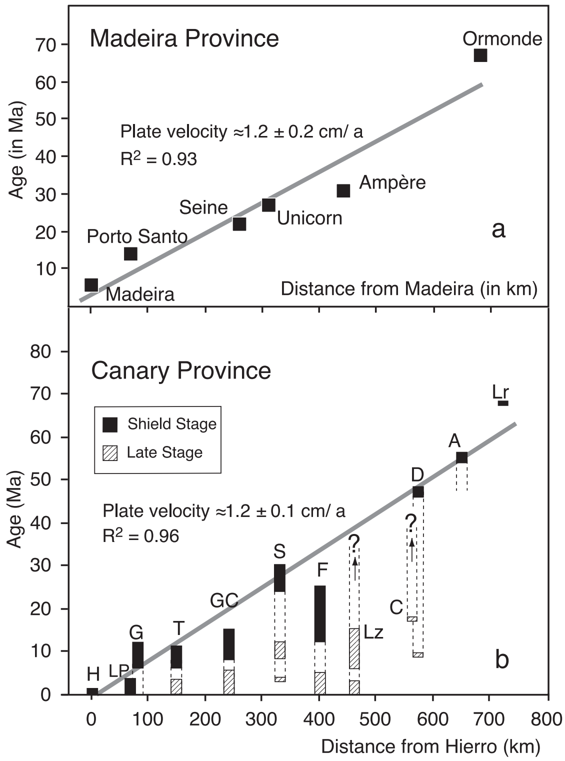


Fig. 5. a: Oldest radiometric ages for volcanic centers of the Madeira province versus distance from Madeira Island, excluding Serra de Monchique data on the European Plate. Additional age data from [9]. 5b: Radiometric ages of shield stages and late stage (rejuvenated or post-erosional stages) of islands and seamounts in the Canary province versus distance from Hierro. Abbreviations for islands and seamounts (with sources for age data): H = Hierro [60], LP = La Palma [61,62], G = Gomera [63], T = Tenerife [38,64], GC = Gran Canaria [65], S = Selvagen Islands [6], F = Fuerteventura [46], Lz = Lanzarote [21], C = Conception Seamount [6], D = Dacia Seamount [this study] A = Anika Seamount (working name) [this study] and Lr = Lars Seamount [6]. Thick grey line: Average Cenozoic plate velocity (~1.2 cm/a). Regression lines calculated for oldest available ages of shield stage volcanism only.

sion. Since the Pb isotope ratio of this sample ($^{206}Pb/^{204}Pb = 19.44$) is within the overlap between shield and late stage volcanism, it is unclear if this sample belongs to the shield stage of the volcano. Excluding this sample from the calculation of the age progression in Fig. 5b, however, does not significantly change the calculated average age progression (1.24 cm/a without Lars seamount). Additional evidence for age progressive volcanism in the northern part of the Canary province comes from geophysical studies. A widespread and time-transgressive seismic layer, interpreted to reflect volcanic ashes from the Canary hotspot, occurs in oceanic sediments marking the Cretaceous/Tertiary boundary near Lars seamount but becomes younger towards the Canary Islands in the south [8].

Elongated, time-progressive volcanic chains, however, might also be formed by volcanism along leaky transform faults or propagating fracture zones (e.g., [4]), in particular in areas with thin lithosphere or near mid-ocean ridges. Unlike most volcanic lineaments in the Pacific Ocean (and South Atlantic) the curved NE–SW alignment of the Madeira and Canary provinces clearly deviates from the E–W orientation of fracture or transform zones in the East Atlantic and there is no evidence of such similar curved faults in the East Atlantic lithosphere (see Anguita and Hernán [13] for overview). Furthermore, the lithosphere is believed to be extremely thick in the East Atlantic, due to its late Jurassic age [26] and therefore upwelling produced by movements along a lithospheric fault would generate only very small volumes of melt. Finally, there is no clear explanation why two roughly parallel curved fracture zones would propagate in the same direction and at the same average rate for >60 Ma in this region. The hotspot model, however, can explain the overall curved shape of both volcanic provinces and the age progression. As shown above, the resulting average age progression of the onset of shield stage volcanism in the Canary province of ~1.2 cm/a (Fig. 5b) is similar to the average Madeira province age progression (Fig. 5a) as expected by the hotspot concept for two areas located in close proximity to each other on the same plate. Although the age progression in Fig. 5 could be further divided into two different trends for 0–30 and 30–70 Ma, yielding slopes corresponding to plate velocities of 1.5–1.6 and 0.6–0.7 cm/a, respectively, such an interpretation is hampered by the limited data base, particularly for the period between 30 and 70 Ma. In conclusion, the observed age progressions of both volcanic provinces are consistent with rotation of the African Plate around common Euler poles located in the NW Atlantic (see below) above two nearly fixed magmatic sources.

5.2. Comparison with other possible hotspot tracks on the African plate

If the plume concept is correct, all hotspot tracks on a single, moving plate should have a common pole of rotation (Euler pole), assuming that the plate behaves as a rigid body. The location of the instantaneous Euler pole, however, can change with time. These changes, as well as the angular velocity of the plate at each given time, should be recorded by all hotspot tracks on the plate. On the other hand, there are a number of reasons why surface hotspot tracks do not exactly record the velocity and direction of the plate above a hotspot. Reasons for discrepancies include: 1) difficulty of obtaining ages for the onset of volcanism at a given site, since the oldest volcanism is often buried by younger eruptive products and submarine bases are difficult to sample, 2) structural control on the ascent of melts through the lithosphere (e.g., [11,27]), and 3) deflection of upwelling plume material by mantle flow or lithospheric drag (e.g., [28–30]). Recently, possible intraplate deformation has been postulated as an additional explanation of the observed misfits [31]. All these factors have a greater influence on potential hotspot surface patterns on slower moving plates, such as the African plate, than on faster plates, such as the Pacific plate. These processes are the reason for the large number of different rotation poles and plate velocities proposed for the African Plate at given time intervals [6,32–36]. Furthermore, to account for the advection of upwelling plumes within the mantle flow, Steinberger [30] calculated three different poles and velocities for the African plate for a given time interval depending on the assumed mantle viscosity and relative plate motion model.

All these rotation models, however, have three common criteria: 1) African Cenozoic rotation poles lie within the North Atlantic between 30° N and 60° N, consistent with rotation poles derived from magnetic seafloor anomalies. 2) Proposed African rotation poles generally move northward with decreasing age resulting in more WSW trending volcanic chains with decreasing age in the late Cenozoic in contrast to a more SSW direction during the early Cenozoic. 3) There is a general increase in age for the onset of volcanism along the tracks from SW to NE. Although it has been questioned if all published $^{40}Ar/^{39}Ar$ ages from proposed African hotspot tracks represent true crystallization ages [37], the simple fact that the SW end of the tracks are marked by young oceanic islands, whereas only submerged seamounts can be found towards the NE, provide strong support for SW to NE age progressions along the volcanic chains.

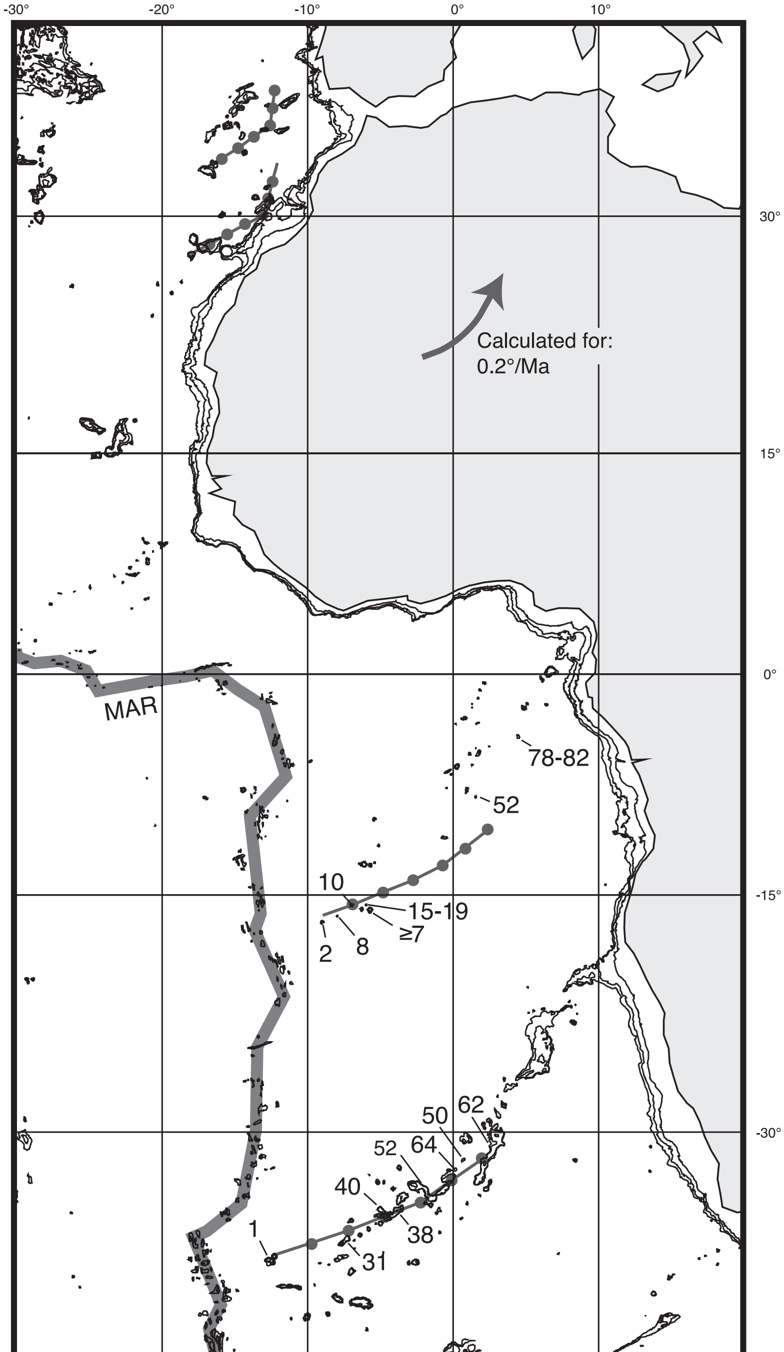
In order to test further the validity of the hotspot model for the African plate we now evaluate if the Tristan/Walvis and St. Helena chains in the South Atlantic can be explained with the same Euler pole and rotation rate as the Madeira and Canary volcanic provinces. Both southern Atlantic chains have been considered as classical hotspot tracks [1,33]. For simplification, only two average poles for the time periods of 0–35 and 35–64 Ma have been modeled at 56° N, 45° W and 35° N, 45° W, respectively. This simple model produces potential hotspot tracks (Fig. 6) that deviate less then 150 km (47 km on average) from the location of dated Cenozoic islands and seamounts of all four chains (with one 240 km large exception in the St.Helena track). The modeled average angular rotation velocity of about $0.20° \pm 0.05°$/Ma corresponds to local plate movements of 1.2 ± 0.3 cm/a (Madeira region), 1.3 ± 0.3 cm/a (Canaries), 2.8 ± 0.7 cm/a (St. Helena), and 3.4 ± 0.9 cm/a (Tristan/ Walvis Ridge) for the time interval of 0–35 Ma. These rates fit well with published age progressions (based on radiometric age data) of 1.2–1.5 cm/a for the Madeira province [9, this study], 1.2–1.6 cm/a for the Canary province [6,38, this study], 2.0 cm/a for St. Helena [39], and 2.9 cm/a for average Tristan/ Walvis Ridge and 3.1 cm/a for Walvis Ridge only [39]. Considering all the uncertainties mentioned above and the lack of precise ages for the onset of volcanism, better agreement cannot be expected.

5.3. Geochemistry of East Atlantic volcanism

The geochemical characteristics of volcanic rocks can also be used to evaluate the origin of intraplate volcanism. The incompatible trace element compositions of the Madeira and Canary shield and late stage volcanism are enriched relative to mid-ocean-ridge basalt (MORB), and are characteristic of intraplate ocean island basalt (OIB) volcanism (Fig. 3) commonly associated with mantle plumes. The Sr–Nd–Pb isotopic data for new samples from Dacia and Anika Seamounts fall within the ranges defined by the Canary Islands, and the Sr–Nd–Pb isotopic data for Unicorn Seamount fall within the range observed for shield stage volcanism on the Madeira Islands, supporting the geochemical distinction between both provinces (Fig. 4). Although the Pb isotope data for Seine Seamount falls within the Madeira Island range, $^{87}Sr/^{86}Sr$ ratios are higher and $^{143}Nd/^{144}Nd$ ratios are lower but fall within the range observed at Ormonde Seamount. The systematically more-enriched isotopic compositions of Ampere, Ormonde and Serra de Monchique igneous rocks with decreasing distance to the continent were interpreted to reflect contamination within the lithospheric mantle, which may have incorporated enriched subcontinental lithospheric mantle (as is located beneath Serra de Monchique) during formation of the oceanic lithosphere shortly after the breakup of Pangaea (e.g., [11,22,23,40,41]).

Although late stage volcanic rocks from the Madeira and the Canary volcanic provinces overlap the Atlantic N-MORB field in isotope composition, all shield stage lavas from the Madeira and the Canary provinces plot to the right of the Atlantic N-MORB field, having either higher $^{206}Pb/^{204}Pb$ isotope ratios or lower $^{207}Pb/^{204}Pb$ for a given $^{206}Pb/^{204}Pb$ than Atlantic, Pacific and Indian N-MORB and most subcontinental mantle xenoliths from Africa and Europe (Fig. 4). Therefore, an origin of the isotopic enriched shield stage endmember from the MORB source (depleted upper mantle, DM) or from subcontinetal lithospheric sources that have been delaminated or

Fig. 6. Modeled Cenozoic hotspot tracks for the Madeira and Canary province compared to the St. Helena and Tristan/Walvis ridge volcanic chains using the same plate tectonic parameters. Bathymetric contours are 1, 2 and 2.5 km depths. For simplicity, tracks have been calculated by rotation around only two Euler poles at 56° N, 45° W (0–35 Ma) and 35° N, 45° W (35–64 Ma). Circles mark age increments of 10 m.y. (at an average velocity of 0.22°/Ma). Numbers are published radiometric age data (in Ma) for volcanic rock samples from the St. Helena and Tristan/Walvis ridge tracks [39,66]. Bathymetry from: GEBCO Digital Atlas [67].



-30°
-20°
-10°
0°
10°
30°
15°
0°
-15°
-30°
-45°
Calculated for:
0.2°/Ma
MAR
78-82
52
10
15-19
≥7
2
8
50
62
52
64
40
38
1
31

introduced into the upper oceanic mantle by upper mantle convection currents appears unlikely.

The Pb isotopic compositions could reflect relatively young recycled oceanic crust with ages of ~0.8–1.5 Ga (e.g., [40–43]). Based on models of mantle convection, heterogeneities in the convecting mantle are unlikely to survive such long time scales (e.g., [44]). It is even more unlikely that a large reservoir of such material spread over at least 700 by 200 and 700 by 400 km (the dimensions of the Madeira and Canary volcanic provinces) could survive intact for >70 Ma. Storage of ≥0.8 Ga ocean crust in a thermal boundary layer, from which mantle plumes are likely to originate, seems to be more feasible. In conclusion, the trace element and Sr–Nd–Pb isotope data from the Madeira/Canary volcanic provinces are consistent with derivation from mantle plumes.

5.4. Spatial distribution of East Atlantic volcanism

Some of the characteristics of the Madeira volcanic province differ from the classical hotspot/plume model: 1) irregular spacing and large gaps between individual islands and seamounts, 2) E–W alignment of individual volcanic centers like Ampère/Coral Patch seamounts and the main rift zone on Madeira. A pulsating hotspot or string of discrete blobs rather than a continuous mantle plume, however, would explain temporal and spatial gaps in hotspot tracks (Fig. 1). It is further possible that the pathways of ascending plume magma is strongly influenced by the lithospheric fabric. The E–W elongation and alignment of the Ampère and Coral Patch seamounts, as well as the E–W striking main rift zone of Madeira Island, are parallel to the direction of fracture zones in the East Atlantic, suggesting a local control of surface volcanism along lithospheric zones of weakness.

In contrast to the relatively narrow chain of the Madeira province, islands and seamounts of the Canary province are more irregularly distributed (Fig. 1). Small-scale upper mantle convection-driven by the thermal contrast of the continent/ocean lithospheric boundary or between the thick root of the African craton (Fig. 1) and the much warmer asthenosphere below the thinner oceanic lithosphere have been proposed to explain a more diffusely distributed volcanism (e.g., [15,16]). These models imply a convection cell with a downwelling branch at the edge of the craton, lateral movement away from the craton at transition zone depths, upwelling under oceanic lithosphere some hundred kilometers away from the continent, and lateral return flow at 200–400 km depths back to the edge of the craton [15]. None of the calculations, however, have included melting, and it is unclear if the upwelling below old and relatively thick oceanic lithosphere reaches shallow enough depths to produce significant amounts of adiabatic melting [45]. In addition, the edge-driven convection model fails to produce any age progression of surface volcanism and predicts a decrease in convection intensity with time [15], both of which are contrary to observations in the Canary province. During the Cenozoic, magmatic activity in the Canary volcanic province appears to have increased rather then decreased (see Fig. 5).

Although edge-driven convection alone seems to be insufficient to explain the East Atlantic volcanism, interaction of a mantle plume with edge-driven convection cells could account for some of the unusual characteristics observed in the Canary volcanic province. It has been proposed that the Canary plume is heterogeneous, consisting of blobs of enriched plume material [10]. Adiabatic melting of the blobs generates isotopically enriched shield stage volcanism. Disturbance of the upwelling blobs by edge-driven convection either in transitional zone depths (ocean-ward) or above 400 km (continent-ward) would lead to lateral deflection resulting in a broader, more irregular pattern of surface volcanism, while still preserving a crude age progression (Fig. 7).

During the Mesozoic the thickness of the oceanic lithosphere along the NW African continental margin must have been much thinner. Upwelling mantle from the edge-driven convection cells could have reached shallower depths thus undergoing greater extents of melting. This could explain regional Mesozoic magmatism such as SiO_2-undersaturated volcanic ash layers within the upper Cretaceous sediments [46] and ~64 Ma old syenitic intrusions [47] in the basal complex of Fuerteventura. The relation of this older magmatism to the much younger shield stage volcanism of Fuerteventura has long been enigmatic. It is possible that edge-driven convection processes could be responsible for small-volume Mesozoic volcanism occurring along a broad zone parallel to the African continental margin. Today, most remnants of this volcanism are buried by younger oceanic sediments or

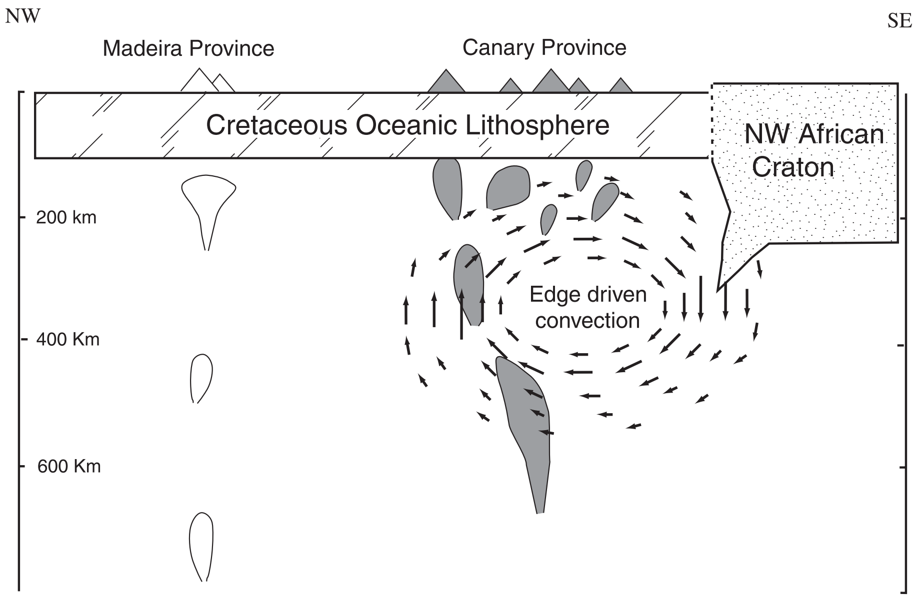


Fig. 7. Model showing possible interaction of small-scale upper mantle convection at the edge of the African craton with a Canary mantle plume. Lateral deflection of upwelling plume or blobs of plume material by convection currents results in a more broad, irregular pattern of surface volcanism. Upwelling in the Madeira region, being farther away from the continent, is significantly less affected.

volcanic edifices. On Fuerteventura, later Cenozoic plutonism (related to the Canary plume) has uplifted these old igneous and sedimentary successions resulting in a rare subaerial exposure of this early magmatism within the sedimentary basal complex of the island.

5.5. *Longevity of individual Canary volcanoes and origin of late stage volcanism*

The 47.4 Ma old shield stage sample of Dacia seamount (450 DR-1) and the 9.2 Ma old [6] late stage lava from Dacia confirm that volcanic activity at single volcanic centers in the Canary volcanic province can occur over exceptionally long intervals of up to 40 m.y. As seen in Fig. 5b, time spans of at least 25–30 m.y. between the oldest available shield stage and youngest late stage volcanic activity are also confirmed for Fuerteventura and the Selvagen Islands [6,46]. In addition, if age progressive growth of Canary shield volcanoes is accepted, then Conception seamount and Lanzarote are also likely to have been active for 25–30 Ma (see Fig. 5b).

Late stage (or post-erosional/rejuvenated) activity is a common feature of ocean island volcanoes and generally differs in volume (usually making up <1% of the total volcano) and geochemical composition from the shield stage. In most cases, late stage magmas display less enriched isotopic compositions, as also seen for the East Atlantic volcanic provinces (Fig. 4). This compositional difference is interpreted to reflect a greater contribution from a more depleted magma source. Late stage melting of depleted portions of an upwelling and bending plume is suggested for Madeira [41], whereas for the Canary province a major contribution of entrained ambient upper mantle material has been proposed (e.g., [10]). To explain the temporal gap at the Hawaiian Islands, Ribe and Christensen [29] describe minor melting in a secondary melting zone located farther downstream of a flexing plume by late stage, adiabatic upwelling due to the ongoing spreading and ascent of plume material. Whereas a similar process is proposed for Madeira [41], the long temporal gap between shield and late stage volcanism on Dacia, Fuerteventura, and Selavagen Islands (as well as the young age of late stage volcanism on Conception and Lanzarote) in the Canary province, however, is difficult to explain in the context of a plume model.

The interplay between a Canary plume and edge-driven convection, however, could account for some of the characteristic features of late stage volcanism in the Canary volcanic province. Long gaps between shield and late stage volcanism as well as multiple periods of late stage activity could result from fluxes of cold, upper mantle material within the melting zone below the volcanoes due to the lateral flow at the top of the convection cells. This mechanism could cause volcanism to temporally cease. Mixing of asthenospheric and plume material during upper and lateral convection flow could provide the sources for the more depleted but hybrid late stage magmas [10].

Alternatively, late stage volcanism in the Canary province could result from small-scale melting of more fusible parts within the upwelling ambient upper mantle. It has been shown that the upper mantle can be heterogeneous on a small scale containing pyroxenite and eclogite layers within a depleted peridotitic matrix [48]. The pyroxenitic layers could either represent recycled oceanic crust (e.g.,[49]) or cumulates and crystallized melts from the upper mantle [50]. The solidus of pyroxenitic/eclogitic material will be crossed at greater depth than that of the depleted peridotitic matrix allowing it to preferentially melt under old thick lithosphere. Whether crystallized upper mantle or young recycled crust, melts from such sources can have depleted MORB-like isotopic compositions but enriched OIB-type trace element signatures as displayed by the late stage volcanic rocks from Dacia seamount. (Fig. 3). Although low volumes of melt, distributed over a wide area, probably cannot establish a focussed magmatic plumbing system, these late stage magmas may use the lithospheric pathways formed by the earlier more voluminous shield stage melts. Some magmas are likely to be erupted on or intruded into the surrounding seafloor, but are difficult to detect because of their low volumes. Pyroxenite/eclogite within the upper mantle MORB source could potentially account for late stage melts on ocean islands in general. Melting of pyroxenitic/eclogitic layers can result from conductive heating by nearby blobs of plume material or through decompression melting if entrained at depth. An additional contribution during late stage volcanism could come from lithospheric sources which have been metasomatized by plume melts during the earlier shield stage of the volcano (e.g., [51]).

Since the Madeira province is >700 km distant from the edge of the African craton (Fig. 1), it is probably not or significantly less affected by edge-driven convection currents, explaining why volcanism in this province, including the well-studied Madeira Islands, has occurred over much shorter time intervals of ≤5 Ma. Instead of entrainment of ambient depleted upper mantle in the plume, late stage volcanism is proposed to originate from an isotopically depleted plume component (probably recycled lower oceanic crust and lithosphere) in the downstream part of the plume head [41]. A similar model has recently been proposed by Frey et al. [52] for Hawaiian rejuvenated volcanism.

6. Summary and conclusions

This study investigates the origin of intraplate oceanic volcanism in the central East Atlantic using new geochemical and age data from key seamount volcanoes. Based on isotopic composition, central East Atlantic volcanism can be grouped in two geochemically distinct regions, the Madeira and the Canary volcanic provinces. Initial shield stage volcanism in both provinces shows isotopically enriched ocean island basalt (OIB)-type compositions, distinct in trace element and isotopic composition from Mid-Atlantic MORB. Since it is difficult to maintain large-scale geochemical domains with distinct compositions within the convecting uppermost sublithospheric mantle for 60 m. y. or more, an origin from deeper, compositionally distinct sources (e.g., thermal boundary layers containing subducted oceanic crust) is favored.

The new $^{40}Ar/^{39}Ar$ age determinations from Seine and Unicorn seamounts NE of the Madeira archipelago and from Dacia and Anika seamounts NE of the Canary islands confirm average age progressions of ~1.2 cm/a in both provinces. Fracture zones in the oceanic crust cross-cut the Madeira volcanic belt at a high angle and therefore volcanism along leaky fracture zones can be discounted. Nevertheless these zones of lithospheric weakness may locally control the location and orientation of volcanic structures. The overall geographical pattern of central East Atlantic volcanism can be modeled approximately by rotation of the African plate around two Euler poles at

56° N, 45° W (0–35 Ma) and 35° N, 45° W (35–64 Ma). The modeled plate parameters also yield a good fit for the two prominent St.Helena and Tristan/Walvis volcanic chains in the South Atlantic, which are also believed to represent hotspot tracks. In conclusion, the hotspot hypothesis still provides the best explanation for the origin of major volcanic chains on the African plate. In detail, however, imperfect age relationships and spatial offset of some individual volcanic centers from the track require the influence of important secondary effects. For example, several features of the Canary volcanic province are not easy to explain within the context of the classical hotspot hypothesis: 1) the exceptional longevity of volcanic activity of single volcanic centers in the Canary province (up to 25–40 m.y.), 2) the presence of late Mesozoic volcanism in the eastern Canary Islands, and 3) the broad and irregular Canary volcanic belt. It is proposed that interaction of a Canary plume with edge-driven convection processes can account for these apparent inconsistencies in the mantle plume model.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2005.04.037.

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