ELSEVIER
Earth and Planetary Science Letters 173 (1999) 257–269
EPSL
www.elsevier.com/locate/epsl

Mid-Atlantic Ridge–Azores hotspot interactions: along-axis migration of a hotspot-derived event of enhanced magmatism 10 to 4 Ma ago

Mathilde Cannat [a,*], Anne Briais [b], Christine Deplus [c], Javier Escartín [a,d], Jennifer Georgen [e], Jian Lin [e], Serguei Mercouriev [f], Christine Meyzen [g], Mark Muller [a,1], Gaud Pouliquen [c], Aline Rabain [a], Pedro da Silva [h]

[a] Laboratoire de Pétrologie, CNRS–UPMC, 4 Pl. Jussieu, Paris 75252 Cedex 05, France
[b] GRGS–CNRS, Toulouse, France
[c] IPGP–CNRS, Paris, France
[d] Institute of Earth Sciences Jaume Almera–CSIC, Barcelona, Spain
[e] WHOI, Woods Hole, MA, USA
[f] Russian Academy of Sciences, St. Petersburg, Russia
[g] CRPG–Université de Nancy, Nancy, France
[h] Centro de Geofisica, Lisbon University, Lisbon, Portugal

Received 7 May 1999; revised version received 15 September 1999; accepted 22 September 1999

Abstract

A recent survey of the Mid-Atlantic Ridge over the southern edge of the Azores Platform shows that two anomalously shallow regions located off-axis on both sides of the ridge are the two flanks of a single rifted volcanic plateau. Crustal thickness over this plateau is up to twice that of surrounding oceanic areas, and original axial depths were near sealevel. The lack of a coherent magnetic anomaly pattern, and the near absence of fault scarps over the plateau suggest that its formation involved outpouring of lava over large distances off-axis. This volcanic plateau formed in Miocene times during an episode of greatly enhanced ridge magmatism caused, as proposed by P.R. Vogt [Geology 7 (1979) 93–98], by the southward propagation of a melting anomaly originated within the Azores hotspot. This melting anomaly could reflect excess temperatures of ~70ºC in the mantle beneath the ridge. It propagated at rates of ~60 mm/yr and lasted no more than a few million years at any given location along the ridge. Enhanced magmatism due to this melting anomaly played a significant role, some 10 Ma ago, in the construction of the Azores Platform.

Keywords: mantle; hot spots; mid-ocean ridges; Azores

1. Introduction

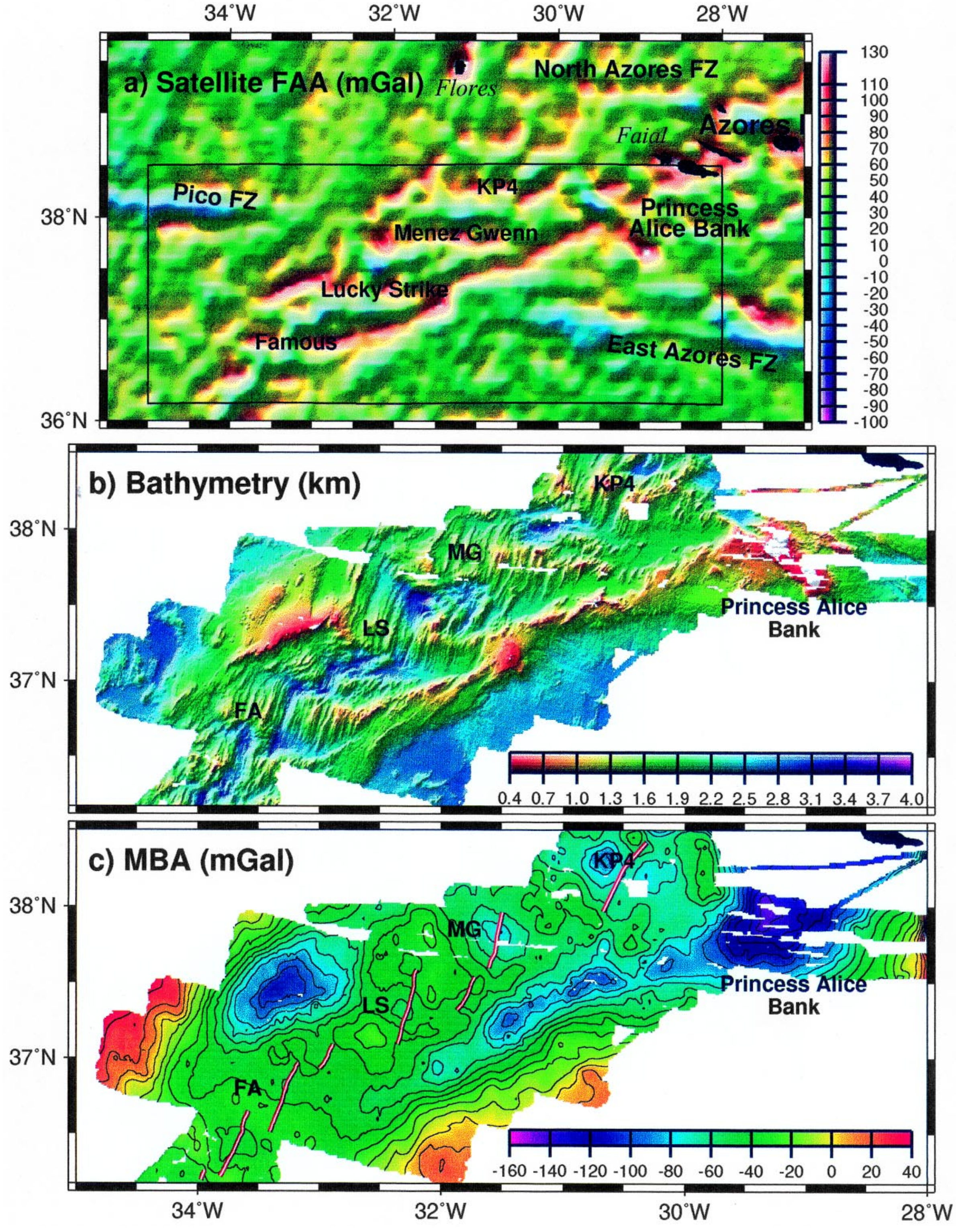
The Mid-Atlantic Ridge deepens gradually southward from the Azores region near 40ºN (axial depth: 1800 m on average [1]) to about 26ºN (axial depth: 3850 m on average [2]). This long bathymetric gradient coexists with similarly long gradients of gravity anomalies and basalt geochemistry, suggesting that regional crustal thickness, the buoyancy of the upper mantle beneath the ridge, and its content in incompatible chemical elements, all decrease slowly away from the Azores [3,4]. Similar bathymetry, gravity,

---

[*] Corresponding author: Tel.: +33 1 44 27 51 92; Fax: +33 1 44 27 39 11; E-mail: cannat@ccr.jussieu.fr

[1] Present address: Anglo American corporation, Marshalltown, South Africa.

PII: S0012-821X(99)00234-4


a) Satellite FAA (mGal)
Flores
North Azores FZ
Faial
Azores I
Pico FZ
KP4
Princess Alice Bank
Menez Gwenn
Lucky Strike
Famous
East Azores FZ
34°W
32°W
30°W
28°W
38°N
36°N
130
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
b) Bathymetry (km)
KP4
MG
LS
FA
Princess Alice Bank
38°N
37°N
0.4
0.7
1.0
1.3
1.6
1.9
2.2
2.5
2.8
3.1
3.4
3.7
4.0
c) MBA (mGal)
KP4
MG
LS
FA
Princess Alice Bank
38°N
37°N
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
34°W
32°W
30°W
28°W

and geochemical gradients exist in the vicinity of other near-ridge volcanic islands such as Iceland, Tristan da Cunha, and the Galapagos. They indicate that the plumes of anomalously hot and/or enriched mantle ('hotspots') that are thought to feed volcanism on these islands also divert toward nearby ridges and spread laterally along-axis over distances of a few hundred to two thousand kilometers. This along-axis flux of plume material is thought to be a function of as yet poorly constrained variables such as the plume's geometry, temperature and dynamics [5–9]. Studying the temporal and spatial variations of ridge-directed plume fluxes is a way to constrain these variables. The present study focuses on the Azores region and brings evidence for a relatively short lived, but pronounced episode of enhanced magmatism at the Mid-Atlantic Ridge axis in Miocene times. This excess magmatism could be due to a marked change in the temperature of mantle material provided by the Azores hotspot and channeled along the ridge during this period.

2. General setting of the study area

The Azores hotspot corresponds with a broad (a few hundred kilometers in diameter) domain of anomalously low S-wave velocities in the 100 km to 200 km depth range, centered somewhat to the east of the Mid-Atlantic Ridge [10]. The distribution of recent volcanism in the Azores Archipelago suggests a similar location (100 to 200 km to the east of the ridge, near the island of Faial; Fig. 1a) for the hotspot center [5,7].

Volcanism leading to the formation of the Azores Archipelago has been focused along the NW–SE-trending Terceira Rift, a dextral transtensional structure [13,14], for at least the past 5.5 Ma [15]. Formation of the anomalously shallow Azores Platform may have started as early as 36 Ma ago [16], with the onset of the northward migration of the Africa–North America–Eurasia (AFR–NAM–EUR) triple junction from the latitude of the Pico and East Azores Fracture Zones (Fig. 1a), to the vicinity of the North Azores Fracture Zone, where it is located at present [17]. Two elongated regions of anomalously shallow depths can be seen as V-shaped positive anomalies on the free-air satellite gravity map (Fig. 1a). These anomalously shallow regions were identified by Vogt [18] as the Faial and Flores ridges, and interpreted as volcanic features caused by enhanced hotspot activity in Miocene time.

The ridge in our study area is part of the NAM–AFR plate boundary, with an instantaneous spreading rate of 22 mm/yr on an azimuth of 110° [19]. Time-integrated spreading kinematics across this boundary between 28°N and 40°N are well constrained for the past 10 Ma [17,20,21] and have varied little (22–25 mm/yr rate on an azimuth of 98–108°) through time and along axis for the past 7 Ma. Prior to that, spreading rates appear to have been faster over the whole area and particularly over the Azores Platform (up to 40 mm/yr between 8.7 and 10.2 Ma [17]). The AFR plate moves very slowly to the southwest [22,23] relative to the hotspot reference frame. The Mid-Atlantic Ridge in the study area therefore migrates to the west-southwest, away from the Azores hotspot, at rates slightly less than the half-spreading rate.

3. Off-axis relicts of a rifted volcanic plateau

Multibeam bathymetry and gravity data recorded during the SudAçores cruise (R.V. *L'Atalante*; July–August 1998) extend to magnetic anomaly 5 on both sides of the axis over the FAMOUS, North FAMOUS, and Lucky Strike ridge segments, and all the way to Princess Alice Bank off-axis from the Menez Gwen and KP4 segments (Fig. 1). They complement data previously recorded over the ridge axis (FARA-SIGMA cruise [12]). A description of along-axis bathymetry and gravity in the area of

Fig. 1. (a) Shaded satellite free-air gravity map of the Mid-Atlantic Ridge in the Azores region [11] (illumination from N150°). Box marks the location of (b) and (c). (b) Shaded multibeam bathymetry (SIMRAD EM12) from the SudAçores (this study) and FARA-SIGMA [12] cruises onboard *L'Atalante*. *MG* = Menez Gwen; *LS* = Lucky Strike; *FA* = FAMOUS. Note the anomalously shallow region east of the ridge axis between Princess Alice Bank and FAMOUS, and its western counterpart at the latitude of the Lucky Strike segment. (c) Mantle Bouguer anomaly map (MBA) for the same area. Note the prominent gravity lows at the location of the shallow areas.

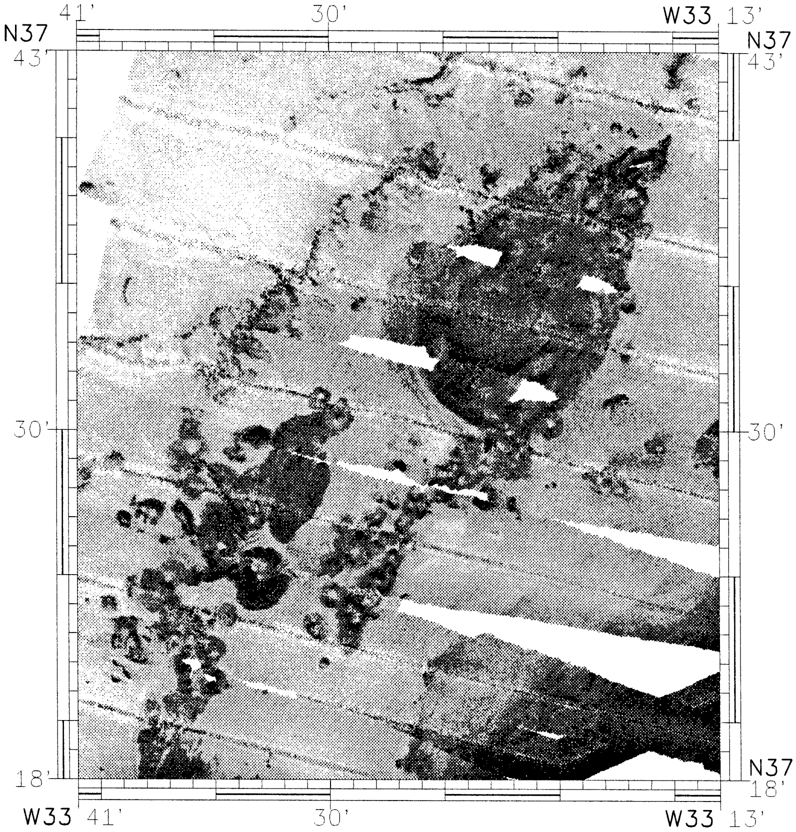


Fig. 2. SIMRAD reflectivity image of intact volcanic cones on the western flank of the volcanic plateau, off-axis from the Lucky Strike segment (location: see inset in Fig. 3a). Reflective areas (dark grey) correspond to slopes of volcanic edifices. Low reflectivity areas (pale gray and white) are flat and sedimented zones. The large volcano at 37°35′N is ~18 km in diameter. Smaller cones, 1 to 4 km in diameter, tend to align in a NNE–SSW direction, parallel to the regional trend of the ridge axis.

Fig. 1, based on FARA-SIGMA results, can be found in Detrick et al. [1].

The new off-axis bathymetry data show that the two regions of anomalously shallow depth identified by Vogt [18] as the Faial and Flores ridges are indeed volcanic features, with numerous intact volcanic cones, up to 18 km in diameter (Fig. 2). These anomalously shallow regions lack the regular pattern of ridge-parallel abyssal hills that is so prominent in younger off-axis areas (Fig. 3a). Magnetic anomalies in these younger areas are well defined. Fig. 4 shows the observed magnetic profile at the mid-point of the Lucky Strike segment. Up to the beginning of anomaly 3A this observed profile fits (with slightly slower spreading rates) a synthetic model (model 1; Fig. 4) in which the bathymetry is inferred to follow a simple subsidence curve (for a constant spreading rate of 24 km/Ma). The edges of the anomalously shallow volcanic regions on both flanks of the axis are marked by very high amplitude magnetic anomalies (Fig. 3b and Fig. 4). Magnetic anomalies over the shallow volcanic regions are dominantly positive (especially in the western region; Fig. 4) and do not fit model 1. Model 2 (Fig. 4) involves a magnetic layer of constant thickness (400 m as in model 1) which follows the seafloor topography. It shows that while topographic effects can account for the high amplitude of magnetic anomalies associated with the edges of the shallow volcanic regions, they do not reproduce the observed, dominantly positive magnetic signal over these regions.

The shallow region to the west of the ridge axis is roughly triangular in shape and is widest at the latitude of the Lucky Strike segment (Fig. 1b). Its

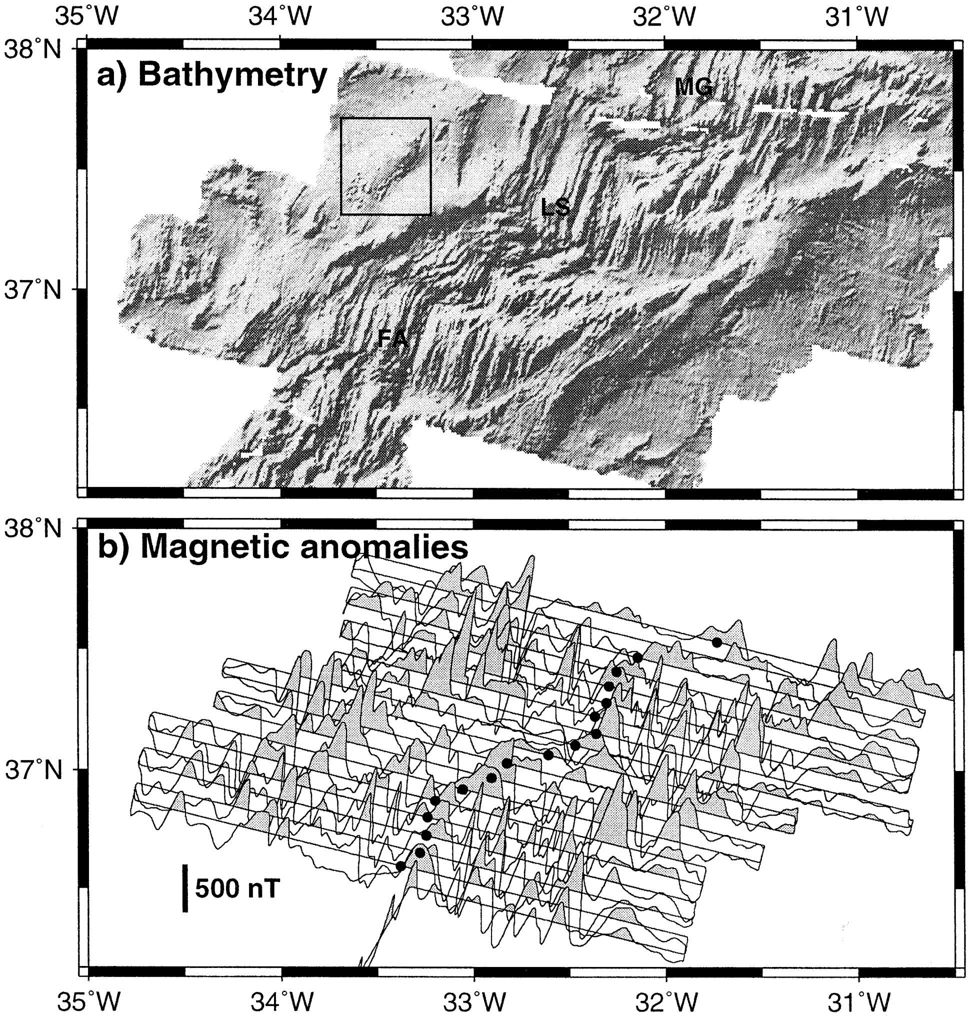


Fig. 3. Shaded bathymetry and magnetic anomalies over the Mid-Atlantic Ridge south of the Azores. (a) Shaded bathymetry. Abbreviations: see Fig. 1b. Illumination from N320° enhances the contrast between smooth topography on the two flanks of the volcanic plateau, and numerous ridge-parallel and oblique scarps in the intervening younger seafloor. Inset shows the location of Fig. 2. (b) Magnetic anomalies projected along tracks of the SudAçores cruise. Dots mark the modeled position of the axial anomaly. Note the high amplitudes of magnetic anomalies over the two edges of the volcanic plateau.

possible extension north of the Menez Gwen segment has yet to be mapped. The shallow region to the east of the ridge axis is not as wide, but extends all the way from the FAMOUS segment in the south, to Princess Alice Bank in the north, with a mean azimuth of 64° (Fig. 1b). Its western flank is a steep NE–SW-trending scarp, with a short N–S-trending portion at the latitude of the Lucky Strike segment. Similarities in the shape of ridgeward scarps for the western and eastern shallow regions at this latitude suggest that they can be fit back together by closing the more recently accreted intervening seafloor. The study of magnetic anomalies [21] confirms this hypothesis, showing an excellent fit of the two scarps between anomalies 3 and 3A with rotation parameters virtually identical to those determined at 28°–29°N for this same period [20]. The two off-axis shallow regions in Fig. 1b therefore appear to be the two flanks of a rifted volcanic plateau. Volcanic cones over this plateau are commonly strongly re-

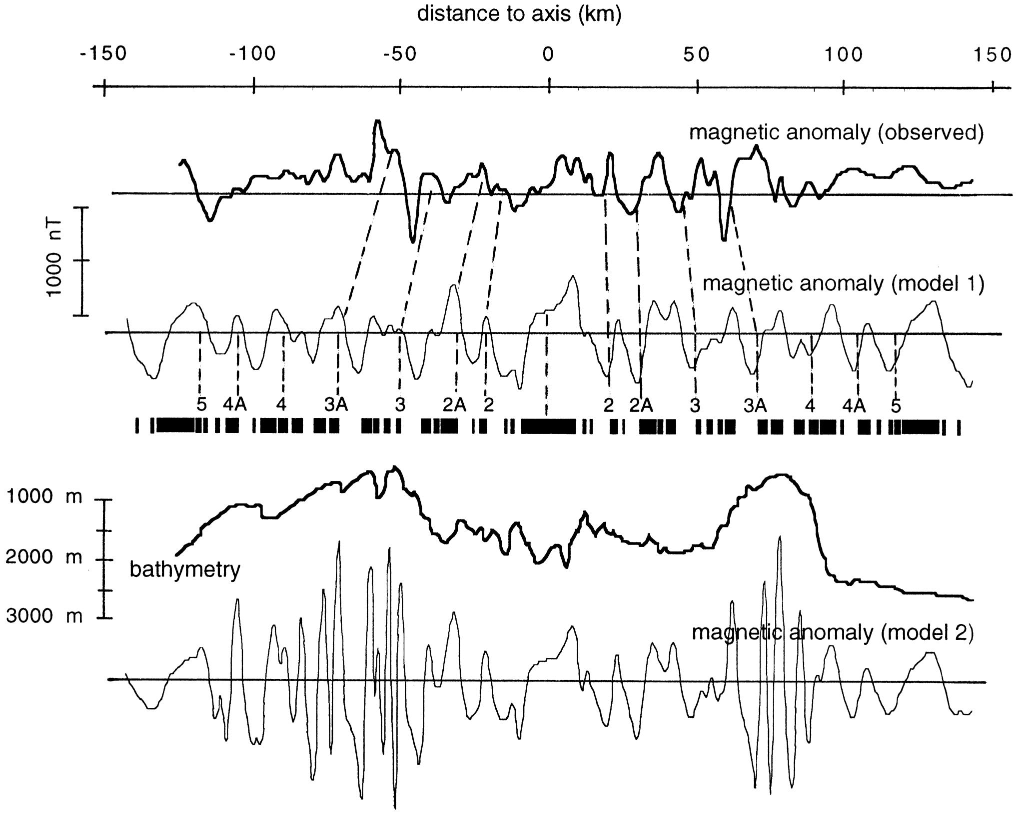


Fig. 4. Magnetic and depth profiles along a flow line (azimuth N104°) crossing the ridge axis in the center of Lucky Strike segment (37°16.46∼N). Magnetic models 1 and 2 are calculated with the geomagnetic timescale of Cande and Kent [24] for a constant full spreading rate of 24 km/Ma, a 400 m thick magnetic layer and a 3.2 km wide transition zone. Magnetic model 1 assumes that the magnetic layer follows a subsidence curve with an axial depth of 1500 m. In magnetic model 2, the magnetic layer follows the topography of the seafloor.

flective (Fig. 2). This is due to the combination of relatively steep slopes and small thicknesses of loose sediment and is probably not an indication that these cones represent recent volcanism. The lack of a coherent magnetic anomaly pattern, and the near absence of fault scarps over the volcanic plateau indicate that its formation did not occur within the confines of a narrow axial spreading region, but probably involved outpouring of lava over large distances off-axis, burying any earlier fault scarps and blurring the magnetic anomaly signal.

Mantle Bouguer anomalies (MBA) were derived from free-air anomaly (FAA) data by subtracting the gravity effect of the topography and the Moho, assuming a constant crustal thickness of 6 km and crustal density of 2700 kg/m^3 and using Parker's [25] method. The two flanks of the volcanic plateau correspond to marked lows in the MBA pattern (Fig. 1c). The maximum MBA contrast between the two flanks of the plateau and immediately adjacent younger seafloor reaches ∼60 mGal at the latitude of the Lucky Strike segment, and over 80 mGal at the latitude of Princess Alice Bank (Fig. 1c). Lithospheric cooling with age is modeled using Phipps Morgan and Forsyth's [26] passive mantle flow model, with a half spreading rate of 12 mm/yr. The thermal gravity is removed from the MBA to calculate the residual MBA (RMBA). Gravity corrections for spatial variations in sediment thickness determined using 6-channel seismic reflection (up to 750 m in the oldest parts of the study area) are minor (typically <10 mGal) and do not alter significantly the observed RMBA patterns (J. Escartín et al., in prep.). Relative crustal thickness variations are

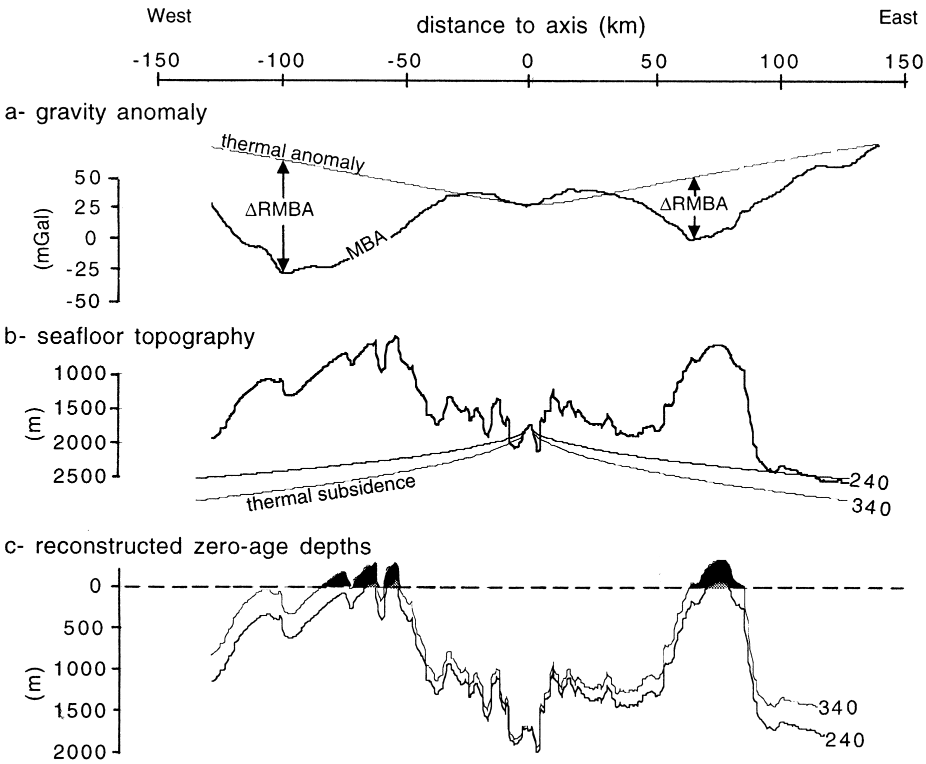


Fig. 5. Gravity and depth profiles along a flow line (azimuth N104°) crossing the ridge axis in the center of Lucky Strike segment (37°16.46∼N). (a) MBA (thick line), and thermal gravity anomaly ([26], thin line). Arrows show minimum ΔRMBAs values (with respect to present-day axis) for the two flanks of the volcanic plateau. (b) Bathymetry (thick line) and subsidence curves [28] calculated for $C = 240$ and 340 m/Ma$^{1/2}$. (c) Zero-age depths calculated with subsidence curves shown in (b). Possible former volcanic islands (calculated axial depths above sea level) are shown in gray and black.

calculated by downward continuation of the RMBA [27], assuming that they are solely produced by spatial variation in crustal thickness.

The western and eastern flanks of the volcanic plateau on the same flow line as the mid-point of the Lucky Strike segment have minimum ΔRMBAs of −90 and −51 mGal, respectively, with respect to on-axis values (Fig. 5a). These RMBA lows correspond to an excess crustal thickness of up to 5–6 km under the plateaus with respect to the ∼7–8 km crust inferred from gravity at the center of the Lucky Strike segment [1]. The maximum crustal thickness beneath the volcanic plateau would therefore be of the order of 12–14 km on the corresponding flowline, representing a two-fold increase (relative to present day) in the magma supplied to the ridge during the formation of the plateau. A similar pattern is observed at Princess Alice Bank with respect to the present crustal thickness of 8–9 km [1] at the center of the KP4 segment.

Axial depths at the time of formation of the plateau can be estimated using the empirical depth (D) vs age (t) curve of Parsons and Sclater [28] ($D(t) = Ct^{1/2} + D(t = 0)$) and assuming symmetrical spreading about the location of the present-day axis (Fig. 5b,c). We used two values of the subsidence factor $C = 340$ m/Ma$^{1/2}$ is the world average [28]; and $C = 240$ m/Ma$^{1/2}$ fits the slower subsidence of the magma-rich northern Reykjanes Ridge [29]. These two C values correspond to the upper and lower bounds of the C values observed from bathymetry off-axis along the MAR at the latitude of the Lucky Strike and FAMOUS segments (J. Escartín et al., in prep.). In both cases, the shallowest regions of the plateau appear to have formed at depths either very close to or above sealevel (Fig. 5c).

4. Southward migration of hotspot-derived magmatic pulse

The study of magnetic anomaly patterns [21] indicates that enhanced magmatism leading to the formation of the volcanic plateau in the FAMOUS–Lucky Strike area occurred after the time of anomaly 5 (10.1 Ma), and that rifting of this plateau occurred sometime between anomalies 3A (5.69 Ma) and 3 (3.85 Ma). The marked obliquity between the di-

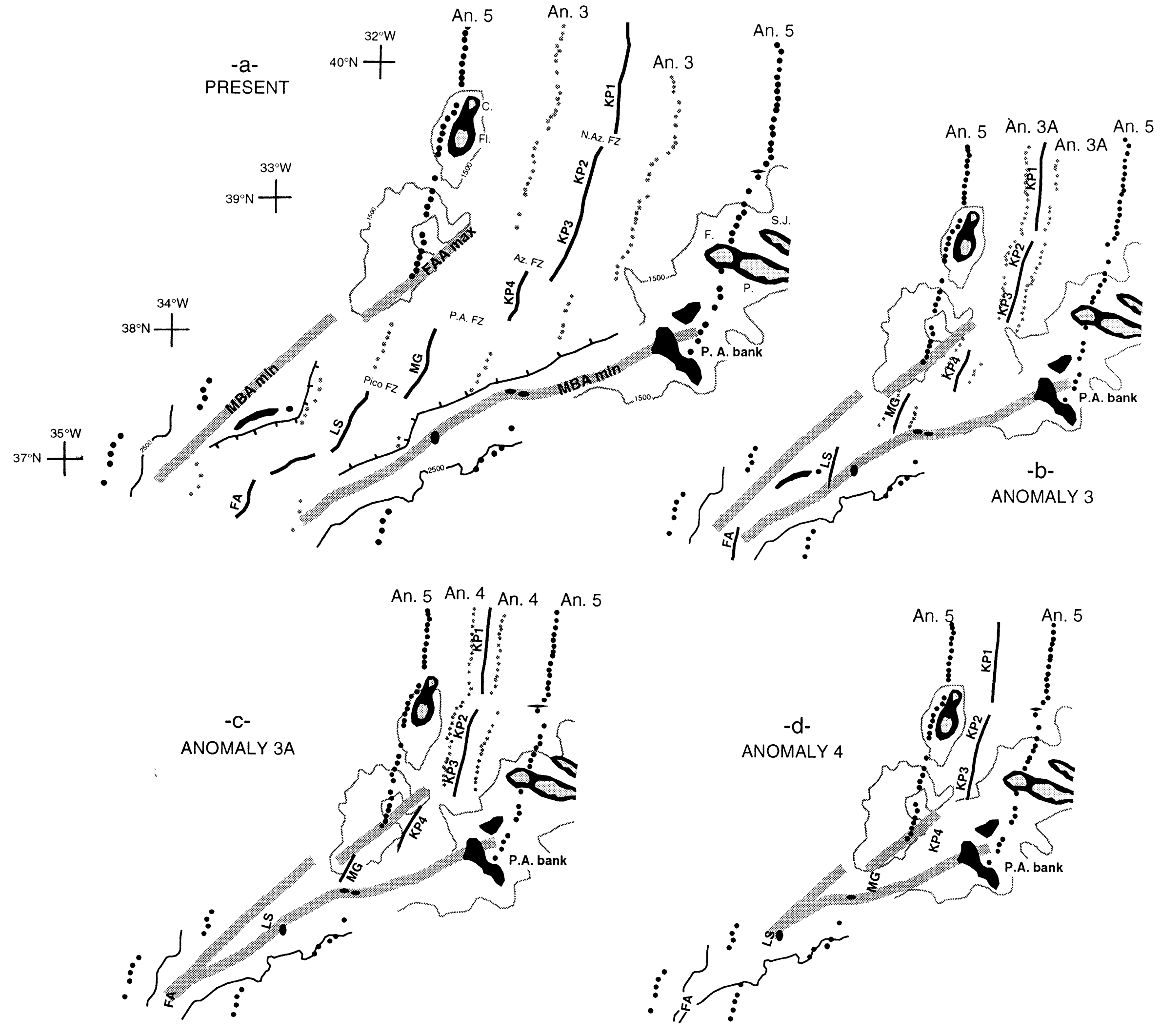


Fig. 6. Sketches showing location of selected bathymetric and gravity features at present (a), and at the time of magnetic anomalies 3 (b; 3.85 Ma), 3A (c; 5.69 Ma), and 4 (d; 7.01 Ma). For the sake of readability, each sketch only shows two magnetic anomalies [17,21]: An 5, and the most recent anomaly identified in off-axis records. The ridge axis is drawn at each step of the reconstruction based on these anomalies. Thick gray lines: MBA minima over the two edges of the volcanic plateau and FAA maxima in satellite-derived gravity map (see Fig. 1a); dented black lines: ridgeward scarps that mark the transition from plateau to younger seafloor; thin black line labelled 2500 in (a): trace of 2500 m isobath in Fig. 1b; thin gray line labeled 1500 in (a): trace of 1500 m isobath in off-axis regions of the Azores Platform from a compilation of GEBCO and NGDC data [17]; black: areas shallower than 500 m. Abbreviations: *N. Az. FZ* = North Azores Fracture Zone; *P. A. FZ* = Princess Alice Fracture Zone; *Az. FZ* = Azores Fracture Zone; *P. A. Bank* = Princess Alice Bank; *C.* = Corvo Island; *Fl.* = Flores Island; *S. J.* = Sao Jorge Island; *F.* = Faial Island; *P.* = Pico Island; *MG* = Menez Gwen; *FA* = FAMOUS; *LS* = Lucky Strike.

rection of spreading (N100–110º) and the average trends of depth and MBA anomalies over the east and west flanks of the plateau (N64º and N47º, respectively; Fig. 1) suggests that both the event of enhanced magmatism and the subsequent rifting of the volcanic plateau occurred first to the north and migrated southwestward. The migration azimuth for the magmatic event is ~N244º (line bisecting the angle between the two trends of MBA minima), parallel to the regional trend of the ridge, and the migration rate is ~60 mm/yr, assuming a half spreading rate of 12 mm/yr.

Fig. 6a shows the present-day configuration of a few structural elements over the Azores Platform and down to our study area. These structural elements include selected isobaths, the MBA minima that we interpret as the maximum crustal thickness on the two flanks of the volcanic plateau (Fig. 1c), and a prominent high in the satellite-derived FAA map ([11]; Fig. 1a) to the west of segment KP4. We interpret this FAA high, which trends parallel (azimuth N47º) to the MBA low mapped to the west of the ridge during the SudAçores cruise, as the northward continuation of the west flank of the rifted volcanic plateau. Fig. 6b–d shows schematic reconstructions (made by fitting together corresponding magnetic anomalies with a uniform N105 spreading direction) of these structural elements, for the times of magnetic anomalies 3, 3A and 4.

These reconstructions suggest that the maximum magmatic activity at the latitude of the Lucky Strike segment occurred ~7 Ma ago (anomaly 4), corresponding to the fit on-axis of the MBA minima over the two flanks of the plateau (Fig. 6d). The 2500 m isobath is considered as the outer edge of the volcanic plateau in our study area (see Fig. 1b and Fig. 5b). It lies at the center of FAMOUS at the time of anomaly 4 (Fig. 6d). Assuming an average along-axis propagation rate of 60 km/Ma, the distance between the center of Lucky Strike (maximum magmatic activity at that time) and FAMOUS (initiation of enhanced magmatism) corresponds to ~1.5 Ma. The onset of enhanced magmatism at the latitude of Lucky Strike may therefore have occurred ~1.5 Ma prior to the time of anomaly 4 (~8.5 Ma ago). Rifting of the volcanic plateau there occurred 4 to 5 Ma ago (prior to anomaly 3, Fig. 6b). The estimated duration of excess magmatism at the latitude of Lucky Strike is therefore of ~4 Ma. This estimated duration is a maximum because the plateau may have formed in less time, with extensive off-axis volcanism and plutonism. Better constraints on the duration of this magmatic event require further detailed studies of seafloor morphology, magnetic and gravity data.

Rifting of the volcanic plateau at the latitude of the KP4 segment occurred sometime between anomaly 4 (7.01 Ma; Fig. 6d) and anomaly 3A (5.69 Ma; Fig. 6c). It took about 3 Ma (at 60 mm/yr) for the magmatic pulse to cover the distance between KP4 and Lucky Strike. Enhanced magmatism was therefore probably at a peak near KP4 some 10 Ma ago. Total duration of enhanced magmatic activity at the latitude of KP4 may have been longer than further to the south, judging from the along flow-line width and amplitude of depth and gravity anomalies mapped over Princess Alice Bank (Fig. 1). Additional off-axis bathymetry and gravity data over the west flank of the ridge north of 38ºN are needed to better constrain this duration.

At the time of anomaly 5 (10 Ma ago), the two anomalously shallow off-axis regions (delimited by the 1500 m isobath in Fig. 6a) around the Azores Islands and Princess Alice Bank overlapped over the future location of segments KP2 to KP4 (Fig. 6d). This is where the episode of enhanced magmatism responsible for the formation of the volcanic plateau appears to have originated. This part of the ridge is at present time also the closest to the inferred location of the Azores hotspot, and based on absolute plate motion models [22,23] it was presumably even closer to the hotspot 10 Ma ago.

5. Discussion: ridge magmatism and the temperature and dynamics of hotspot-derived material

The volcanic plateau documented in this paper formed during an event of anomalously high melt production, quite likely due to a change in the temperature, composition, or dynamics of the mantle supplied to the Mid-Atlantic Ridge by the Azores hotspot. Whatever the nature of this change, it had to be sufficient to approximately double the crustal thickness formed at the ridge axis. It also had to be of limited duration at any given location along the ridge, and to migrate away from the hotspot at a rate of ~60 km/Ma.

It is generally thought that the rate of melt production beneath a ridge is primarily controlled by mantle temperature [5,7,30,31]. It has, however, also been proposed that H_2O and CO_2-enriched domains in the mantle, rather than anomalously high mantle temperatures, can account for enhanced magmatism in the Azores region [32]. Higher temperatures or higher volatile contents in the mantle both translate into increased decompression melting, a larger magma supply, and shallower axial depths. The presence of volatiles is known to lower the melting temperature of the mantle [33,34] but this effect is not yet sufficiently well understood to be incorporated in decompression mantle melting models (e.g., [35]). Previous works relating variations in the elevation (R) of mid-ocean ridges, and in the thickness of the oceanic crust (inferred to represent changes in the magma supply M), to ridge–hotspot interactions have therefore neglected the possible effect of volatiles on mantle melting [5,7,30,31]. These works have also assumed passive upwelling of the mantle beneath the ridge. Applying this approach with the parameters of Ito and Lin ([7]; $\Delta T \sim 38\Delta R$) and White et al. ([30]; $\Delta T \sim 14\Delta M$), to maximum changes in ridge elevation ($\Delta R \sim 1.8$ km; Fig. 5c) and in crustal thickness ($\Delta M \sim 5$ km) associated with the volcanic plateau at the latitude of the Lucky Strike segment, yields a maximum temperature variation (ΔT) of ~70° for the upper mantle beneath the ridge. For comparison, a ΔT of only ~30° has been calculated in the same way for V-shaped topography and gravity anomalies near the Reykjanes Ridge south of the Iceland hotspot [30]. These variations in upper mantle temperature could reflect a change in the temperature of the plume itself, and/or a significant change in the ridgeward and along-axis velocities of plume-derived material (higher velocities would translate into lower rates of conductive cooling [7] for plume-derived material). Faster spreading rates recorded in the magnetic anomaly pattern for the period of 10 to 7 Ma [17,20] during the emplacement of the volcanic plateau, could be related to such a change in velocity of plume-derived material. A correlation between periods of high magmatic discharge and periods of more rapid spreading is also mentioned by Vogt [36] for the Reykjanes Ridge south of Iceland.

One point to keep in mind is that the geometry and upwelling velocity of the melting region also significantly affect melt production beneath a ridge [37]. While it seems reasonable to assume that these parameters fit a passive upwelling setting when averaged over long time periods and along-axis distances [31], discrete events of dynamic upwelling cannot be ruled out, especially if upper mantle temperatures undergo rapid changes. ΔT values given in the above paragraph could then be overestimated. Another point to keep in mind is that the duration of the episode of enhanced magmatism at any given location along the volcanic plateau south of the Azores is not well constrained at present. Extensive off-axis volcanism and plutonism could have led to the formation of the plateau in less time than suggested by plate reconstructions (Fig. 6). As an example, along flow-line variations of gravity anomalies suggest ~300 km^2 excess crustal production during the formation of the plateau at the latitude of Lucky Strike (Fig. 5a). If emplaced over the 4 Ma suggested by plate reconstructions, this amount of excess magma corresponds with an average ΔM of ~3 km (with a peak of ~5 km at the time of magnetic anomaly 4, some 7 Ma ago; Fig. 6). Emplacement over only 2 Ma would correspond with an average ΔM of ~6 km some 8 to 6 Ma ago. Assuming passive upwelling, the value of ΔT given earlier in this section could thus be underestimated.

The episode of enhanced magmatism responsible for the formation of the volcanic plateau migrated southwestward along the ridge at rates (V_x in Fig. 7) of ~60 mm/yr. Vogt [36] equated the faster migration rates (100–200 mm/yr) he calculated for the V-shaped topography and gravity anomalies near Reykjanes Ridge, to the along-axis velocity of the upper mantle beneath the ridge (V_{mx} in Fig. 7). However, the sketch in Fig. 7 suggests that these along-axis migration rates do not in fact offer such a direct constrain on mantle velocities. It shows that the angle of incidence (α) of the temperature (or volatile content) anomaly responsible for enhanced magmatism should also be taken into account, so that V_{mx} may actually be significantly smaller than V_x. Fig. 7 also shows that the total duration (d) of enhanced magmatism at any given location along the ridge should depend both on the local thickness (H) of the anomalous mantle domain, and on the

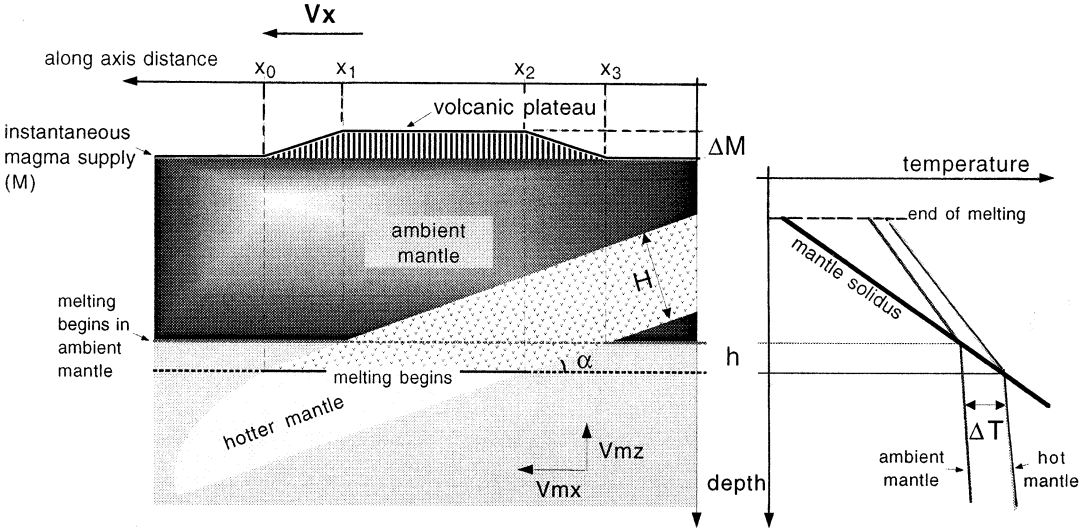


Fig. 7. Possible configuration for mantle melting anomaly that caused the formation of the South Azores volcanic plateau. A domain of anomalously hot mantle enclosed within colder mantle migrates upward (vertical velocity: V_{mz}) and along the ridge (horizontal velocity: V_{mx}). Depth difference (h) between solidus for anomalously hot mantle and colder ambient mantle is a function of ΔT. Excess magmatism (ΔM) is produced when hotter mantle enters the interval between the two solidi. Mantle of normal temperature but anomalously high volatile content would have essentially the same effect. The ridge portion affected by excess magmatism at any given time is x_0 to x_3, with maximum magmatism between x_1 and x_2. Excess magmatism migrates along the ridge at rate (V_x). It can be shown that $V_{mx} = V_x - V_{mz}/tg\alpha$ (with $90° > \alpha > 0°$). The total duration (d) of enhanced magmatism at any location along the ridge is a function of the thickness (H) of the anomalous mantle domain at that location: $d = (H + h\cos\alpha)/(V_x \sin\alpha)$; with $\alpha > \mathrm{Arctg}\, h/(V_x d)$. Fading away of topographic and gravity anomalies south of FAMOUS (Fig. 1) suggests that the anomalous mantle domain thins out to the south.

angle α. This angle could vary as a function of the initial shape of the anomalous mantle domain in the plume's head, and of the dynamics of its entrainment along the ridge. Analogue [38] and numerical [39] models do indeed suggest that plume heads have a geometrically complicated structure. Given that the subsequent entrainment of this plume head material toward and along the ridge is likely to induce further complexities (e.g., [6,8,9,40,41]), it is safe to allow for a large range of possible values for the angle α, and consequently for important parameters such as H and V_{mx} (see caption for Fig. 7).

Finally, the fact that topographic and gravity anomalies associated with the two flanks of the volcanic plateau fade away south of FAMOUS (Fig. 1) indicates either that the anomalous mantle domain thinned out to the south, as represented in Fig. 7, or that its excess temperature (ΔT) or volatile content relative to the surrounding sub-axial mantle had decreased to negligible values. Conductive cooling should indeed affect an anomalously hot mantle domain as it moves away from the hotspot, causing ΔT (and therefore ΔM) to decrease progressively with time, and southwestward, during the formation of the volcanic plateau. This prediction of the model does in first approximation fit with the observed general southwestward increase of MBA values from Princess Alice Bank to FAMOUS on the east flank of the plateau (Fig. 1c) and will be examined in more details in a forthcoming paper (J. Escartín et al., in prep.).

Acknowledgements

We thank the captain (G. Tredunit) and crew of R.V. *L'Atalante* for their most efficient work during the SudAçores cruise, B. Gueguen, J. Le Pavec, J.M. Schramm and their teams for their help with data acquisition, G. Ito and an anonymous referee for their reviews of the paper, and C. Rommevaux-Jestin for helping with data compilation prior to the cruise.

The GMT software [42] was extensively used in this study. J. Escartín was partially supported by CIRIT (Spain; grant 1997SGR00020) and M. Muller by the European Commission MAST 3 ‘AMORES’ program. The study is funded by CNRS–INSU. ***[FA]***

References

[1] R.S. Detrick, H.D. Needham, V. Renard, Gravity anomalies and crustal thickness variations along the Mid-Atlantic Ridge between 33°N and 40°N, J. Geophys. Res. 100 (1995) 3767–3787.

[2] R. Thibaud, P. Gente, M. Maia, A systematic analysis of the Mid-Atlantic Ridge morphology and gravity between 15°N and 40°N: constraints on the thermal structure, J. Geophys. Res. 103 (1998) 24223–24243.

[3] P.R. Vogt, Plumes, subaxial pipe flow, and topography along the mid-oceanic ridge, Earth Planet. Sci. Lett. 29 (1976) 309–325.

[4] J.-G. Schilling, Upper mantle heterogeneities and dynamics, Nature 314 (1985) 62–67.

[5] J.-G. Schilling, Fluxes and excess temperatures of mantle plumes inferred from their interaction with migrating mid-ocean ridges, Nature 352 (1991) 397–403.

[6] M.A. Feighner, M.A. Richards, The fluid dynamics of plume–ridge and plume–plate interactions: an experimental investigation, Earth Planet. Sci. Lett. 129 (1995) 171–182.

[7] G. Ito, J. Lin, Oceanic spreading center–hotspot interactions: constraints from along-isochron bathymetric and gravity anomalies, Geology 23 (1995) 657–660.

[8] N.M. Ribe, U.R. Christensen, J. Theissing, The dynamics of plume–ridge interaction, 1: ridge-centered plumes, Earth Planet. Sci. Lett. 134 (1995) 155–168.

[9] C. Kincaid, J.G. Schilling, C. Gable, The dynamics of off-axis plume–ridge interactions in the uppermost mantle, Earth Planet. Sci. Lett. 137 (1996) 29–43.

[10] Y.-S. Zhang, T. Tanimoto, Ridges, hotspots and their interaction as observed in seismic velocity maps, Nature 355 (1992) 45–49.

[11] D.T. Sandwell, W.H.F. Smith, Marine Gravity Anomaly from Satellite Altimetry, map Geological Data Center, Scripps Institution of Oceanography, 1995.

[12] H.D. Needham, M. Voisset, V. Renard, H. Bougault, O. Dauteuil, R. Detrick, C. Langmuir, Structural and volcanic features of the Mid-Atlantic Rift Zone between 40°N and 33°N (abstract), Eos 73 (1991) 552.

[13] R.C. Searle, Tectonic patterns of the Azores spreading center and triple junction, Earth Planet. Sci. Lett. 51 (1980) 415–434.

[14] J. Madeira, A. Ribeiro, Geodynamic models for the Azores triple junction: a contribution from tectonics, Tectonophysics 184 (1990) 405–415.

[15] G. Féraud, I. Kaneoka, C.J. Allègre, K/Ar ages and stress pattern in the Azores: geodynamic implications, Earth Planet. Sci. Lett. 46 (1980) 275–286.

[16] A. Campan, J.-Y. Royer, P. Gente, J.-L. Olivet, R.D. Muller, Evolution of the Azores–Gibraltar plate boundary for the last 36 Ma (abstract), Eos 74 (1993) 586.

[17] J. Freire Luis, J.M. Miranda, A. Galdeano, P. Patriat, J.-C. Rossignol, L.A. Mendes Victor, The Azores triple junction evolution since 10 Ma from an aeromagnetic survey of the Mid-Atlantic Ridge, Earth Planet. Sci. Lett. 125 (1994) 439–459.

[18] P.R. Vogt, Global magmatic episodes: new evidence and implications for the steady-state mid-oceanic ridge, Geology 7 (1979) 93–98.

[19] C.R. DeMets, R.G. Gordon, D.F. Argus, S. Stein, Current plate motions, Geophys. J. Int. 101 (1990) 425–478.

[20] H. Sloan, P. Patriat, Kinematics of the North American–African plate boundary between 28 and 29°N during the last 10 Ma: evolution of the axial geometry and spreading rate and direction, Earth Planet. Sci. Lett. 113 (1992) 323–341.

[21] G. Pouliquen, J. Escartín, M. Cannat, A. Briais, C. Deplus, J. Georgen, J. Lin, S. Merkouriev, C. Meyzin, M. Muller, A. Rabain, P. da Silva, Reconstruction of a rifted volcanic plateau in the FAMOUS–Lucky Strike region of the Mid-Atlantic Ridge (abstract), Eos 79 (1998) 856.

[22] A.E. Gripp, R.G. Gordon, Current plate velocities relative to the hotspots incorporating the NUVEL-1 global plate motion model, Geophys. Res. Lett. 17 (1990) 1109–1112.

[23] R.D. Müller, J.-Y. Royer, L.A. Lawver, Revised plate motions relative to the hotspots from combined Atlantic and Indian Ocean hotspot tracks, Geology 21 (1993) 275–278.

[24] S.C. Cande, D.V. Kent, Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic, J. Geophys. Res. 100 (1995) 6093–6095.

[25] R.L. Parker, The rapid calculation of potential anomalies, J. Geophys. Res. 31 (1973) 447–455.

[26] J. Phipps Morgan, D.W. Forsyth, 3-D flow and temperature perturbations due to a transform offset: effects on oceanic crustal and upper mantle structure, J. Geophys. Res. 93 (1988) 2955–2966.

[27] R.L. Parker, S.P. Huestis, The inversion of magnetic anomalies in the presence of topography, J. Geophys. Res. 79 (1974) 1587–1593.

[28] B. Parsons, J.G. Sclater, An analysis of the variation of ocean floor bathymetry and heat flow with age, J. Geophys. Res. 82 (1977) 803–827.

[29] B. Johansen, P.R. Vogt, O. Eldholm, Reykjanes Ridge: further analysis of crustal subsidence and time-transgressive basement topography, Earth Planet. Sci. Lett. 68 (1984) 249–258.

[30] R.S. White, J.W. Bown, J.R. Smallwood, The temperature of the Iceland plume and origin of outward-propagating V-shaped ridges, J. Geol. Soc. London 152 (1995) 1039–1045.

[31] E.M. Klein, C.H. Langmuir, Global correlations of ocean ridge basalt chemistry with axial depth and crustal thickness, J. Geophys. Res. 92 (1987) 8089–8115.

[32] E. Bonatti, Not so hot ‘hot spots’ in the oceanic mantle, Science 250 (1990) 107–111.

[33] D.H. Green, Experimental melting studies on a model upper mantle composition of high pressure under H_2O-saturated and H_2O-undersaturated conditions, Earth Planet. Sci. Lett. 19 (1973) 37–45.

[34] B.O. Mysen, I. Kushiro, Compositional variations of coexisting phases with degree of melting of peridotite in the upper mantle, Am. Mineral. 62 (1977) 843–865.

[35] D. McKenzie, The generation and compaction of partially molten rock, J. Petrol. 25 (1984) 713–765.

[36] P.R. Vogt, Asthenosphere motion recorded by the ocean floor south of Iceland, Earth Planet. Sci. Lett. 13 (1971) 153–160.

[37] D.W. Forsyth, Geophysical constraints on mantle flow and melt generation beneath mid-ocean ridges, in: J. Phipps Morgan et al. (Eds.), Mantle Flow and Melt Generation at Mid-Ocean Ridges, Am. Geophys. Union, Geophys. Monogr. 71 (1992) 1–66.

[38] I.H. Campbell, R.W. Griffiths, R.I. Hill, Melting in an Archean mantle plume: heads its basalts, tails its komatiites, Nature 339 (1989) 697–699.

[39] P. Olson, G. Schubert, C. Anderson, P. Goldman, Plume formation and lithosphere erosion: a comparison of laboratory and numerical experiments, J. Geophys. Res. 93 (1988) 15065–15084.

[40] N.H. Sleep, Lateral flow of hot plume material ponded at sublithospheric depths, J. Geophys. Res. 101 (1996) 28065–28083.

[41] M.M. Yale, J. Phipps Morgan, Asthenosphere flow model of hotspot–ridge interactions: a comparison of Iceland and Kerguelen, Earth Planet. Sci. Lett. 161 (1998) 45–56.

[42] P. Wessel, W.H.F. Smith, Free software helps map and display data, Eos 72 (1991) 445–446.