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Interaction between the Mid-Atlantic Ridge and the Azores hot spot during the last 85 Myr: Emplacement and rifting of the hot spot-derived plateaus

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[1] Multiple- and single-beam bathymetric data are compiled over the Azores plateau to produce a 1 km × 1 km grid between latitudes 32°N and 49°N and longitudes 22°W and 43°W. Mantle Bouguer anomalies are then calculated from this grid and the satellite-derived gravity. These grids provide new insights on the temporal and spatial variations of melt supply to the ridge axis. The elevated seafloor of the Azores plateau is interpreted as resulting from the interaction of a mantle plume with the Mid-Atlantic Ridge (MAR). The presence of a large region of elevated seafloor associated with a thick crust between the Great Meteor Seamounts and the Azores platform on the Africa plate, and less developed conjugate structures on the North America plate, favors genetic relations between these hot spot-derived structures. This suggests that a ridge-hot spot interaction has occurred in this region since 85 Ma. This interaction migrated northward along the ridge axis as a result of the SSE absolute motion of the Africa plate, following a direction grossly parallel to the orientation of the MAR. Kinematic reconstructions from chron 13 (∼35 Ma) to the present allow a proposal that the formation of the Azores plateau began around 20 Ma and ended around 7 Ma. A sharp bathymetric step is associated with the beginning of important melt supply around 20 Ma. The excess of melt production is controlled by the interaction of the ridge and hot spot melting zones. The geometry and distribution of the smaller-scale features on the plateau record episodic variations of the hot spot melt production. The periodicity of these variations is about 3–5 Myr. Following the rapid decrease of widespread volcanism, the plateau was subsequently rifted from north to south by the Mid-Atlantic Ridge since 7 Ma. This rifting begins when the MAR melting zone is progressively shifted away from the 200-km plume thermal anomaly. These results bear important consequences on the motion of the Africa plate relative to the Azores hot spot. They also provide an explanation to the asymmetric geochemical signature of the Azores hot spot along the Mid-Atlantic Ridge.

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Theme: Plume-Ridge Interaction **Guest Editor:** David Graham

1. Introduction

[2] The Azores area (Figure 1) is considered by numerous authors to reflect a typical ridge-hot spot interaction because of an elevated spreading ridge [*Vogt*, 1976; *Schilling*, 1985; *Gente*, 1987; *Thibaud et al.*, 1998], basalt geochemistry [*Schilling*, 1975; *White et al.*, 1976; *Bougault and Treuil*, 1980; *Schilling et al.*, 1983; *Dosso et al.*, 1999], and gravity anomalies [*Detrick et al.*, 1995; *Thibaud et al.*, 1998] (Figure 2). The interaction processes have mainly been studied in terms of an influence of the Azores hot spot along the present-day spreading axis. This along-axis influence appears asymmetrical to the north and south of the Azores hot spot, with a more limited northward extension [*Yu et al.*, 1997; *Dosso et al.*, 1999; *Goslin et al.*, 1998, 1999].

[3] *Vogt* [1976], *Cande et al.* [1985], *Gente* [1995] and, more recently, *Cannat et al.* [1999] have proposed to divide the off-axis volcanic plateau, which extends on both flanks of the Mid-Atlantic Ridge and is topped by the Azores archipelago, into distinct sub-regions. This plateau extends to the west at least to magnetic anomaly 6 (noted hereafter chron 6, ~20 Ma) [*Cande et al.*, 1985; *Gente*, 1995]. *Bougault et al.* [1985], from results of DSDP Leg 82, show that the basalts dredged on the seafloor between chron 6 and the present (i.e., on the Azores plateau) include hot spot signature, while the basalts from the seafloor older than chron 6 have a normal MORB signature. South of the Azores domain, the Great Meteor volcanic group on the Africa plate and the Corner seamounts on the America plate are interpreted as having been emplaced above the New England hot spot close to the North America-Africa plate boundary [*Tucholke and Smoot*, 1990; *O'Connor and Duncan*, 1990; *Müller et al.*, 1993a] or above two different hot spots [*Morgan*, 1983] (Figure 1).

[4] The main objectives of this paper are 1) to gain insight into the ridge-hot spot interactions that led to the initial emplacement of the Azores plateau; 2) to investigate the subsequent evolution of this Plateau by stressing the importance of rifting processes since 7 Ma; and 3) to elucidate the relationships with the major nearby structures including the Great Meteor seamounts. Particular attention will be paid to the importance of lithospheric structural discontinuities in shaping the expression of the magmatic products issued from the mantle plume. To better understand these different processes and relationships, a high-resolution bathymetric map was produced from a synthesis of all available multibeam bathymetric data and complemented by a compilation of single beam data. Combined with satellite gravity measurements, this map also allows calculation of a Mantle Bouguer anomaly map, which may then be inverted to estimate crustal thickness. The effects of subsidence and lithosphere cooling have been removed to better identify the elevated relief associated with regions underlain by thick crust. While these new bathymetry and MBA maps of the Azores area allow fine-scale analysis of tectonic features in many places, this paper addresses in a general way the extension of the Azores platform, its evolution, and its relationships with the surrounding structures. These features mark the evolution of ridge-hot spot interactions in this

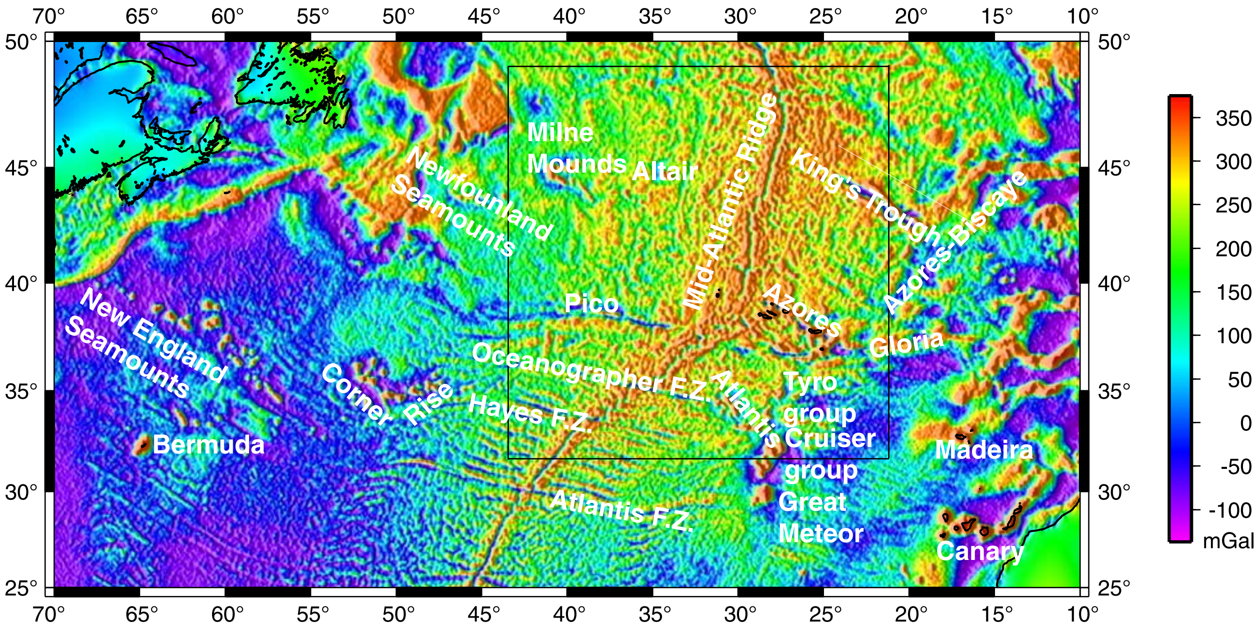


Figure 1. Free air anomaly map of the North Atlantic [*Sandwell and Smith*, 1997] with locations of the different structures discussed in this paper. A new detailed bathymetric map was produced for this study within the black frame.

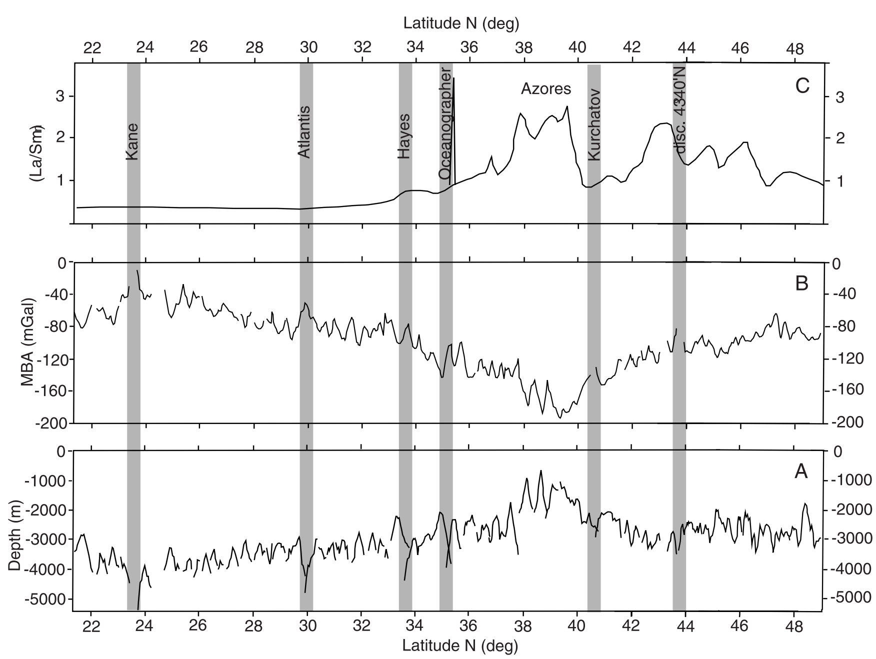


Figure 2. Along-axis bathymetry (A), Mantle Bouguer Anomaly (MBA) (B) profiles and highest value in trace elements ((La/Sm)n) in the basalts (C) along the Mid-Atlantic Ridge between 21°N and 49°N. Data are from *Thibaud et al.* [1998], *Goslin et al.* [1999] and this study for the geophysical data and from *Yu et al.* [1997] and *Dosso et al.* [1993, 1999] for the geochemical data. The major fracture zones south of the Azores and second-order discontinuities north of the Azores are located.

region and constrain the absolute motion of the MAR axis.

2. Geological Setting

2.1. Kinematic Framework: The Azores as a Triple Junction

[5] The Azores domain is the present-day site of the triple junction between the North America, Eurasia-Iberia and Africa plates [*Le Pichon*, 1968] (Figure 1). This triple junction has jumped from King's Trough to the Azores domain between Chron 13 and Chron 6 [*Laughton et al.*, 1975; *Srivastava et al.*, 1990], synchronous with the final stage of the Iberia-Eurasia suture [*Olivet et al.*, 1984; *Roest and Srivastava*, 1991]. The Mid-Atlantic Ridge (MAR) spreading rate increases from South (35°N) to North (40°N) between 20 to 22 mm/yr [*DeMets et al.*, 1990] and has been almost constant since 40 Ma [*Cande et al.*, 1985]. The boundary between the Eurasia and Africa plates in the Atlantic Ocean is comprised of three sections. It includes, from east to west, a compression domain, the Horseshoe seamounts, abutting the Iberian margin; the Gloria transform fault; and a transtensional domain, the Azores region [*McKenzie*, 1972; *Laughton and Whitmarsh*, 1974; *Grimison and Chen*, 1986; *Buforn et al.*, 1988; *Madeira and Ribeiro*, 1990]. The Pico fracture zone represents the fossil trace of the Gloria fault on the North America plate, and was most likely the location of the triple junction between Chrons 13 and 6 [*Krauze and Watkins*, 1970; *Bonnin*, 1978; *Olivet et al.*, 1984; *Srivastava et al.*, 1990]. Global present-day plate kinematic models of the Azores region imply a right lateral transtensional regime with an extensional component of 3–4 km/Myr [*Minster and Jordan*, 1978; *DeMets et al.*, 1990]. This ENE-WSW extension was confirmed by recent detailed bathymetry surveys conducted within the Azores archipelago [*Lourenço et al.*, 1998; *Miranda et al.*, 1998]. *Lourenço et al.* [1998] proposed that the Azores domain constitutes a diffuse plate boundary acting both as an oblique, ultra-slow spreading center and a transfer zone accommodating dextral differential shear motion. Conversely, *Olivet et al.* [1984] proposed that alternate episodes of transform and spreading activity have been active in the Azores region for the last ~20 Myr (Anomaly 6 [*Archambault*, 1984]). Finally, no clear evidence for a discrete triple junction has been observed west of Faial island, where the diffuse plate boundary separating Eurasia-Iberia and Africa intersects the MAR axis [*Searle*, 1980; *Frere Luis et al.*, 1994; *Lourenço et al.*, 1998; *Miranda et al.*, 1998].

2.2. Deeper Structure: The Azores as a Mantle Plume

[6] The presence of a hot spot under the Azores plateau has been inferred from long-wavelength observations along the MAR (Figure 2), including ridge-axis elevation [*Anderson et al.*, 1973; *Le Douaran and Francheteau*, 1981; *Vogt*, 1976; *Gente*, 1987; *Thibaud et al.*, 1998], geoid topography [*Bowin et al.*, 1984; *Cazenave et al.*, 1992] and geochemical anomalies [*Schilling*, 1975; *White and Schilling*, 1978; *Bougault and Treuil*, 1980; *Yu et al.*, 1997; *Dosso et al.*, 1999]. Low-velocity heterogeneities are clearly observed under the MAR down to 200- to 250-km depth between latitudes 20°N and 45°N [*Zhang and Tanimoto*, 1992; *Silveira et al.*, 1998]. *Silveira et al.* [1998] emphasize the good correlation between a North-South trending low-velocity anomaly down to 300- to 400-km depth and the surface expression of hot spot in the Azores-Great Meteor region.

[7] Finally, the Azores platform is a region of elevated topography with an overall triangular shape in map-view (Figure 3), including the Azores archipelago itself east of the MAR and the conjugate Faial and Corvo-Flores ridges which extend as far as 36°30′N to the south [*Vogt*, 1976; *Cannat et al.*, 1999; *Escartin et al.*, 2001] (Figure 4). *Cannat et al.* [1999] propose that these volcanic ridges result from hot spot activity, which migrated southwestward along the MAR at a rate of about 60 km/Myr. These authors also show that the southern part of the FAMOUS-Lucky Strike area plateau was rifted about 5 Myr ago.

[8] Other authors consider that the Azores hot spot is probably located about 200 km to the east of the

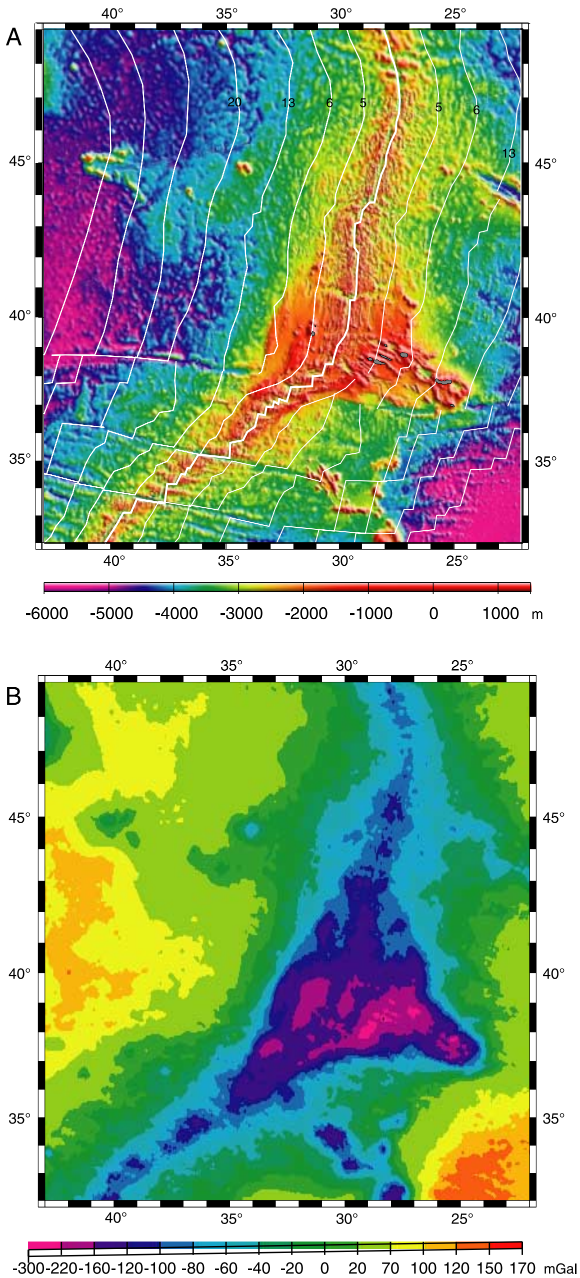


Figure 3. Shaded bathymetry from a 1 × 1 km grid, isochrons (A), and Mantle Bouguer Anomaly map (B) over the study area. The bathymetric map is computed from all available multibeam bathymetric data and from a compilation of single beam data made available to us by the French Service Hydrographique et Oceanographique de la Marine (SHOM). This latter compilation was provided by SHOM at a grid interval of 1 km. Isochrons are modified from *Müller et al.* [1997].

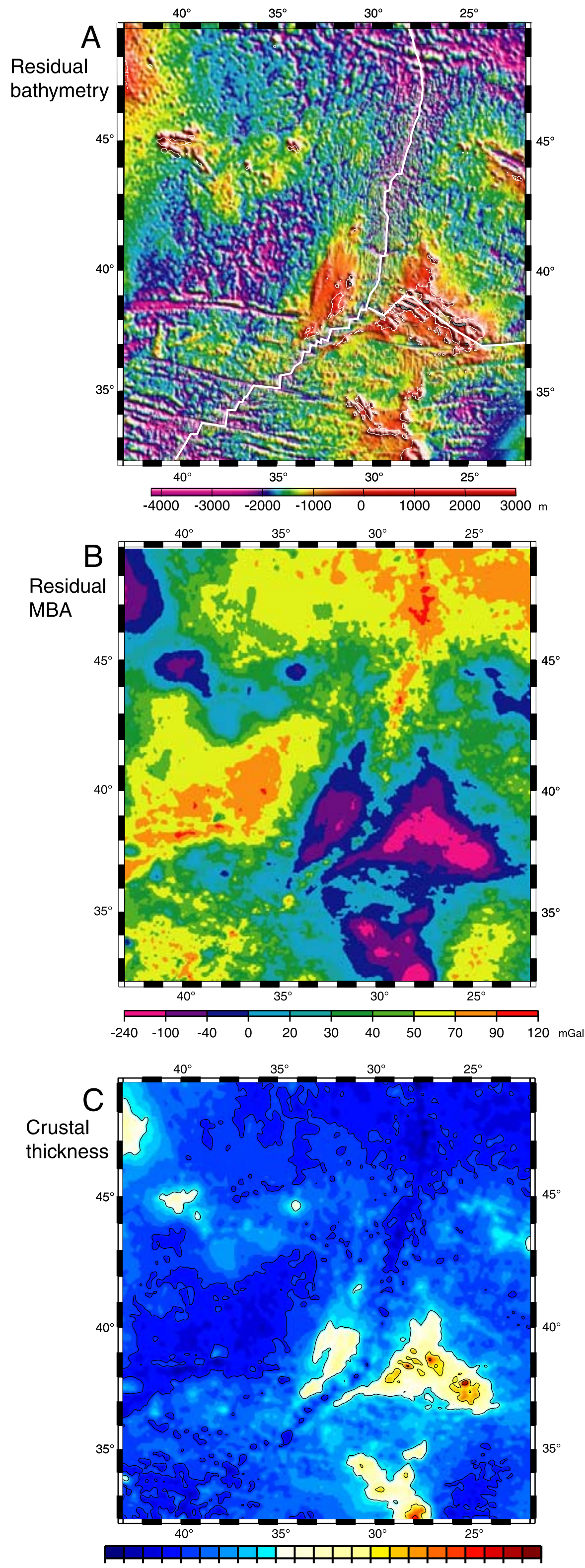


Figure 4. (opposite) Residual (subsidence-corrected) topography (A), residual MBA (B) and crustal thickness (C). The residual topography is obtained by subtracting the estimation of the subsidence to the bathymetric map (Figure 3a).

MAR, under the group of islands between Faial and Terceira [*Ito and Lin*, 1995; *Moreira et al.*, 1999]. The size, depth and the precise location of this mantle anomaly are still debated.

3. Data Compilation and Analysis

[9] We compiled all available bathymetry and gravity data in the region located between latitudes 32° and 49° N and longitudes 22° and 43° W (Figure 1). The grids resulting from this compilation are shown as shaded maps on Figures 3a and 3b. To emphasize possible relationships among older structures, the grids were corrected for the effect of seafloor subsidence and used for paleogeographic reconstructions. This representation allows us to depict the evolution of topographic highs, rough seafloor areas and ridge segments, and to distinguish between different crustal domains, and thus to gain insight on the history of ridge-hot spot interactions.

3.1. Bathymetry

[10] The bathymetric map (Figure 3a) is based on the synthesis of all available multibeam bathymetric data in this area, already compiled at a grid spacing of 500m by *Thibaud et al.* [1998], and supplemented by data from two recent French cruises (Cruise ‘‘Triatnord’’, 40°30′N–45°N [*Goslin et al.*, 1999] and Cruise ‘‘Sudaçores’’, 36°30′N–38°N and 34°30′N–35°30′N [*Cannat et al.*, 1999]). To complement this grid, a compilation of single beam data (both classified and unclassified) has been kindly provided by the French Service Hydrographique et Oceanographique de la Marine (SHOM) at a grid interval of 1 km. The final bathymetric grid is computed at a grid interval of 1 km (Figure 3a).

3.2. Gravity

[11] Over the study area, shipborne and satellite-derived free-air anomalies are roughly equivalent at wavelengths longer than 30 km, as shown by our previous work on the MAR segmentation between 15 and 40°N [*Thibaud et al.*, 1998]. Satellite-derived free-air gravity anomaly data [*Sandwell and Smith*, 1997], with regionally homogeneous coverage and quality, are much easier to handle than the uneven shipborne gravity data available from various sources. The method used to compute a Mantle Bouguer Anomaly (MBA) from satellite-derived gravity data is similar to the usual approach for shipborne data. The effects of the topography and of the crust-mantle interface (assuming a constant crustal thickness of 6 km) are computed using a Fast Fourier Transform (FFT) algorithm [*Parker*, 1972]. For MBA calculations (Figure 3b), the bathymetric grid is re-sampled with a coarser grid interval of 2 km, the satellite-derived free-air gravity grids being at a similar grid interval. Water, crust, and mantle density values of 1130, 2700 and 3300 kg/m3 are assumed. The residual MBA (Figure 4b) is obtained by removing the gravity effect due to the cooling of the lithosphere, following *Rommevaux et al.* [1994].

[12] The residual MBA (RMBA) is then inverted for crustal thickness (Figure 4c) following the method of *Kuo and Forsyth* [1988]. This approach assumes that all signal in the RMBA arises from crustal thickness variations. While this can be considered a reasonable proxy for ridges away from hot spots [e.g., *Hooft et al.*, 2000], studies on ridge-hot spot interactions showed that in such contexts, part of the RMBA signal is related to mantle density variations due to the thermal and compositional effects of the nearby hot spot [e.g., *Canales et al.*, 2002]. Off-axis hot spots are often related to broad bathymetric swells partly compensated by crustal thickening and partly by density variations in the mantle [e.g., *McNutt and Shure*, 1986]. Estimating the relative contributions from crust and mantle to the gravity signal near a hot spot is a difficult exercise in the absence of independent crustal thickness estimates given by seismics. *Canales et al.* [2002] estimate that mantle density variations can contribute up to 40% to the bathymetry and gravity signal, the remaining 60% being due to crustal thickness variations. This is in reasonable agreement with estimates from *Ito et al.* [1996] for Iceland, derived from numerical models. In this paper, the choice to interpret the whole RMBA signal as due to crustal effects, in the absence of seismic constraints, yields absolute crustal thickness values

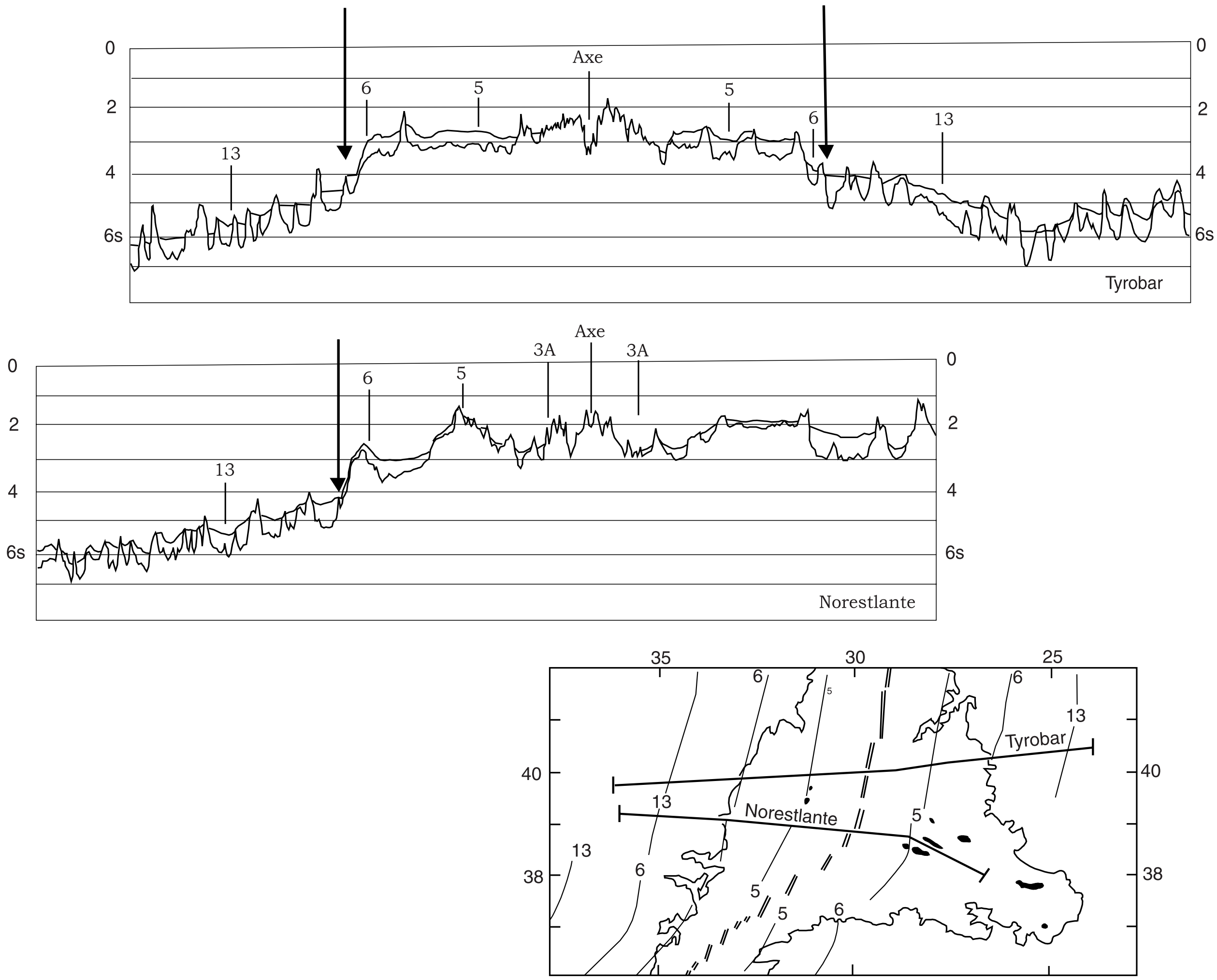


Figure 5. Two seismic profiles from the Tyrobar cruise (1982, Kroonvlag project, Vening Meinesz Laboratorium, Utrecht, Holland) and from the Norestlante cruise (1989, "N/O Jean Charcot") are shown together with their location. The arrows show the edges of Azores platforms.

that are too high. Crustal thickening and low mantle densities are directly related and result from excess melting and elevated temperatures due to the plume. Since our main objective is to evaluate the spatial influence of the Azores hot spot rather than to precisely quantify the amount of crust produced by the hot spot, such a simplification remains valid. It must be kept in mind that the crustal thickness values given here are therefore overestimated upper bounds.

3.3. Sediments

[13] The sediment thickness increases progressively toward older oceanic crust (Figure 5). It does not exceed one-second two-way travel time on the seismic profiles. The sediments are mainly confined to the basins, and the sediment thickness on the highs is negligible. At chron 6, the thickness of the sediment is about 600m [*Bougault et al.*, 1985]. Because sediment thicknesses are small, we have not applied any correction of the sediment thickness for MBA calculation and for the subsidence-corrected topography map. As an a posteriori confirmation of our approach, the resulting topography and gravity maps do not present any clear, systematic variation with the age of the seafloor (Figures 4a and 4b). The profiles shown on Figure 5 indicate that the Azores platform is delimited on both flanks

by a bathymetric step, located around chron 6, which corresponds to a sharp elevation change of the seafloor by more than 1500 m. The Azores platform, generally located between chrons 5 and 6, is characterized by smooth seafloor topography. Outside this domain, the ocean floor exhibits the typical roughness of a slow spreading center.

3.4. Isochrons, Age Map, and Subsidence

[14] *Royer et al.* [1992] compiled a global set of isochrons deduced from magnetic anomaly identifications compiled from various sources, and *Müller et al.* [1997] used these isochrons to compute a global age map of the seafloor with a grid interval of 0.1°. In the Central and North Atlantic near the Azores, their work mostly relies on the studies of *Klitgord and Schouten* [1986], *Müller et al.* [1993b], and *Srivastava and Tapscott* [1986]. This age map had been compiled before the detailed satellite-derived gravity anomaly maps [*Sandwell and Smith*, 1997] were published, and while the age map of *Müller et al.* [1997] is a good first-order approximation, a closer look reveals some inconsistencies at a regional scale. Thus we modified the isochrons of *Müller et al.* [1997] to take into account the precise geometry of the fracture zones given by the satellite gravity data (Figure 3a). We adjusted the new isochrons to be consistent with the picks used by *Müller et al.* [1997] to build their isochrons (J.-Y. Royer, personal communication, 2000). We then built a new map of the seafloor age in the Azores area from the new isochrons, using an interpolation technique similar to *Müller et al.* [1997]. To avoid interpolation at the main age discontinuities, the interpolation is applied within separate regions bounded by the major fracture zones. Subsequently, the ages are juxtaposed to create a 0.1° interval age map of the study area. The expected subsidence of the seafloor is calculated using the relation

$$S = 0.35 \text{ sqrt } (t)$$

where t is the age in Myr and S is the subsidence in kilometers [*Parsons and Sclater*, 1977]. The subsidence-corrected (or residual) topography is obtained by subtracting this predicted subsidence from the bathymetric map (Figures 4a and 6a).

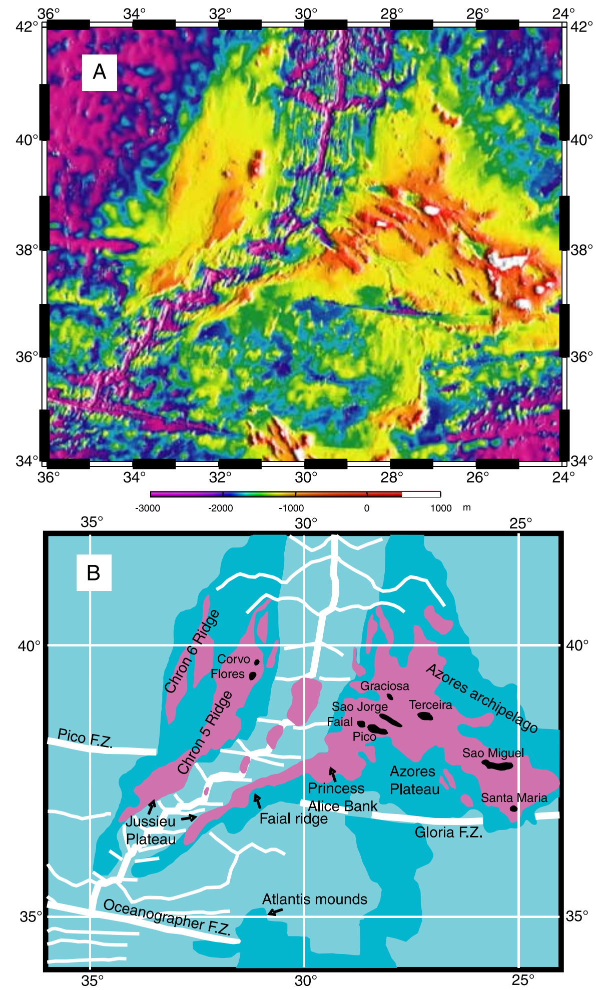


Figure 6. Residual (subsidence-corrected) topography zoomed in over the Azores plateau (A) and location of islands and major structures in this area (B). The dark blue-color areas show the elevated seafloor features and the purple-color areas the shallowest ridges on the Azores plateaus. The islands are marked in black. The ridge axis and the major fracture zones are shown as thick white lines. Thinner white lines show the off-axis traces of more minor discontinuities.

3.5. Kinematic Parameters and Plate Reconstructions

[15] The new isochrons and fracture zones may require different parameters of finite rotation to properly fit the structures and isochrons. We find that the finite poles used by *Campan* [1995] produce slightly better fits that those compiled

Table 1. Finite Rotation Parameters Used for the Reconstructions[a]

Age (Anomaly Number)	Plates (Mobile/Fixed)	Latitude, degrees	Longitude, degrees	Angle, degrees
Anomaly 13	AFR/NAM	76.04	5.96	−9.77
Anomaly 13	IBE/NAM	54.14	143.47	−7.33
Anomaly 13	EUR/NAM	63.39	137.45	−7.35
Anomaly 6	AFR/NAM	80.84	33.66	−5.24
Anomaly 6	EUR/NAM	66.48	136.05	−4.83
Anomaly 5	AFR/NAM	80.31	51.90	−2.48
Anomaly 5	EUR/NAM	63.92	137.59	−2.40

[a]Following *Campan* [1995]. Ages correspond to anomalies 5 (∼10 Ma), 6 (∼20 Ma) and 13 (∼35 Ma); plates are Africa (AFR), Eurasia (EUR), Iberia (IBE), and North America (NAM). Angles are positive clockwise.

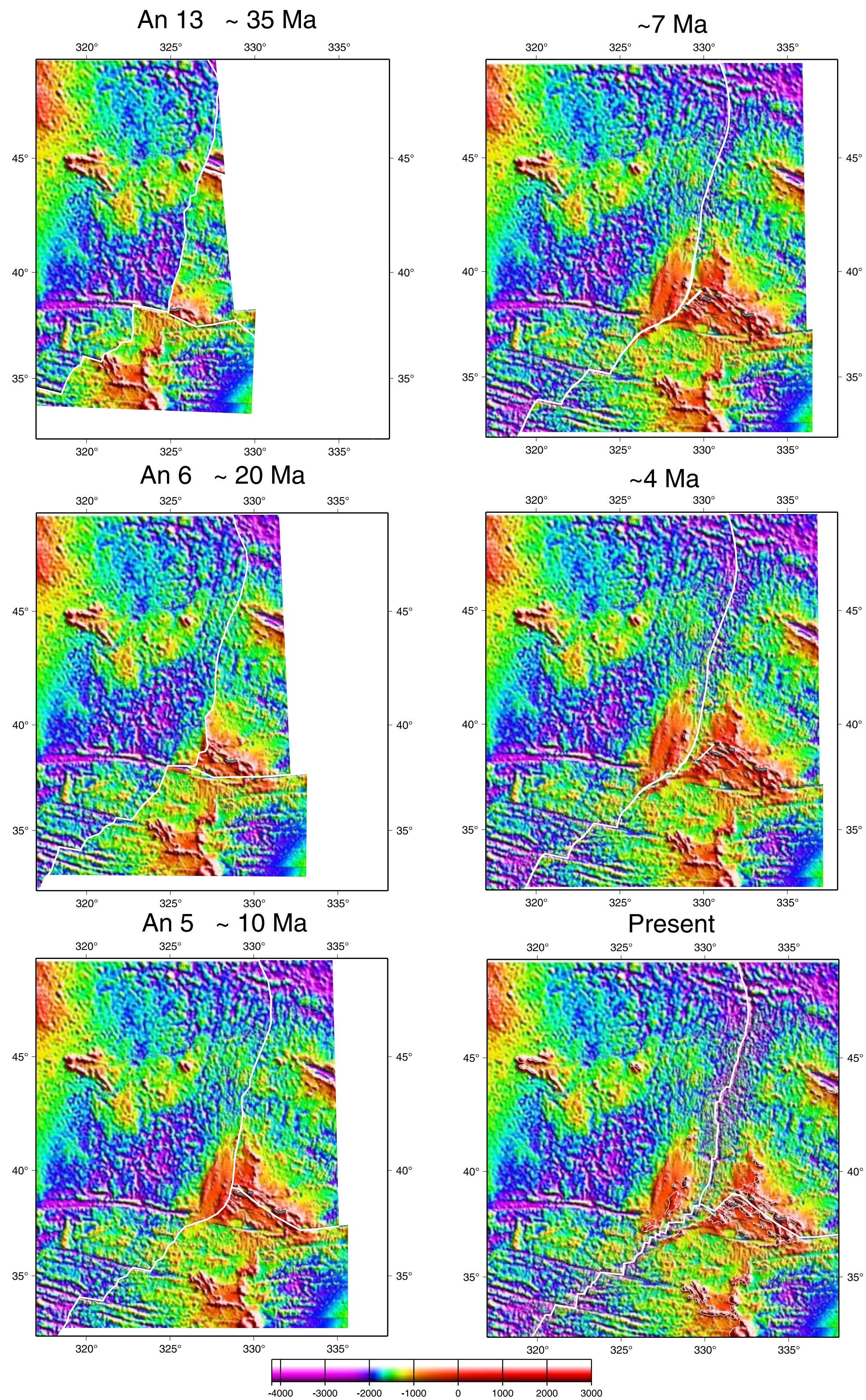
by *Müller et al.* [1997] for anomalies 5, 6 and 13, although they are most often statistically indistinguishable given the uncertainty ellipses provided by *Campan* [1995]. The finite rotation parameters used in this study are given in Table 1. It should be noted that both *Royer et al.* [1992] and *Campan* [1995] combine rotation parameters from different sources, which may create problems because the picking of magnetic anomalies is not entirely consistent between different studies. A complete reassessment of the magnetic anomalies in the Central and North Atlantic Ocean would therefore be required to derive more accurate plate kinematics around the Azores triple junction. Such a work is, however, beyond the scope of this paper. The finite rotations given in Table 1, which rely on directly measurable motions between North America on one hand, Eurasia, Iberia and Africa on the other, are precise enough for the needs of this work. Conversely, the absence of magnetic anomalies related to seafloor spreading along the diffuse Azores archipelago boundary on the Eurasia plate precludes direct assessment of the evolution of this boundary, which can be determined only from the combination of EUR-NAM and AFR-NAM reconstructions. Therefore, considering the uncertainties of AFR-EUR motion and in the location of the Africa-Eurasia plate boundary through the considered period, no precise inference should be drawn from our reconstructions on the detailed evolution of the Azores-Gibraltar line that marks the Africa-Eurasia plate boundary. Similarly, the motion across King's Trough, considered as the Iberia-Eurasia plate boundary at chron 13 is not well constrained because it results from the combination of EUR-NAM and IBE-NAM rotation parameters.

[16] Figure 7 presents paleo-positions of the residual topography at chrons 13, 6, and 5, and (interpolating the angle of rotation between chron 5 and present) at 7 and 4 Ma. The residual bathymetry, corrected for thermal subsidence, presents a narrower range of variation than the total topography and can thus be visualized more easily. Residual topography also allows direct comparisons between topographic features at different periods. Reconstructions in Figure 7 are obtained by juxtaposing the different plates, limited by masks which follow the corresponding isochrons and projected using oblique Mercator projection parameters deduced from the finite rotation parameters. In Figure 7, North America is fixed and the other plates are moved to their past positions relative to North America. All projections are computed on a spherical Earth, using the Generic Mapping Tool (version 3.0) [*Wessel and Smith*, 1991]. These reconstructions display the evolution of the various bathymetric features of the Azores area.

4. Possible Links Between the Azores Domain and Nearby Features

[17] Although the uneven bathymetric coverage and the variation of sediment thickness in the area preclude a detailed study of the seafloor roughness, we can distinguish in Figure 3a different domains by considering two different criteria: the presence of elevated relief and the texture of the seafloor.

[18] In Figure 3a, the most prominent bathymetric structure is the Azores platform, roughly outlined


An 13 ~ 35 Ma
~7 Ma
An 6 ~ 20 Ma
~4 Ma
An 5 ~ 10 Ma
Present
320°
325°
330°
335°
45°
40°
35°
-4000
-3000
-2000
-1000
0
1000
2000
3000

by the 2000 m isobath. It represents the apex of the MAR topography both along-axis and along isochrons on its flanks since at least chron 6. Other structures can be observed such as the Great Meteor seamounts (from north to south: Atlantis, Tyro and Cruiser mounts) located south of 35°N on the Africa plate, King's Trough around latitude 44°N on the Eurasia plate, and Milne seamounts around 45°N on the America plate. North and South of the Azores region, the MAR axis trends N13°E and N53°E respectively. Three large fracture zones (FZ) are present south of the Azores (Figure 1). These are, from south to north, Hayes FZ, Oceanographer FZ, and a system made of Pico FZ (on the North America plate) and Gloria FZ (on the Africa plate). Whereas both Hayes and Oceanographer FZ intersect the present MAR axis, the Pico-Gloria FZ system is interrupted by the southern tip of the Azores platform around chron 6.

[19] The residual bathymetry (Figures 4a and 6a) presents a different picture. The Azores platform is not a single feature (Figure 6), but is made of two separate domains on both sides of the MAR axis. The residual depth of these domains is shallower than 1000 m, including several islands. The residual depth represents the depth at which the seafloor was emplaced, only if no thermal perturbation or volcanic episode has subsequently affected the area. This latter condition may have not been fulfilled over the Azores platform. Between the two platform domains, the residual depth of the spreading axis shallows to an average depth of 2600 m.

[20] Two seismic profiles run across the Azores domain illustrate the change in seafloor roughness between the Azores platform and the normal oceanic crust (Figure 5). The Azores platform, roughly located along the seismic profiles between chrons 5 and 6, is characterized by smooth seafloor topography. Between the two domains, the MAR axis, between chrons 3A on the seismic profiles exhibits the typical high roughness of a slow-spreading center. The Azores platform is limited on both flanks by sharp steps, located near chron 6, which corresponds to a rapid increase in the seafloor depth by more than 1500 m, as seen along profile Tyrobar and on the western section of profile Norestlante (Figure 5).

[21] Other off-axis elevated structures, located in the study area, share similarities with the Azores platform. For instance, both the Great Meteor group and the Milne seamounts display smooth topography. Some of these areas may have been subaerial at some times in the past. The shallowest parts of these structures correspond to elongated ridges comparable to the ridges associated with the islands in the Azores archipelago. On the residual topography (Figure 4a), it appears that the Great Meteor group is linked to the Azores archipelago through a continuous elevated rise between Oceanographer and Pico-Gloria fracture zones. This high was present on both sides of the spreading axis around chron 20 (Figures 4a and 4b). The shallower parts of the Great Meteor elevated structures, with the exception of the Atlantis seamount, are oriented roughly parallel to the ridge or to the transform directions, implying a lithospheric control for these volcanic constructions. In contrast, the Milne seamounts and associated elevated seafloor, between latitudes 43° and 45°N, are clearly separated from the Azores platform. These highs represent a 300-km-wide W-shaped band separated from the MAR axis since more than 10 Ma (chron 5). Some highs are clearly parallel to the spreading direction (Milne seamounts), but many others present a round shape.

[22] All these topographic features have marked gravity signatures (Figures 3b and 4b). The most negative MBA contour exhibits a triangular shape mirroring the shape of the Azores platform as defined by the topography. Along the MAR axis, classical Bull's eye MBA anomalies [*Lin et al.*, 1990; *Blackman and Forsyth*, 1991; *Detrick et al.*, 1995; *Gente et al.*, 1995] characterize the second-order segmentation. The amplitude of this short wavelength in the along-axis gravity profile

Figure 7. (opposite) Plate reconstructions of the residual topography at chrons 13, 6, and 5, and (by interpolation) at 7 and 4 Ma. North America plate is fixed. The finite rotation parameters used for these reconstructions are listed in Table 1.

does not change with the distance to the Azores triple junction (Figure 2). The residual mantle Bouguer gravity anomaly map emphasizes the two separate domains of the Azores platform on both flanks of the MAR axis, the most negative anomalies located under the Azores archipelago (Figure 4b). This map reveals a continuous gravity signature between the Great Meteor group and the Azores platform, thus confirming the possible structural link between these two features, that was inferred above from the residual topography map (Figure 4a). North of the Azores, the Milne seamounts and associated elevated relief between latitudes 43° and 45°N, also have a negative MBA, forming a W-shaped band. This band seems to be unconnected to the Azores platform.

[23] The plate reconstruction at chron 13 (Figure 7) does not show the presence of anomalous topography on the America plate north of the Pico-Gloria fracture zone that can be linked to the Azores plateau. On the Iberia plate, the high located immediately north of the Gloria FZ has no conjugate on the America plate, and is therefore considered as having been emplaced during a later volcanic episode within the Azores archipelago. Shallower seafloor and volcanic features are present south of the Pico-Gloria FZ and extend at least up to the Great Meteor group. The Atlantis seamounts obliquely connect the Great Meteor group to the MAR axis (at this time) near the Oceanographer FZ. To the north, the Milne-King's Trough W-shaped structure is connected to the MAR axis at this period, without evidence for interaction with the highs located south of Pico-Gloria FZ.

[24] The reconstruction at chron 6 (Figure 7) illustrates the initiation of the Azores platform formation, while the emplacement of the Great Meteor group and the Milne-King's Trough structure seem, for a large part, completed. The precise boundary of the Azores platform at this stage is difficult to pinpoint because later volcanism on the Azores diffuse extension zone has overprinted most of the initial relief built by the MAR on the Iberia (and, later, Eurasia) plate. However, the existence of the Pico-Gloria transform fault at this stage suggests that the Azores plateau was limited at chron 6 to a small region north of this fracture zone, between latitudes 39 and 40°N. The bathymetric step observed near chron 6 on the North America plate strongly suggests a significant increase of the volcanism in this area at that time, which could be considered as the initiation of the main phase of Azores plateau construction.

5. Construction and Rifting of the Azores Platform

5.1. Construction of the Azores Plateau

[25] The Azores platform is a shallow domain bounded by bathymetric steps, more than 1.5 km high, especially well marked on the America plate, and has an oldest age of 20 Myr (chron 6). The platform extends to ~42°N to the north and to ~35°50′N to the south. The step in the northern part of the platform is located on oceanic crust dated at about 10 Ma (chron 5), and in the southern part at about 4 Ma (chron 3) (Figure 3a). The plateau is characterized by relatively smooth topography, interrupted by some elongated ridges. Within the Azores archipelago, the most conspicuous ridges are grouped into a 100-km-wide band with a N130 trend, sub-parallel to the islands of the Central Group. These ridges correspond to the diffuse transtensional boundary in this area [*Lourenço et al.*, 1998]. On the west flank of the MAR, the platform is characterized by two major ridges, sub-parallel to the MAR axis, roughly located along isochrons 6 and 5 (Figures 3a and 6). These ridges correspond to a seafloor shallowing of 1000 m to 2000 m, and are separated by a 50-km-wide flat depression. Each of these main ridges, 300–400 km long, is composed of two or three 100- to 150-km-long en echelon smaller ridges (Figure 6). The ridge which follows chron 6 is 300 km long. It abuts the western end of the Pico fracture zone to the south and extends past latitude 40°30′N to the north. It is made of two en echelon smaller ridges, 100 and 200 km long centered on latitudes 39°N and 39°40′N, respectively. The ridge located along chron 5, is 400 km long and includes Corvo and Flores islands. This ridge terminates immediately north of Corvo island and extends to at least 37°N to the south. It is made of three aligned 100- to 150-km-long ridges, and the Jussieu Plateau [*Cannat et al.*, 1999] is the

southernmost of these three ridges. This complex chron 5 ridge is 60 km wide on average, wider than the chron 6 ridge which is only 30–40 km wide. The chron 5 ridge has a conjugate on the eastern flank of the MAR, named the Faial Ridge by *Vogt* [1976] (Figure 6). Both ridges are associated with MBA lows (Figure 3b) and therefore probably underlain by a thick crust (Figure 4c). The lowest MBA values, and thus the thickest crust, are located within the Azores archipelago itself, with a maximum MBA contrast of about 100 mGal between the ridges and adjacent seafloor at the latitudes of Princess Alice Bank [*Cannat et al.*, 1999; *Escartin et al.*, 2001] or Pico and Faial islands [*Luis et al.*, 1998]. The MBA contrast on the western major ridges reaches −80 mGal. *Luis et al.* [1998] and *Cannat et al.* [1999] consider that these values in MBA correspond to a crustal thickness of 10–14 km, to be compared to the 6–7 km of the "normal" oceanic crust. Their results are confirmed by this study (Figure 4c). Along the MAR axis section which cuts across the Azores platform, *Detrick et al.* [1995] have observed a maximum crustal thickness of 9–10 km for the longest segment centered on 39°N.

[26] The smooth and elevated topography, the anomalous crustal thickness of the Azores platform, and the elevated ridges described above, can be interpreted as the result of excess volcanism, as was proposed from recent observations over the southern part of the Azores plateau [*Cannat et al.*, 1999]. From an analysis of the southern part of the Faial-Flores (or chron 5) ridge, *Cannat et al.* [1999] suggest that the formation of such volcanic ridges is not limited to a narrow axial spreading region, but probably involves widespread off-axis outpouring of lava. They consider the absence of major fault scarps and the lack of coherent magnetic anomalies over the plateau as arguments in favor of this hypothesis.

[27] Our new precise bathymetric compilation over these ridges indeed does not reveal the presence of numerous faults scarps. We propose however, that an important control is the rheology of the oceanic lithosphere that is modified by higher mantle temperatures, which caused the abundant volcanism, thus resulting in a lack of major tectonic features on these volcanic ridges. The smooth tectonic fabric of the Azores platform is similar to that observed on fast spreading centers such as the East Pacific Rise, where abundant volcanism prevails over tectonic extension. The disturbed magnetic anomaly pattern reported by *Cannat et al.* [1999] is not a general character of the Azores platform: several magnetic profiles which cut across the different ridges on the western flank of the MAR show still identifiable anomalies, even though they are affected by the topographic variations [*Cande et al.*, 1985] (Figure 8). Most of the magnetic profiles presented by *Cannat et al.* [1999] between 36°30′N and 38°N also present coherent magnetic patterns which locally have strong amplitudes and high frequencies related to the shallow water depth.

[28] We therefore propose that the construction of the main volcanic ridges identified on the western Azores platform occurred, in large part, at the MAR spreading axis. Smaller off-axis eruptions certainly contributed to the final construction of the ridges, as testified by the recent volcanism (less than 1 Ma) observed on Flores island [*Féraud et al.*, 1980]. In comparison, the WNW-ESE ridges located within the Azores archipelago itself are influenced by different structural conditions, which result from their complex formation within a diffuse plate boundary in close vicinity of a hot spot.

5.2. Rifting of the Azores Plateau

[29] The axial domain of the MAR is marked, along the section that cuts across the Azores plateau, by rough topography comprised of subparallel abyssal hills. The MAR axis segmentation in this section is clearly defined with non-transform discontinuities. Except for the longest and most robust segment centered on 39°N [*Detrick et al.*, 1995; *Thibaud et al.*, 1998], the segmentation along the MAR axis has similar wavelengths and axial relief north and south of the Azores (Figure 2) [*Thibaud et al.*, 1998; *Goslin et al.*, 1999]. This recent spreading is comparable with the older domain located outside of the Azores platform, as both have abyssal hills 10–30 km in length and 500 to 1000 m high. In the recent spreading, shorter wavelength abyssal hills with lower relief

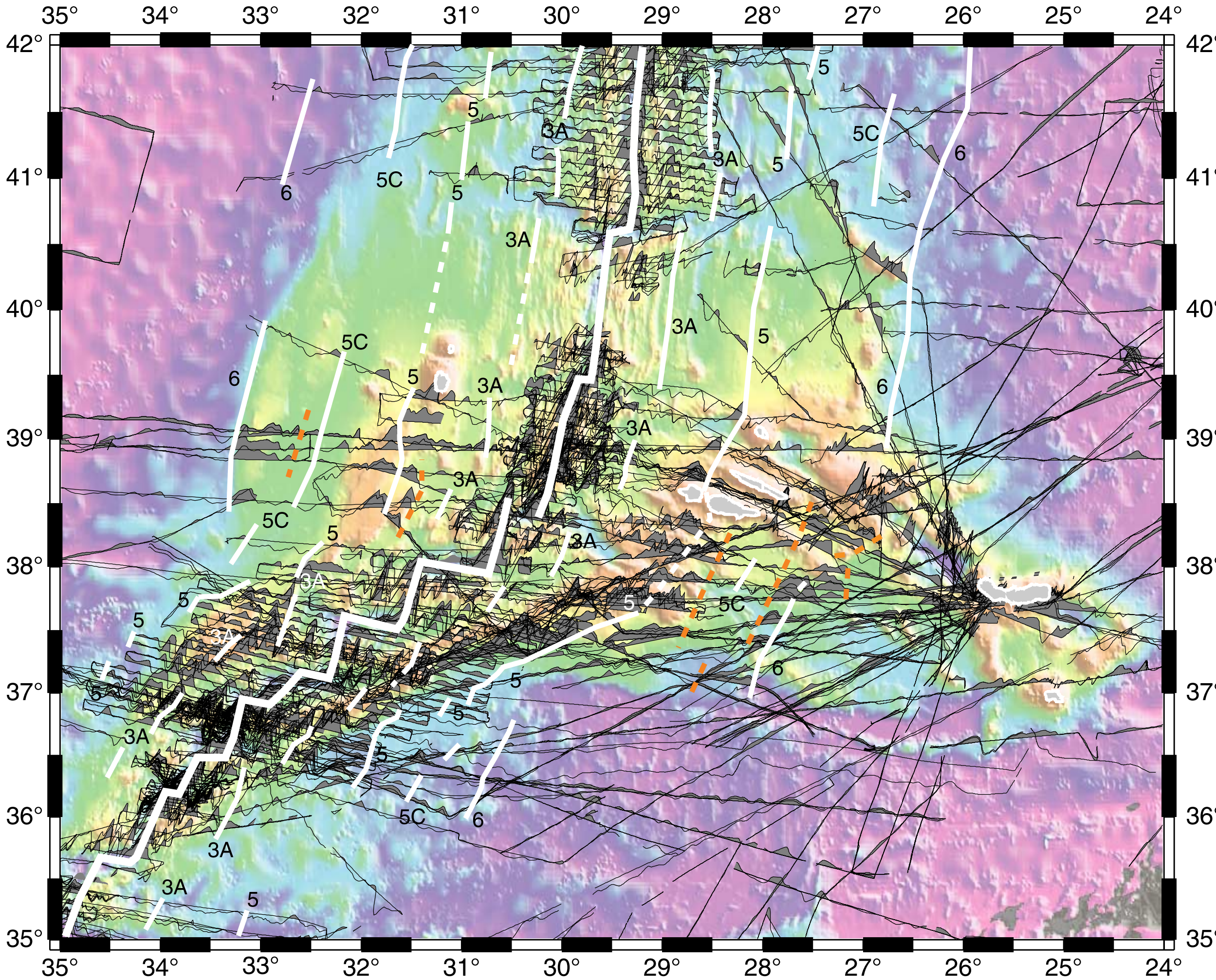


Figure 8. Surface-towed magnetic anomaly data available over the Azores area, projected along the tracks (positive anomaly shaded). Colored background: seafloor topography; white lines: identified magnetic lineations; numbers: anomaly identification; dotted white lines: interpolated isochrons; orange dotted lines: other magnetic lineaments. Indexed anomalies are 3A young (5.9 Ma), 5 old (10.9 Ma), 5C young (16.0 Ma), 6 old (20.1 Ma) (ages from *Cande and Kent* [1995]).

amplitude are also present. These later hills are not seen on the older seafloor, because of thicker sediment cover and poorer resolution of the bathymetry in this domain.

[30] The boundary between the Azores platform and the MAR axis consists of a steep wall divided in a series of steps. This steep wall contrasts with the smoother outward-facing slopes (Figure 6). It can be interpreted as a large fault scarp (or series of scarps) marking the rifting of the volcanic plateau. This feature has been noted by *Vogt* [1976] and *Cannat et al.* [1999] for the southern part of the youngest ridge of the Azores platform, the Jussieu Plateau. The rifted features extend clearly to the north, to at least 38°30′N on both flanks of the MAR. Further north, the steep wall yields to a less abrupt boundary made of several distinct small scarps. The width of the rough domain increases northward, from 74 km south of the Azores to 175 km to the north, the rifting episode initiating about 4 Ma (chron 3) at the southern end and about 8–9 Ma at the northern end (Figure 7). This observation suggests a southward propagation of the rifting at a rate of ~150 km/Myr. Such a propagation is not progressive and continuous along the axis, but occurs successively along discrete segments. These segments, about 200 km

to 40 km long, become shorter toward the south, in relation with the increasing of the MAR obliquity relative to the spreading direction. Less than 1 Myr separates the rifting of two adjacent segments. The present-day segmentation of the MAR axis still follows the geometry inherited from the initial rifting episode, while second-order discontinuities mark the ends of the spreading segments. The segmented oceanic crust within the rifted domain between the platforms presents typical abyssal hills construction, suggesting that the plume influence on the MAR spreading processes is much reduced relative to the period of maximum activity associated with the emplacement of the Azores plateau.

5.3. History of the Azores Plateau

[31] The plate reconstruction of chron 6 (20 Ma) residual topography (Figure 7) shows the beginning of the Azores plateau construction, marked by a 1500m high step. Between chron 6 and chron 5, the plateau extended along the MAR axis, with a maximal along-axis extent of ~550 km at chron 5 (10 Ma). The maximal northward extension of the volcanic activity occurred at chron 5. To the south, volcanism propagated across the Pico transform starting at about 15 Ma. The probable Azores spreading axis related to Africa-Europe motion is oriented N123°E at this stage, and presents a very oblique trend with the spreading direction of the MAR.

[32] The maximum southward extent of the Azores volcanism occurs between 7 and 6 Ma as already suggested by *Cannat et al.* [1999], with a southward propagation rate of about 40 km/Myr before this time. At this time, the rifting of the northern part of the Azores plateau had already been going on for 2–3 Myr. Since about 4 Ma, a "normal" slow spreading center separates the two parts of the Azores plateau (Figure 7).

[33] The rapid change in accretionary processes (construction of a Plateau and rifting) along the MAR axis in the Azores area is related to excess of magmatism due to an interaction between the ridge and a hot spot. Our new observations provide important constraints on the evolution of the ridge-hot spot interaction, discussed below. We also discuss the predictable consequences of the evolution of this interaction on the geochemical signature of MAR basalts.

6. Discussion

6.1. Hot Spot/Ridge Relative Motion

[34] The present location of the Azores hot spot is not precisely known. However, it is estimated that the Azores hot spot is located about 150–200 km east of the MAR [*Ito and Lin*, 1995], probably centered under the Central Group of islands [*Moreira et al.*, 1999], on the boundary of the Africa and Eurasia plates.

[35] The motion of the plates in the Azores region, with respect to the hot spot reference frame, is poorly constrained. The absolute motion of the Africa plate is essentially constrained by the Reunion hot spot in the Indian Ocean and the Tristan da Cunha hot spot in the South Atlantic Ocean, both located in its southern part for ages older than 30 Ma, while only the Reunion hot spot track is used for ages younger than 30 Myr [*Minster and Jordan*, 1978; *Müller et al.*, 1993a; *Gripp and Gordon*, 1990, 2002]. The absolute motion of the North America plate is constrained by a single hot spot track, the New England seamounts, for ages between 103 and 70 Myr [*Müller et al.*, 1993a]. The present-day motion of the MAR relative to the Azores hot spot, since 5 Ma, is estimated to have a N247 direction and a velocity varying between 22 and 33 km/Myr [*Gripp and Gordon*, 2002].

6.1.1. Formation of the Azores Platform

[36] The paleo-positions of the residual topography in the Azores region since chron 13 (33 Ma) (Figure 7) illustrate the construction of the Azores platform, which started at about Chron 6, followed by the symmetrical rifting of the plateau which began between chron 5 (10 Ma, north) and chron 3 (4 Ma, south). The schematic plots of the MAR axis and major topographic features with respect to a fixed Azores plume at different times (Figure 9) further show the coincidence between the early stage of the construction of the Azores plateau and the beginning of the plume-ridge interaction at chron 6 (20 Ma). Later, the maximum extent of

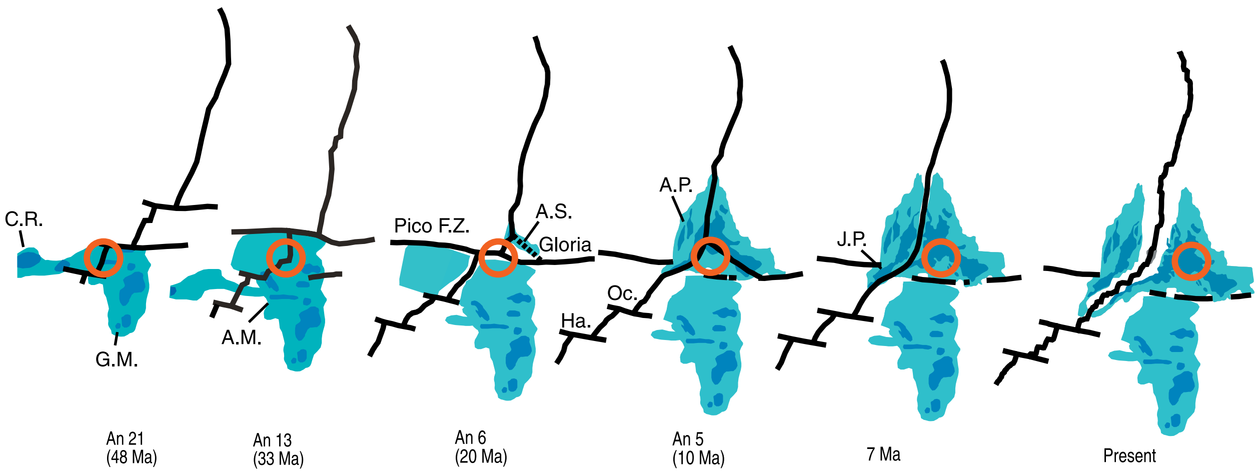


Figure 9. Schematic reconstructions of the relative movement between the Mid-Atlantic Ridge (MAR) and a hot spot, supposed to be localized under the Azores archipelago and centered under Terceira island. The hot spot (thermal anomaly) is assumed to 200 km in diameter and shown by a red circle. C.R.: Corner Rise, G.M.: Great Meteor, A.M.: Atlantis Mound, A.S.: Azores Spreading center, A.P.: Azores plateau, Oc.: Oceanographer F.Z., Ha.: Hayes F.Z., J.P.: Jussieu Plateau.

the plateau along the MAR axis at Chron 5 (10 Ma) is observed when the plume is the closest to the Azores triple junction. The progressive southward rifting of the plateau then takes place when the primary melting zone of the MAR, whose width can be estimated to a maximum of 200 km (e.g., MELT experiment [*Toomey et al.*, 1998]), is progressively shifted away from the 200-km thermal plume. The interaction between the two melting zones would have produced the abundant volcanism required to build an oceanic crust twice thicker than normal. This abundant volcanic production extended along the MAR axis, and certainly also along the Azores diffuse plate boundary, at least 300 km away from the thermal plume center. The sudden stop of this volcanism, synchronous with the rifting of the Plateau, suggests that the abundant melt production requires the interaction of the two melting zones as proposed by *Maia et al.* [2001] for the Foundation hot spot-Pacific/Antarctic ridge interaction. When this interaction ceases, "normal" magmatic production resumes along the ridge axis.

6.1.2. One Plume at the Origin of Great Meteor Complex and Azores?

[37] We proposed above that the Great Meteor Seamounts and the Azores platform are connected by a shallow rise that establishes a continuity between these two features. The K/Ar age determinations of the Great Meteor seamounts vary between 16 and 9 Myr [*Wendt et al.*, 1976] (Figure 10). However, Wendt et al. acknowledge that these ages are not very reliable because of the samples themselves (lack of glass, high vesicularity of the rocks) and because the sampled rocks correspond to the last volcanic events in the Great Meteor seamounts and thus may not reflect the age of the whole structure. Indirect age estimates of seamounts in the Great Meteor-Cruiser-Tyro-Atlantis complex, based on the determination of the elastic thickness of the lithosphere, give an age of 65 Myr for the Cruiser group, and a range of 38–47 Myr for most of the other seamounts including Great Meteor seamount itself [*Verhoef*, 1984]. The K/Ar ages of the Great Meteor seamounts suggest that recurrent volcanic episodes have certainly affected some of the seamounts till 20–30 Ma [*Wendt et al.*, 1976]. *Tucholke and Smoot* [1990], from the analysis of the seamounts subsidence, propose ages varying between 21 and 75 Myr for the same complex, and ages between 86 and 50 Myr for the conjugate Corner Seamounts on the North America plate (Figure 10). These seamounts are considered as marking the first interaction of the MAR with the New England hot spot as a result of the westward component of the ridge's "absolute" motion

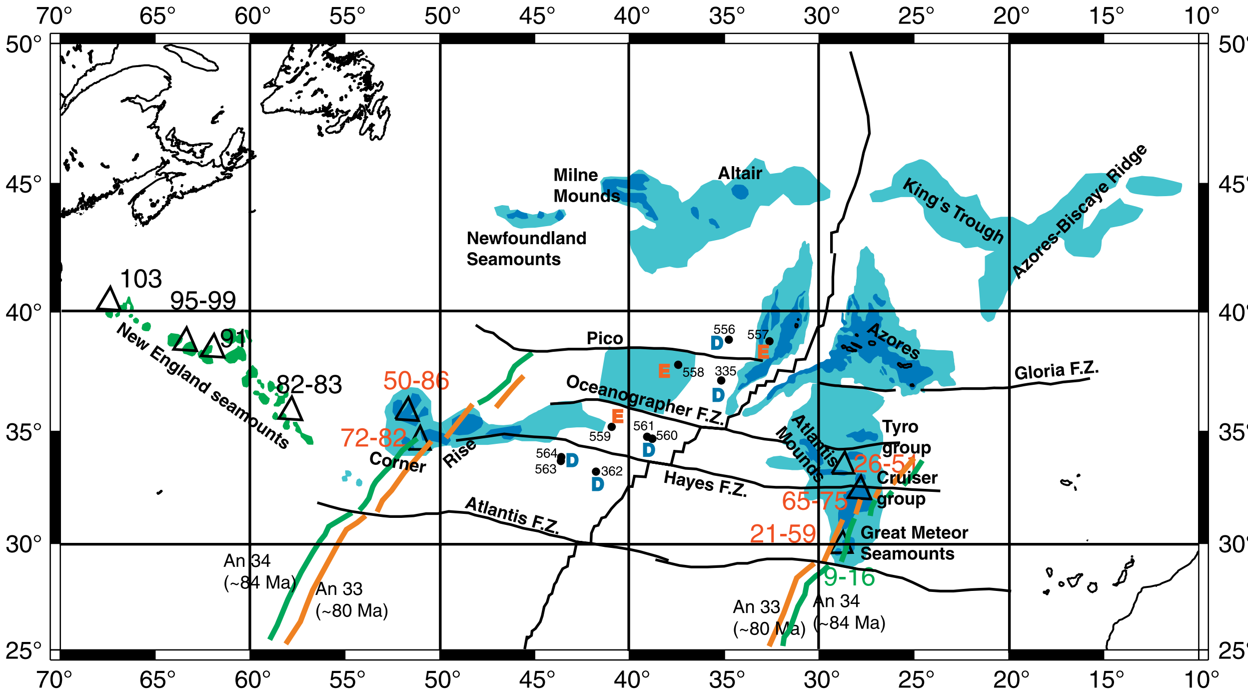


Figure 10. Summary of the different features discussed in the text. The main structures are labeled. The blue-color areas show the elevated seafloor and the dark blue-color the shallowest ridges in these areas. The New England seamounts are showed in green. The triangles correspond with the seamounts where an age is obtained; by geochronology (K/Ar) on basalts (*Duncan* [1984] in black and *Wendt et al.* [1976] in green); by indirect method (see text) in red [*Verhoef*, 1984; *Tucholke and Smoot*, 1990]. The isochrons 33 (80 Ma) (in brown) are from *Klitgord and Schouten* [1986]. Geochemical character of the basalts drilled during DSDP legs 37, 49 and 82 (the black dots) [*Bougault et al.*, 1985] in the Azores area, varying from depleted (D) to enriched (E) basalts.

[*Duncan*, 1984; *Tucholke and Smoot*, 1990; *O'Connor and Duncan*, 1990].

[38] The New England seamounts on the America plate, which originated from the New England hot spot, formed between 103 and 82 Ma [*Duncan*, 1984]. If one considers that the Corner seamounts on the America plate are conjugates of the Great Meteor-Cruiser group on the Africa plate, their emplacement age must correspond with the age of the oceanic crust, between 90 and 80 Ma, above a hot spot close to the North America-Africa plate boundary [*Tucholke and Smoot*, 1990; *Müller et al.*, 1993a]. Hot spot activity would then have occurred along the New England chain which is located at more than 500 km from the MAR axis at this time. We propose that two different hot spots are at the origin of these structures, as suggested by *Morgan* [1983], instead of a single one.

[39] We have shown that a series of conjugate structures located between the Cruiser group and the Azores is progressively younger to the north, and follows the formation of the Great Meteor complex. A conjugate structure of the Atlantis Seamounts, though somewhat deeper, can be found on the North America plate, and would have an age between 50 and 40 Myr. Between the Atlantis Seamount and the Azores platform, excess volcanism mainly causes the anomalously shallow depths observed on both flanks in the residual topography map between 40 and 25 Ma. The symmetrical location of these features suggests that they were emplaced at the ridge axis by a hot spot close to the MAR axis. The age of these structures could then be determined by the magnetic anomalies (Figures 3 and 10). Their formation would be the consequence of the relative motion between the America-Africa plate boundary above a plume. This hypothesis allow us to propose a relatively constant southward absolute motion of the Africa since 85–90 Ma, the same plume causing the emplacement of the Great Meteor complex and of

the Azores plateaus. The shallower ridges observed on the Africa plate would be explained by a slightly off-axis location of the hot spot under the Africa plate.

[40] To account for the previous observations, we plotted the motion of the MAR axis with respect to a hot spot since 55 Ma (Figure 9). We represent the plume by a broad (200 km) thermal anomaly [*McNutt et al.*, 1989; *Wolfe et al.*, 1997] in Figure 9, presently centered under Terceira Island. We assume that the same hot spot was located beneath the Corner Seamounts at 80 Ma and beneath Atlantis Seamounts at 40 Ma, and we interpolate the motions of the Africa plate and of the MAR axis above the hot spot between 50 Ma and present. This leads to a rate of 13 km/Myr toward a SSE direction for the Africa plate absolute motion in this area. The present-day absolute motion of Africa would be oriented N215, closed to the trends computed by *Gripp and Gordon* [2002] from the HS3-NUVEL1A model (N235) or from HS2-NUVEL1 model (N225). The area of ridge-hot spot interaction migrates northeastward along the MAR axis between 50 Ma and the present to form the shallow seafloor areas between Hayes and Pico fracture zones, which (despite being less developed than the surrounding plateaus) display enriched basalt [*Bougault et al.*, 1985] (Figure 10). Finally, the Azores platform is emplaced. Again, the rifting of the conjugate shallow areas between Hayes and Pico FZ is less clearly evident than within the Azores platform, most likely because of the poorer resolution of the available bathymetry in these areas.

[41] Finally, we propose that the MAR geometry plays an important role in the duration of the ridge-hot spot interactions and therefore in the resulting amount of volcanism: the more oblique the ridge is to the spreading direction, the shorter is the interaction and the less developed is the volcanic construction.

6.2. Episodic "Hot Spot" Activity

[42] An alternative hypothesis is to consider that the hot spot activity is episodic [e.g., *Vogt and Tucholke*, 1979; *Epp*, 1984] and yields variations in the amount of volcanism and size of the resulting structure. The interpretation of the MBA map shows that the crust beneath the Azores and Great Meteor plateaus thickens to about twice to three times its normal thickness, to reach a maximum of 16 km (Figure 4c). These values are similar to those calculated by *Cannat et al.* [1999] and *Escartin et al.* [2001] for the Jussieu plateau. Furthermore, we propose that the highs located on the plateaus, associated with the thickest crust, 5–8 km thicker than the thickness of the surrounding crust, indicate a discontinuous magmatic activity, with a recurrence of 3 to 5 Myr. Such fluctuations may result from variations in the degree of melting of the upper mantle, from temperature variations, and/or from variations with time of the volume of plume material. For instance, *Cannat et al.* [1999] calculated that a mantle temperature rise of 70° beneath the MAR would account for a 5-km-thicker crust beneath the Jussieu plateau south of the Azores. An alternate hypothesis is that the plume itself is heterogeneous, some parts yielding excess magma and/or hotter material. When the plume produces an excess of magma (or temperature), it can migrate along the ridge axis [cf. *White et al.*, 1995; *Ito*, 2001]. *Schilling and Noe-Nygaard* [1974] propose for the Faeroe-Iceland plume system an episodic upwelling of plume material with time (rising blobs model). In their study, two blobs are separated by several tens of millions of years, as a consequence of the decreasing of the viscosity in the upper mantle [*Van Keken et al.*, 1992]. However, the periodicity of volcanic excess which we observe is 6 to 10 times shorter than the periodicity proposed by *Schilling and Noe-Nygaard* [1974]. Our results would imply more rapid variations in the plume structure than can be modeled considering a periodicity of 8 Myr in the volume flux of upwelling plume material [*Ito*, 2001].

6.3. Geochemical Consequences

[43] Following our model, two different hot spots would be at the origin of the New England chain and of the Great-Meteor-Azores complex. The basalts sampled along the New England chain (GEOROC database [*Taras and Hart*, 1987]) have

a chemical signature following a HIMU trend [*White*, 1985; *Zindler and Hart*, 1986], while the basalts from the Azores (GEOROC database [*Dupré et al.*, 1982; *Halliday et al.*, 1992; *Turner et al.*, 1997; *Widom et al.*, 1997]) have a EM trend, clearly implying two different sources. Chemical analysis of samples collected along the Great Meteor-Corner rise-Cruiser-Atlantis complex are not presently available.

[44] The geochemical signature of the Azores hot spot along the MAR axis is asymmetric [*Schilling et al.*, 1983; *Yu et al.*, 1997; *Dosso et al.*, 1999] (Figure 2): from Terceira Island, this signature extends at least 250 km to the north, and at least 1000 km to the south (to the Hayes FZ, or even further south). The more rapid decrease of the hot spot-related geochemical anomaly to the north has not been convincingly explained so far. Concerning the off-axis data, the geochemical signature of the rocks drilled during the DSDP Legs 37, 49 and 82 (*Bougault et al.*, 1985) shows complexity in their geographical distribution (Figure 10). Samples from Hole 556 located west of the Azores plateau, on crust ~35 Myr old (chron 12) [*Cande et al.*, 1985], show a normal MORB signature [*Bougault and Cande*, 1985]. Samples from the Azores plateau (Hole 557) show a typical enriched signature, and those located south of Pico fracture zone (Holes 558 and 335), and west of the Jussieu plateau, present both enriched and normal MORB signatures [*Schilling et al.*, 1977; *Bougault and Cande*, 1985]. All basalt samples collected south of Hayes fracture zone are depleted (Holes 562, 563 and 564 [*Bougault and Cande*, 1985]). The basalt samples obtained around the FAMOUS area (from Holes 332, 333, 334, 411, 412 and 413) present flat to enriched light rare earth elements signature [*Schilling et al.*, 1977] reflecting heterogeneous mantle. This apparent complexity is in agreement with our model (Figure 9). Our model of evolution, which relates the Corner seamounts, the Great Meteor seamount group, the anomalous shallow areas located on both flanks between Oceanographer and Pico FZ, and the Azores platform to the interaction of the MAR with an unique hot spot, results in an apparent northward migration of the ridge-hot spot interaction zone along the MAR during the last 50 Ma, and it can explain the geochemical off-axis signatures. The gently decreasing hot spot signature south of the Azores would reflect the diachronous character of previous ridge-hot spot interaction episodes along the MAR. If the upper mantle is fertilized by deep material during the passage of the ridge axis above the hot spot, the upper mantle south of the Azores would have been fertilized long before the formation of the Azores platform. The present-day MAR melting zone south of the Azores actually could later sample this fertilized upper mantle. It can be further proposed that the hot spot signature progressively decays with time, possibly as a result of the faster consumption of its incompatible elements in the MAR basalts. Conversely, the sharp limit of the Azores hot spot influence northward along the MAR, at about 40°30′N [*Goslin et al.*, 1999], would reflect the presence of unfertilized mantle north of this limit. The geochemical anomaly observed between 43°N and 46°N [*Yu et al.*, 1997; *Goslin et al.*, 1999] would be related to another cause, possibly related the formation of Milne mounds-Altair on the America plate and King's Trough-Azores Biscaye ridge complex on the Africa plate.

7. Conclusion

[45] The new bathymetric map and gravity data on the Azores–Great Meteor plateaus give insight on the temporal and spatial variations of melt supply to the ridge axis resulting from the interaction of the Azores hot spot with the Mid-Atlantic Ridge. The presence of a large region of shallow seafloor between the Great Meteor Seamounts and the Azores platform on the Africa plate, and between their less developed conjugate structures on the North America plate, suggest a quasi continuous MAR–Azores hot spot interaction since 85–90 Ma. This interaction has taken place in an area which progressively migrated northward, as a result of the SSE absolute motion of the Africa plate and the grossly parallel orientation of the MAR. This hot spot is distinct from this at the origin of the New England seamounts. The interaction between the Azores hot spot and the ridge axis has produced abundant melt production which was mostly emplaced on-axis, forming large plateaus underlain

by a thick crust. After the cessation of the interaction, the plateaus were progressively rifted; the best example of this process is the Azores plateau itself, which was affected by progressive southward rifting, when the MAR melting zone shifted away from the 200-km plume thermal anomaly. The sharp interruption of the volcanic construction, associated with the rifting episode, suggests that the abundant melt production requires the interaction of the two melting zones. Our results bear important consequences on the motion of the Africa plate relative to the hot spot reference frame. They also contribute to explaining the asymmetric signature of the Azores hot spot related geochemical anomaly along the Mid-Atlantic Ridge.

Acknowledgments

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