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# Crustal thickness of V-shaped ridges south of the Azores: Interaction of the Mid-Atlantic Ridge (36°–39°N) and the Azores hot spot

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**Abstract.** V-shaped ridges propagating along the Mid-Atlantic Ridge axis south of the Azores and Iceland hot spots indicate that ridge-hot spot interactions produce temporal and spatial variations in melt supply to the ridge axis. Estimates of relative crustal thickness variations associated with the ridges south of the Azores hot spots, based on gravity and bathymetry data collected during the SudAçores cruise (1998), provide constraints on the rate of propagation of these melt anomalies and on the variations in melt production along the axis and in time. The maximum apparent crustal thickness along the Azores V ridge is ~14 km near the Azores, decreasing to normal crustal thickness of ~6 km toward the south. This crustal thickness variation may be explained by enhanced melt production associated with the propagation of a mantle temperature anomaly that initiated ~10 Myr ago at the Azores hot spot. The temperature anomaly decreased as it propagated southward, reaching ambient mantle temperatures at the present time at its predicted location under the axis. The excess melt was emplaced on axis forming discrete, shallow (<1000 m) oceanic plateaus (~100 km in diameter at ~37.5°N) that are isostatically compensated. The numerous seamounts, lack of normal faults, and smooth basement at the summit of these plateaus suggest high effusion rates that persisted for ~5 Myr or less, with little or no tectonic strain. As the melt anomaly propagated along axis, the magmatic activity at the plateaus ceased, resulting in rifting of the plateau and onset of normal seafloor spreading. The variations in crustal thickness inferred for the V ridges south of the Azores are at least twice that inferred for the Iceland structures. In both cases the V ridges record temporal variations in temperature and/or mantle flux that affect melt production under the ridge axis, but the fluctuations are larger for the Azores than for the Iceland hot spot.

## 1. Introduction

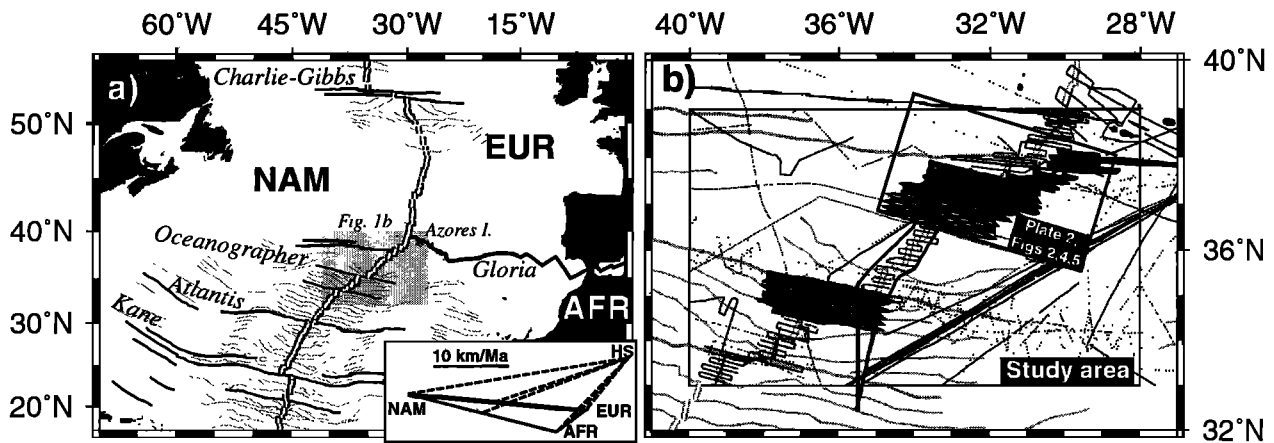
The interaction of hot spots with nearby mid-ocean ridges strongly modifies melting of the mantle under the ridge and the accretion of the oceanic crust [e.g., *Schilling et al.*, 1983]. This ridge-hot spot interaction typically results in shallower seafloor and thicker crust than expected for normal seafloor spreading away from hot spots, as observed over Iceland or the Azores along the Mid-Atlantic Ridge (MAR). These bathymetric and gravity anomalies extend several hundred kilometers along the axis and away from hot spots [*Cochran and Talwani*, 1978; *Le Douaran and Francheteau*, 1981; *Ito and Lin*, 1995a, 1995b], indicating increased mantle temperatures and melt production towards the hot spot. The geochemical signature of hot spots (indicated by major element, trace element, and isotope ratios in basalts sampled along the axis [e.g., *Schilling et al.*, 1983; *Dosso et al.*, 1999]) has a shorter along-axis extent. For example, the Azores hot spot produces a bathymetric anomaly extending along ~2000 km of the MAR axis (from ~40°N to the Kane Fracture

Zone at ~24°N) compared with the geochemical anomaly of ~1000 km (from ~40°N to the Hayes Fracture Zone at ~33.5°N). The differences in along-axis extent between the geochemical and geophysical signatures indicate that melting processes may be partially decoupled from larger-scale thermal effects of hot spots.

Laboratory [e.g., *Kincaid et al.*, 1995], theoretical [*Ribe et al.*, 1995; *Ribe*, 1996; *Sleep*, 1996; *Ribe and Delattre*, 1998], and numerical studies [e.g., *Yale and Phipps Morgan*, 1998; *Ito et al.*, 1999] have shown that the interaction of mantle plumes with nearby mid-ocean ridges is complex and not fully understood. The effect of hot spots on ridge bathymetry and melt production depends primarily on the flux of the plume (mainly a function of the temperature anomaly and diameter of the plume), viscosity structure of the mantle, spreading rate of nearby mid-ocean ridges, and relative motion of the ridge with respect to the plume. In the case of the northern MAR, the mantle temperature anomalies required to explain the geophysical (bathymetry and gravity) and geochemical observations are ~180°C and ~70°C for Iceland and the Azores, respectively [*Ito and Lin*, 1995b; *Ito et al.*, 1999]. These differences in temperature anomalies are consistent with Iceland being one of the hot spots with largest flux [*Sleep*, 1990; *Schilling*, 1991]. Ridge-hot spot interaction can vary at long timescales as a consequence of the motion of the

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**Figure 1.** (a) Location of the study area, SW of the Azores and immediately south of the North American (NAM)–Eurasian (EUR)–African (AFR) triple junction. Double line shows the location of the ridge axis, and the heavy and light lines the off axis traces of fracture zones and nontransform offsets. Inset shows the relative (solid lines) and absolute motions of the NAM, AFR, and EUR plates and of the NAM–AFR and NAM–EUR ridges (dashed lines), using the HS1-NUVEL2 [Gripp and Gordon, 1990]. These velocities are calculated for 37.5°N and 32.5°W, corresponding approximately to the center of Lucky Strike segment (Plate 2). (b) Ship tracks from the Sudaçores cruise [Cannat *et al.*, 1999] (bold lines), the FARA-SIGMA cruise [Detrick *et al.*, 1995], and along ship tracks from the NGDC database (thinner lines). The compilation and data analysis have been done over an area larger than that of the analysis presented in this paper.

ridge relative to hot spots [e.g., Ribe and Delattre, 1998]. The migration of the Galápagos hot spot away from the Cocos–Nazca Ridge may explain the decrease in the apparent axial thermal anomaly from ~90° to ~25°C during the past ~8 Myr [Ito and Lin, 1995b].

Variability in ridge-hot spot interactions at timescales of <5 Myr has been reported for both the Iceland and Azores hot spots. Vogt [1976, 1979] interpreted a series of shallow bathymetric ridges emanating from the Azores and forming a southward propagating V (V-shaped ridges) as evidence for flow of hot spot material along the axis. These structures can be identified on the satellite free-air gravity data [Sandwell and Smith, 1997] (Faial and Flores Ridges from Vogt [1979], Plate 1, top) and are similar to a series of V-shaped ridges south of Iceland (Plate 1, bottom). V-shaped ridges may be caused by fluctuations in mantle temperature [White *et al.*, 1995] or by along-axis flow of mantle asthenosphere below the ridge [e.g., Vogt, 1979] with a periodicity of 2–3 Myr [Vogt, 1976, 1979]. The inferred rates of along-axis propagation are ~100–200 mm/yr [Vogt, 1971; White *et al.*, 1995] and ~60 mm/yr [Cannat *et al.*, 1999] for the Iceland and Azores V ridges, respectively.

The general structure, geodynamic setting, and tectonic evolution during the last 10 Myr of the V-shaped ridges south of the Azores have been constrained using shipboard geophysical data from a recent cruise on board *R/V L'Atalante* [Cannat *et al.*, 1999]. In this paper we present a detailed analysis of bathymetry and gravity data to constrain regional changes in crustal thickness, which are interpreted as melt production variations with distance from the hot spot (along axis) and in time (across axis). Early work by Vogt [1976, 1979] on these structures south of Iceland and the Azores was based solely on sparse bathymetry data. More recent estimates of temporal variations in mantle temperature anomalies south of Iceland [White *et al.*, 1995] used limited seismic crustal thickness estimates [Ritzert and Jacoby, 1985; Smallwood *et al.*, 1995] and existing satellite gravity data [Sandwell and Smith, 1997] (Plate 1). The study of Cannat *et al.*

[1999] and the one presented here provide to date the most detailed constraints on structure, crustal thickness and tectonic evolution of V-shaped ridges resulting from the interaction of the Azores hot spot with the northern MAR.

## 2. Tectonic Setting and Geological Background

An area immediately south of the Azores platform was surveyed during the Sudaçores cruise on board *R/V L'Atalante* (France) in June–July 1998 [Cannat *et al.*, 1999], extending off axis the earlier survey of Detrick *et al.* [1995] (location and ship tracks in Figure 1). The study area covers the ridge axis between ~36°N and ~39°N (Figure 2), over the AMAR, French–American Mid-Ocean Undersea Study (FAMOUS), North FAMOUS, Lucky Strike, Menez Gwenn, and Princess Alice segments (PO-4, PO-3, PO-2, PO-1, KP-5, and KP-4 segments of Detrick *et al.* [1995]). The survey extends off axis to ~10 Ma old oceanic crust, over the Faial and Flores Ridges, which form the V-shaped ridges propagating southward from the Azores (Plates 1 and 2). The west branch of the V ridge is surveyed off the FAMOUS, North FAMOUS, and Lucky Strike segments, while the coverage of the east branch is more complete, extending close to the Azores Islands off the Princess Alice segment (Figure 1 and Plate 2).

The study area is immediately south of the present location of the North America/Eurasia/Africa triple junction at ~38°50'N (Faial Fracture Zone (FZ)), which shifted from its original position at ~38°N (East Azores FZ) [Luis *et al.*, 1994; Searle, 1980]. The present full spreading rate at 37.5°N (Lucky Strike segment) is ~20.3 mm/yr on a 103° azimuth (HS1-NUVEL2 model [Gripp and Gordon, 1990]), with highly asymmetric accretion along the FAMOUS segment during the last 0.7 Myr (7 mm/yr to the west and 13.4 mm/yr to the east [Macdonald, 1977]). The recent spreading history of the area is complex, with variations in polarity of asymmetry [Macdonald, 1977] and in spreading rate and direction of spreading during the last 10 Ma

[Sloan and Patriat, 1992; Luis et al., 1994; Cannat et al., 1999]. The absolute motion of the ridge axis relative to the Azores hot spot is ~20 mm/yr along a ~250° azimuth (see inset in Figure 1).

The Azores hot spot produces a long-wavelength bathymetry and gravity gradient (~4 m/km, >20-3 mGal/100 km, respectively) between 33°N and 39°N, with a minimum depth and gravity anomaly over the Azores Platform at ~39°N [Detrick et al., 1995]. A similar gradient in axial bathymetry and gravity is observed from ~40.5°N to 45°N [Goslin and Party, 1999]. The hot spot signature in trace element and isotope ratios [Schilling et al., 1983; Schilling, 1986; Dosso et al., 1999] extends to the Hayes FZ at 33.5°N and is highly asymmetric towards the north [Goslin and Party, 1999]. Morphologically, an axial high and lack of a clear axial valley (Plate 2) characterize segments north of the 37.5° offset (Menez Gwenn, Princess Alice, Plate 2). The Lucky Strike segment shows a transitional morphology, with the disappearance of the axial valley at its center and with evidence for recent volcanism [Ondreas et al., 1997]. The segments south of the 37.2°N discontinuity (North FAMOUS, FAMOUS, and AMAR, Plate 2) show well-developed axial valleys and outcrops of serpentinized peridotites associated with low-temperature hydrothermalism (i.e., south of FAMOUS [Gràcia et al., 2000]). As the spreading rate does not change substantially throughout the area, these variations in geology and ridge morphology may be attributed to hot spot-induced changes in thermal regime and/or magma supply for each of these segments [Detrick et al., 1995]. To first order, this observation is supported by apparently high amounts of neovolcanism along the Menez Gwenn and Lucky Strike segments relative to the other segments [Parson et al., 2000] and by the presence of high-temperature hydrothermalism (>220°C-330°C) at these two segments [Fouquet et al., 1994; Wilson et al., 1996; Langmuir et al., 1997] compared with lower-temperature hydrothermalism along the FAMOUS and AMAR segments and discontinuities [Bougault et al., 1998; Gràcia et al., 2000].

Systematic segment-scale variations in depth and gravity are superimposed on the long-wavelength hot spot gradient. All the segments are associated with centered axial highs and mantle Bouguer gravity lows, indicating focused magmatic accretion [Lin et al., 1990] and representing crustal thickness variations of ~2 km in amplitude [Detrick et al., 1995]. Despite the proximity to the hot spot, the outcrop of peridotites at or near numerous discontinuities [Gràcia et al., 2000] suggests that the thin crust at segment ends is heterogeneous (composed of peridotite and gabbro and capped by basalt), as inferred for other MAR segments away from the influence of the Azores hot spot [Cannat et al., 1995].

The ridge segmentation history can be traced back from the present time to ~10 Ma or less, as the traces of the nontransform offset can only be followed to the inner walls of the V ridges off axis, with no evidence of continuity further off axis (see Plates 1 and 2). The faulted abyssal hill terrain within the V-ridges is similar to that found elsewhere along the MAR [e.g., Tucholke et al., 1997], with an abrupt transition to the smooth (unfaulted), shallow (<1.5 km) seafloor along the V ridges, which contain numerous seamounts. Off axis of the Lucky Strike segment the transition is parallel to the axis, while off North FAMOUS it is highly oblique (~45° to spreading, Plate 2). Reconstruction based on magnetic anomalies shows a large (>100 km in diameter) oceanic plateau (named Jussieu Plateau hereafter, Plate 2) rifted asymmetrically ~3.9-5.7 Ma [Pouliquen et al., 1998; Cannat et al., 1999]. Assuming that Princess Alice Bank is part of a similar rifted oceanic plateau and lacking data over its conjugate side to

the west (Plate 2) to better constrain the tectonic history of the area, the estimated time of rifting was 5.7-7 Ma [Cannat et al., 1999]. The temporal and spatial variations in melt production and mode of crustal construction are quantified below, in order to constrain the temporal variability in melt supply to the axis associated with the interaction of the Azores hot spot with the MAR.

### 3. Data Collection and Processing

Bathymetry, gravity, magnetic and six-channel seismic data were collected on board R/V *L'Atalante*. The surveyed area covered the ridge between 36°40' and 38°N, and extended over Princess Alice Bank, near the Azores, following the east branch of the V-shaped ridge (Plate 2). Ship tracks were run subparallel to the spreading direction (~104° for the Lucky Strike area), spaced between 7.4 and 8.3 km. Additional shorter tracks were run to fill bathymetry gaps in shallow areas and during dredging operations, and across track, during transits (Figure 1 and Plate 2). The data were complemented with multibeam bathymetry and gravity from the FARA-SIGMA cruise [Detrick et al., 1995] and with ship track data from the National Geophysical Data Center (NGDC) database (Figure 1):

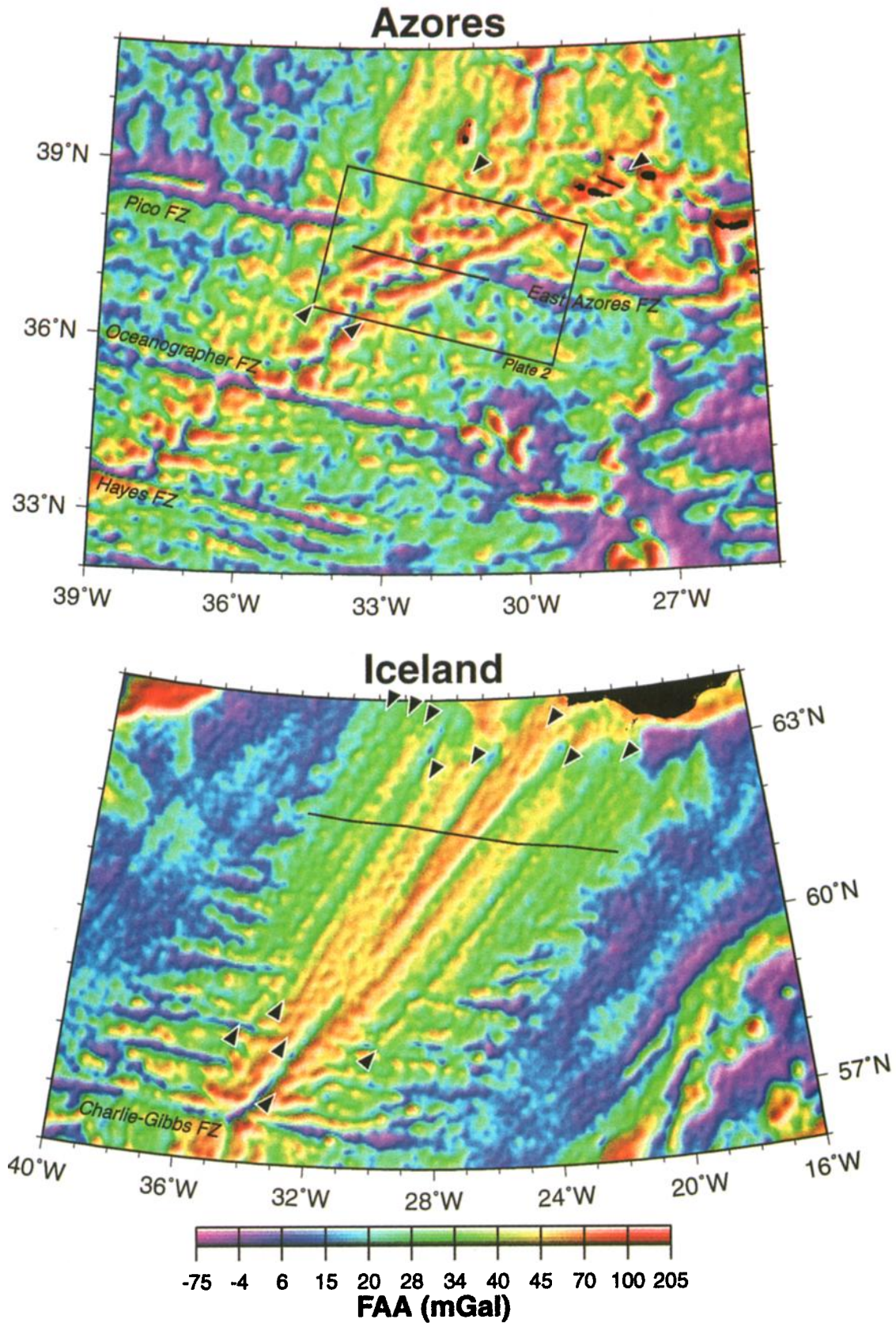
1. Bathymetry data were acquired with a SIMRAD EM-12 multibeam system [Cannat et al., 1999] and combined with the data from the FARA-SIGMA cruises [Detrick et al., 1995]. The CARAIBES software (Institut Française de la Recherche pour l'Exploitation de la Mer, France) was used to process the data on board and to obtain bathymetry grids at ~100-m grid spacing (Plate 2).

2. Gravity data were recorded with a Bodenseewerk GSS30 gravimeter. The Eötvös and drift corrections were removed to obtain the free-air gravity anomaly (FAA). The rms crossover error for the cruise data was ~1.8 mGal. FAA data from the FARA-SIGMA cruises [Detrick et al., 1995] and the NGDC data catalog were manually edited to remove bad profiles and data points and shifted to a common base level using the satellite-derived FAA as a reference field. The resulting rms crossover error of the combined data sets was ~2.5 mGal. The FAA ship track data were gridded at 1' using a minimum surface tension algorithm [Wessel and Smith, 1991]. The resulting FAA map (Figure 2a) reflects primarily the effect of seafloor bathymetry.

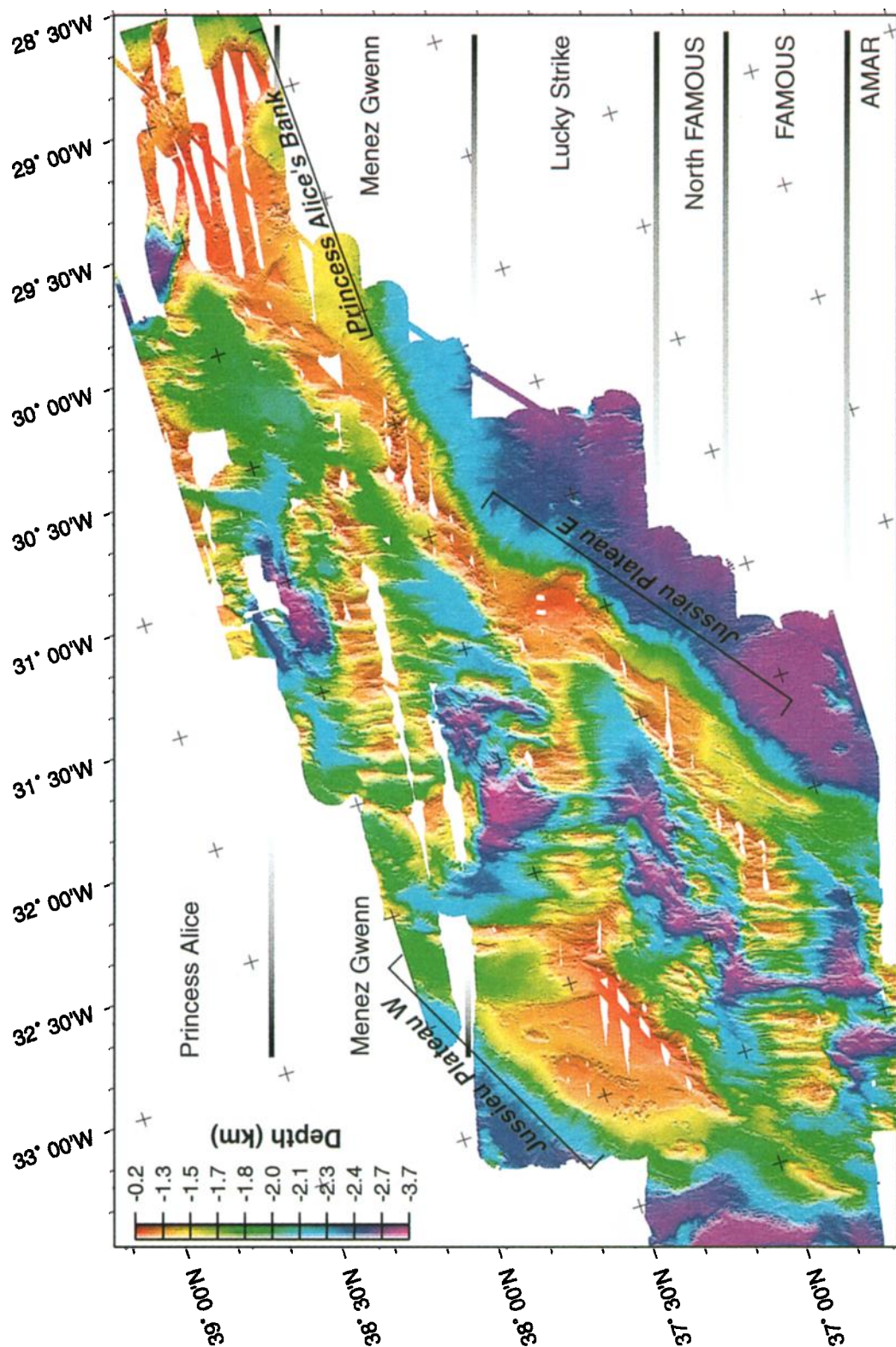
3. Total magnetic field was measured at 6-s intervals with a Berringer proton magnetometer towed ~325 m behind the ship. Magnetic anomalies were calculated using the 1995 International Georeference Magnetic Field [International Association of Geomagnetism and Aeronomy, 1996]. The root-mean-square (RMS) error at crossover of tracks was ~15 nT. Details of the processing and interpretation of the magnetic data will be given in a later paper, and only the interpreted magnetic anomalies [Pouliquen et al., 1998; Cannat et al., 1999] will be used in this study.

### 4. Thermal Modeling, Seafloor Subsidence, and Residual Bathymetry

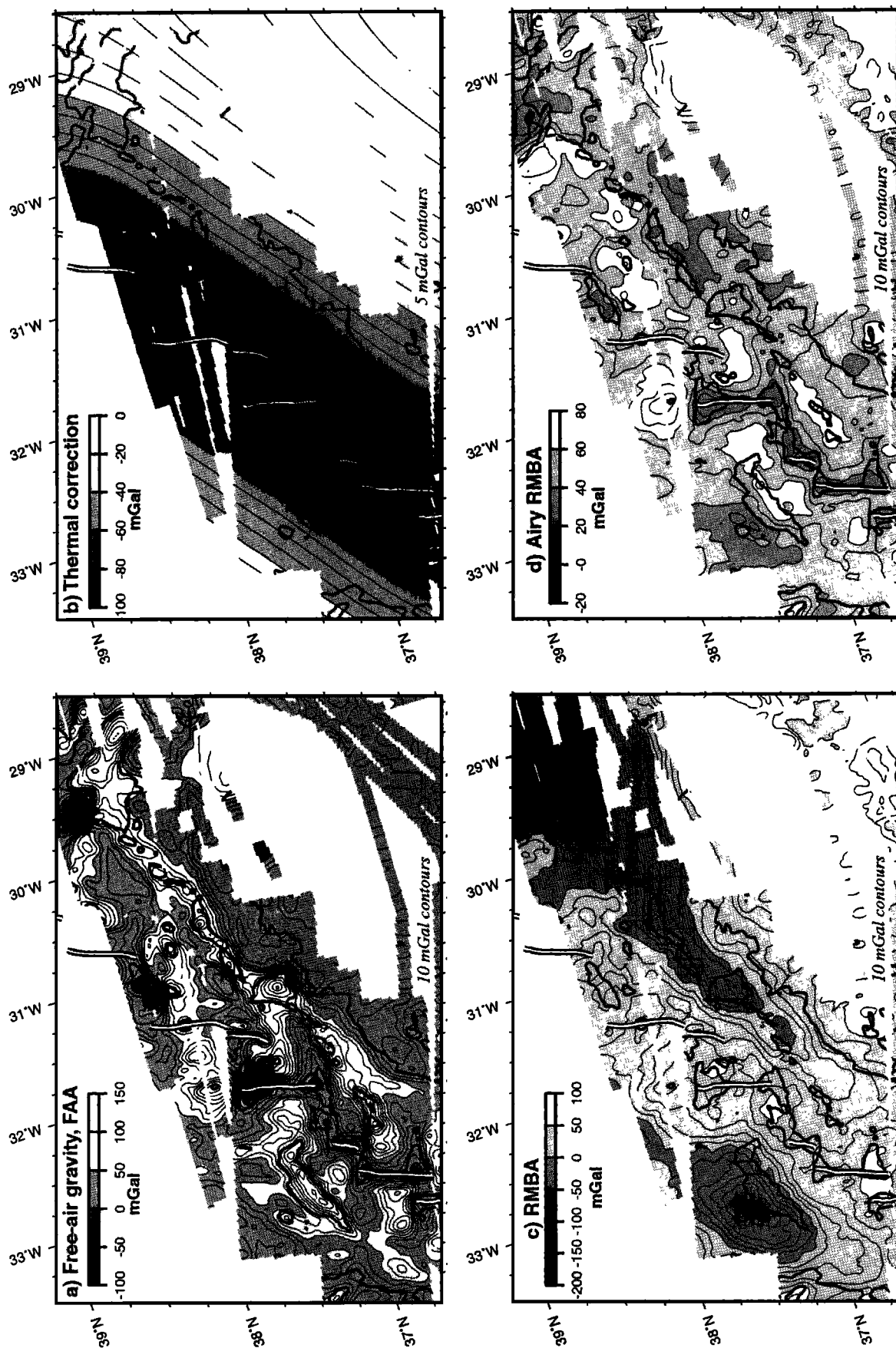
The cooling of the lithosphere as it ages causes an important long-wavelength effect on both bathymetry and gravity. This effect can be predicted using a three-dimensional (3-D) passive mantle upwelling model [Phipps Morgan and Forsyth, 1988] and then removed from the data to obtain a residual bathymetry. Residual bathymetry can be interpreted in terms of crustal



**Plate 1.** Comparison of the V-shaped ridges propagating south of (top) the Azores and (bottom) Iceland hot spots, indicated by the black triangles. Iceland V-shaped ridges are more continuous, linear and longer than the one found south of the Azores. The free-air satellite gravity data (FAA) are from *Sandwell and Smith* [1997]. The box on the Azores panel indicates the approximate position of the maps in Plate 2 and Figures 2-5, and the across-axis lines mark the location of the profiles in Figure 10.



**Plate 2.** Oblique Mercator projection of high-resolution (~100-m grid spacing) shaded multibeam bathymetry of the study area (see Plate 1 and Figure 1). The horizontal grey/black bars indicate the approximate projection off axis of the present-day nontransform offsets bounding ridge segments. Note that the V ridges (Plate 1) are very shallow and present smooth topography, lack faults, and are covered with numerous seamounts (some >10 km in diameter). The seafloor within the V ridges show abyssal hill terrain subparallel to the ridge axis, typical of faulted slow-spreading oceanic crust. The shallowest portion of the V ridges off axis from the North FAMOUS and Lucky Strike segments are referred to as the west and east Jussieu Plateau, and the shallow zone of the east branch of the V ridge at ~29°N corresponds to Princess Alice Bank; no data from the conjugate side are available.



**Table 1.** Observed and Modeled Subsidence Rates

|                                                             | $C, \text{m Ma}^{-1/2}$ |
|-------------------------------------------------------------|-------------------------|
| <i>Observation</i>                                          |                         |
| Whole area                                                  | 320, 345 <sup>a</sup>   |
| West flank                                                  | 415, 430 <sup>a</sup>   |
| East flank                                                  | 180, 225 <sup>a</sup>   |
| <i>Thermal model</i>                                        |                         |
| $\alpha = 2.5 \times 10^{-5} \text{ }^{\circ}\text{C}^{-1}$ | 281                     |
| $\alpha = 3.0 \times 10^{-5} \text{ }^{\circ}\text{C}^{-1}$ | 337                     |
| $\alpha = 3.5 \times 10^{-5} \text{ }^{\circ}\text{C}^{-1}$ | 393                     |

<sup>a</sup>Estimates are calculated using both ship track (first entry) and gridded bathymetry (second entry) data. See text for discussion.

thickness variations and mantle density changes that are not associated with cooling. The predicted subsidence rate depends primarily on the ridge segmentation geometry and on the coefficient of thermal expansion  $\alpha$  of the mantle, which allows the conversion of the 3-D mantle temperature field into density. Subsidence rates for the study area have been calculated using the compiled bathymetry (Figure 1b) and available digital seafloor age [Müller *et al.*, 1997], using a simple square root of age  $t$  dependence of the bathymetry  $h$  [Parsons and Sclater, 1977]:

$$h = C \times t^{1/2} + h_{t=0},$$

where  $h_{t=0}$  corresponds to the zero-age axial depth and  $C$  is the subsidence rate. As data are sparse and inhomogeneously distributed (Figure 1), we use two estimates of  $C$ , one grouping all the data along ship tracks for the west flank, east flank, and the whole area, and another using a coarse 2-minute bathymetry grid over the same areas. The axial valley, which may be dynamically supported [Neumann and Forsyth, 1993], the shallow V-shaped ridges off axis (Plates 1 and 2), and the nearby Atlantis-Meteor seamount complex [Verhoef and Collette, 1985] have not been included, as these features reflect processes different from subsidence with age of normal oceanic crust.

Subsidence rate  $C$  for the area is highly asymmetric, with an average value (320–345 m Myr<sup>1/2</sup>) consistent with global and Atlantic averages (350 m Myr<sup>1/2</sup> [Parsons and Sclater, 1977] and m Myr<sup>1/2</sup> [Malinverno, 1990], respectively). This average  $C$  value is consistent with  $\alpha = 3.0 \times 10^{-5} \text{ }^{\circ}\text{C}^{-1}$  (Table 1, Figure 3a), and will be used in the gravity calculations (see below and Figure 3).  $C$  values on the west flank (415–430 m Myr<sup>1/2</sup>) double those on the East flank (180–225 m Myr<sup>1/2</sup>), and may be more consistent with model subsidence rates for  $\alpha = 3.5$  and  $2.5 \times 10^{-5} \text{ }^{\circ}\text{C}^{-1}$ , respectively (see Table 1 and Figure 3). Asymmetric

subsidence may be caused by asymmetric mantle flow under the ridge due to the absolute ridge motion (~20 mm/yr in a 250° azimuth, comparable to the full spreading rate, Figure 1) that is not predicted by passive flow models with symmetrical spreading [e.g., Phipps Morgan and Forsyth, 1988].

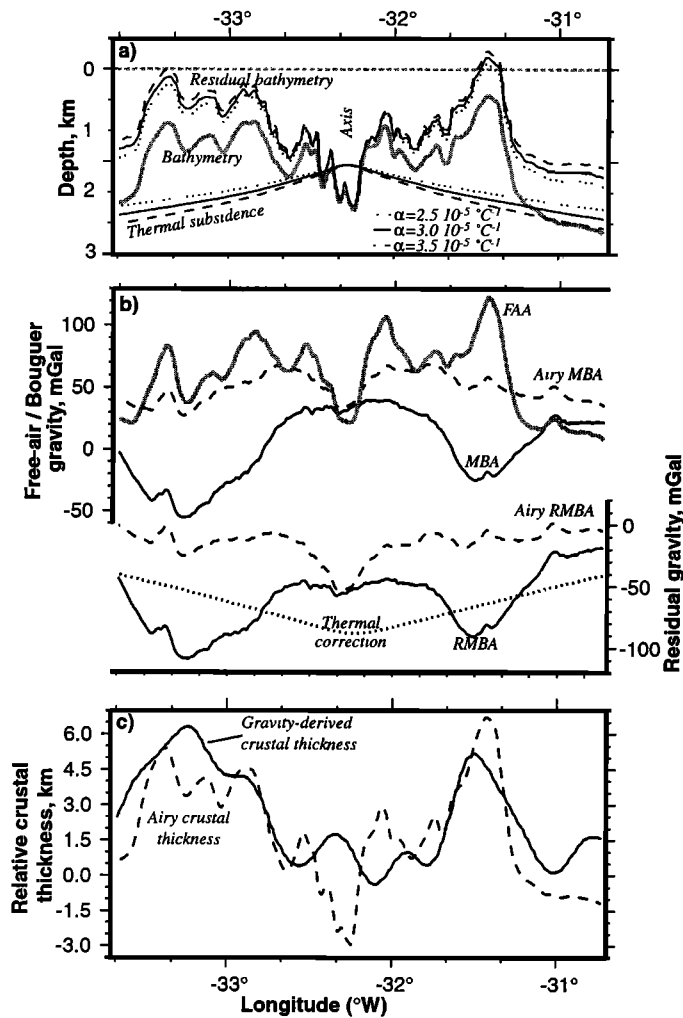
## 5. Mantle Bouguer and Residual Mantle Bouguer Gravity Anomalies

The FAA gravity data (Figure 2a) are reduced to obtain mantle Bouguer and residual mantle Bouguer anomalies (MBA and RMBA, respectively) following the procedures described by Prince and Forsyth [1988] and Kuo and Forsyth [1988]. The gravity effects of the water-crust and crust-mantle density interfaces were calculated using Parker's [1973] upward continuation method, then removed from the FAA at each point along ship tracks (Figure 3), and gridded in the same fashion as the FAA to obtain the MBA grid [Cannat *et al.*, 1999, Figure 1]. Densities, crustal thickness, and other parameters used in the calculations are given in Table 2.

The gravity effects of cooling with age and ridge offset intersections in Figure 2c were calculated using a 3-D passive upwelling model [Phipps Morgan and Forsyth, 1988] and  $\alpha = 3.0 \times 10^{-5} \text{ }^{\circ}\text{C}^{-1}$  (Figure 2b). The thermal correction was removed from the MBA at each point along ship tracks (Figure 3b) and gridded to obtain the RMBA grid in Figure 2c. The RMBA reflects primarily variations in crustal thickness and/or density [Lin and Phipps Morgan, 1992; Sparks and Parmentier, 1993] and/or upper mantle density variations. It also preserves the long-wavelength along-axis gravity gradient (Figure 2c) associated with the Azores hot spot [e.g., Detrick *et al.*, 1995].

The RMBA map (Figure 2c) shows that the off axis gravity lows correlate with the shallow areas of the V-shaped ridge. The largest gravity low (>100 mGal in amplitude) is associated with the Princess Alice Bank to the north, extends continuously toward the southwest, and disappears at ~36.5°N, coinciding with the southern termination of the east branch of the V-shaped ridge and its intersection with the axis (Plate 2). The gravity low on the west flank (>70 mGal) is associated with the west Jussieu Plateau (Figure 2c and Plate 2), also extends toward the southwest, and disappears off the AMAR segment. A series of small gravity highs and lows (~10–20 mGal in amplitude) are located at the discontinuities between segments and at the center of segments, respectively, as shown earlier by Detrick *et al.* [1995]. The amplitude of these axial variations in gravity and

**Figure 2.** (a) Free-air gravity map of the study area. Double lines in this and following panels mark the axis of ridge segments. The bold lines in all the panels correspond to the 2500- and 1000-m isobaths (see Plate 2). (b) Calculated thermal gravity correction from a passive 3-D mantle upwelling model [Phipps Morgan and Parmentier, 1988]. See text for discussion and model parameters. (c) Residual mantle Bouguer gravity anomaly (RMBA) calculated after removing the thermal gravity effect in Figure 2b from the mantle Bouguer gravity anomaly (not shown; see Figure 1c of Cannat *et al.* [1999]). Note the large gravity lows (~100 and ~80 mGal in amplitude) associated with the shallow Princess Alice and east Jussieu Plateaus (Plate 2). The along-axis variations in the gravity structure associated with ridge segmentation have a lower amplitude (<40 mGal). (d) Airy residual mantle Bouguer gravity anomaly (Airy RMBA) calculated after removing the gravity effects of an isostatically compensated crust and the thermal effect in Figure 2b from the FAA (see Figure 3b and text for details). The lack of gravity structure and the small amplitude of the gravity anomaly off axis indicate that the V-shaped ridges are isostatically compensated. The gravity low associated with the axial valley is due to the dynamic support of the rift, unaccounted for by the assumption of Airy isostasy.



**Figure 3.** Bathymetry, gravity, and relative crustal thickness profiles across the Lucky Strike segment (see profile location in Plate 2 and Figure 5). (a) Observed and residual bathymetry, calculated after removing the thermal subsidence. Thermal calculations for three different thermal expansion coefficients for the mantle are shown. (b) Observed free-air gravity anomaly (FAA), mantle Bouguer anomaly (MBA), Airy MBA, residual MBA (RMBA), and Airy RMBA. The "standard" and the Airy Bouguer anomalies are calculated assuming a constant thickness and a variable crustal thickness isostatically compensated, respectively. The residual Bouguer anomalies are calculated after removing the thermal correction of the mantle (dotted line). See text for details. (c) Relative crustal thickness calculated by downward continuation of the RMBA (Figures 2c, 3b, and 4; see text for details) and the isostatically compensated crustal thickness. The crustal thickness is relative to a standard, 6-km-thick oceanic crust (see Figure 4).

their good correlation with segmentation are common in other portions of the MAR [Lin et al., 1990; Detrick et al., 1995; Escartín and Lin, 1998] and indicate focused magmatic accretion at the axis [Lin et al., 1990]. There is no correlation between the axial and off axis gravity structure, indicating that the present segmentation and associated focused magma supply were established after the rifting of the volcanic plateaus that form the present V-shaped ridge.

## 6. Residual Bathymetry, Airy Isostasy, and Airy Bouguer Gravity Anomalies

To determine the mode of compensation of the crust, we correct the observed FAA for the predicted gravity anomalies associated with a crust of variable thickness that is compensated locally (Airy isostasy) and cools with age and obtain an Airy RMBA (Figures 2d and 3). The obtained Airy RMBA can be compared with the RMBA to determine if there is regional isostatic compensation of the topography and crust. Assuming Airy isostasy, the relief of the Moho  $M$  can be estimated as [Turcotte and Schubert, 1982]:

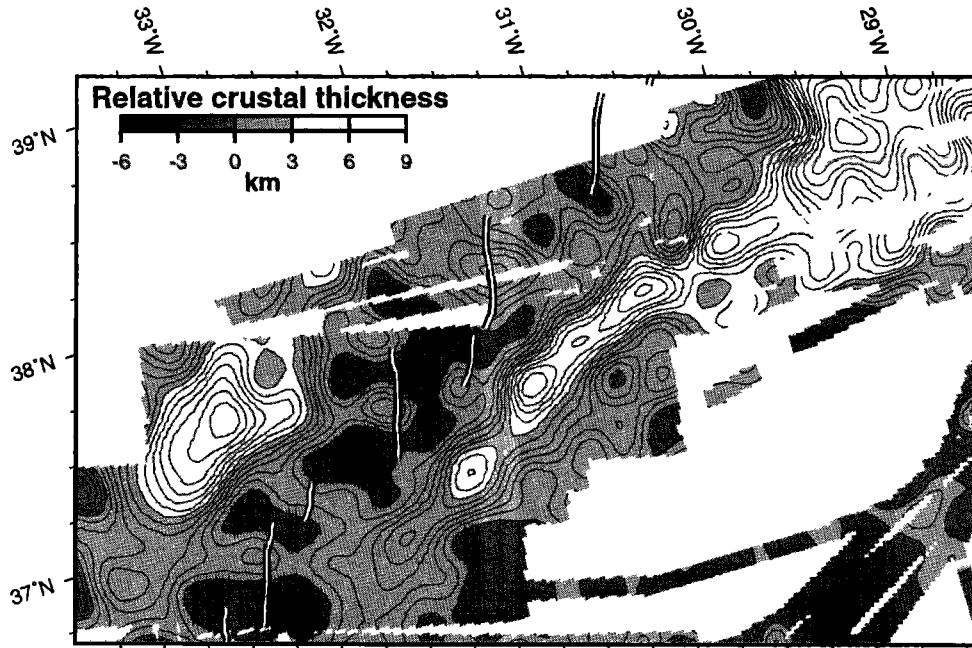
$$M = A + D (\rho_c - \rho_w) / (\rho_m - \rho_c)$$

where  $D$  is the bathymetry isostatically compensated;  $\rho_w$ ,  $\rho_c$ , and  $\rho_m$  are the densities of the water, crust, and mantle, respectively; and  $A$  is a constant crustal thickness value. The total crustal thickness is then  $M - D + A$ . As the observed bathymetry reflects seafloor subsidence with age, it is necessary to remove the modeled thermal subsidence  $\alpha = 3.0 \times 10^{-5} \text{ } ^\circ\text{C}^{-1}$ , Table 1) from the bathymetry (Figure 1c) to obtain a residual bathymetry  $D$  (Figure 3a). Assuming that the residual bathymetry  $D$  is isostatically compensated, we calculate the Moho relief,  $M$ . An average crustal density of  $2750 \text{ kg m}^{-3}$  was chosen for the crustal thickness and gravity calculations (Table 2, dashed line in Figure 3c), although calculations for a wide range of crustal densities ( $2500\text{--}2900 \text{ kg m}^{-3}$ ) did not yield significantly different Airy gravity anomalies. To estimate the absolute crustal thickness, we used a value of  $A = 6 \text{ km}$ , which minimizes the differences between the crustal thickness required for Airy compensation and that predicted from the residual gravity data relative to a constant 6-km-thick crust (Figures 3c and 4). To calculate the Airy MBA and RMBA anomalies, we upward continued [Parker, 1973] the water-crust (bathymetry) and crust-mantle (calculated Moho relief  $M$ ) interfaces, subtracted this crustal correction and the thermal gravity effect (Figure 2b) from the FAA at ship track points (Figure 3b), and gridded the data to obtain the Airy RMBA map in Figure 2d.

The Airy RMBA data over the V-shaped ridges show short-wavelength variations of small amplitude ( $<20 \text{ mGal}$ , Figure 2c) that are uncorrelated with the topography (Plate 2) and lack the large gravity lows observed on the RMBA (Figure 2c). Along the ridge axis there is a strong correlation between Airy RMBA and ridge morphology. The Lucky Strike, North FAMOUS, FAMOUS, and AMAR segments have a prominent low in the Airy RMBA data that mimics the axial valley that characterizes these segments (Figure 2c). In contrast, the Airy RMBA

**Table 2.** Parameters Used in the Thermal model, Gravity Calculations, and Crustal Thickness Inversion

| Parameter                                               | Value                    |
|---------------------------------------------------------|--------------------------|
| Gravitational constant, $\text{N m}^2 \text{ kg}^{-2}$  | $6.6673 \times 10^{-11}$ |
| Gravitational acceleration, $\text{m}^2 \text{ s}^{-1}$ | 9.80                     |
| Water density, $\text{kg m}^{-3}$                       | 1030                     |
| Crustal density, $\text{kg m}^{-3}$                     | 2750                     |
| Mantle density, $\text{kg m}^{-3}$                      | 3300                     |
| Crustal thickness, $\text{km}^{-3}$                     | 6                        |
| Half-spreading rate, $\text{km Ma}^{-1}$                | 12                       |
| Thermal boundary layer thickness, km                    | 100                      |
| Asthenospheric temperature, $^\circ\text{C}$            | 1350                     |
| Coefficient of thermal expansion, $^\circ\text{C}^{-1}$ | $3.0 \times 10^{-5}$     |



**Figure 4.** Crustal thickness variations across the area relative to a constant ~6-km-thick oceanic crust (see text for details of calculation). The off axis V-shaped ridges are associated with thick crust. Maximum relative crustal thickness on the east branch is ~9 km (Princess Alice plateau), tapering to normal thickness toward the SW (~0 km); the crustal thickness over the west Jussieu Plateau is ~6 km. Crustal thickness variations along individual ridge segments (double lines) are similar to those seen elsewhere along other Mid-Atlantic ridge segments. Contours every 0.5 km.

signature of the Menez Gwenn and Princess Alice segments, characterized instead by an axial high (Plate 2), is similar to that found elsewhere off axis. These results indicate that the V-shaped ridges are isostatically compensated, while the axial valley is dynamically supported [e.g., Neumann and Forsyth, 1993]. Short-wavelength and small-amplitude variations in the Airy RMBA may reflect a small degree of dynamic support locally and/or to variations in crustal density unaccounted for by the assumed constant-density model (Table 2). These observations are consistent with the on-axis emplacement of an oceanic plateau over weak, young oceanic lithosphere.

## 7. Crustal Thickness

Relative crustal thickness variations were calculated by downward continuation of the RMBA [Parker and Huestis, 1974] (see model parameters in Table 2), using a low-pass cosine taper filter beginning at 35-km wavelength with a cutoff at 25-km wavelength to ensure convergence (Figures 3 and 4). The overall crustal thickness pattern closely mimics the RMBA map (Figure 2c). A maximum relative crustal thickness of ~9 km is found over the shallow Princess Alice Plateau (Plate 2) and the associated gravity low (Figure 2c), and decreases to ~0 km toward the southwest end along the east branch of the V-shaped ridge. The relative crustal thickness associated with the west Jussieu Plateau is ~6 km, also decreasing toward the south to normal crustal thickness. Minimum crustal thicknesses are found at ridge offsets near the axis, and the predicted variations in crustal thicknesses along individual ridge segments are ~2 km in amplitude.

Gravity-derived crustal thickness is nonunique and model dependent, although it provides constraints on crustal thickness

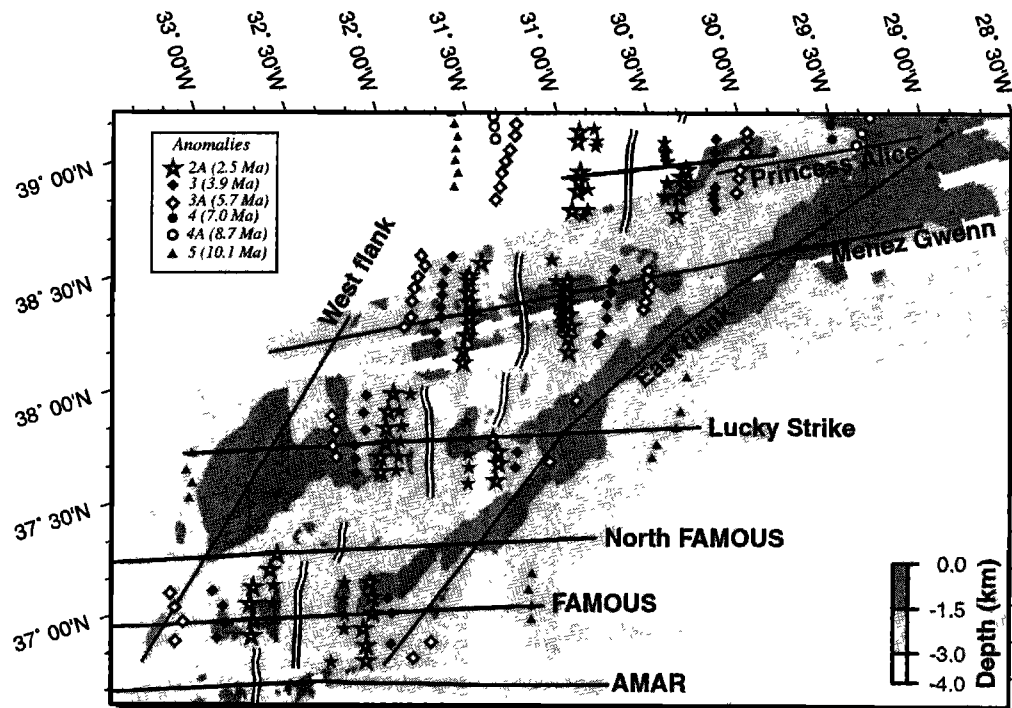
variations regionally. Gravity data at segment OH1 (35°N, MAR) are generally in good agreement with seismically determined thicknesses (within ~1 km or less) [Canales *et al.*, 2000], indicating that seismic- and gravity-derived first-order variations in crustal thickness are well constrained. The outcrop of serpentinized peridotites [Goud and Karson, 1985; Gracia *et al.*, 2000] indicates that the crust is heterogeneous [e.g., Cannat *et al.*, 1995] and that the magmatic crustal thickness may be overestimated. In contrast, filtering and smoothing of the gravity data may result instead in an underestimation of crustal thickness variations when compared with seismic estimates, particularly at ridge offsets or inside corners where the crust is thinnest [e.g., Minshall, 1996; Escartín and Lin, 1998]. Thus we believe that gravity data provide constraints on crustal thickness variations with an accuracy of the order of 1 km.

## 8. Temporal and Spatial Variations in Magma Supply

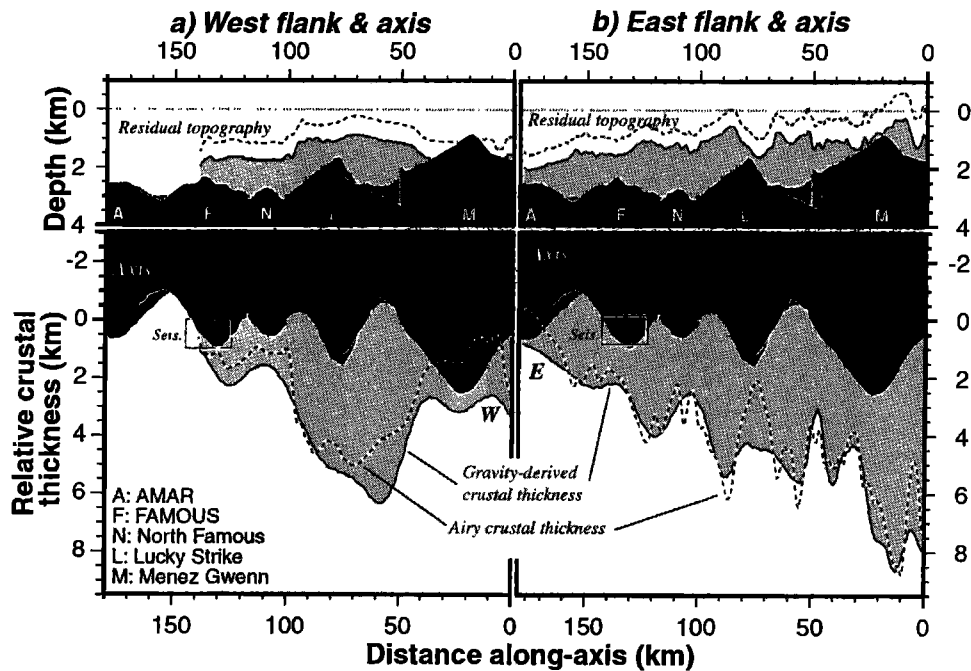
Crustal thickness variations and magnetic data (Figure 5) are used to determine spatial and temporal variations in melt supply to the ridge. These data constrain the present-day and temporal evolution of the Azores hot spot in terms of crustal production along the Mid-Atlantic Ridge, the possible fluctuation in temperature of the mantle associated with the hot spot, and the mode of emplacement of the excess melt responsible for the formation of the V-shaped ridges.

### 8.1. Present-Day Ridge Segmentation and Crustal Thickness Variations

The morphology of the axial valley along individual ridge segments depends on the distance to the hot spot. Lucky Strike



**Figure 5.** Interpreted magnetic anomalies from shipboard magnetic profiles. The data from the *SudAçores* cruise [Cannat *et al.*, 1999] are complemented on the northern part with anomaly picks from an aeromagnetic survey [Luis *et al.*, 1994]. The solid lines correspond to the profiles in Figures 6 and 7.



**Figure 6.** Depth and relative crustal thickness for the profiles running over the (a) western and (b) eastern branches of the Azores V-shaped ridge (light shaded area), compared with the axial profile (dark shaded area) for reference. The vertical scale of the relative crustal thickness plots is inverted to mimic the depth to Moho. The dashed lines correspond (top) to the residual bathymetry along the V-shaped ridges and (bottom) to the isostatically compensated crustal thickness. The off axis profiles show the the shallow topography of the V-shaped ridges is well correlated with thick crust. There is a clear lack of correlation between the present-day variations in bathymetry and crustal thickness along the ridge segments and that off axis. There is also good agreement between the gravity-derived and the Airy crustal thickness, indicating that most of the topography and overthickened crust of the V-shaped ridges are compensated isostatically. Crustal thickness over the Lucky Strike segment, determined from early refraction studies [Fowler and Mathews, 1974; Fowler, 1976; Poehls, 1974], is estimated to ~6-7 km (white and thin line boxes labeled "seis."). These estimates provide a constraint in absolute crustal thickness that can be used to interpret the gravity-derived relative crustal thickness in terms of absolute crustal thickness.

shows a transitional morphology, with the disappearance of the axial valley at the segment center, while the segments to the north show an axial high, and those to the south show an axial valley (Plate 2). In all cases the crust is ~2 km thicker at the segment center than at the ends (Figure 6; crustal thickness patterns presented are almost identical to those of *Detrick et al.* [1995] from near-axis data), indicating focused magmatic accretion [e.g., *Lin et al.*, 1990].

A gradual increase in the average crustal thickness northward suggests an augmentation in melt supply to individual ridge segments towards the Azores hot spot. The relative crustal thickness inferred from gravity for the FAMOUS, Lucky Strike, Menez Gwenn, and Princess Alice segments are 0.1, 0.6, 1.0, and 2.23 km in average, respectively. Limited seismic data available in the study and nearby areas show a similar trend. The average crustal thickness of segments OH3, OH2, and OH1 (35.5°–33.5°N, MAR) are 5.0 km, 5.4 km (6.1 km off axis) to 5.5 km (6.0 km off axis), respectively [*Canales et al.*, 2000; *Hooft et al.*, 2000], gradually increasing toward the north. Early seismic refraction data at Lucky Strike indicate an average crustal thickness of ~6–7 km [*Fowler and Mathews*, 1974; *Fowler*, 1976; *Poehls*, 1974], consistent with the ~6.6 ± 1 km inferred from gravity (assuming a reference crust of 6 km, Figure 6). The increase in average crustal thickness is also accompanied by an increase in the amplitude of crustal thickness variations along individual ridge segments (Figure 6), indicative of more efficient focusing of the magmatic accretion. The change in ridge morphology around Lucky Strike and the presence of high-temperature hydrothermalism [*Fouquet et al.*, 1994; *Wilson et al.*, 1996; *Langmuir et al.*, 1997] associated with evidence for recent volcanism [*Ondreas et al.*, 1997; *Parson et al.*, 2000] along Lucky Strike and Menez Gwenn segments are consistent with a hotter thermal structure of the lithosphere toward the Azores hot spot.

Part of the inferred increase in crustal thickness along the study area may be caused by along-axis gravity and bathymetry gradients caused by thermal and/or dynamic support of the Azores hot spot, in addition to isostatic compensation of variable thickness crust. *Ito and Lin* [1995b] estimated that ~70–75% of the gravity and bathymetry gradients along the Cocos-Nazca Ridge may be attributed to crustal thickness variations caused by the Galápagos hot spot. These results suggest that the thermal and/or dynamic contribution of the Azores hot spot on the observed gradients may be small (<30% of the inferred crustal thickness variations). However, additional seismic constraints on crustal thickness between the AMAR and Princess Alice segments are required to quantify this thermal and/or dynamic contribution.

## 8.2. Temporal and Spatial Variations in Magma Supply

Comparison of the axial and the two off axis profiles over the summit of the V-shaped ridge (Figures 5 and 6) shows important variations in melt supply to the ridge axis both in space (along axis) and in time (across axis). The crust under the V-shaped ridges is substantially thicker than normal oceanic crust, with maxima under Princess Alice's and west Jussieu Plateaus (~9 and ~6 km, respectively). The profile along the east branch of the V-ridge (Figure 6) shows a gradual decrease in the bathymetry and in relative crustal thickness away from the hot spot; this trend cannot be observed on the west branch owing to limited geophysical coverage of this flank (Figures 1 and 6). Smaller variations in crustal thickness, superimposed on the gradient along the V ridge, do not correlate with those along the ridge axis

segmentation or along the conjugate side (Figure 6). The asymmetry and lack of correlation between the bathymetry and gravity of the east and west branches (Plate 2 and Figure 6) may be attributed, at least partially, to the asymmetric rifting of the volcanic plateaus [*Cannat et al.*, 1999] after their emplacement on-axis (see discussion below). Differences with the axial gravity structure also indicate that the accretion of the V-shaped ridges was not organized along well established ridge segments as observed today. The present-day segmentation history is not a long-lived feature (<10 Ma at Princess Alice segment, and <7 Ma at North FAMOUS and Lucky Strike segments), as geometry of the axis was organized after rifting of the volcanic V-shaped ridges.

The relative crustal thickness map (Figure 4) and the seafloor ages inferred from the magnetic anomalies (Figure 5) can be interpreted as spatial and temporal changes in melt supply to the ridge axis (crustal production). To quantify these variations, we have selected across-axis ship tracks subparallel or slightly oblique to the spreading direction and crossing near the center of each ridge segment (Figures 5 and 7). The average bathymetry and crustal thickness are calculated for each profile and time interval, determined from the position of picked or extrapolated magnetic anomalies (Figures 5 and 7). When available, the bathymetry and crustal thickness of the west and east flanks are averaged to quantify the total magmatic production, yielding estimates independent of asymmetric rifting, as observed along these V-shaped ridges [*Cannat et al.*, 1999], or of asymmetric accretion, commonly observed along the MAR [e.g., *Macdonald*, 1977; *Allerton et al.*, 2000]. The average and maximum crustal thickness and bathymetry for different time intervals and for each profile, shown in Figure 8, provide a record of temporal and spatial variations of crustal accretion along the ridge axis.

The V-shaped ridges south of the Azores record the rapid southward propagation (~60 km/Ma [*Cannat et al.*, 1999]) of a magmatic pulse that initiated some 10 Myr ago [*Cannat et al.*, 1999]. The initiation of this pulse is recorded off Menez Gwenn by the anomalously thick crust (>4-km excess crust with respect to normal 6-km-thick crust) prior to anomaly 5 (>10.1 Ma). The Azores hot spot is located <300 km east of the ridge axis, probably in the vicinity of Sao Miguel or nearby islands. As the absolute migration of the ridge is ~20 km/Ma toward the southwest, the Azores hot spot was at or near the ridge axis at the time of the formation of Princess Alice Plateau and the initiation of the along-axis propagation of the mantle anomaly.

This melt anomaly propagated south, reaching excess crustal thickness of ~3–4 km off Lucky Strike between anomalies 5 and 3A (10.1–5.7 Ma). At the same time, the maximum relative crustal thickness (>6.5 km) found off Princess Alice (PA) between anomalies 5 and 4 (10.1–7.0 Ma) decreased to normal relative thickness (~1 km) between anomalies 4 and 3A (7.0–5.7 Ma). Between anomaly 3A and the present time the effect of the Azores hot spot is subdued, and the melt anomaly has weakened and disappeared. The average bathymetry data (Figure 8) show a pattern similar to that of the relative crustal thickness, consistent with the isostatic compensation of the crust inferred from the Airy RMBA (Figure 2d).

The maximum relative crustal thickness of >6.5 km at Princess Alice Bank may indicate the time and location of the highest melt supply to the ridge axis. Asymmetric rifting of the Princess Alice Bank is unconstrained lacking geophysical coverage over the conjugate west flank (Plate 2 and Figure 8), and the inferred excess melt for this time period may be lower instead. Owing to the proximity to the Azores, ongoing

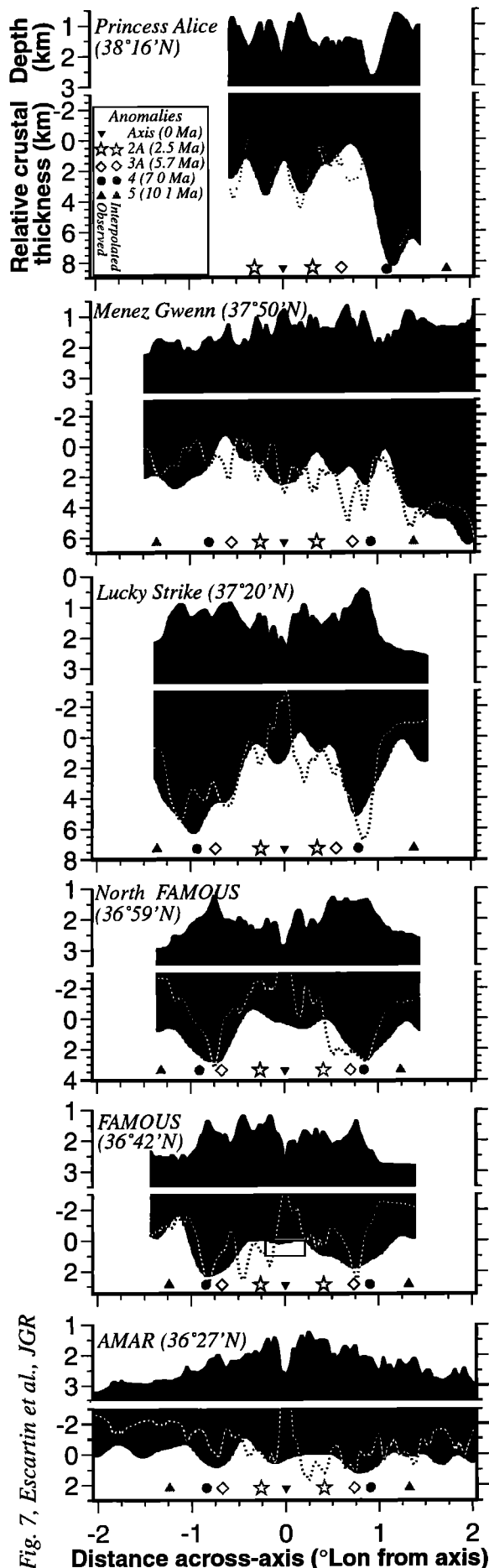


Fig. 7, Escartin et al., JGR

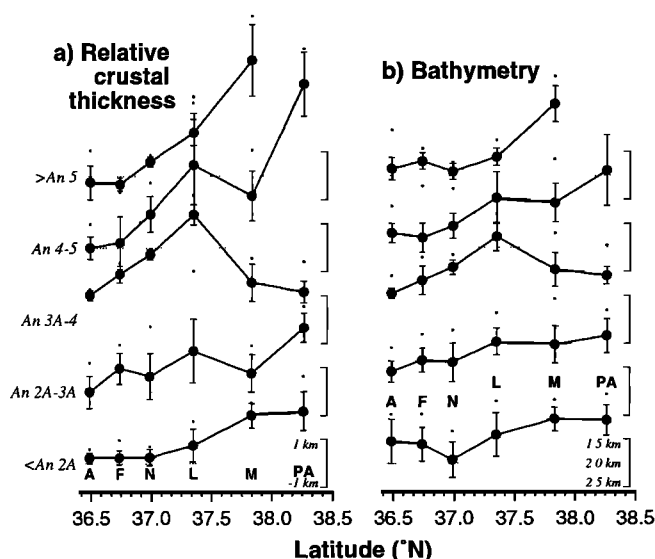
magmatism since the time of emplacement of Princess Alice plateau could have contributed to crustal construction. In this case, the excess melt reported here may correspond to both the excess melt emplaced on axis and additional later volcanism. Sediments partially covering the seamounts over the Jussieu Plateau, and the lack of fresh basaltic glass on the dredged volcanoes suggests that there has been no recent volcanic activity at this latitude, but no data are available for the Princess Alice Plateau.

The transition from the volcanic plateau to "normal" seafloor terrain along a flow line (Plate 2 and Figure 7) is very abrupt and contrasts with the gradual decrease in crustal thickness along the V-shaped ridge (Figure 6). The inner limit of the east and west Jussieu Plateaus (Plate 2) is a large fault scarp with >1 km of vertical relief locally, which corresponds to the rifting of the plateau [Cannat et al., 1999]. This abrupt change in seafloor character, from smooth to abyssal hill terrain, indicates that once the plume anomaly migrated south of the Jussieu Plateau, the excess melt decreased suddenly and normal, ~6 km-thick-crust was produced instead. In contrast, the gravity signature across the axis shows a more gradual transition from low to high values toward the axis, suggesting instead rapid but gradual waning of magmatism from the V-shaped ridge to "normal" crust (Figures 2d, 4, and 7). A decoupling between deep magmatic processes of crustal accretion (underplating, lower crustal intrusions) and shallow magmatic (extrusive) and tectonic (faulting) processes may account for the differences in the transition from overthickened to "normal" oceanic crustal thicknesses inferred from bathymetry and from gravity. The nature of this transition and the relative proportion of extrusives, intrusives, and underplated material cannot be determined from the gravity and bathymetry alone, and seismic constraints on the velocity and internal structure of the crust are needed both along flow-lines and along the V-shaped ridge.

### 8.3. Origin, Emplacement, and Tectonic Evolution of the V-Shaped Ridges

The bathymetry, tectonic structure, and gravity data demonstrate that the V-shaped ridges result from the emplacement of anomalously large volumes of magma at the ridge axis. The shallow areas are covered by a thin layer of sediments (typically <200 m) have a basement with very smooth

**Figure 7.** Bathymetry and relative crustal thickness profiles across the center of each segment (see Figure 5 for location). For each panel the bathymetry is shown on top (dark shaded area), and the axis of the relative crustal thickness, which has been inverted to mimic the Moho depth and show the correlation between crustal thickness and bathymetry, is shown at the bottom. The relative crustal thickness inverted from gravity is shown by the dark shaded area, and the Airy crustal thickness, by the black-white line. Magnetic anomalies in solid symbols correspond to those identified along the profiles (reported in Figure 5), while those in light symbols have been extrapolated using the position of adjacent anomalies and/or calculated spreading rates from the area and from nearby studies [e.g., Sloan and Patriat, 1992; Luis et al., 1994]. Note the gradual increase toward the north (Azores hot spot) of the crustal roots associated with the V-shaped ridges. Agreement between the Airy and gravity-derived crustal thickness is good except at the ridge axis, where the axial valley is dynamically supported [Neumann and Forsyth, 1993].



**Figure 8.** Calculated average (solid circles with  $\pm 1$  standard deviation as error bars) and maximum (small circles) gravity-derived (a) crustal thickness and (b) bathymetry along each of the profiles in Figure 7, for different time intervals. There is a good correlation between crustal thickness and bathymetry, consistent with an isostatically compensated crust. Note the propagation of the maximum crustal thickness from the present day Princess Alice segment (PA) toward the south, the peak off Lucky Strike between anomalies 3A and 4, and the progressive decrease in the excess crustal thickness and bathymetry toward the south at all time intervals.

relief, and the upper crust shows shallow-dipping seismic reflectors plunging towards the present-day ridge axis. In addition, the seafloor is unfaulted (e.g., Jussieu Plateau, Plate 2) and presents abundant seamounts, some  $>10$  km in diameter (see Figure 2 of Cannat *et al.* [1999] and Plate 2). These characteristics suggest that volcanic construction was characterized by long periods of elevated magma supply and high effusion rates. The maximum duration of magmatism at the latitude of the present-day Lucky Strike segment was estimated at  $\sim 4$  Myr, or shorter if off axis volcanism and/or long lava flows contributed substantially to the construction of the V-shaped ridges, as indicated by the incoherent pattern of the magnetic anomalies over the plateau [Cannat *et al.*, 1999]. Dipping reflectors observed in the 6-channel seismic records (A. Rabain, personal communication, 2000) may correspond to long lava flows buried by later volcanic eruptions, similar to the interpreted extensive volcanism and buildup of basement dipping reflectors at other oceanic plateaus [e.g., Schlich *et al.*, 1993; Ito *et al.*, 1995] or volcanic margins [e.g., Oh *et al.*, 1995].

The bathymetry shows important changes in the width of the V-shaped ridges that are well correlated with crustal thickness (e.g., west Jussieu and Princess Alice Plateaus, Plate 2 and Figure 4). These changes are indicative of along-axis variations in excess melt supply to the axis, duration of volcanism, and/or mode of emplacement and rifting of the overthickened crust. Tectonic and magnetic data indicate that the magmatic anomaly that produced the V-shaped ridge south of the Azores was initiated at 10 Ma [Cannat *et al.*, 1999] at the latitude of Princess Alice Bank ( $\sim 38^\circ\text{N}$ , Figures 1 and 9) and near or at the North American/Eurasian/African (NAM/EUR/EFR) triple

junction, at the intersection of the Mid-Atlantic ridge with the Pico-East Azores FZs [Luis *et al.*, 1994].

The Jussieu Plateau was emplaced on axis  $\sim 8.5$  Myr ago and rifted  $\sim 5.7$ – $3.9$  Myr ago,  $\sim 2$ – $3$  Myr later ( $\sim 7$ – $5.7$  Myr ago) than the rifting of the Princess Alice Plateau [Pouliquen *et al.*, 1998; Cannat *et al.*, 1999]. At the same time the V ridges intersected the Pico-East Azores FZs, and the triple junction moved north of  $38^\circ\text{N}$  (Figure 9) [Luis *et al.*, 1994]. A strip of shallow, overthickened crust, joins the rifted oceanic plateaus, and extends southward, giving the continuous V-shaped ridge observable in the satellite gravity and bathymetry (Plates 1 and 2). These observations demonstrate that the excess melt was supplied to the axis in a discontinuous manner, with preferential buildup of oceanic plateaus on axis as the melt anomaly moved away from the hot spot (Figure 9).

The formation of discrete volcanic plateaus along the axis indicates that the excess melt fluctuated during the propagation of the melt anomaly and/or that the excess melt was not extracted continuously but was instead focused, building the oceanic plateaus. Melt could ascend as discrete mantle or melt "diapirs" [e.g., Whitehead, 1986], constructing individual volcanic plateaus, as invoked to explain the organization of volcanic edifices along the Hawaiian-Emperor seamount chain [e.g., Cox, 1999]. Once the melt anomaly has moved away from the plateau and the excess melt associated with the melt/mantle anomaly is exhausted, normal seafloor spreading is initiated after rifting of the oceanic plateau (Figure 9). The Azores V-shaped ridges are thus the result of excess magmatism associated with the Azores hot spot, of rifting and tectonic extension after the excess melt is exhausted once the melt anomaly propagates southward, and of temporal variations associated with these two processes. The observed decrease in the melt anomaly with time may be caused by conductive cooling [Cannat *et al.*, 1999] and/or by tapping and extraction of melt by the ridge as it propagates away from the hot spot.

## 9. Comparison With Iceland V-shaped ridges

Comparison of the V-shaped ridges emanating from the Iceland and Azores hot spots (Plate 1 and Table 3) provides constraints on the nature of the melt anomalies that originate them and on the temporal variability associated with ridge-hot spot interaction. The Azores V-shaped ridges are shorter ( $\sim 400$  km versus  $\sim 700$  km) and propagate slower ( $60 \text{ km Ma}^{-1}$  versus  $75$ – $200 \text{ km Ma}^{-1}$  [Vogt, 1976; White *et al.*, 1995; Cannat *et al.*, 1999]) than those south of Iceland (Plate 1 and Table 3). In addition, the V-shaped ridges in Iceland show a marked periodicity of 3–5 Myr with variable width and amplitude of the different V-shaped ridges, while only one event can be identified south of the Azores hot spot. The Iceland ridges show both a clearer continuity and constant width along their run (Plate 1).

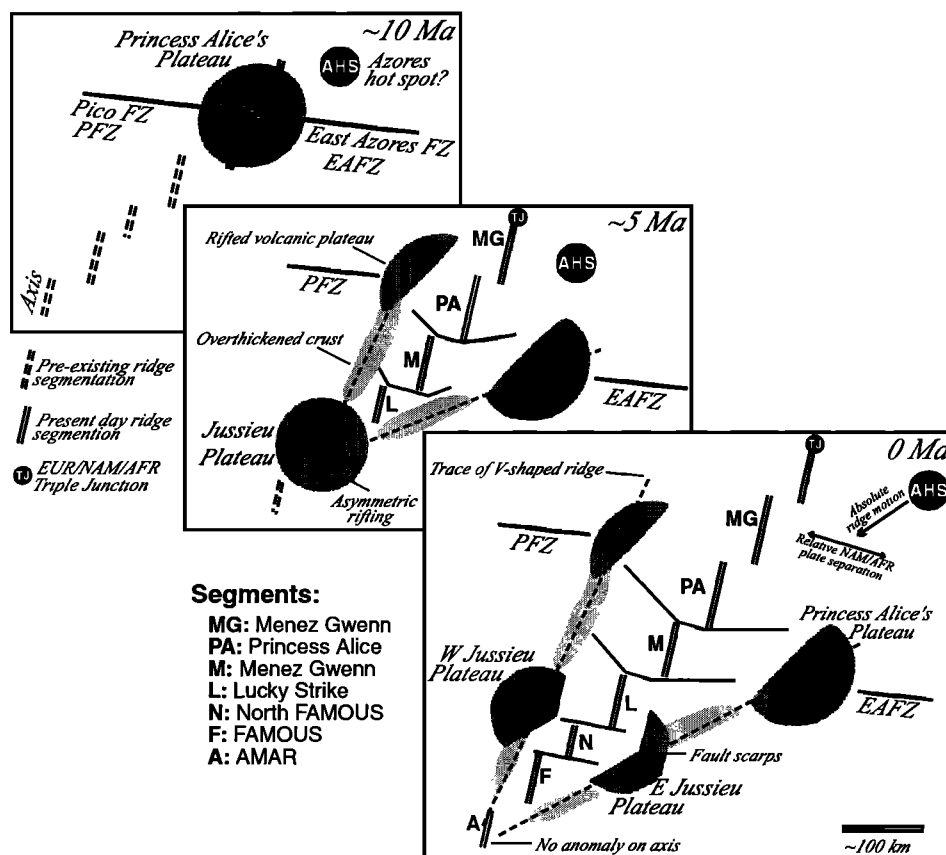
**Table 3.** Comparison of the Azores and Iceland V-Shaped Ridges

|                                              | Azores          | Iceland                |
|----------------------------------------------|-----------------|------------------------|
| Along-axis length, km                        | $\sim 400$      | $\sim 700$             |
| Periodicity, Myr                             | ...             | 3–5                    |
| Propagation rate, $\text{km Myr}^{-1}$       | 60 <sup>a</sup> | 75–200 <sup>b</sup>    |
| Gravity amplitude (MBA/RMBA), mGal           | 0–100           | $\sim 20$              |
| Crustal thickness variation, km              | $>6$ – $0$      | $\sim 2$ <sup>c</sup>  |
| Mantle temperature anomaly, $^\circ\text{C}$ | 130–0           | $\sim 30$ <sup>c</sup> |

<sup>a</sup> From Cannat *et al.* [1999].

<sup>b</sup> From Vogt [1976] and White *et al.* [1995].

<sup>c</sup> From White *et al.* [1995].

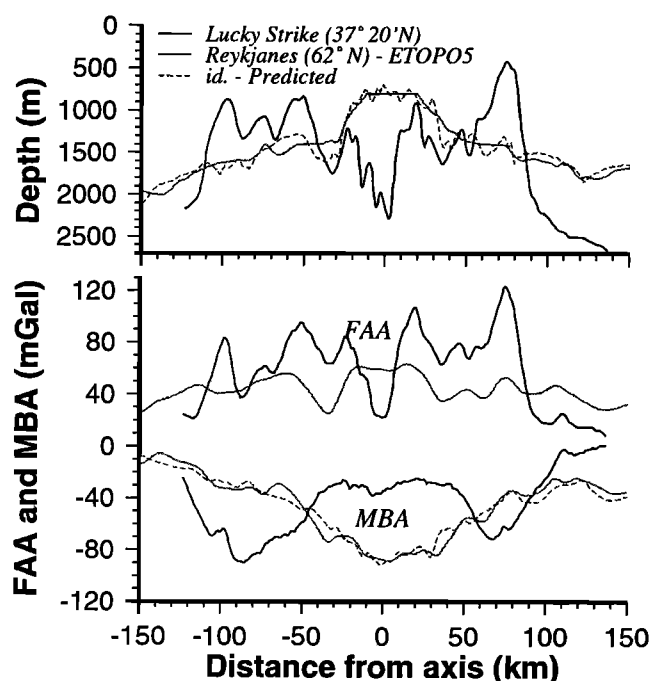


**Figure 9.** Cartoon of the propagation of the melt anomaly along the axis south of the Azores hot spot (AHS), and emplacement of the associated V-shaped ridges (see Cannat *et al.* [1999] for magnetic reconstructions). The melt anomaly initiated ~10 Ma ago, constructing the former Princess Alice plateau on axis. The melt anomaly propagated southward, after rifting of the Princess Alice plateau, constructed the former Jussieu Plateau (off Lucky Strike-North FAMOUS segments), and left a trail of shallow, overthickened crust joining the two structures. Jussieu Plateau rifted asymmetrically ~5 Myr ago, and the melt anomaly continued to propagate southward. The oceanic crust within the V-shaped ridges is of normal thickness and shows axis-parallel fault terrain (Plate 2). The lack of a clear bathymetry and crustal thickness anomaly at the AMAR segment at the present time indicates that the anomaly waned and disappeared. At 10 Ma the NAM/EUR/AFR triple junction (TJ) was located at the intersection of the Pico-East Azores Fracture Zone (see Plate 1) and jumped north to its present position at ~38°50'N [Luis *et al.*, 1994].

Gravity and limited seismic data indicate that the variations in crustal thickness associated with the Azores V-shaped ridges are ~2-3 times larger than those south of Iceland. Lacking high-resolution geophysical surveys off the Reykjanes Ridge axis, we used both ETOPO5 bathymetry and bathymetry predicted from combined ship track bathymetry and satellite gravity data [Smith and Sandwell, 1994] to obtain two estimates of the MBA anomaly (see procedures in section 5 and parameters in Table 2). The variations in MBA are much smaller across the Reykjanes Ridge (~30 mGal for the FAA and ~20 mGal for the MBA in amplitude) than across the Azores ridges (up to 100 mGal, Plate 2 and Table 3). Crustal thickness variations estimated from limited seismic data near the Reykjanes Ridge are ~2 km [White *et al.*, 1995], smaller than the ~6-km variation in crustal thickness inferred for the profile across Lucky Strike (Figures 7 and 10) and consistent with the differences in gravity amplitude (Figure 10). In addition, the Iceland V-shaped ridges are very linear and regular and do not disrupt the magnetic lineations (see Figures 2 and 3 of White [1997] and Plate 1). The excess melt was supplied to the axis and accreted to the oceanic crust in a

continuous manner south of Iceland, without the formation and later rifting of oceanic plateaus observed south of the Azores.

The larger variations in crustal thickness associated with the Azores ridges require larger mantle temperature anomalies than those responsible for the Iceland V-shaped ridges. The mantle temperature anomaly required to produce the Iceland V-shaped ridges is ~30°C [White *et al.*, 1995], assuming a simple 1-D decompression melting model [McKenzie, 1984; McKenzie and Bickle, 1988]. Using the same melt thickness-potential temperature curve (Figure 4 of White *et al.* [1995]), the mantle temperature anomalies for the Azores would vary from 130°C ~10 Myr ago near the Azores (15-km crustal thickness) to 0°C at the present time (normal ~6-km-thick crust, Figures 7 and 8). Other simple models may explain the propagation of melt anomalies, such as variable flow of asthenospheric material under the axis [e.g., Vogt, 1971], or ascent of anomalously hot mantle of variable size and/or temperature [e.g., Cannat *et al.*, 1999]. Although the Iceland and Azores V-shaped ridges may have a similar origin, the clear differences observed indicate that the thermal structure, the dynamics of the interaction with the MAR,



**Figure 10.** Comparison of the bathymetry, FAA, and MBA across the Lucky Strike segment (37°20'N) and the Reykjanes Ridge (62°N; see Plate 1 for profile location). The profile across Lucky Strike shows the largest amplitude variations in both bathymetry and gravity. Inferred crustal thickness variations across the Azores V ridges are ~6 km, while those across the Iceland V ridges are ~2 km [White *et al.*, 1995].

and/or their temporal variability differ. Constraints on melt production and crustal construction at the axis require models of ridge-hot spot interaction that incorporate realistic mantle temperature and dynamics [e.g., Ito *et al.*, 1999]. Variations in the flux of mantle plumes (i.e., temperature anomaly and/or diameter of the plume) produce variations in crustal thickness similar to V-shaped ridges. Comparison of observed and predicted variations in crustal thickness at both the Azores and Iceland are required to constrain model parameters and understand the physical processes behind temporal variability of ridge-hot spot systems.

Finally, the Azores hot spot, which was close to or at the ridge axis at ~10 Ma, is located ~300 km east of the ridge but strongly interacts with the Mid-Atlantic Ridge [e.g., Cochran and Talwani, 1978; Schilling *et al.*, 1983; Ito and Lin, 1995a], as indicated by the geochemical, geophysical and morphological anomalies observed over the larger Azores Plateau. In contrast, the Iceland hot spot is ridge centered (Plate 1). The NAM/EUR plate boundary at ~65°N shows a marked eastward embayment, suggesting a thermal "anchoring" of the ridge under the Iceland hot spot as it migrated westward. A less marked embayment at ~40°N may be attributed to the Azores hot spot [Vogt 1986]. The melting, temperature anomaly, or flux associated with the Azores is smaller than that of Iceland [e.g., Schilling 1991; Ito and Lin, 1995b], consistent with the presence of an axial valley along most of the ridge instead of an axial high (Plate 1) and with the greater depth of the ridge axis around the Azores than around Iceland. The presence of a single set of V-shaped ridges south of the Azores may be attributed to the progressive separation of the ridge axis from the hot spot, which may not be able to record

small temporal variations in plume flux occurring since the emplacement of the first V-shaped ridge. Alternatively, the Azores V-ridges correspond to the propagation of a large magmatic anomaly (i.e., plume head [Olson *et al.*, 1988]) responsible for the formation of the larger Azores Plateau to the north, and the flux to the Azores hot spot has remained stable since.

## 10. Conclusions

Bathymetry and gravity data on the FAMOUS-Lucky Strike area provide constraints on temporal and spatial variations of melt supply to the ridge axis that result from the interaction of the Azores hot spot with the Mid-Atlantic Ridge. The presence of a shallow V-shaped ridge south of the Azores is associated with anomalous crustal thickness that decreases from ~15 km near the Azores to normal crustal thickness of ~6 km at the ridge axis. The origin of the V-shaped ridges was caused by a melt anomaly initiated ~10 Myr ago that propagated southward (60 km/Ma). Assuming a simple 1-D decompression melting model, the temperature anomaly required to produce this excess of crustal thickness is >100°C, decreasing to ambient mantle temperature at the present time. This excess melt was emplaced on axis, forming large (~100 km in diameter) and shallow (500-0 m) volcanic plateaus that were near the surface or subaerial (see residual bathymetry in Figure 6). These plateaus are characterized by a lack of faulting, a very smooth topography, basement dipping reflectors, and the presence of numerous volcanic edifices, all indicative of high effusive rates. The transition to "normal" slow-spreading seafloor topography, indicative of low effusion rates and extensional tectonism, is abrupt and coincides with the rifting of the volcanic plateaus. Compared with Iceland, the V-shaped ridges south of the Azores are more discontinuous, shorter, and were produced by a melt anomaly that resulted in crustal thickness variations ~2-3 times larger. Additional constraints on the dynamics of ridge-hot spot interactions may be obtained from the direct comparison of observed temporal and spatial variations in crustal thickness with predictions from numerical models incorporating time-dependent mantle dynamics.

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