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Lithospheric Control on the Spatial Pattern of Azores Hotspot Seafloor Anomalies: Constraints from a Model of Plume-Triple Junction Interaction

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Lithospheric control on the spatial pattern of Azores hotspot seafloor anomalies: Constraints from a model of plume-triple junction interaction

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[1] The Azores hotspot is located near a plate boundary triple junction (TJ) consisting of the Terceira Rift (TER) and two branches of the Mid-Atlantic Ridge (MAR). The seafloor expression of the Azores hotspot has a complex spatial pattern. Latitudinal anomalies in seafloor depth and other data along the MAR extend farther to the south of the inferred location of the mantle heterogeneity than to the north. Longitudinal anomalies span a greater distance to the east of the MAR (along the TER) than to the west. A finite element model is used to investigate how the divergence of three plates away from a TJ may affect the spatial dispersion of thermally buoyant material simulating a mantle plume. Prescribed plate motion vectors approximate the kinematics of the Azores TJ during a main phase of plateau formation ~7 Ma. The plume is located off axis to the southeast of the simulated triple junction, following several studies that suggest that the present-day conduit is located near the islands of Faial and Pico. Asymmetry in the divergence of the three plates with respect to the triple junction tends to drive plume material preferentially southward and eastward, consistent with observed anomalies.

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1. Geological Setting of the Azores Triple Junction

[2] Significant variations in seafloor depth, geochemistry, and other types of geological data have been observed along mid-ocean ridges located near mantle plumes. Over 20% of the global mid-ocean ridge system is plume-affected, making investigation of ridge-hotspot interactions critical to understanding oceanic crustal accretion. This study focuses on the interaction of the Azores hotspot and a plate boundary triple junction (TJ) formed by two nearby divergent systems, the Mid-Atlantic Ridge (MAR) and the Terceira Rift (TER) (Figure 1). The MAR spreads with a half-rate of 1.1–1.2 cm/yr. The precise nature of the TER has been debated. Some investigations describe the boundary as a zone of distributed deformation or as an extensional strike-slip fault [e.g., *Luis et al.*, 1998]. However, similar to *Vogt and Jung* [2004], this study treats the TER as an ultra-slow diverging ridge with a half-rate of 0.4 cm/yr. Spreading has occurred along the TER over the last ~25 Ma [*Luis and Miranda*, 2008].

[3] The Azores region has been marked by excess volcanism for an extended period of geologic time. A main phase in the formation of the Azores plateau commenced ~10 Ma [*Cannat et al.*, 1999; *Escartín et al.*, 2001], although anomalous volcanism in the broader northern Atlantic region occurred prior to then [*Gente et al.*, 2003]. This chief plateau-building episode ended ~3–7 Ma, depending upon latitude [*Cannat et al.*, 1999; *Escartín et al.*, 2001; *Gente et al.*, 2003; *Maia et al.*, 2007]. Since then, rifting has been a dominant process shaping the plateau, although several islands in the archipelago remain active in recent times.

[4] Several lines of evidence point to the existence of a mantle heterogeneity in the Azores area [e.g., *Schilling*, 1991; *Dosso et al.*, 1993; *Detrick et al.*, 1995]. For example, seismic and gravity determinations of crustal thickness range to up to ~8–12 km [*Searle*, 1976; *Detrick et al.*, 1995; *Luis et al.*, 1998; *Gente et al.*, 2003; *Georgen and Sankar*, 2010]. Bathymetric V-shaped ridges, similar to those south of Iceland, mark a pulse of elevated magmatism [*Cannat et al.*, 1999; *Escartín et al.*, 2001]. Although seismic tomography studies of the upper mantle differ in some respects, investigations generally find a low-velocity region near the Azores [e.g., *Montelli et al.*, 2006; *Silveira et al.*, 2006]. Overall, many of these observations are consistent with the existence of a thermal plume under the Azores plateau. Although several studies have suggested that the mantle anomaly has a compositional component [e.g., *Bonatti*, 1990; *Asimow et al.*, 2004], this modeling study treats the anomaly as entirely thermal in nature for computational simplicity.

[5] One of the salient characteristics of the Azores Plateau is its shape in plan form (Figure 1). Trends in several types of seafloor data are asymmetric in an east-west direction about the MAR. For example, seafloor depths are shallow over much of the 550 km length of the TER [*Vogt and Jung*, 2004], but bathymetry is anomalous over a shorter distance to the west of the MAR. Anomalies in gravity, bathymetry, and geochemical data are also asymmetric about the inferred plume center along the MAR, extending significantly farther southward than northward [e.g., *Dosso et al.*, 1993; *Detrick et al.*, 1995; *Thibaud et al.*, 1998; *Goslin et al.*, 1999; *Maia et al.*, 2007; *Shorttle et al.*, 2010]. Studies using these data place the maximum northward extent of Azores influence in the vicinity of the Kurchatov FZ or an axial relay zone at 42°–43°40′ [e.g., *Goslin et al.*, 1999; *Maia et al.*, 2007]. To the south, seafloor anomalies in gravity and depth persist at

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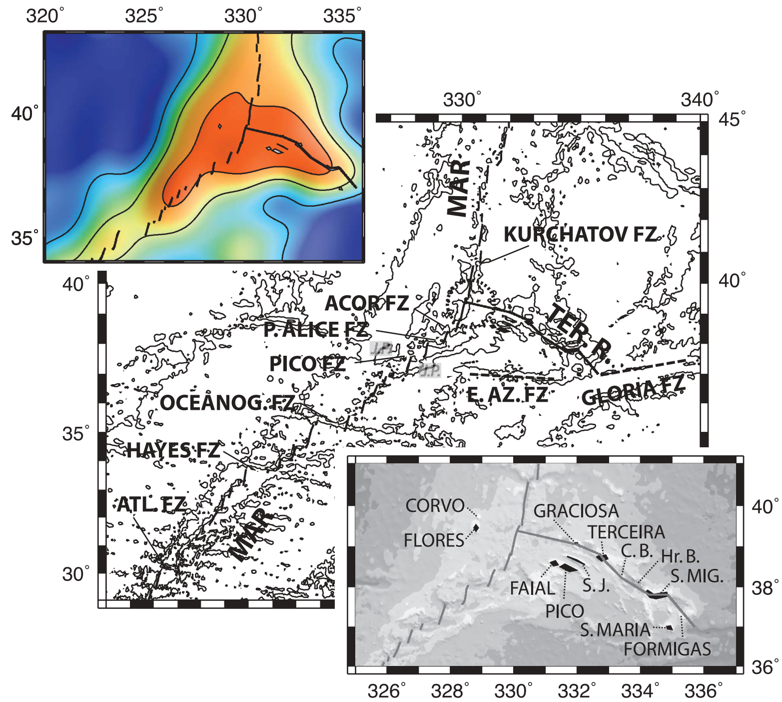

Figure 1. Geological setting of the Azores. Azores TJ is indicated with a dashed circle. MAR = Mid-Atlantic Ridge, TER. R. = Terceira Rift, E. Az. FZ = East Azores FZ, and J.P. = Jussieu Plateau. (Left inset) Filtered bathymetry of the Azores plateau. A lowpass filter with a cutoff wavelength of 300 km was applied to the bathymetry data of *Smith and Sandwell* [1997]. Contour lines indicate 1.9, 2.7, and 3.5 km depth. (Right inset) Locations of islands in the Azores Archipelago. S.J., S. Mig, C.B., and Hr. B. are Sao Jorge Island, Sao Miguel Island, Castro Bank, and Hirondelle Basin, respectively.

least as far as the Atlantis FZ [e.g., *Detrick et al.*, 1995; *Thibaud et al.*, 1998].

[6] With respect to the MAR, the cause of the asymmetry of seafloor anomalies in depth, gravity, and other data has generally been attributed to two sources. First, rifting history and relative plate motion (i.e., the southwest motion of the MAR away from the Azores hotspot) contribute to the spatial distribution of Azores seafloor volcanism [e.g., *Cannat et al.* 1999; *Gente et al.* 2003]. Second, instantaneous interactions between the hotspot and the MAR have also been asymmetric. Studies that examine specific stages in the emplacement of the plateau at selected chrons find that enhanced volcanism was preferentially directed to the south [e.g., *Cannat et al.*, 1999; *Escartín et al.*, 2001; *Maia et al.*, 2007].

[7] This study uses a steady-state model of mantle flow to assess how three ridges interacting with a mantle plume may affect plume dispersion in the upper mantle. Multiple factors may make the spatial distribution of a plume rising near a TJ more complex than that of an intraplate plume or a plume interacting with a single ridge. First, material can upwell along three extensional plate boundaries. Also, plate motion vectors diverging in three directions away from a TJ can result in an azimuthal dependence of upper mantle plume advection. Additionally, the dispersion of plume material can be influenced by the "inverted duct" structure formed by the lithosphere-asthenosphere boundary as a plate cools moving away from a mid-ocean ridge [e.g., *Schilling*, 1991]. In a single-ridge setting, buoyant plume material may be anisotropically guided along a ridge axis by the thickening plates. In a TJ setting, however, lithospheric cooling away from three ridge axes results in a 3D structure to the lithosphere-asthenosphere boundary, potentially channeling plume flow in a more complex spatial pattern.

2. Numerical Model Design

[8] A finite element model is used to study the flow field of a buoyant plume upwelling under three plates (Figure 2). The general numerical approach and governing equations are provided by *Georgen and Sankar* [2010]. For example, the conservation equations for mass, momentum, and energy are solved using the finite element software package COMSOL. Also, the velocity boundary condition for each plate is prescribed as a two-dimensional vector relative to a fixed TJ point [e.g., *Georgen*, 2008; *Georgen and Sankar*, 2010], with magnitude and direction dictated by a plate kinematic (or TJ velocity triangle) solution [*Luis et al.*, 1994; *Luis and Miranda*, 2008]. Here, only the aspects of the methodology that differ from *Georgen and Sankar* [2010] are described. One significant difference is the addition of a thermal plume source, discussed below. Another difference is that *Georgen and Sankar* [2010] focused only on processes along the slowest-spreading ridge in an Azores-like TJ, the analogue of the TER. Thus, their model domain could be limited to only two surface plates. Here, investigation of the 3D distribution of plume material requires use of three plates. All vertical, side boundaries are open to flow.

[9] The model is designed to examine plume-TJ interactions ~7 Ma, during a time of particularly intense magmatism

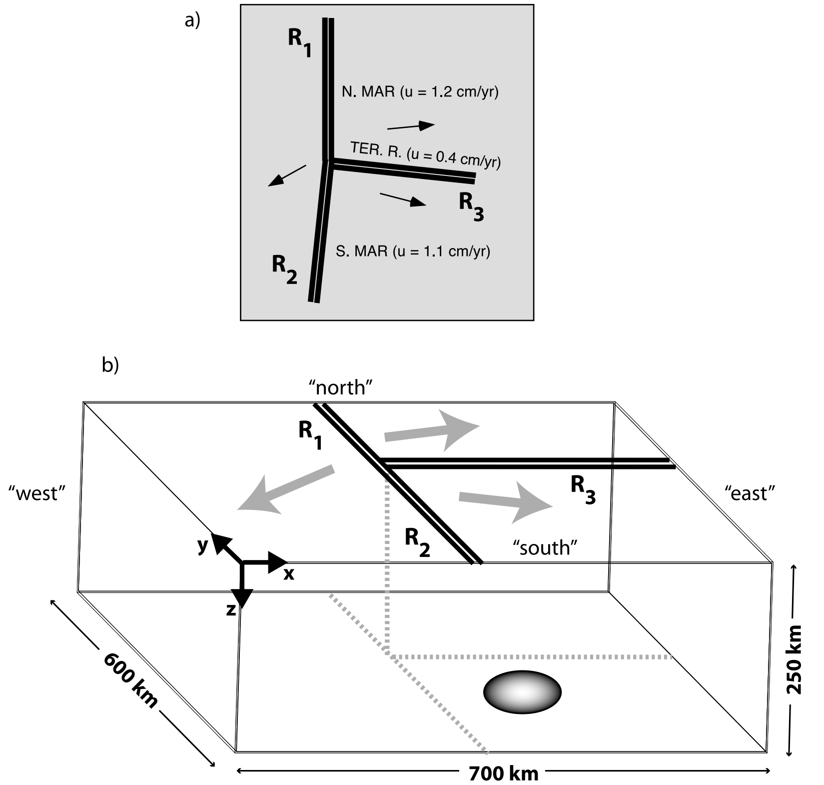

Figure 2. (a) Schematic representation of the Azores TJ. Arrows show the relative motion of the Eurasian, North American, and African plates with respect to a fixed TJ point. The half-spreading rate (u) for each ridge is indicated. (b) Representation of the computational domain. Three plates diverge from a fixed TJ located at (x = 350 km, y = 400 km). R_1, R_2, and R_3 are the analogues of two branches of the MAR and the TER, respectively. At the bottom of the model domain, the gray-shaded region denotes the location of a thermal plume conduit and gray dashed lines are the projection of the surface plate boundaries, for reference. For ease of discussion in the text, the sides of the model domain are labeled "west," "east," "south," and "north."

marking the formation of seafloor features such as the Jussieu Plateau south of the TJ [*Cannat et al.*, 1999; *Escartín et al.*, 2001]. At that time, Azores influence did not extend as far along the MAR as at present: The most pronounced bathymetric anomalies reached only ~300–400 km south and ~100–200 km north of the TJ [e.g., *Cannat et al.*, 1999; *Escartín et al.* 2001; *Maia et al.*, 2007]. Accordingly, this study uses a numerical domain that is 700 km by 600 km in horizontal extent. The dimensions of the domain permit investigation of 200 km along the branch simulating the MAR to the north of the TJ (R_1, Figure 2) and 400 km along the branch simulating the MAR to the south of the TJ (R_2). The branch representing the TER (R_3) is 350 km in length. Additionally, although some previous modeling studies have examined depths to or beyond the mantle transition zone, these investigations have generally found that most plume-lithosphere interaction occurs in the upper ~200 km of the domain. Thus, the model domain is limited to 250 km depth to save computational effort. Grid resolution varies from <6 km where gradients are highest (e.g., near the TJ and plume conduit, and at the top of the domain) to ~14 km near the side and bottom edges of the model box. Resolution tests were performed to ensure that grid spacing is sufficient to simulate the physical processes of interest.

[10] At the bottom of the model domain, a plume source is simulated by adding a circular temperature anomaly that decays in a Gaussian fashion to 0°C at a specified radius, following earlier studies [e.g., *Ribe et al.*, 1995]. Uncertainty exists in the buoyancy flux of the Azores plume: Studies interpreting the Azores hotspot as a thermal anomaly suggest a range of permissible excess temperatures (~100–200°C) [e.g., *Schilling*, 1991; *Escartín et al.*, 2001] and there is little direct constraint on the size of the mantle heterogeneity at ~7 Ma. Here, previous plume-ridge interaction studies are used as a guide to assign the simulated plume a maximum excess temperature of 180°C and a radius of 50 km, resulting in a mid-range buoyancy flux. There is also some degree of uncertainty about the location of the mantle heterogeneity. At 7 Ma, reconstructions suggest that the MAR would have been closer to the inferred location of the Azores plume than it is today [e.g., *Cannat et al.*, 1999; *Escartín et al.*, 2001]. Several studies [e.g., *Cannat et al.*, 1999; *Shorttle et al.*, 2010] put the present-day conduit roughly coincident with Faial and Pico islands, ~200 km to the east of the MAR. Thus, this investigation places the plume 50 km to the "east" of the R_1-R_2 axis, and 100 km to the "south" of R_3 (Figure 2).

[11] To simulate the mantle, this numerical experiment explores the fluid dynamics of a simple bottom-heated fluid. Following studies such as *Albers and Christensen* [2001], thermal buoyancy is incorporated but other buoyancy sources such as melt depletion and melt retention are neglected.

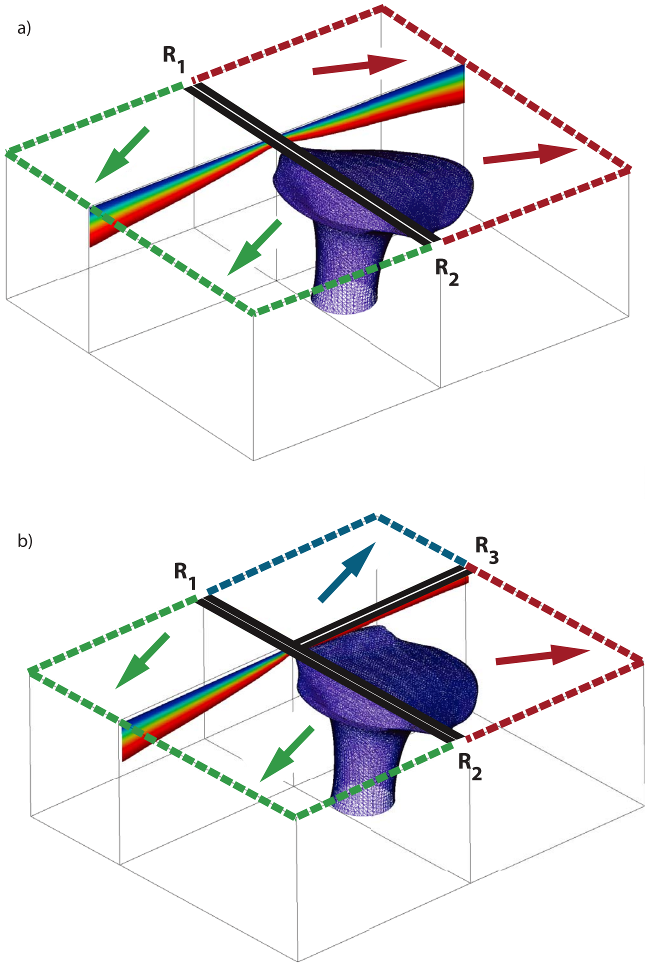

Figure 3. Temperature solution for a portion of the numerical domain for (a) Model 1 and (b) Model 2. Purple wireframe delineates 1420°C isosurface. Variably-colored bands show thickening of the lithosphere perpendicular to the R_1-R_2 axis, with blue representing the top surface boundary condition of 0°C, and red indicating $0.9*T_m$ and tracing out the thermally-defined base of the lithosphere. In panel (a), red and green arrows indicate the motion of two plates, whereas in panel (b), three plates diverge from the TJ point, and spreading occurs along R_3.

Mantle viscosity is assumed to vary with temperature and pressure. The viscosity contrast between the ambient mantle and cooling lithosphere is roughly two orders of magnitude, and the viscosity contrast between plume material and ambient mantle is approximately an order of magnitude. Equations for thermal buoyancy and mantle viscosity, including physical constants and the choice of reference viscosity, are presented by *Georgen and Sankar* [2010].

[12] To investigate the degree to which the TJ configuration can affect dispersion of the thermal plume, this study performs two numerical experiments. In Model 1, the numerical domain is run as a two-plate system, with the simulated Eurasian plate (bounded by R_1 and R_3) assigned the same motion vector as the simulated African plate (bounded by R_2 and R_3). Thus, no divergence is permitted along R_3 in this model. In Model 2, the simulated Eurasian plate moves "northeast" with respect to the TJ, resulting in divergence along R_3. This approach is designed to isolate the potential importance of the TER in plume-TJ interactions.

3. Model Results and Discussion

[13] Along the R_1-R_2 axis, predictions of plume dispersion for Model 1 and Model 2 are not significantly different (Figure 3). Resolved onto the plane of R_1-R_2, the motion vector of the simulated North American plate has a "southward" component. Similarly, the vector for the simulated African plate drives surface flow "southward" along R_2. Thus, in both Model 1 and Model 2, the motions of these two plates tend to advect plume flow "south" of the TJ. For example, at a depth of 80 km, both model results predict elevated axial temperatures for a distance of ~250 km to the "south" of the plume center but only about ~150 km to the "north" of it. This corresponds to about 350 km of elevated temperatures along the R_2 axis to the "south" of the TJ, compared to only ~50 km to the "north" of the TJ along R_1.

[14] Model-predicted thermal (or isostatic) topographic variation Δh was determined using $\Delta h = \int [\alpha\rho_m(T - T_o)/(\rho_c - \rho_w)]\, dz$, where thermal expansion coefficient $\alpha = 3 \times 10^{-5}$ °C^{-1}, reference mantle temperature T_o = 1350°C at depth z = 200 km, and densities ρ_m (reference mantle), ρ_c (crust), and ρ_w (water) are 3300 kg/m^3, 2700 kg/m^3, and 1030 kg/m^3, respectively [e.g., *Phipps Morgan and Forsyth*, 1988]. Vertical columns of mantle are assumed to be in isostatic equilibrium at z = 200 km. Consistent with studies of MBA along the Galapagos Spreading Center [*Canales et al.*, 2002], mantle thermal variations are taken to contribute ~45% to the observed topography, with the remainder due to crustal sources.

[15] Both Model 1 and Model 2 predict axial isostatic bathymetry anomalies extending ~200 km "north" of the TJ, roughly consistent with observed seafloor depths extracted along the 7 Ma isochron to the west of the MAR (Figure 4a). To the "south" of the TJ, anomalous depths are predicted for axial distances of ~300 km, somewhat less than observations. Underprediction of the length of plume-ridge interaction along R_2 could be caused by a combination of several factors, including (a) placing the location of the plume conduit too close to the TJ, and (b) the use of an excess temperature or plume radius that was somewhat too low, or a ratio of ambient mantle viscosity to plume viscosity that was too high. Either of the latter factors could inhibit plume material from spreading longer axial distances [e.g., *Albers and Christensen*, 2001]. However, the general sense of the R_1-R_2 asymmetry is consistent with observations that the instantaneous emplacement of Azores plume material was stronger to the south of the TJ than to the north [e.g., *Cannat et al.*, 1999; *Escartín et al.*, 2001; *Maia et al.*, 2007].

[16] In comparison, plume dispersion patterns for Model 1 and Model 2 differ in an "east-west" sense along R_3. Compared to Model 2, the dispersion of the plume in Model 1 is reduced along R_3 (Figures 3 and 5). In Model 2, allowing spreading along R_3 establishes a vertical pathway for material to upwell between the diverging plates, and creates an inverted "lithospheric duct" along which plume material can be preferentially channeled "eastward." The "northeastward" vector of the simulated Eurasian plate may promote advection of thermally buoyant material toward R_3.

[17] Preferential dispersion of plume material to the "east" is consistent with observed bathymetry (Figure 1). For

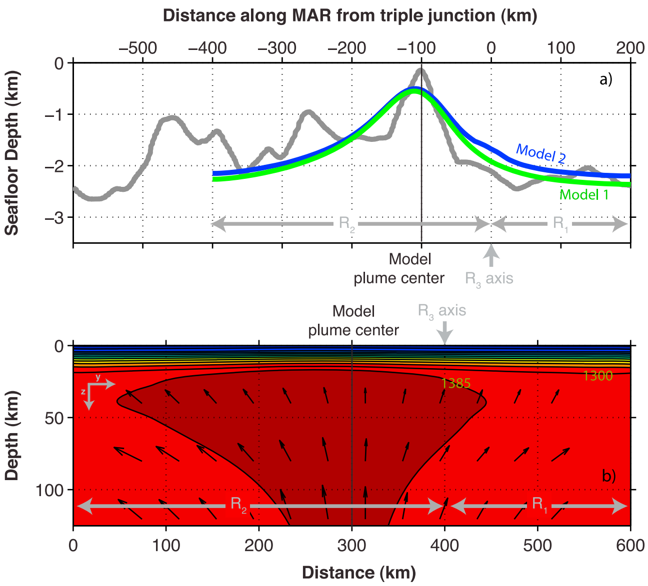

Figure 4. (a) Comparison of observed seafloor topography and model-predicted isostatic (or thermal) depths for the simulated and actual MAR. Models 1 and 2 are indicated with a green and blue line, respectively. Thick gray line shows seafloor depths (from *Smith and Sandwell* [1997]) extracted from along the 7 Ma isochron of the North American plate [*Mülller et al.*, 2008], the time period simulated by the numerical modeling. Since this off-axis profile includes relatively localized variations related to seafloor aging and segment-scale processes, depths have been smoothed slightly using a 20 point running mean on data sampled at a 1 km increment. The zero level for isostatic bathymetry is arbitrary, so calculated curves are shifted vertically to overlap with observed depths. (b) Temperature solution for Model 1 along the R_1-R_2 axis for depths from z = 0 km to z = 150 km. Solution for Model 2 is nearly visually indistinguishable and is not shown. Black arrows indicate flow vectors, with length proportional to mantle speed. Isotherms for temperatures <1300°C are in 100°C increments. (Note that "north"-"south" distances are not aligned in panels (a) and (b)).

Model 2, predicted isostatic bathymetry deepens by ~1 km along 300 km of R_3, compared to ~3 km over the same distance for Model 1 (Figure 5a). For the observed data, bathymetry changes along the TER are defined by using the deepest points between volcanic edifices, and eliminating the stretch of TER axis between the TJ and the 7 Ma MAR isochron on the Eurasian and African plates. With these constraints applied, the TER deepens by roughly 1–1.5 km over 300 km, more consistent with the predictions of Model 2. As an additional qualitative aside, the asymmetry in island distribution across the MAR (e.g., an elongated chain to the east but comparatively limited extent in the west) is also more consistent with the plume dispersion patterns predicted in Model 2 than those in Model 1.

[18] Thus, it is likely that the presence of three plates in the vicinity of the Azores plateau is important in the distribution of plume material in the upper mantle and the spatial pattern of seafloor volcanism. This simple fluid dynamics modeling exercise points to the control that lithospheric structure and plate boundaries may exert on the seafloor expression of Azores magmatism, and suggests that Azores plume-ridge interaction cannot completely be treated using only one ridge, the MAR. Geochemical studies of the symmetry of melting trends and source composition perpendicular to the MAR have been recently published [e.g., *Beier et al.* 2008, 2010], and rigorous comparison of numerical calculations to these investigations awaits.

[19] Subsequent plume-TJ interaction models may incorporate additional factors to refine these simple predictions. For example, these steady-state models cannot account for time-dependent behavior, including variations in plume flux related to pulsing [*Cannat et al.*, 1999; *Escartín et al.*, 2001] and migration of the ridge with respect to the plume [e.g., *Ito et al.*, 1997]. Also, these model results are dependent on the location assigned to the plume anomaly. Recent studies suggesting that the TJ was at ~39°N by ~10 Ma [*Luis and Miranda*, 2008], combined with investigations of the distribution of excess volcanism along the MAR [e.g., *Escartín et al.*, 2001], point to a plume position to the southeast of the TJ during the formation of features such as the Jussieu

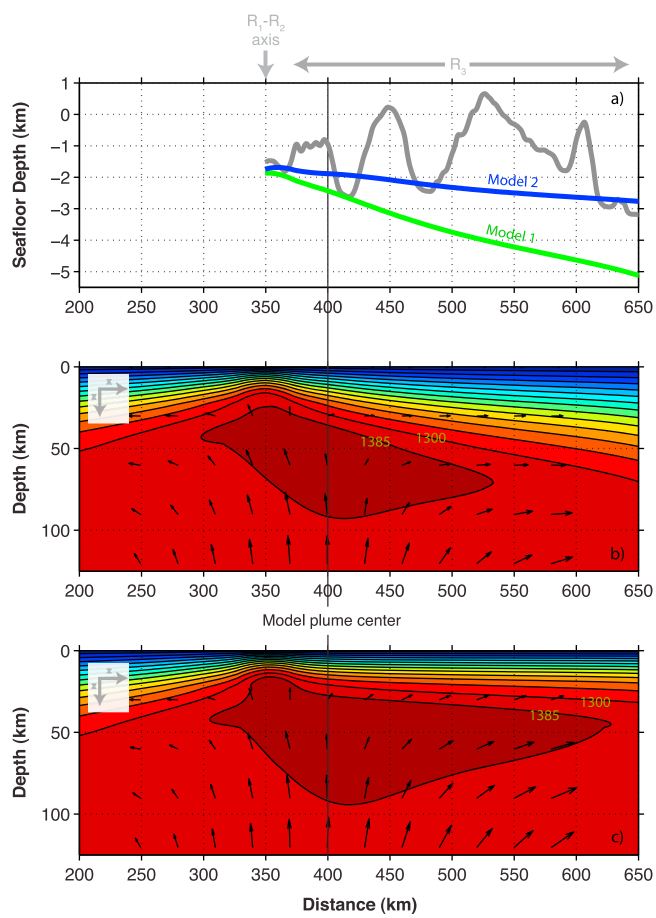

Figure 5. (a) Comparison of observed seafloor topography and model predicted isostatic (or thermal) depths perpendicular to the R_1-R_2 axis, covering R_3. Color keys are described in the caption to Figure 4. The portion of the seafloor depth profile corresponding to crust created <7 Ma along the MAR has been removed, and the remaining profile has been shifted "west" to align with the TJ. For this present-day axial profile, depths have not been smoothed using a running mean. (b) Temperature solution for Model 1 at y = 400 km. (c) As in Figure 5b but for Model 2.

Plateau. This is the location used in this modeling effort. However, future studies may perform a systematic investigation of the sensitivity of plume dispersion to conduit location. If the plume is located to the "northeast" of the TJ [e.g., *Yang et al.*, 2006], for example, preliminary models suggest that less plume material reaches the simulated MAR (J. E. Georgen, manuscript in preparation, 2011). Finally, subsequent models could include melting, to facilitate the comparison with geochemical studies noted above and to account for latent heat and chemical sources of buoyancy.

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