Control of the symmetry of plume-ridge interaction by spreading ridge geometry

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[1] The Iceland, Galápagos, and Azores plumes have previously been identified as interacting asymmetrically with adjacent spreading centers. We present evidence that the flow fields in these plume heads are radially symmetric, but the geometry of the mid-ocean ridge systems imparts an asymmetric compositional structure on outflowing plume material. First, we quantify the degree of symmetry in geophysical and geochemical observables as a function of plume center location. For each plume, we find that bathymetry and crustal thickness observations can be explained using a single center of symmetry, with these calculated centers coinciding with independently inferred plume center locations. The existence of these centers of symmetry suggests that the flow fields and temperature structure of the three plume heads are radially symmetric. However, no centers of symmetry can be found for the incompatible trace element and isotopic observations. To explain this, we develop a simple kinematic model to predict the effect of mid-ocean ridge geometry on the chemical composition of outflowing plume material. The model assumes radially symmetric outflow from a compositionally heterogeneous plume source, consisting of a depleted mantle component and enriched blebs. These blebs progressively melt out during flow through the melting regions under spreading centers. Asymmetry in trace element and isotopic profiles develops when ridges on either side of the plume center receive material that has been variably depleted according to the length of flow path under the ridge. This model can successfully explain compositional asymmetry around Iceland and Galápagos in terms of an axisymmetric plume interacting with an asymmetric ridge system.

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Theme: Geochemical Heterogeneities in Oceanic Island Basalt and Mid-ocean Ridge Basalt Sources: Implications for Melting Processes and Mantle Dynamics

Guest Editors: C. Beier and P. Asimow
1. Introduction

[2] The role of mantle plumes in generating geochemical and geophysical anomalies is well documented [Schilling, 1973; Schilling et al., 1982; Yu et al., 1997; Hooft et al., 2006] and has been linked to their anomalous temperatures [Courtney and White, 1986], flow fields [Macleanman et al., 2001] and compositions [Hart, 1971]. On impacting the base of the lithosphere plume material is forced to flow laterally, advecting the thermal and compositional signal of the plume away from the upwelling stalk. When spreading ridges lie close to plumes, the geochronological and geophysical consequences of this plume outflow for ridge magmatism can be pronounced: oceanic crustal thickness, ridge axial depth, axial morphology and erupted basalt geochemistry all show pronounced long-wavelength (∼1000 km) deviations. It is the along-ridge distribution of this plume signal that concerns the current study.

[1] The simplest conceptual model for the interaction of plumes and ridges has been of axisymmetric plume influence along adjacent spreading centers. This model naturally leads to the prediction that geochronological and geophysical observables along ridges should be the same at a given radial distance from the plume center. However, it has been suggested that this idealized situation does not hold for the Iceland, Galápagos and Azores plumes, from the observation that the geophysical and geochemical signatures are not distributed symmetrically along the ridge axes. Comparing oceanic crustal thickness and bathymetric profiles north and south of Iceland (Figure 1a), Hooft et al. [2006] observed a 200–500 m greater elevation and 2–2.5 km thicker crust along the Reykjanes Ridge compared with the Kolbeinsey Ridge beyond 150 km radial distance from the plume center. Along-ridge geochemical profiles, constructed from analyses of dredged basalts, have also been identified as differing either side of the plume. In particular, Sr and Pb isotopic compositions at the Reykjanes Ridge south of Iceland are enriched in comparison with those at the Kolbeinsey Ridge to the north [Poreda et al., 1986; Mertz et al., 1991; Schilling et al., 1999; Blichert-Toft et al., 2005]. These studies suggest that the Iceland plume is conveying its thermal and compositional signature to the south more effectively than to the north.

[5] Both symmetric and asymmetric plume-ridge interaction has been reported between the Galápagos plume and the Galápagos Spreading Center (Figure 1c). Schilling et al. [2003] observed symmetric Pb-Hf-Sr-Nd isotope gradients, but noted that ridge axis elevation is systematically ~500 m greater in the east. On the basis of three component mixing models, Schilling et al. [2003] calculated a greater dilution of plume material reaching the eastern GSC than that reaching its western half, at an equal radial distance. Christie et al. [2005] locate different points of symmetry between 90°30′W and 92°10′W for each of Pb-Hf-Sr-Nd isotope profiles and ridge axial depth. The grouping of these points of symmetry into two regions leads Christie et al. [2005] to infer the presence of two primary locations of material transfer from plume to ridge.

[5] A pronounced asymmetry in plume-ridge interaction has been reported around the Azores (Figure 1b). Geophysical studies of the Mid-Atlantic Ridge (MAR) about the Azores [Goslin and Party, 1999; Maia et al., 2007] have indicated a decline in plume influence on crustal accretion over the region 43–44°N, much closer to the plume center than is observed south. Similarly, from studying Nd isotopes which indicate a greater southward extent of enriched material, Yu et al. [1997] inferred a plume preferentially discharging to the southwest.

[6] Various dynamical scenarios have been proposed to account for the apparent asymmetry in many of the observations. Recourse has been made to tilted plumes [Shen et al., 2002; Yang et al., 2006; Yu et al., 1997], lithospheric damming of outflow [Vogt and Johnson, 1975], bulk asthenospheric flow [Chase, 1979; Mertz et al., 1991], ambient mantle compositional anomalies [Mello et al., 1999] and plume zonation [Murton et al., 2002]. One reason for this proliferation of dynamical scenarios is that there is no generally accepted global model for plume-ridge asymmetry. A second cause is that a given plume can have some observables that are symmetrically distributed and others that are asymmetrically distributed, a result arising from this study. A globally consistent model of plume-ridge dynamics must simultaneously explain these two sets of observations.

[7] The purpose of this paper is to explore the nature of plume-ridge interaction for each of the Iceland, Galápagos and Azores plumes. We find that many reported cases of asymmetry are artifacts of subjective choices of plume center. Quantifying the degree of symmetry of any given observable is critical in order to identify a plume center objectively, and we develop a method of quantifying...
symmetry in section 2. By making an objective choice of plume center, observations related to asthenosphere flow and temperature structures (e.g., bathymetry and crustal thickness) turn out to be consistent with radially symmetric plumes. However, we find that the asymmetry in incompatible trace element and isotopic compositions is pronounced, and much stronger than any found in bathymetry or crustal thickness. Since geophysical observations related to asthenosphere structure appear to be most consistent with a symmetric plume head, we search for a model in which the compositional asymmetry is imparted by the geometry of the ridges and the way they allow plume mantle to be processed through melting regions. In section 3, we develop a simple kinematic model of radially symmetric plume outflow beneath a spreading ridge geometry that can be asymmetric about the plume center. This model provides a remarkably good fit to the first-order features of compositional asymmetry found on mid-ocean ridges close to Iceland and the Galápagos Islands.

2. Symmetry of Along-Ridge Observables

[8] Radially symmetric outflow represents the simplest kinematic model of plume dispersal in the
asthenosphere. Symmetric outflow models should only be rejected if systematic and objective observational tests necessitate greater dynamical complexity. Failure to perform such tests can give rise to a false inference of asymmetry in along-ridge observables. The application of a symmetric outflow model also has a dynamical basis. Numerical and analogue models show that a plume head will spread symmetrically from the top of the plume conduit if the base of the lithosphere is flat and if relative motion between the plume head and the lithosphere does not cause significant drag [Ito, 2001; Campbell, 2007; Campbell and Griffiths, 1990]. This latter requirement is met by the low viscosity of the asthenosphere, which thermal, geodetic and rheological constraints place as being 10–100 times lower than adjacent lithospheric mantle [Buck and Parmentier, 1986; Robinson et al., 1987; Rabinowicz et al., 1990; Hirth and Kohlstedt, 1996]. The asthenosphere’s low viscosity makes it unlikely to be strongly coupled to movement of the lithosphere, and hence plume outflow to a first order might be expected to be symmetric. There is also evidence that the upper boundary to the asthenosphere is flat, defined not by the thermal lithosphere, but by the dry solidus [Hirth and Kohlstedt, 1996]. The origin of this definition of the base of the lithosphere is the sensitivity of peridotite viscosity to its volatile content. These volatile elements are rapidly extracted during the first few percent of melting, producing order of magnitude increases in mantle viscosity [Hirth and Kohlstedt, 1996]. In consequence, ridge axes are unlikely to provide channels for plume material and transform faults are unlikely to act as barriers to plume outflow, as the dry solidus will not vary with plate age. Taken together, these lines of argument at least justify a symmetric plume outflow model as a starting point for models of plume-ridge interaction [Jones et al., 2002; Poore et al., 2009; Rudge et al., 2008].

[8] Despite the strong case for symmetric outflow, many studies choose plume centers which render the observables asymmetrically distributed. If the underlying data really is symmetrically distributed, why have inappropriate plume centers been chosen in many studies? Partly the answer is historical inertia. Once one study has chosen a plume center location, there will be a tendency for it to be quoted and reused without determining if it is appropriate to newer data sets. In addition, many plume centers are constrained by relation to surface features. For example, the Iceland plume is often said to be centered on the Grímsvötn caldera. While volcanoes act as a useful proxy for plume locations, magma transport in the crust and mantle also plays an important role in determining the locus of magma accumulation. This makes volcano locations an imperfect indicator of the distribution of plume material. Beyond using surface features, there are methods both geophysical, for example mantle tomography [Hooft et al., 2003], and geochemical, such as locus of high ³He/⁴He over an ocean island [Kurz and Geist, 1999], for constraining a plume’s location. All approaches however, are fundamentally limited by their resolution, leaving considerable flexibility in assigning plume centers and thereby allowing for possible misidentification of asymmetry. A systematic approach is required, combining all available data sets to select a plume center best able to create symmetry in along-ridge observables and match independent plume center estimates. Thus, any asymmetry that remains when a preferred plume center is chosen can be attributed to a genuine asymmetry in the plume-ridge system.

2.1. Quantifying Symmetry

[10] Given the simple starting hypothesis of symmetric radial plume outflow, a convenient method for determining the geometry of interaction in plume-ridge systems is to plot along-ridge geochemical and geophysical observables as a function of radial distance from the plume center. Thus, any asymmetry in plume interaction with ridges will be manifest as deviations between the profiles. However, making such plots requires a priori knowledge of the plume center’s location. Selection of an inappropriate position for the putative plume center could result in the false appearance of asymmetry, a scenario illustrated in Figure 2. In practice the spatial distribution of plume material in the mantle is only inferred from geochemical and geophysical observations, so our choice of a reference frame in which to view the data is key. We begin by quantifying symmetry about trial plume centers, with the aim of identifying points that render the observables symmetrically distributed.

[11] The raw data used for this study are presented in Figure 3. In order to assess symmetry, these data points must be interpolated onto regular distance intervals from a trial plume center. Raw geochemical data are first smoothed using a traveling Gaussian filter and then the points linearly interpolated between to provide the required sample spacing. It is useful in comparing misfit between observables, for the profiles’ geochemical or geo-
physical parameters to be normalized. This is achieved by converting to nondimensional $z$ scores
\[
(z_i = (x_i - \mu)/\sigma),
\]
where the estimated mean of the population ($\mu$) is subtracted from an individual observation ($x_i$) and the result is divided by the population’s estimated standard deviation ($\sigma$). Misfit calculated from these profiles is then expressed as $z$ score root-mean-square misfit ($Z$-RMS); details of this calculation are in Appendix A. Topographic profiles are produced from a low-pass filtered (wavelength 85 km) version of the GEBCO_08 global elevation and bathymetry gridded data set (version 20090202, http://www.gebco.net). Further details regarding the processing of the profiles are discussed in detail in Appendix B.

[Z]-RMS misfits were calculated using data within a spatial window chosen to exclude data with no clear plume signal. The corresponding ridge lengths are shown in Figures 1 and 3. In the case of Iceland the result is a truncation of data north and south at a radial distance of ~500 km from Iceland’s center, where a Jan Mayen signature becomes dominant in mid-ocean ridge basalt (MORB) chemistry. The large increase in the chemical variability of on-land data from Iceland makes spatial averaging difficult, so we limit geochemical profiles to the submarine ridge sections. Data along around the Galápagos plume is included as far east and west along the GSC as there is data coverage. For the Azores hot spot, an anomalous mantle regime to the north of the Kurchatov Fracture Zone, previously associated with dense garnet-rich mantle [Mello et al., 1999], limits the length of profile being matched.

[13] We use a grid search method to find the centers of symmetry for each observable in each plume-ridge system. The algorithm is as follows.

1. Select a point within one of the boxed regions in Figure 1 as a trial plume center.
2. Replot the data set of interest as a function of distance from the trial center.
3. Calculate misfits between data at common distances either side of the trial center at 1 km increments.
4. Calculate $Z$-RMS misfits for the whole profile.
5. Complete the misfit grid by repeating steps 1–4 for all trial plume centers within the boxed region, at intervals of 0.01 degree. Hence identify the loci of centers of symmetry for this observable.
6. Repeat steps 1–5 for the remaining observables.
7. Compare the centers of symmetry for all the observables with plume centers inferred from independent data sets not restricted to the mid-ocean ridge.

Figure 2. These diagrams demonstrate the importance of careful plume center selection. Points A and B mark two putative plume centers, overlain on top of a synthetic Gaussian plume swell (for zero age crust), the center of which underlies point B. Dotted lines delineate the profile of an adjacent spreading center, which has its axial depth affected by the plume as a function of radial distance from the plume center. Non-plume-influenced ridge has a depth, $z$, of 0. In the two plots, the along-ridge profiles for depth are recorded as a function of radial distance from each of the putative plume centers. Red and blue lines denote the two sections of ridge depth profile, split at the ridge’s closest approach to the points A or B. When an inappropriate plume center is selected, as is the case for point A, the depth profiles appear asymmetric, with the right-hand length of ridge (blue) being systematically shallower than the left (red). This is rectified by plotting the ridge profiles about point B, which corresponds to the true plume center.
Figure 3. Maps and plots of the unprocessed geophysical and geochemical data. Ridge names are marked on for reference. Grey bars mark the latitude or longitude of ocean islands. (a) Map of the distribution of samples north and south of Iceland. Associated graphs show three of the six geochemical and geophysical observables considered for Iceland in this study, plotted against latitude. Data from Schilling et al. [1983], Mertz et al. [1991], Mertz and Haase [1997], Murton et al. [2002], Jakobsson et al. [2008], Thirlwall et al. [2004], Schilling et al. [1999], Devey et al. [1994], Blichert-Toft et al. [2005], and Peate et al. [2009]. (b) Map of samples along the Eastern and Western GSC. The raw Galápagos data comprising the profiles used in this study, elevation, εNd, and ⁸⁷Sr/⁸⁶Sr are plotted alongside. Data from Schilling et al. [2003] and Ingle et al. [2010]. (c) MAR around the Azores, sample map and raw elevation and isotopic profiles. Data from Yu et al. [1997], Debaille et al. [2000], and Dosso et al. [1999].
2.2. Searching for Centers of Symmetry

[14] A center of symmetry is characterized by having a low Z-RMS misfit. Perfect symmetry of an observable about a plume center would return a Z-RMS misfit score of zero, like the synthetic profile B in Figure 2. However, all observables record analytical uncertainty as well as natural variability unrelated to plume dynamics. This uncertainty means real data sets will never exhibit perfect symmetry. We therefore adopt an approach of considering relative symmetry between observables. The presence and position of the centers of symmetry found can then be combined with volcanological, seismic tomographic and geochemical constraints on plume center location to decide if a particular observable is symmetric.

[15] Results of searching for centers of symmetry of the Iceland plume are presented in Figure 4 in terms of Z-RMS misfit. Common to most of the maps is a region of high symmetry (low Z-RMS misfit) oriented southeast-northwest. This feature is a function of the lack of constraint that a single two-dimensional geochemical or geophysical profile can place on the center of a three-dimensional distribution of plume material in the mantle. Significant though is the location of the region of high-symmetry trial plume centers: For crustal thickness and elevation the high-symmetry region extends into central Iceland, close to where the plume center is presumed to lie from mantle tomographic and previous crustal thickness studies [Shen et al., 2002; Darbyshire et al., 2000]. For Na$_8$, symmetry is generally poor across the searched area, and the lowest values of Z-RMS misfit are displaced ~50 km to the southwest of the elevation and crustal thickness high-symmetry regions. For isotopic profiles the most favorable symmetry center locations lie further southwest still, at ~100 km from the elevation high-symmetry region. Zr/Y in contrast shows no region of low misfit (Figure 4). From the along-ridge profile of Zr/Y in Figure 4, it is clear that this absence of a high-symmetry zone is a result of the fundamentally asymmetric nature of the profiles attempting to be matched: significant depletion of Zr/Y along the Kolbeinsey ridge makes its profile unmatchable with the enrichment trend seen along the Reykjanes ridge. However, for the other geochemical observables, Figure 4 demonstrates that the profiles are sufficiently similar in shape that a center of symmetry can be found, although plume centers placed too far to the southwest begin to appear unrealistic given what is known of Iceland’s geodynamics.

[16] The process of identifying centers of symmetry has been repeated for plume centers in the Galápagos and Azores regions and the results are presented in Figures 5 and 6, respectively. As with the maps for Iceland, a region of trial plume centers with low Z-RMS misfit extends away from the ridges roughly perpendicular to their strike. For the Galápagos (Figure 5) the high-symmetry region from elevation extends directly over the presumed plume location beneath Fernandina Island [Schilling et al., 2003]. High-symmetry fits to the isotope profiles however, requires trial plume centers displaced to the west from this point, away from the active intraplate volcanism. Thus, while the influence of the plume swell on ridge depth appears axisymmetric about a physically reasonable hot spot center, the isotopic composition of erupted basalts records an asymmetry in plume-ridge interaction.

[17] A similar scenario exists with the Azores plume, although in this instance the data coverage along the southern ridge profile is poor, due to the combined effects of an along-ridge sampling gap and a fracture zone offsetting the spreading center away from the Azores. The result is to leave the southern profile unconstrained over a distance range for which the northern profile has a more continuous distribution of samples. Given also that the Azores profiles are limited in distance to the radial extent of the plume’s influence on geochemistry, the distance over which profiles are well constrained is ultimately very short, ~30 km. With these caveats in mind, the displacement of the isotopic high-symmetry regions to south of the Azores should be treated with caution. The elevation profile however, which is the most continuous, does show a region of trial plume centers with high symmetry elongate in the direction of Faial Island. Therefore, despite poor constraints on the geochemical symmetry, the bathymetric expression of the plume’s presence is consistent with it being centered under the Azores platform and interacting in a radially symmetric fashion with adjacent ridges.

2.3. Choosing Plume Centers

[18] The maps of trial plume center symmetry in Figures 4–6 are next used to choose a preferred plume center location. Greatest weight is placed on observables that most directly reflect the physical plume such as spreading ridge crustal thickness and axial elevation, which both depend directly on asthenosphere temperature. Given these observables also showed centers of symmetry systematically offset from the geochemical observables, the
geophysical and geochemical sets of observations are grouped separately in considering their centers of symmetry. These data sets were then compared with the results from global seismic tomography and $^3$He studies, in order to improve constraints on the plume location perpendicular to the spreading axis. These combined observations can be used to test simple radially symmetric models of plume outflow.

Plume centers generating high symmetry in observables are identified based upon the combined and averaged symmetry maps of the geochemical
and geophysical observables. The result is the grey (geophysical misfit) and pale yellow (geochemical misfit) regions marked on in Figure 7, which correspond to the low Z-RMS misfit regions of these averaged maps. Figure 7 also shows the independent constraints on plume center locations. For each plume-ridge system studied, the geophysical profile high-symmetry regions correspond closely to these independently constrained plume locations. The geochemical centers of symmetry however, are consistently offset from global seismic and $^3$He constraints.

[20] Plume center positions estimated from crustal thickness maps and mantle tomographic images are displayed for Iceland in Figure 7a. Our preferred plume center, that obtains symmetry in both the crustal thickness and elevation profiles, lies at 17.4°W 63.95°N. This is ~60 km south of the cluster of plume centers estimated from crust and shallow mantle seismic constraints, but within error of the estimates from deeper mantle structure. A study of the arrival times of P to S transition zone conversions beneath the Galápagos hot spot, recovered a plume center location of 91.7 ± 0.8°W 0.7 ± 0.8°S [Hooft et al., 2003]; from our symmetry mapping we place the plume center ~40 km northeast at 91.45°W 0.40°S beneath Fernandina island, but within the locus of the Hooft et al. [2003] estimate.
For the Azores, Yang et al. [2006] have produced a P wave velocity model that centers the hot spot at 38.5°N 28.5°W. We use this constraint to place our preferred plume center at the eastern extent of the high-symmetry region drawn in Figure 7b, beneath Faial island. For each plume the preferred hot spot locations are marked in Figure 7 as red and white bull’s-eyes.

2.4. Symmetric or Asymmetric Plume Outflow?

Preferred plume center locations have been selected, incorporating both the results from symmetry mapping and the independent plume center estimates. It is now possible to replot the data about these plume centers and assess the symmetry present in each observable. Interpretation of these plots places important constraints on the dynamics of plume outflow.

Table 1 provides a summary of the RMS and Z-RMS misfits for profiles taken about each plume center, including both minimum misfit plume centers and those we selected as our preferred plume centers. The latter have had standard deviations calculated for the Z-RMS misfit of elevation. This calculation was performed to test the sensitivity of the Z-RMS misfit to the low resolution and discontinuous nature of sample collection represented in the geochemical profiles. The bathymetry data was repeatedly randomly resampled at a resolution of 10–20 samples per profile, the Z-RMS misfit recalculated and the standard deviation then determined from the population of Z-RMS misfit values thus obtained.

Figure 8 demonstrates that for Iceland, although the preferred plume location is able to generate symmetric elevation and crustal thickness profiles, the isotopic and incompatible trace element profiles...
created are asymmetric. Table 1 records the Z‐RMS misfit for elevation and crustal thickness to be less than 0.6, while the Z‐RMS misfit for the chemical observables is at least twice this and many times outside the standard deviation of the elevation Z‐RMS estimate. When plotted about our favored plume center the northern profile is systematically more depleted than the southern (Figure 8). The major element trends show more scatter, likely a result of their sensitivity to crustal processes, which are poorly deconvolved from mantle derived signals by the simplistic linear regression correction applied. Despite this, Na records depletion of the Kolbeinsey ridge with respect to the Reykjanes ridge, albeit over a shorter distance than the trace elements and isotopes, 300‐410 km compared 300‐550 km for 87Sr/86Sr.

For the Galápagos plume, Sr and Nd isotopic analyses have been considered alongside ridge axial elevation (Figure 9). The Z‐RMS misfit for elevation (Table 1) is overall low at 0.41, but results partly from a slightly shallower eastern GSC compared to the western GSC, as noted by Schilling et al. [2003]. In particular, for 150 km along its length the eastern GSC is an average 140 m shallower than the western GSC at equivalent distances; however this feature does not persist beyond 450 km from the plume center. The isotopic data, when plotted as a function of radial distance from the same point as the bathymetry, shows a marked and consistent offset to more depleted values along the eastern GSC. This asymmetry in eNd averages a Z‐RMS misfit of 0.94 and extends from approximately 200‐800 km from the hot spot center, the actual offset varying along its length. Comparing the Z‐RMS misfits between data sets indicates that the geochemical observables are much more asymmetric than the geophysical observables, with Z‐RMS misfits more than twice that seen in the ridge elevation.

As already discussed, the less continuous nature of the Azores geochemical data leaves symmetry harder to constrain. The elevation data shows a moderate Z‐RMS misfit of 0.64 (Table 1) but with
only ~75 km of profile fitted; this is not representative of the longer-wavelength swell. Visual inspection of Figure 10 suggests a rough correspondence between bathymetry further from the Azores, although the segmented nature of the MAR in this region again makes trends in offset difficult to follow. There is a single cluster of isotopic data in Figure 10 between 100–150 km south along the MAR, which falls within the distance range of the misfit calculations. The Z-RMS misfit from this cluster with respect to the data north along the ridge is high at 1.75, which exposes a shortcoming of the method; a single smoothed line has been fitted to the data and the dispersion of sample compositions about the mean not fed into the misfit calculations. While this is suitable for the Galápagos and offshore Iceland, where generally the variability of data at a given distance is low and the offset between profiles high, in the Azores there is a large variability in the data. The result is an apparent discrepancy between chemistry north and south of the Azores, but which is lessened when the overlap of data is considered. Therefore, it remains uncertain whether the north and south profiles are different over the regions for which there is evidence that the plume is the dominant geodynamic feature.

The ability of the preferred plume centers to match elevation and crustal thickness along-ridge with a low Z-RMS misfit, while simultaneously falling close to seismological constraints on plume location, indicates that dispersal of Iceland and Galápagos plume material is symmetric. That these same plume centers are not centers of symmetry for the incompatible element and isotope ratio profiles

Figure 7. Maps marking independent estimates of plume center locations, compared with our preferred plume center positions for (a) Iceland, (b) the Azores, and (c) the Galápagos. In each map, bathymetry is contoured at 1 km intervals, and the areas of trial plume center grid searches are included as black rectangles. The averaged high-symmetry regions from the symmetry mapping calculations are marked in grey (geophysical observables) and pale yellow (geochemical observables). When the results of tomographic studies are used, the approximate center of any low-velocity anomaly imaged is taken as representing the axis of the plume. For constraints from transition zone thickness, the center of the region of thinned transition zone is taken as representing the axis of the plume at the base of the upper mantle. In 3He studies, the locus of lavas displaying the maximum 3He/4He is taken to be the center of the plume. Shen et al. [2002] used crustal thickness as a proxy for the location of the plume center in the shallow mantle. As such, points representing estimates of maximum crustal thickness have been included. In Figure 7b, the ridge perpendicular extension of the region of maximum along-ridge crustal thickness, as determined by Detrick et al. [1995], is drawn in light blue. In Figure 7c, the dashed green line marks the region of thinned transition zone imaged by Hooft et al. [2003].
suggests a decoupling between geochemical and geophysical tracers of plume dispersal.

3. Kinematic Modeling

[27] The result of section 2 indicates that asymmetry in geochemical observables must be superimposed upon an essentially symmetrically outflowing plume head. Therefore, the lithospheric damming of outflow [Vogt and Johnson, 1975], bulk asthenospheric flow [Chase, 1979; Mertz et al., 1991] and tilted plume [Shen et al., 2002; Yang et al., 2006; Yu et al., 1997] models cannot account for the asymmetry in the geochemical profiles. All of these processes would affect the advection of the plume’s thermal signal, and be recognizable as asymmetry in ridge elevation and crustal thickness, an asymmetry we do not observe in either of the Iceland or Galápagos plume–ridge systems. Another possibility is that the plumes are compositionally zoned [e.g., Fitton et al., 1997; Murton et al., 2002; Geist et al., 1988; Hoernle et al., 2000], and this zonation in the plume conduit is being advected to the ridges [Thirlwall et al., 2004]. Alternatively, an asymmetry intrinsic to plume-ridge systems, which could influence the geochemistry of erupted basalts, is the distribution of mid-ocean ridges around the plume center. In this section we demonstrate with a simple kinematic model how ridge locations can give rise to asymmetric geochemical profiles, from a symmetrically outflowing plume. The key process is the partial melting of plume material as it flows under spreading ridges. First, the dynamics of the scenario are described, followed by a description of the kinematic model.

3.1. Dynamical Basis of Model

[28] Depending on the geometry of the plume–ridge system, there is the potential for different plume outflow paths to have traveled through variable lengths of melt region at a given distance from the plume center. This feature is evident from Figure 1, in which radially symmetric flow paths from each plume experience quite different lengths of subridge flow. This outflowing plume material will interact with the spreading centers it passes under. Corner flow beneath ridges creates regions of passive upwelling within the shallow asthenosphere, as mass moves in response to plate divergence. Hot plume material, flowing out beneath the high-viscosity lid of the anhydrous melt region, will decompress as material in the layer above upwells. Thus, different outflow paths cause plume material to have decompressed by varying amounts at a given radial distance from plume center.

Table 1. RMS and z Score RMS Misfits of the Maximum Symmetry Solutions From Misfit Mapping and From the Profiles Generated by Plotting About Our Preferred Plume Centers*  

<table>
<thead>
<tr>
<th>Observable</th>
<th>Maximum Symmetry</th>
<th>Preferred Plume Center</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>RMS</td>
<td>Z-RMS</td>
</tr>
<tr>
<td>Iceland</td>
<td></td>
<td></td>
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<td>Elevation</td>
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<tr>
<td>Crustal thickness</td>
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<td>$^{87}$Sr/$^{86}$Sr</td>
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<td>0.53</td>
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<td>$\varepsilon$Nd</td>
<td>0.38</td>
<td>0.60</td>
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<td>Zr/Y</td>
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<td>1.50</td>
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<td>Na</td>
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<td>0.86</td>
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<td>Galápagos</td>
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<tr>
<td>$^{87}$Sr/$^{86}$Sr</td>
<td>7.4 ($\times 10^{-5}$)</td>
<td>0.41</td>
</tr>
<tr>
<td>$\varepsilon$Nd</td>
<td>0.66</td>
<td>0.61</td>
</tr>
<tr>
<td>Azores</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elevation</td>
<td>0.06 km</td>
<td>0.29</td>
</tr>
<tr>
<td>$^{87}$Sr/$^{86}$Sr</td>
<td>4.9 ($\times 10^{-5}$)</td>
<td>0.41</td>
</tr>
<tr>
<td>$\varepsilon$Nd</td>
<td>0.50</td>
<td>0.38</td>
</tr>
</tbody>
</table>

*Z-RMS, z score root-mean-square. The error on the preferred plume center elevation Z-RMS misfits is one standard deviation.
previously, the rheological step that defines the top plume channel is likely the anhydrous peridotite solidus [Hirth and Kohlstedt, 1996]. Therefore, plume material will only melt below this depth if it is more fusible than typical depleted peridotite [Hirschmann et al., 1999]. However, there is compelling evidence to suggest that the mantle is compositionally heterogeneous on short length scales, consisting of enriched components within a depleted matrix [Zindler et al., 1979; Allègre and Turcotte, 1986; Stracke et al., 2003; Sobolev et al., 2005; Kokfelt et al., 2006; Maclennan, 2008]. These enriched portions of the mantle are likely to be lithologically distinct eclogitic or pyroxenitic blebs set within a more depleted peridotite matrix. The results of experimental petrology indicate that these assemblages have a lower solidus temperature than peridotite [e.g., Yaxley and Green, 2000; Kogiso et al., 1998; Hirschmann et al., 2003; Dasgupta et al., 2006; Yaxley and Sobolev, 2007], and as such begin melting at depths below the top of the plume channel. We thus envisage decompression of the plume material beneath spreading centers to generate small degree melts from the enriched blebs, while the depleted peridotite matrix remains unmelted. As the first few percent of melting will preferentially strip from the residue all the most incompatible elements, the bulk incompatible element concentration and isotopic composition of outflowing plume material will become progressively weighted to the depleted matrix. In this way, along-ridge gradients in geochemical proxies for plume dispersal can be generated, and asymmetry developed as a function of flow path.

Figure 8. Geochemical and geophysical data plotted as a function of radial distance from the preferred plume center for Iceland. Fracture zones are drawn as grey bars, in rough proportion to the distance range they cover and labeled the same color as the ridge segment they offset. SFZ, Spar Fracture Zone. The chemical data were Gaussian filtered at 85 km wavelength to produce running means and represent the smoothed profiles used in calculating misfit. Representative analytical error bars for the geochemical data are included for reference. While crustal thickness and elevation are broadly symmetric off-land, the trace element ratios and isotopes delineate a more depleted Kolbeinsey ridge. Asymmetry in Na$_8$ is less clear, with asymmetry present for just the first 75 km following the Tjornes Fracture Zone (TFZ).
Figure 9. Profiles plotted about the preferred plume center for the Galápagos. Details as in Figure 8. Ridge segments are split here as in Figure 1c. Isotopically, the eastern GSC shows a more depleted signature than the western sections of the ridge, with systematically higher $cN$ and lower $^{87}$Sr/$^{86}$Sr for most of its length. In elevation, ridge profiles are broadly symmetric east and west of the plume center, although slightly shallower depths (140 m) are found on the eastern segment west of the 95.5W transform. IFZ, Inca Fracture Zone; EFZ, Ecuador Fracture Zone; PFZ, Panama Fracture Zone.

Figure 10. Profiles plotted about the preferred plume center for the Azores. Details as in Figure 8. Ridge segments are split here as in Figure 1b. The filtered mean lines (thin blue and red lines) for the Azores are drawn only as far as data was fitted north and south of the plume center, the limit being the transition in chemistry north of the Kirchov Fracture Zone (KFZ) to increasingly enriched signatures, presumably associated with the transition to a separate (non-Azores influenced) mantle regime. A sampling gap between 38.0 and 38.4°N makes it difficult to constrain the near-plume symmetry, but for the data that are present the chemistry appears symmetric within the natural variability and analytical uncertainty. PFZ, Pico Fracture Zone.
The model is generated in two steps. First, a simple distance calculator is run to determine the distance plume material flows through deep subridge melt zones: these are the parts of the melt region where solid material has a significant horizontal component to its velocity and melt generation is predominantly from enriched fusible blebs. Above this depth, in the shallow melt region, the velocity field is dominated by corner flow and melt production is mostly from the depleted plume matrix. The distances calculated are then combined with simple models of melt extraction in order to track the depletion of a 1D column of plume material as it passes beneath spreading centers.

### 3.2. Melt Region Traversal Distance

The initial stage of the modeling is to determine the distance traveled through the deep melt regions by material reaching a ridge. A kinematic model is used in which a plume source flows radially outward from plume centers, intersecting ridge segments and their melt regions as it does so. The width of the deep melt region is a poorly constrained parameter in these calculations. Controlling factors are likely to be the ridge angle, itself at least partly a function of mantle viscosity, spreading rate, diffusivity and melt-solid density contrast [Spiegelman and McKenzie, 1987], and the depth at which plume material is spreading. Beneath a spreading center the latter parameter is assumed to be ~60–160 km, governed by the onset of dehydration melting, which provides a viscosity barrier to any shallower buoyant upwelling [Hirth and Kohlstedt, 1996; Ito et al., 1999; Hall and Kincaid, 2003]. The ridge angle however is unknown, thus given these uncertainties, a simplifying assumption is made of a constant 112 km across-axis width for all model runs (see Figure 1). For the purposes of trying to understand how asymmetry is generated, the absolute width is less significant than relative differences between melt region traversal distances. When calculating the distance through a deep melt region, the plume flow is reduced to a single dimension. Therefore, despite the plume material having some vertical thickness and depth range, which might be expected to feed into the width of the melt region for the enriched blebs, traversal distance is calculated only at a single depth of flow.

Maps illustrating the plume-ridge systems for each of the Iceland, Galápagos and Azores hot spots are presented in Figure 1. From these diagrams it is possible to qualitatively assess the asymmetry present in ridge geometry in each system, and therefore the effect this may have on trace element and isotopic symmetry. For Iceland, with the plume placed at the south eastern edge of the island, flow lines reaching the Kolbeinsey ridge must first traverse the base of the Northern Volcanic Zone, while plume material is fed to the Reykjanes ridge obliquely and without prior passage under a major spreading center (Figure 1a). Along the GSC the 91°W transform, ~2° north of the plume center, steps the eastern GSC south toward the Galápagos Islands. Simply from visual inspection of Figure 1c, it is clear the result of this transform is to cause material to enter the base of the eastern GSC melt region more obliquely than it does the western GSC. Therefore, the deep melt region path length of material destined for the eastern GSC is increased. In contrast to the previous two settings, where a pronounced asymmetry is visible, the Azores system appears essentially symmetric (Figure 1b).

The calculations of deep melt region distance traversed for flow lines reaching ridges around the Iceland, Galápagos and Azores plumes, are presented in Figure 11. For Iceland (Figure 11a) the north-south asymmetry identified from the map (Figure 1a), is manifest as a maximum difference in melt region distance traveled of ~390 km. Plume material reaching the Kolbeinsey ridge has systematically traveled a greater distance beneath melting regions than that reaching the Reykjanes ridge at an equivalent distance. This pattern is repeated in Figure 11e around the Galápagos plume, in which the eastern GSC is receiving plume material that has traveled obliquely along its length. Consistent with our previous inference of symmetry around the Azores, this system shows matching distances of melt region traversal north and south of the plume center. We have excluded the ultraslow spreading Terceira rift [Vogt and Jung, 2004; Beier et al., 2008] from consideration in these calculations, because its spreading rate is less than a tenth that of the adjacent MAR and thus its affect on asthenospheric velocity gradients is minimal.

The significant result of these simple distance calculations is that material traveling along axisymmetric flow paths from a plume can have experienced quite different degrees of interaction with spreading centers at the same radial distance.

### 3.3. Plume Material Preconditioning by Subridge Flow

Having established the distance that plume material is traveling through the subridge mantle,
prior to reaching spreading centers, it is possible to extend the calculation to tracking the material’s composition. Pearce [2005] defines and models mantle preconditioning for a variety of geodynamic scenarios, but primarily examines the geochemical consequences in isotope-trace element ratio space. Here, the modeling emphasis is placed on the need to relate spatial variables (upwelling rate, ridge location and plume position) to the source trace element chemistry. A simpler petrological model than that of Pearce [2005] is thus considered, in which the low degrees of melting modeled (5% maximum) allows for the melting reaction to be assumed constant. The model set up is illustrated in Figure 12.

[36] Plume material is modeled to contain a fusible enriched component present as a short-wavelength heterogeneity. These enriched blebs are progressively depleted by melting, up to a point where most of their incompatible element load will have been extracted. A fictive element, $\Psi$, with the properties of a light REE, is used to track the effect of partial melting on a 100 km thick column of this plume material. A fictive element is used because of the model’s simplicity, which makes predictions of actual source chemistry inappropriate. Our fictive tracer is given partition coefficients of 0.0005 in olivine and 0.033 in clinopyroxene and garnet. Mineral-melt partition coefficients are kept constant during melting. Initial mineral modal abundances are taken to be that of an enriched assemblage, 45:34.5:20.5 clinopyroxene:olivine:garnet, melting in the ratio 55:20:25. Partial melting of these blebs is calculated using Shaw [1970, equation 1]:

$$C_f = \frac{C_0}{(1-F)} \left(1 - \frac{\rho F}{\rho D}\right)^{1/\eta},$$

Figure 11. The cumulative deep melt region distance traveled by plume material reaching a given point on the ridge, plotted as a function of radial distance from plume center, for (a) Iceland, (c) the Galápagos, and (e) the Azores. The dark grey triangular area in each plot indicates the >1:1 region, and vertical light grey bars denote fracture zones. For Iceland and the Galápagos, material flowing north and east, respectively (red lines), traverses a greater melt region distance than that traveling south or west (blue lines); however, for the Azores no significant differences in melt region traversal distance occur north or south of the plume center. The Nd isotopic profiles around (b) Iceland, (d) Galápagos, and (f) Azores for comparison with the model result.
where $C_f$ is the source composition following melting by some fraction $F$, $C_0$ is the initial source composition and $P$ and $D$ are the bulk reaction coefficient and partition coefficient, respectively.

As the plume layer passes beneath spreading centers it is allowed to upwell. Using a simplified approximation of ridge driven corner flow, upwelling in the center of the deep melt region is taken to be $\frac{2}{3}V_x$, where $V_x$ is the half spreading rate, decreasing linearly to zero at 56 km from the spreading axis. The Euler poles for calculation of plate spreading rates are taken from DeMets et al. [1994]. In order to determine how far material upwells, a horizontal velocity also needs to be assigned to the outflowing material. Here we simply take the velocity for the whole radially outflowing plume layer ($\bar{u}$) to be that of the mean across stream velocity for Poiseuille flow, using the equation from Rudge et al. [2008, Appendix A], $\bar{u} = \frac{q}{2\pi r}$, where $r$ is radial distance from plume center and $q$ the mean area flux ($q = \frac{Q}{2h}$, $Q$ = volume flux and $h$ = channel width, 100 km). Velocity is thus expected to decrease with distance from plume center, causing melt region traversals to take longer and greater depletion and thinning of the plume layer to occur. Given the model’s aims are limited to describing relative differences in melting history of axisymmetric plume outflow, the effect of differences between the plumes is a secondary concern and thus $q$ is taken to be fixed for all plumes at $1.3 \times 10^6$ km$^2$/Ma.

Combining the melting and outflow kinematics enables the composition of enriched material within the plume layer to be tracked. Each increment of upwelling is translated into a fraction of melt generation ($F$), by taking traversal of the 100 km layer height to represent a total 5% melting and linearly relating smaller steps to this. After every stepped melting phase, the modal mineralogy and bulk partition coefficients are recalculated prior to melting progressing further. By this method an initial 100 km thick plume layer is generated at the top of the plume conduit, with a depletion gradient from the least melted at the bottom (as it has traveled only a short vertical distance across the plume channel) to the most depleted at the top. This melting above the stalk of the plume is analogous to intra-plate melting, where ocean island basalts are generated from the deep melting of plume material. The initial melting event is followed by further partial melting as the outflowing layer passes beneath ridges, with the top becoming entrained into the...
melting regions according to the amount of passive upwelling in the layer above. This subridge upwelling effectively drives the depletion of the enriched plume column. A material at the base is upwelled to replace that lost above, in doing so it melts and loses some of its trace element inventory. On reaching a particular segment of ridge, the plume channel will thus have been thinned and the bulk chemistry driven to more depleted compositions. The material flowing in below the plume layer to replace that lost at its top is depleted ambient upper mantle. This last point reflects the nature of the model we propose, in which the plume material represents a long-wavelength compositional anomaly in the mantle, consisting of small heterogeneities.

The model described above has been run for each of the Iceland, Galápagos and Azores plume-ridge systems, taking into account their varying along-ridge spreading rates and ridge geometries. The effect of the incremental fractional melting from subridge flow is recorded by the concentration of the fictive element $\Psi$, which is assigned properties similar to that of a LREE. Further details of the modeling can be found in section 3.1. For both Iceland and the Galápagos (Figures 13a and 13c), the plume source becomes variably depleted with distance. The Azores, however (Figure 13e), is essentially symmetric in source depletion about the plume center. Gaussian smoothed along-ridge Sr isotopic profiles for comparison with model results from (b) Iceland, (d) Galápagos, and (f) Azores.

**Figure 13.** (a, c, and e) Results of the kinematic modeling of source depletion during radial plume outflow. A single 100 km thick column of mantle is tracked from under the plume center, where an initial melting event occurs, to points along the ridge. Source depletion is tracked by the fictive element $\Psi$, which has been assigned properties similar to that of a LREE. Further details of the modeling can be found in section 3.1. For both Iceland and the Galápagos (Figures 13a and 13c), the plume source becomes variably depleted with distance. The Azores, however (Figure 13e), is essentially symmetric in source depletion about the plume center. Gaussian smoothed along-ridge Sr isotopic profiles for comparison with model results from (b) Iceland, (d) Galápagos, and (f) Azores.
Both Iceland and the Galápagos (Figures 13a and 13c) gradually develop a relative depletion of the material outflowing in one direction compared with the other, indicated by low concentrations of $\Psi$. This difference in depletion is fundamentally the result of plume material having upwelled further and having undergone more melting, before reaching a given point along the Kolbeinsey ridge or eastern GSC, than the material flowing south to the Reykjanes ridge or to the western GSC. More upwelling is experienced by material spending longer flowing under ridges, but also from vertical velocities under ridges being higher, which in this model is the result of an increased half spreading rate. For the Galapagos, spreading rate and melt region traversal distance (Figure 11c) are acting sympathetically to deplete plume material outflowing beneath the eastern GSC, the along-ridge gradient in plate spreading velocity being an increase toward the east, so that by 900 km from the plume center the eastern GSC is spreading $>20$ mm yr$^{-1}$ faster than the western GSC [DeMets et al., 1994]. However around Iceland, the along-ridge gradient of plate spreading velocities is a slight northward decrease [DeMets et al., 1994]. Despite this drop in spreading rate, the much greater melt region distance traveled by north flowing material counters the upwelling velocity effect and the north-south depletion offset develops. The Azores (Figure 13e), as expected from the distance calculation (Figure 11c), shows little difference in depletion about the plume center for the first $\sim$$350$ km. Beyond this distance, the northern MAR profile develops depletion with respect to the southern segment, however this is after the point at which the geochemical profiles can be compared for the Azores.

4. Discussion

Plots of along-ridge observables as a function of radial distance from preferred plume centers indicate that for trace elements, isotopic ratios and to a lesser extent major elements, significant asymmetry in along-ridge profiles is present. In contrast, the signal of plume swell at the ridge axis was shown to be essentially radially uniform at a given distance and misfit between the profiles, when present, was generally not systematic along ridges. There is thus the appearance of a decoupling between the geophysical and geochemical components of plume-ridge interaction. In an attempt to understand these observations a simple kinematic model was developed, which used the observation that melt region distance traversed by plume outflow is likely to be asymmetric about plume centers, as a function of the plume-ridge geometry. The concentration of a fictive element $\Psi$, was then tracked in the enriched portion of an outflowing mantle column, to explain in a very simple sense how the variable depletion of plume material at a given distance could be generated.

The model included a number of simplifying assumptions in order to track the depletion of material spreading out from the plume. These can be broadly grouped into assumptions regarding mantle velocity fields, about the dynamics of melting and of the composition, and compositional structure, of mantle plumes. It is useful to study these assumptions to determine which of the possible scenarios for plume-ridge interaction are consistent with the processes envisaged in our model and with the observed asymmetries around plume centers.

4.1. Mantle Velocity Fields

The velocity structure of the convecting interior of the earth is extremely difficult to measure through direct or indirect observation; this therefore places an emphasis on numerical modeling to provide constraints. However, the fluid mechanical properties of the mantle, which are vital for accurate simulation of plume dynamics, are also subject to uncertainties at the order of magnitude level. Within the confines of the physical or kinematical relations expressed in a model’s governing equations, there is thus a range of possible plume-ridge interactions as a function of input parameters. While the models therefore define a population of valid scenarios, observations of plume-ridge interaction on the earth must identify those that apply.

Modeling of plume-ridge systems has been undertaken by Ribe et al. [1995], Ribe [1996], Ito et al. [1999], Ribe and Delattre [1998], Hall and Kincaid [2003], and Ruedas et al. [2004], and a clear result from these studies is the importance of dehydration melting in controlling the nature of plume outflow. Hall and Kincaid [2003] find, in particular, that dehydration melting at the top of the conduit of an upwelling plume generates a plug of viscous material, flattening the rheological boundary layer and forcing plume material to flow out horizontally. In our model we have considered this horizontal flow to be axisymmetric about the plume center, interacting with the ridges only by gaining a vertical upwelling velocity and having its upper sections entrained into the shallow melt region.
Previous researchers, however, have suggested that flow can occur that is channelized under the ridge axis [White et al., 1995; Albers and Christensen, 2001]. Given the tendency of dehydration melting reactions to flatten the basal topography of the rheological lithosphere, the approximation of radial outflow seems justified and is consistent with independent constraints [White and Lovell, 1997; Jones et al., 2002; Poore et al., 2009]. Our conceptual model of asymmetry generation does not require radial outflow though and it would be possible for material flowing along the ridge axis to experience gradual extraction of the plume component in a similar manner to that proposed for radially spreading material. In this case the magnitude of asymmetry would be set by the relative proximity of ridges to the plume center, but in general channelized outflow would promote more symmetric along-ridge geochemical distributions.

A second question regarding the flow of plume material in the mantle is whether the tilt of plumes, coupled with plate shear, can cause the preferential advection of plume material in a particular direction. As noted previously, tilt of the Iceland, Galápagos and Azores plumes have all been used to explain asymmetry in along ridge observables [Shen et al., 2002; Schilling et al., 2003; Yang et al., 2006]. Our tests for symmetric plume centers allow for these conclusions to be reexamined. The key result from the misfit mapping is that when the geochemical and bathymetric profiles are plotted about a preferred plume center, bathymetry is symmetric (low Z-RMS misfit), but isotope and trace element profiles retain a strong asymmetry (Figures 8–10 and Table 1). This indicates the operation of a process to which the incompatible elements of the plume source are sensitive, but which essentially leaves the advection of the plume’s thermal signal unchanged. Preferential flow of plume material in the direction of plume tilt and/or in the direction of plate shear would not produce these observations; one would instead expect an asymmetry of this kind to concurrently influence basalt trace element chemistry and elevation at the ridge axis. The fact that we observe symmetry in bathymetry is thus consistent with a mainly radially uniform horizontal advection of the plume’s thermal signature.

We propose that the process which acts on this background of axisymmetric flow to generate asymmetry in the incompatible element and isotopic composition of ridge basalts, is deep partial melting of enriched components within the plume source during its transit beneath spreading centers. This process would have a minimal effect on the outflow of plume material. First, it would require only a small supply of latent heat from the overall thermal reservoir advected by plume material, the melt fractions modeled being at most 5%. Second, this low degree of melting is anticipated to occur before material intersects the anhydrous peridotite solidus, the point at which the greatest increases in viscosity are predicted [Hirth and Kohlstedt, 1996]. Finally, although the model includes thinning of the sheet of outflowing plume material as it is incorporated into the shallow subridge melt regions, only the uppermost several kilometers are lost this way, which would have a minimal isotatic effect. The anticipated absence of strong geophysical tracers of this partial melting event are why geochemical and geophysical profiles can become decoupled along ridges adjacent to a plume.

Fracture zones have also been suggested as potentially interacting with plume outflow, damping the spread of buoyant asthenosphere as it meets a step-like change in lithospheric thickness [Vogt and Johnson, 1975]. The likely importance of this process seems minimal however, given the previously discussed control of melting on the rheological lithosphere’s basal topography. The results of our model runs are sensitive to fracture zones though, and Figures 11 and 13 show that rapid changes in the deep melt region distance traversed and depletion of Ψ are present when ridge steps occur. This is a product of the simplicity of the model, which considers melt regions as discrete triangular zones of upwelling. With a more realistic corner flow model, these discontinuities in melt region distance profiles and Ψ would become smoothed, as the velocity field at depth is made continuous.

4.2. Plume Composition

There remain fundamental questions surrounding the composition and compositional structure of mantle plumes. Elevated incompatible trace element concentrations over regions of mid-ocean ridge have for a long time been taken as evidence for plumes supplying enriched material to the upper mantle [Schilling, 1973]. However, the superposition of compositional anomalies in the plume with its high upwelling velocity and elevated temperature, means that basalt chemistry records a convolution of source and dynamical signals [Maclennan et al., 2001; Ito and Mahoney, 2005]. A further uncertainty lies in the mapping of the
compositional variation from the mantle into volcanic systems in the crust, during which information on the spatial distribution of heterogeneities is lost [Rubin et al., 2009]. An important implication of this study is that ridge geometry’s influence in processing of mantle geochemical signals should also be included in future refinements of models that seek to use MORB compositions to extract the wavelength of mantle heterogeneity [Agranier et al., 2005; Meyzen et al., 2007].

Despite these hindrances to observing plume compositional structure, it is possible to make predictions about what the source material must be like in order for certain processes to be operating. In the case of our model, the development of asymmetry is dependent upon the presence of an enriched fusible component within the source. This component progressively melts out as the plume material is decompressed in the deep part of subridge melt regions, allowing for the development of plume material that is variably depleted in its enriched component as a function of deep melt region distance traversed. The model used to calculate the depletion of $\Psi$ specifically required a long-wavelength heterogeneity in the mantle, associated with the upwelling plume material. This is because lateral plume outflow was constrained to occur within a channel beneath the base of anhydrous melt regions. Had the mantle upwelling to compensate for the loss of plume material to the shallow melt regions been of the same composition and compositional structure (enriched blebs in a more depleted matrix) as the plume material, then there would have been no net change in source reaching the melt regions with distance from plume center. In such a scenario neither asymmetry nor a decrease in plume signature would have developed with distance from the plume center. Thus our model required ambient mantle to consist of a more depleted bulk composition to match the observations.

However, the assumption that plumes carry an enrichment that is either not present, or present only at much lower proportions, in the ambient mantle, does not have to hold. Outflow of the plume material in a channel below the anhydrous melt region, as in our model, is only one of multiple possible dynamical scenarios. If this constraint is relaxed, more complex situations can be explored involving the effects of temperature, composition and flow field, which could produce asymmetry without a long-wavelength compositional anomaly. One example would be allowing for some lateral flux of plume material within the anhydrous part of the melting region. In this event, ambient mantle material subjected to plume like flow fields, could create along-ridge incompatible element and isotopic profiles similar to those predicted for long-wavelength compositional anomalies. The requirement is, again, a compositionally heterogeneous source, with fusible components and a depleted matrix. Thus, the results of this study do not provide evidence for or against long-wavelength compositional variation in the mantle. Our model is simply one possible method for generating asymmetry, having used the assumption that plumes represent material of a different bulk composition to ambient mantle.

In the model of Murton et al. [2002], sheaths of transition zone and upper mantle material are wrapped around the Iceland plume during its ascent through the upper mantle. The effect is envisaged to be a plume with radially symmetric compositional zonation, mapped into MAR basalts as an along-ridge gradient in chemistry. We model the plume as heterogeneous, but in contrast to the Murton et al. [2002] model, with the enriched component uniformly dispersed. Although plumes may have internal compositional zonation, we do not consider it necessary in the case of either the Iceland or the Galápagos hot spots; both asymmetry in observables about the plume center and along ridge gradients in geochemical profiles can be explained simply by the progressive depletion of outflowing plume material.

4.3. Melting Dynamics

The feasibility of our model is dependent upon the greater fusibility of enriched heterogeneities compared with more depleted material, which enables there to be a decoupling in melting histories between components in the plume source. The matrix material, modeled as undergoing no melting in the deeper part of the melt region, is imagined to have lower water contents and a more refractory mineralogy, only beginning to melt when the anhydrous solidus is intersected. There is good reason to suspect that water content at even ppm level and a modal mineralogy richer in clinopyroxene and/or garnet, can produce mantle components that intersect their solidus at greater pressures than anhydrous peridotite. From both thermodynamic models [Hirschmann et al., 1999] and experimental constraints [Hirth and Kohlstedt, 1996; Pertermann and Hirschmann, 2003] it is likely that water can lower the depth of solidus intersection by 20–90 km and a pyroxenitic source composition.
by 35–50 km, depending upon the particular thermal and compositional regime studied. Nichols et al. [2002] have identified the Iceland plume as potentially having up to 920 ppm of water in its source. Were this volatile enrichment to be spatially coincident with the enrichment of other incompatible elements, then these enriched blebs would be particularly prone to subanhydrous solidus melt extraction. It therefore seems reasonable to suppose that partial melting of the enriched component within the mantle plume could be occurring at depths at which matrix peridotite remains subsolidus.

[53] An important assumption regarding the low-degree melting modeled, is that the melt generated is able to be extracted to the surface. Given the likely small overall melt fractions produced at this depth [Hirschmann et al., 1999], significant retention of the melt phase until major melting begins at the anhydrous solidus would dampen the development of depletion, possibly masking the effect altogether. However, from constraints placed on retained melt fractions from uranium series disequilibria, it is likely that separation of melt from source occurs once melting has exceeded only a few tenths of a percent [McKenzie, 2000]. It therefore seems plausible for the small melt fractions we model to be rapidly lost to the surface and the plume isotopic and incompatible element signature with them.

5. Conclusions

[54] Long-wavelength swell and isotopic profiles along the mid-ocean ridges adjacent to the Azores, Galápagos and Iceland hot spots have been assessed for their symmetry about an array of potential plume centers. It was found that the bathymetric profiles could be largely reconciled with symmetric plume outflow with little systematic depth anomaly between ridge segments. However, around Iceland and the Galápagos, isotopic profiles (and in the case of Iceland the incompatible element profiles) are fundamentally asymmetric. The Kolbeinsey ridge and Galápagos Spreading Center east of the 91° West Transform, both showed a more rapid decline back to MORB like εNd and 87Sr/86Sr values than corresponding ridge segments on the other side of the plume. In the region where comparisons are meaningful and given the scatter of the data, the Mid-Atlantic Ridge around the Azores records more symmetric plume-ridge interaction.

[55] In order to understand these observations a kinematic model was developed examining the role of plume-ridge geometries in imprinting differing source characteristics on the plume material reaching ridges. The key assumptions of the model are that plume outflow is radial and that the plume material consists of an enriched phase embedded in a more depleted matrix. The greater fusibility of the enriched material leads to its melting at a higher pressure than the matrix, allowing for a decoupling in the melting histories of the two components. Thus, by partial melting of the more fusible heterogeneities during flow under spreading centers, the isotopic composition of the plume material is progressively weighted to that of the remaining matrix. In consequence ridge source material is depleted as a function of melt region distance traversed and distributed about the plume center symmetrically or asymmetrically according to the particular plume-ridge geometry.

[56] The result of applying this model to the Icelandic and Galápagos plume-ridge systems is an asymmetry in source depletion consistent with their observed along-ridge geochemical profiles; the greater melt region distance traveled by material flowing north in Iceland’s case and east from the Galápagos, results in it being more heavily depleted, which is expected to produce a more depleted erupted basalt chemistry along these ridge segments. For the Azores, source depletion is predicted to be similar north and south of the plume, although the limited data available render this poorly constrained. After the initial decay in Azores plume influence, the transition to increasingly enriched lavas north of the Azores cannot be explained by the model and thus another geodynamic forcing is required. However, for the Iceland and Galápagos plumes it is possible to predict an asymmetry in the sense observed, without need for plume zonation, tilt or lithospheric damming of outflow. In fact, the strong symmetry present in bathymetric and crustal thickness profiles indicates that plume dispersal is essentially radially symmetric. Geochemical asymmetry can be generated solely by the variable degree of partial melting of fusible heterogeneities in the plume source.

Appendix A: Calculating z Score Root-Mean-Square Misfit

[57] The z score root-mean-square misfit (Z-RMS) is calculated according the equation, Z-RMS = (∑x=−d0 (px − qx)²/N)⁰.⁵, where px and qx are values of the normalized geophysical or geochemical observable along each profile at a distance x from
the plume center and \( N \) is the total number of points along the profile considered. The starting distance \( d_0 \), is the common distance of closest approach of each profile to the plume center and \( d \), the common furthest distance along each profile. When profiles are different lengths the distance of the longer is reduced to the same range as the shorter.

**Appendix B: Handling of Geophysical and Geochemical Data**

[58] Elevation: Axial profiles of elevation were picked from a low-pass filtered version of the GEBCO_08 global elevation and bathymetry gridded data set (version 20090202, http://www.gebco.net). The filtering was applied using the same technique as Canales et al. [2002], with an 85 km cutoff wavelength such that the picked topography reflected long-wavelength swell and not variations in ridge morphology. For Iceland, data was included south along the Northern Volcanic Zone to 64.75°N, this southern limit placed due to a transition to the propagating Eastern Volcanic Zone.

[59] Crustal thickness: Estimates of crustal thickness have only been included for the Iceland plume-ridge system. Data from Darbyshire et al. [2000] was used for the on-land sections of ridge, Hooft et al. [2006] data for the Kolbeinsey ridge and Poore [2008] for estimates of crustal thickness along the Reykjanes ridge. The resolution at which crustal thickness is mapped being already low, this data was neither smoothed nor filtered.

[60] Geochemical profiles: For the purposes of calculating Z-RMS misfit between two profiles either side of a plume center, the scattered raw data needs to be represented by a single “mean” line. Equally, short-wavelength variability in the chemical signal needs to be removed in order to expose the longer-wavelength signature of plume influence. To meet these requirements, raw chemical data was smoothed by a Gaussian filter of 85 km width (standard deviation 14.2 km) and it was this profile that was interpolated for misfit mapping. Although the techniques differ, this wavelength of smoothing is in accordance with the wavelength used to filter bathymetric data, thus profiles of geochemical and geophysical observables preserve spatial variability on similar scales.

[61] The major elements have been corrected in an attempt to compensate for the effects of low-pressure fractionation according to the scheme of Klein and Langmuir [1987] and are presented as \( X' \), where “8” indicates a shift back to the concentration of X at 8 wt % MgO; however, rather than use a fixed regression line, a local correction gradient was calculated from all available data, giving the equation \( Na = Na_2O + 0.27(MgO - 8) \). Only lavas with MgO concentration between 5 and 8.5 wt % MgO have been included for correction. Incompatible trace element ratios can be moderately sensitive to fractional crystallization, although only in the most evolved melts, therefore lavas with MgO <6 wt % have been excluded from the profiles.

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**References**


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