Melting, dehydration and the geochemistry of off-axis plume-ridge interaction

Paul S. Hall* and Chris Kincaid (*corresponding author)

Graduate School of Oceanography, University of Rhode Island, Narragansett, RI 02882; 401.874.6573 (phone); 401.874.6811 (fax); phall@gso.uri.edu, kincaid@gso.uri.edu

Abstract. We present results from a series of two-dimensional numerical experiments in which synthetic melt compositions are calculated for a system in which a thermally buoyant, off-axis mantle plume interacts with a nearby ridge axis. Spatial gradients in synthetic melt properties are compared to observed spatial gradients in geochemistry from the Easter – Salas y Gomez system in an effort to constrain the dynamics of mantle flow in off-axis plume-ridge systems. Results indicate that observed gradients in isotope ratios between the ridge axis and the plume require significant heating of the ambient mantle adjacent to the plume. This heating allows ambient mantle to melt off-axis, but also attenuates the flow from the plume to the ridge. When increases in viscosity due to dehydration during melting are considered, spatial gradients in the geochemical properties of synthetic melts become extremely sharp, at odds with the observational data. This may indicate that viscosity increases due to dehydration are not significant in off-axis plume-ridge systems.

1. Introduction

The nature of the interaction between mantle plumes and the global mid-ocean ridge system has been the subject of study and speculation since plumes were first proposed as the dynamical mechanism behind hotspots by Morgan [1971]. This interaction is most dramatic where the plume is located directly beneath or immediately adjacent to a ridge segment (e.g., Iceland, Azores), and the earliest studies focused on both the geophysical [Vogt, 1971] and geochemical [Hart et al., 1973; Schilling, 1973; Sun et al., 1975] manifestations of interaction at these on-axis systems. Subsequently, plumes located at appreciable distances off-axis (e.g., Galapagos, Easter-Salas y Gomez) were proposed to interact with the ridge system via pipeline-like flows along the base of the lithosphere (Figure 1a) [Morgan, 1978]. This hypothesis, made on the basis of seafloor morphology, has since been supported by studies of off-axis variation in gravity and bathymetry [Ito and Lin, 1995; Small, 1995], along-axis variation in geochemistry [Schilling et al., 1983; Schilling et al., 1985; Poreda et al., 1993; Douglas et al., 1995; Douglass et al., 1999] and across-axis variation in geochemistry [Hanan and Schilling, 1989; Haase and Devey, 1996; Kingsley and Schilling, 1998; Pan and Batiza, 1998; Harpp and White, 2001; Kingsley, 2002; Kingsley et al., 2002]. Consideration of the length of along-axis geochemical anomalies and excess crustal production at the associated ridge segments suggests that such flow between a ridge and an off-axis plume is possible for plume-ridge separation distances of as much as 1700 ± 250 km [Schilling, 1991].

The dynamics of off-axis plume-ridge interaction has been investigated using both laboratory [*Kincaid et al.*, 1995] and numerical [*Kincaid et al.*, 1996; *Ribe*, 1996; *Ito et*

al., 1997; *Hall and Kincaid*, 2003] models of mantle flow. Laboratory models of thermally buoyant off-axis plumes have suggested the viability of the pipeline model of plume-ridge flow [*Kincaid et al.*, 1995], while numerical models have been used to develop scaling laws relating the spread of plume material along axis to the flux of plume material in the conduit and the spreading rate [*Ribe*, 1996; *Ito et al.*, 1997]. Numerical models have also suggested the importance of the slope of the base of the lithosphere in modulating flow to the ridge axis from the plume [*Kincaid et al.*, 1996; *Hall and Kincaid*, 2003]. Recently, the affect of melting on the dynamics of off-axis plume-ridge interaction has been investigated [*Hall and Kincaid*, 2003]. In particular, viscosity increases related to dehydration during melting have been found to lead to the creation of a large viscous plug on the base of the lithosphere above the plume (Figure 1b) [*Hall and Kincaid*, 2003]. The issue of dehydration is particularly important to studies of plumes, since plumes generally have higher water contents than the ambient upper mantle [*Schilling et al.*, 1983; *Wallace*, 1998; *Dixon et al.*, 2002].

We use numerical models of mantle flow to examine spatial variations in the geochemistry of melts generated in off-axis plume-ridge systems. Significant differences in flow between systems in which viscosity is only a function of temperature [i.e., $\eta(T)$] and systems in which viscosity is a function of temperature and water content [i.e., $\eta(T,F)$] lead to differences in the geochemical signatures of the resulting melts. Comparison of the properties of these synthetic melts to geochemical data from off-axis plume-ridge systems therefore provides a means of constraining the dynamics of these systems.

2. Model

2.1. Conceptual Model

Plume-ridge interaction may be described by the plume-source/ridge-sink model (Fig. 1a). A near-ridge plume moves vertically through the mantle due to buoyancy forces until it impinges on the sloping base of the lithosphere, where the plume begins to spread horizontally along the base of the lithosphere. The subsequent horizontal dispersion of the plume is governed by the balance between the viscous drag imparted by the motion of the overlying plate and the ambient mantle and gravitational spreading of the buoyant plume material, which drives the plume material upslope along the base of the lithosphere (i.e., towards the nearby ridge) [*Ribe*, 1996]. This force balance is controlled in part by the difference between plume and ambient mantle viscosities [Griffiths and Campbell, 1991]. Recent laboratory experiments suggest that the presence of water may have a profound effect on the viscosity of peridotite, reducing the viscosity by between 2 and 3 orders of magnitude relative to dry mantle at the same pressure and temperature [Hirth and Kohlstedt, 1996]. As a consequence, initially wet peridotite will experience a substantial increase in viscosity as it undergoes dehydration early in the melting process. This has been shown to affect mantle flow and melting at ridge axes [Braun et al., 2000; Hall and Parmentier, 2000], in on-axis plume-ridge systems [Ito et al., 1999] and in off-axis plume-ridge systems [Hall and Kincaid, 2003]. In off-axis systems, an increase in viscosity due to dehydration during melting leads to the creation of a large viscous plug at the base of the lithosphere above the plume (Figure 1b) [Hall and Kincaid, 2003]. The resulting mantle flow differs significantly from flow in systems in which viscosity is not a function of water content. These differences in flow lead to differences in the spatial distribution of melting and therefore in the chemistry of the resulting melts. A comparison of synthetic melts from these different systems to observational geochemical data should therefore provide constraints on the dynamics of off-axis plume-ridge systems, and in particular on role of viscosity increases due to dehydration.

2.2. Numerical Model

Numerical experiments were conducted which modeled mantle flow in the plumeridge system as convection of a viscous, Boussinesq, Newtonian fluid within a twodimensional (2-D), regular Cartesian domain representing a vertical slice through the upper mantle oriented perpendicular to the ridge axis and passing through the center of the plume (Figure 2). The aspect ratio of the model domain is 3:1, corresponding to horizontal and vertical dimensions of 1200 km and 400 km, respectively. The computational grid is regular and Cartesian, with 288 elements in the horizontal and 96 in the vertical. The top boundary is impermeable and has a fixed temperature (T=0). The bottom boundary is permeable and stress-free with a fixed temperature ($T=T_m$). Sidewalls are permeable, stress-free and insulating. Material is free to enter or leave the domain through the bottom or either of the side boundaries.

Spreading plates are represented by a divergent horizontal velocity imposed along the upper boundary. A horizontal velocity $\pm U_0$, corresponding to the plate velocity, is assigned along the top boundary. A plate speed of 4.8 cm/yr was adopted for these experiments. This prescribed plate speed is zero at the ridge axis and increases linearly to a constant value within three grid points on either side of the ridge axis. The velocities on each side of the ridge axis are equal in magnitude, but opposite in sign, so as to induce a symmetric corner flow. Plate scale flow within the model domain is therefore assumed to be a passive response to the motion of plates which are driven by body forces concentrated far outside the boundaries of the model.

In order to best utilize the model to investigate flow between the plume and the ridge axis, the ridge and plume are both positioned off-center within the model domain. The ridge is located to the left of center, while the plume is located to the right. While previous studies have demonstrated that the flux of plume material from an off-axis plume to a ridge decreases with increasing plume-ridge separation [*Kincaid et al.*, 1996], the distance between the plume and the ridge is held constant in these experiments ($L_{pr} = 450 \text{ km}$).

Lagrangian particles are used to track the plume and model the melting process. Two separate clouds of particles, designated 'plume mantle' and 'ambient mantle', are initially distributed within the model domain as in Figure 2. Additional particles are added to the domain along the bottom boundary as particles are advected away with the flow so as to maintain a relatively constant density of particles. Particles leaving the model domain through the bottom or either of the side boundaries are no longer tracked. Thermal buoyancy is imparted to the plume particles by assigning temperatures which are elevated relative to the ambient mantle rising through the bottom boundary to the nodes in the plume source region. We assume a plume temperature anomaly, or excess temperature, of 200 °C in this region.

The relevant system of dimensionless model equations to be solved includes the conservation of mass, momentum and energy. Viscosity is modeled using an Arrhenius law modified by several pre-exponential coefficients, i.e.,

$$\eta = A_1(T)A_2(F)\eta_0\left\{\max\left(1, \exp\left[E\left(\frac{1}{T}-1\right)\right]\right)\right\}$$
(1)

where *T* is dimensionless potential temperature, *F* is degree of melting (or depletion), E is a dimensionless activation energy (E = 30 in this study) and η_0 is a reference mantle kinematic viscosity. The exponential term creates a highly viscous rheological boundary layer (RBL), corresponding to the lithosphere, along the cold upper boundary of the model domain. The pre-exponential term *A*₁ accounts for reductions in viscosity due to the high temperatures associated with the plume:

$$A_{1} = \frac{1}{1 + \left[\left(\frac{\Delta \eta_{T} - 1}{2} \right) \left(1 + \tanh\left(\gamma \left(T - T_{p}\right) \right) \right) \right]}$$
(2)

Here γ controls the sharpness of the decrease in viscosity, $\Delta \eta_T$ controls the magnitude of the viscosity reduction ($\Delta \eta_T = 0.1$ in this study), and T_p is the dimensionless plume potential temperature (i.e., T_p = T_m + 200 °C) [Kincaid et al., 1996]. Note that the 'max' function, which returns the maximum of either the exponential term or one, allows the high temperature effects to be isolated within the pre-exponential term A_1 . The magnitude and character of this effect can then be varied without impacting the RBL. The effect of dehydration on viscosity is modeled with the second pre-exponential coefficient, A_2 . We assume an abrupt increase in viscosity by a factor of 50 during the first 1% melting at the dry solidus, so that A_2 has a value of 1 for F = 0 and a value of 50 for $F \ge 0.01$ [*Ito et al.*, 1999, *Hall and Kincaid*, 2003]. A_2 increases linearly between F = 0 and F = 0.01. Thus for experiments which do not consider the effects of dehydration on viscosity, $A_2 = 1$ and viscosity is only a function of temperature [i.e., $\eta(T)$]. For experiments that do consider viscosity increases due to dehydration, viscosity is a function of both temperature and degree of melting [i.e., $\eta(T,F)$].

A maximum cut-off viscosity of $\eta_{max} = 100\eta_0$ is used in these experiments, and the minimum model viscosity, found in the hot plume, is $\eta_{min} = 0.1\eta_0$. This allows a maximum viscosity variation of 10^3 within the model domain. A detailed description of the numerical model and the viscosity law is given in *Hall and Kincaid* [2003].

2.3. Melting and Synthetic Melt Properties

A non-diffusive Lagrangian particle technique is employed for tracking the plume and implementing melting [*Kincaid et al.*, 1996; *Manglik and Christensen*, 1997; *Hall and Kincaid*, 2003; *Kincaid and Hall*, 2003]. Individual particles are transported through the model domain by solving the advection equation for each particle using a Runge-Kutta step. Melting is modeled on the scale of the individual particles, and melt is extracted at every time step (i.e., fractional melting). For a given particle, the energy available for melting is related to the difference between the temperature of the particle and the temperature of its solidus at that depth. In order to determine the incremental degree of melting, ΔF , this energy is partitioned between heat loss to latent heating and isobaric melt production [*Langmuir et al.*, 1992], i.e.,

$$\Delta F = \frac{T_R - T_s}{\frac{\mathrm{d}T}{\mathrm{d}F}\Big|_{\mathrm{p}} + \frac{T_R \Delta S}{C_{\mathrm{p}}}}$$
(3)

where T_R is the particle temperature, including the mantle adiabatic gradient (dT/dz=0.5°C km⁻¹), T_s is the solidus temperature, ΔS is the entropy of fusion for peridotite ($\Delta S =$ 400 J kg⁻¹ °C⁻¹), C_p is the heat capacity of peridotite (C_p = 1250 J kg⁻¹ °C⁻¹), and (dT/dF)|_p is the inverse of the isobaric melt productivity, which is related to the temperature difference between contours of constant melting at a given depth. We use a parameterization of the peridotite solidus and liquidus [McKenzie and Bickle, 1988], and assume the contours of constant depletion to be spaced uniformly between the solidus and liquidus at any given depth. The small amount of melt produced between the wet and dry solidi (~1% [Hirth and Kohlstedt, 1996]) is ignored, and melting is only calculated relative to the dry solidus. The total degree of melting for a particle, F, is the sum of all of the incremental degrees of melting it has experienced. At the level of the model grid, degree of melting, which is used to calculate viscosity, is determined at the grid nodes by averaging the total degree of melting of the particles in the adjacent computational elements. A full description of the particle tracking and melting routines is given in Hall and Kincaid [2003].

Once the incremental degree of melting for an individual particle has been calculated, the concentration of a given trace element in the resulting melt, C, is calculated assuming fractional melting, i.e.,

$$C = C_0 \frac{1}{D} (1 - F)^{\left(\frac{1}{D} - 1\right)}$$
(4)

where C_0 is the initial concentration of the element in the solid and *D* is the partition coefficient for the element [*Langmuir et al.*, 1992]. In this study, representative trace elements ranging from incompatible (D = 0.01, D = 0.1) to perfectly compatible (D = 1.0) to compatible (D = 10.0) are considered. The melts from all particles within a given column of computational elements are pooled and the properties of the resulting accumulated melt are calculated. The resulting accumulated melts for the individual model grid columns are then averaged using a moving average with a window 17 columns in width, corresponding to a horizontal length scale of ~70 km. This is meant to reflect the pooling of melts at the scale of individual volcanic centers within an island chain, and the chosen length scale reflects the spacing of volcanoes within the Hawaiian Islands [*ten Brink*, 1991; *Hieronymous and Bercovici*, 1999].

3. Results

While a number of quantitative measures can be used to characterize pooled melts, we focus on the relative volumetric contribution of the plume to the accumulated melt (% plume), the average total degree of melting of particles contributing to the accumulated melt (F), the volume weighted mean depth of melting and non-dimensional isotope ratios (I).

The fractional percentage of the total volume of the accumulated melt deriving from the plume is simply the ratio of the volume of melt derived from plume particles to the total volume of the accumulated melt (derived from both plume and ambient mantle particles). This can be expressed as

%plume =
$$\frac{V^p}{V^p + V^a}$$
 (5)

where V^p is the volume of a particular pooled melt that derives from the plume and V^a is the volume that derives from the ambient mantle. These volumes are determined numerically by simply summing the contributions from the individual plume and ambient mantle particles. More explicitly, for m ambient mantle particles and n plume particles contributing to a pooled melt (5) can be written

%plume =
$$\frac{\sum_{j=1}^{n} v_{j}^{p}}{\sum_{i=1}^{m} v_{i}^{a} + \sum_{j=1}^{n} v_{j}^{p}}$$
 (6)

where v_i^a and v_j^p are the volumes of melt from the individual ambient mantle and plume particles, respectively. The fractional percentage of melt derived from the plume can thus vary between 0 (no plume contribution, all ambient mantle) to 1 (all plume, no ambient mantle contribution). This provides a simple measure of the plume contribution to the melt at a given location.

The average degree of melting for the accumulated melt (\overline{F}) is just the average of the total degrees of melting of the individual particles contributing to the melt. For *m* ambient mantle particles and *n* plume particles contributing to the accumulated melt this can be written

$$\overline{F} = \frac{\sum_{i=1}^{m} F_i^a + \sum_{j=1}^{n} F_j^p}{m+n}$$
(7)

where F_i^a and F_j^p are the total degrees of melting for the individual ambient mantle and plume particles, respectively. \overline{F} is a function of both the temperature of the particles at that location and the thickness of the lithosphere. Higher temperatures (i.e., those associated with the plume), lead to higher total degrees of melting and therefore greater depletion of the residual mantle. Similarly, thin lithosphere allows for the ascent of mantle material to shallower levels than thick lithosphere, leading to greater decompression and thereby higher total degrees of melting. The volume weighted mean depth of melting, \bar{z} , is determined by taking the average of the depths of each particle that contributes to the accumulated melt, weighted by the volume of melt produced by that particle. For a melt accumulated from *m* ambient mantle particles and *n* plume particles this is written

$$\overline{z} = \frac{\sum_{i=1}^{m} v_i^a z_i^a + \sum_{j=1}^{n} v_j^p z_j^p}{\sum_{i=1}^{m} v_i^a + \sum_{j=1}^{n} v_j^p}$$
(8)

Here z_i^a and z_j^p are the depths of the individual ambient mantle and plume particles, respectively. As with \overline{F} , the depth of melting is related to the thickness of the lithosphere and the temperature relative to the mantle potential temperature. The depth of melting is of importance geochemically because differences in mineral assemblages with depth, in particular the presence of garnet at depth, lead to variations in the partition coefficients of trace elements with depth. Because of this, melts generated at different depths can have significantly different trace element signatures.

Isotope ratios are particularly useful in studies of plume-ridge interaction because isotopes don't fractionate during melting and plumes and ambient mantle typically have distinct isotopic signatures [e.g., *Sun et al*, 1975; *Hanan and Schilling*, 1989; *Kingsley and Schilling*, 1998; *Harpp and White*, 2001]. Isotopes can thus be used to trace compositionally distinct regions within the mantle (e.g., plumes) much as dyes are used in laboratory fluid dynamic experiments. For a melt accumulated from m ambient mantle particles and n plume particles the isotope ratio for a particular element, I, can be calculated from

$$I = \frac{I^{a} \sum_{i=1}^{m} C_{i}^{a} v_{i}^{a} + I^{p} \sum_{j=1}^{n} C_{j}^{p} v_{j}^{p}}{\sum_{i=1}^{m} C_{i}^{a} v_{i}^{a} + \sum_{j=1}^{n} C_{j}^{p} v_{j}^{p}}$$
(9)

Here I^a and I^p are the isotope ratios and C_i^a and C_j^p are the concentrations of the particular trace element in the incremental melt for the individual ambient mantle and plume particles, respectively. For convenience, values of $I^a = 0$ and $I^p = 1$ are adopted. C_i^a and C_j^p are calculated from (4) by assuming a value for C_0 for both the ambient mantle and plume components. In particular, a value of $C_0^a = 1$ is assumed for the ambient mantle particles while a value of $C_0^p = NC_0^a$ is adopted for the plume particles. Here N is an enrichment factor that accounts for the fact that the plume and ambient mantle may have different initial concentrations of a particular element. A value of N =1 implies that the elemental concentrations in the plume are the same as in the ambient mantle while N > 1 implies that concentrations in the plume are a factor of N greater than in the ambient mantle. This correction is important because plumes are generally believed to be enriched in incompatible elements relative to the ambient mantle. In this study enrichment factors of N = 1 and N = 5, which define the extremes of enrichment within which the Easter - Salas y Gomez plume is believed to lie [Kingsley and Schilling, 1998], are considered.

I is similar to the volumetric percentage of plume in that it reflects the relative contribution of the plume to the accumulated melt. However, since elements with different distribution coefficients enter the melt in different proportions for a given degree of melting, *I* also takes into account variations in degree of melting in the system. Absolute values of *I* can be scaled to particular isotopes at specific plume-ridge systems

through the choice of I^a and I^p . The patterns of spatial variation in I can be compared directly to observed spatial variations in isotope ratios.

3.1. No Heating of the Ambient Mantle

A set of numerical experiments were conducted in which an excess temperature of 200 °C above the mantle potential temperature was applied to the computational elements representing the plume conduit at the base of the model domain (temperature model T_0). Experiments both with and without dehydration related viscosity increases were considered. Results show that melts derive entirely from the plume ridgeward from the plume to within 50 km of the ridge axis (Figure 3a). In the vicinity of the ridge the contribution from the plume drops off rapidly. This transition is somewhat more abrupt for experiments in which the effects of dehydration on viscosity are considered [i.e., $\eta(T,F)$]. The average degree of melting is also consistently lower for these experiments. This reflects the presence of the viscous plug which effectively thickens the lithosphere, limiting decompression (and hence melting) off-axis. The effect of the viscous plug is also seen in the mean depth of melting, which is greater for experiments with dehydration related viscosity increases than for those without (Figure 3c). There is a marked asymmetry in the depth of melting about the ridge for cases with dehydration viscosity effects, mirroring the asymmetry in mantle viscosity created by the viscous plug [Hall and Kincaid, 2003].

As with the volume fraction of melt (Figure 3a), isotope ratios exhibit a sharp gradient, from entirely plume-derived to entirely ambient mantle-derived, in the vicinity of the ridge axis (Figures 4 and 5). The sharpness of this gradient is a function of

partition coefficient, and the transition is significantly more abrupt for cases with viscosity increases due to dehydration (Figures 4b and 5b) than in those without (Figure 4a and 5a). Gradients in isotope ratios for cases with a plume enrichment factor of N = 5 (Figure 5) are somewhat more gradual than in experiments with N = 1 (Figure 4), but the differences are not very pronounced.

3.2. Heating of the Ambient Mantle

Experiments were conducted to consider the effect of diffusion of heat from the plume conduit to the surrounding ambient mantle. Temperature profiles along the bottom boundary of the model domain were created for different heat transfer scenarios in which the ambient mantle adjacent to the plume was taken to be in contact with the plume conduit for varying lengths of time, depending on the velocity of the ambient mantle material as it travels along the plume conduit. Assumed velocities for the ambient mantle ranged from 5.0 cm/yr (temperature model T₁), which is roughly equivalent to the plate velocities in the experiments, to 2.0 cm/yr (temperature model T₄). Taking the distance traveled along the plume conduit to be ~2600 km (i.e., from the core-mantle boundary to the base of the model domain at 400 km depth) this results in the ambient mantle being in contact with the plume conduit for periods ranging from ~52 Myr (T₁) to ~130 Myr (T₄) prior to reaching the depth of 400 km. Resulting temperature profiles for the various temperature models are shown in Figure 6.

The effect of these different temperature boundary conditions can be visualized by considering the trajectories of individual ambient mantle particles in depth (i.e., pressure) – temperature space. Individual plume and ambient mantle particles can be tracked throughout the model domain. The trajectories for particles with the same initial positions can be very different for cases with and without dehydration (Figure 7). In depth – temperature space the effects of increased temperature on the ambient mantle particles are readily demonstrated. For the ambient mantle particles closest to the plume conduit, temperatures are offset to significantly higher values at the base of the model domain and the particles intersect the solidus at much greater depths than in cases without heating of the ambient mantle (i.e., temperature model T_0), both with and without dehydration related viscosity effects (Figure 8). For ambient mantle particles further removed from the plume conduit, the difference between heating models becomes more pronounced, as the difference in temperatures between models becomes greater (Figure 9). These particles do not experience melting for cases with dehydration, because they are deflected horizontally at depth by the viscous plug (Figure 9b). In cases without dehydration, however, these particles do experience melting in when heating of the ambient mantle is considered (Figure 9a).

Experiments utilizing temperature model T_1 were conducted for cases both with and without dehydration related viscosity increases. Results for cases with dehydration show much the same structure as in experiments without heating of the ambient mantle (i.e., temperature model T_0), though the region in which the transition from plume to ambient mantle derived melt occurs is slightly wider (Figure 10a). This is also apparent in the plots of *I* for the dehydration cases (Figure 11b and 11b). For cases without dehydration related viscosity increases, however, the distribution of the melt properties is dramatically different than in experiments utilizing temperature model T_0 . The transition between plume-derived melts and ambient mantle-derived melts is spread out across almost the entire distance from the plume conduit to the ridge axis. There is also a prominent pulse of ambient mantle-derived melt close to the plume conduit, related to the off-axis melting of the heated ambient mantle material immediately adjacent to the plume conduit (Figure 10a). A similar anomaly is present in the isotope ratios for these experiments (Figures 11 and 12). In addition, average depths of melting off-axis are greater than in experiments using temperature model T_0 , reflecting the melting of this hot, deep ambient mantle material off-axis.

For experiments conducted using temperature model T_4 the flow of plume material to the ridge is substantially decreased. In cases with dehydration related viscosity increases the plume material is actually swept away from the plume conduit in the direction opposite the ridge, and no plume material is observed between the conduit and the ridge (Figure 13a). Accordingly, there is no gradient in isotope ratios between the plume conduit and the ridge for these cases (Figures 14a and 15a). Cases without dehydration related viscosity increases show a broad gradient in plume contribution to melts between the conduit and the ridge axis (Figure 13a). Higher mean degrees of melting and greater depths of melting on the plume side of the ridge axis reflect the deeper melting of hotter ambient plume material (Figure 13b and c). Isotope ratios likewise show a gradient between plume and ambient mantle contributions to the melt between the plume conduit and the ridge. Substantial melting of the hot ambient mantle adjacent to the plume en route to the ridge leads to a large decrease in both the relative volume of plume material contributing to the melt (Figure 13a) and isotope ratios (Figures 14a and 15a) very close to the plume conduit.

4. Discussion

A comparison of the properties of synthetic melts from the numerical experiments to geochemical data from off-axis plume-ridge systems provides a means of constraining the dynamics of these systems. The geochemistry of the Easter – Salas y Gomez system has been studied extensively [Schilling et al., 1985; Hanan and Schilling, 1989; Poreda et al., 1993; Haase and Devey, 1996; Kingsley and Schilling, 1998; Pan and Batiza, 1998; Kingsley et al., 2002; Kingsley, 2002], providing for a good comparison. Of particular relevance, observations of off-axis gradients in isotope ratios exist for a number of isotopic systems, including Pb [Kinglsey and Schilling, 1998], H [Kingsley et al., 2002], and Sr, Nd and Hf isotopes [Kingslev, 2002]. Trends in isotope ratios are grossly consistent amongst these various isotopic systems for Easter - Salas y Gomez. ²⁰⁸Pb/²⁰⁴Pb is taken as a representative isotopic system and available data are shown in Figure 16. Values of ²⁰⁸Pb/²⁰⁴Pb are relatively uniformly elevated in the region surrounding Salas y Gomez, which is taken to be the location of the plume conduit. Values of ²⁰⁸Pb/²⁰⁴Pb then decrease between Easter Island and the East Rift of the Easter Microplate as ambient mantle, with relatively low values of ²⁰⁸Pb/²⁰⁴Pb, begins to contribute substantially to the melt. This gradient thus reflects mixing of plume-derived and ambient mantle-derived melts in different proportions. Between these two regions, in the area to the east of Easter Island, there is a small region in which values of 208 Pb/ 204 Pb show considerable scatter. This may reflect an enhanced contribution of melt from melting of ambient mantle.

The abrupt transition from plume-derived to ambient mantle-derived melts seen in experiments without heating of the ambient mantle by the plume (i.e., temperature model T_0) is at odds with the gradual gradients in isotope ratios seen in the Easter – Salas y Gomez system (Figures 4 and 5). Gradients in melt properties are much more gradual in experiments in which heating of the ambient mantle adjacent to the plume is considered (Figures 11 and 12). This indicates that heating of the ambient mantle surrounding the plume is important to the generation of melts in off-axis plume-ridge systems and should not be overlooked. At the same time, excessive heating of the ambient mantle adjacent to the plume alters the dynamics of flow in the system, leading to decreased flow from the plume to the ridge (Figures 14 and 15). This combination of constraints may prove to be a useful for models of plume ascent through the mantle.

Experiments that consider heating of ambient mantle adjacent to the plume but do not include increases in viscosity due to dehydration show gradual gradients in synthetic melt properties between the plume and the ridge (Figures 11a and 12a). This is consistent with the gradual gradients in isotope ratios seen in the Easter – Salas y Gomez system (Figure 16). There are also intriguing parallels between the pulse of melting associated with the hot ambient mantle adjacent to the plume and the distinct region of markedly unradiogenic isotope ratios between Easter Island and Salas y Gomez (Figure 16). This anomaly shows up consistently in isotope ratios for the Pb [*Kingsley and Schilling*, 1998] and Sr, Nd and Hf [*Kingsley*, 2002] isotopic systems.

Experiments in which viscosity increases due to dehydration during melting also lead to sharp spatial gradients in the properties of synthetic melts (Figures 11b and 12b). This is the result of the viscous plug that forms at the base of the lithosphere above the plume, deflecting the plume so that it flows horizontally between the plume conduit and the ridge. Melting of ambient mantle material is thereby limited to the ridge and its immediate surroundings. The viscous plug is characteristic of off-axis plume-ridge systems in which the effects of dehydration on viscosity are considered and therefore gradual transitions in isotope ratios cannot be achieved these systems. This implies that either viscosity increases due to dehydration are not important in off-axis plume-ridge systems (or at least in the Easter – Salas y Gomez systems) or the parameterization of this viscosity effect is flawed. While the magnitude of the viscosity increase due to dehydration used here is only a fraction of the effect observed experimentally [*Hirth and Kohlstedt*, 1996], it is possible that other factors (e.g., the presence of small volumes of melt in equilibrium with the residual solid) may act to mitigate the effect further. Additionally, potential differences in the solidus of the plume and the ambient mantle, which are not considered here, might also affect the dynamics of the system and therefore the properties of the resulting melts by changing the distribution of melting in the system.

5. Conclusions

We present results from a series of two-dimensional numerical experiments in which synthetic melt compositions are calculated for a system in which a thermally buoyant, off-axis mantle plume interacts with a nearby ridge axis. Spatial gradients in synthetic melt properties are compared to observed geochemical gradients from the Easter – Salas y Gomez system in an effort to constrain the dynamics of mantle flow plume-ridge systems. Results indicate that observed gradients in isotope ratios between the ridge and the plume require significant heating of the ambient mantle adjacent to the plume. This heating alters flow in the system somewhat, in particular curtailing flow from the plume to the ridge. Differences in mantle flow between experiments without

dehydration related viscosity effects [i.e., $\eta(T)$] and experiments that do consider the effect of dehydration on viscosity [i.e., $\eta(T,F)$] lead to significant differences in the properties of the resulting melts (Figure 17). Comparison to off-axis variations in isotope ratios in the Easter – Salas y Gomez system indicates that experiments without viscosity increases due to dehydration during melting reproduce many of the observed trends while systems with dehydration related viscosity effects do not.

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Figure Captions

Figure 1. Cartoon illustrations of mantle flow for the plume-source/ridge-sink model with and without viscosity increases due to dehydration during melting. a) In the absence of dehydration related viscosity increases [i.e., $\eta(T)$] a near-ridge plume rises through the upper mantle and flows along the sloping base of the overlying lithosphere towards the ridge axis. Flow between the plume and the ridge is subhorizontal and plume material undergoes continuous decompression (and therefore melting) en route to the ridge axis. b) Dehydration during melting increases the viscosity of the residual mantle [i.e., $\eta(T,F)$]. This results in a high viscosity boundary at the depth of the solidus for ambient mantle (medium gray) and the creation of a viscous plug above the depth of the plume solidus in the region above the plume (light gray).

Figure 2. Cartoon illustration of the numerical model domain. The initial distribution of plume (red) and ambient mantle (green) particles is shown. Additional particles are introduced at particle injection sites along the bottom boundary as needed (yellow).

Figure 3. Gradients in synthetic melt properties perpendicular to the strike of the ridge axis for cases with (blue) and without (red) dehydration related increases in viscosity for experiments with temperature model T_0 . Distances are given relative to the ridge axis, and the location of the plume conduit is shown in gray. a) Percentage of total volume of melt derived from plume material. b) Mean degree of depletion of material from which melt is generated. c) Volume weighted mean depth of melting.

Figure 4. Gradients in isotope ratio (*I*) perpendicular to the strike of the ridge axis for elements with bulk partition coefficients of D = 0.01 (black), D = 0.1 (blue), D = 1.0 (green) and D = 10.0 (red) for synthetic melts. Experiments shown here assume temperature model T_0 and a plume enrichment factor of N = 1. Distances are given relative to the ridge axis, and the location of the plume conduit is shown in gray. a) Without dehydration related viscosity increase, i.e. $\eta(T)$. b) With dehydration related viscosity increases, i.e. $\eta(T,F)$.

Figure 5. Gradients in isotope ratio (*I*) perpendicular to the strike of the ridge axis for elements with bulk partition coefficients of D = 0.01 (black), D = 0.1 (blue), D = 1.0 (green) and D = 10.0 (red) for synthetic melts. Experiments shown here assume temperature model T_0 and a plume enrichment factor of N = 5. Distances are given relative to the ridge axis, and the location of the plume conduit is shown in gray. a) Without dehydration related viscosity increases, i.e. $\eta(T)$. b) With dehydration related viscosity increases, i.e. $\eta(T)$.

Figure 6. Temperature along the bottom boundary of the model domain in the vicinity of the plume for the various temperature models. For model T_0 (----), no heat is diffused from the plume to the surrounding mantle, and the temperature anomaly is confined to those computational nodes designating the plume conduit. In model T_1 (----) heat is assumed to have been diffused from the plume into the ambient mantle for a period of ~52 Myr. In model T_2 (----) diffusion is assumed to have occurred for ~65 Myr. In

model T_3 (----) diffusion is assumed to have occurred for ~87 Myr. In model T_4 (-----) diffusion is assumed to have occurred for ~130 Myr.

Figure 7. Composition fields, which indicate the distribution of plume particles in the model domain, for experiments with temperature model T_0 . Path lines of selected ambient mantle (solid line) and plume (dotted line) particles are superimposed. Composition is obtained by normalizing the number of plume particles in a given computational cell by the maximum initial number of particles per cell. Thus a composition value of 1 indicates plume material while a value of 0 indicates ambient mantle. a) Without dehydration related viscosity increases, i.e. $\eta(T)$. b) With dehydration related viscosity increases, i.e. $\eta(T,F)$.

Figure 8. Trajectory of the ambient mantle particle immediately adjacent to the plume conduit in depth (i.e., pressure) – temperature space. Trajectories are shown for experiments with temperature models T_0 (—), T_1 (—) and T_4 (—). The peridotite solidus [*McKenzie and Bickle*, 1988] is shown as a dashed line. a) Experiments without dehydration related viscosity increases, i.e. $\eta(T)$. b) Experiments with dehydration related viscosity increases, i.e. $\eta(T,F)$.

Figure 9. Trajectory of an ambient mantle particle initially located \sim 30 km ridgeward of the plume conduit in depth (i.e., pressure) – temperature space. Trajectories are shown for experiments with temperature models T₀ (—), T₁ (—) and T₄ (—). The peridotite solidus [*McKenzie and Bickle*, 1988] is shown as a dashed line. a) Experiments without

dehydration related viscosity increases, i.e. $\eta(T)$. b) Experiments with dehydration related viscosity increases, i.e. $\eta(T,F)$.

Figure 10. Gradients in synthetic melt properties perpendicular to the strike of the ridge axis for cases with (blue) and without (red) dehydration related increases in viscosity for experiments with temperature model T_1 . Distances are given relative to the ridge axis, and the location of the plume conduit is shown in gray. a) Percentage of total volume of melt derived from plume material. b) Mean degree of depletion of material from which melt is generated. c) Volume weighted mean depth of melting.

Figure 11. Gradients in isotope ratio (*I*) perpendicular to the strike of the ridge axis for elements with bulk partition coefficients of D = 0.01 (black), D = 0.1 (blue), D = 1.0 (green) and D = 10.0 (red) for synthetic melts. Experiments shown here temperature model T_1 and a plume enrichment factor of N = 1. Distances are given relative to the ridge axis, and the location of the plume conduit is shown in gray. a) Without dehydration related viscosity increases, i.e. $\eta(T)$. b) With dehydration related viscosity increases, i.e. $\eta(T)$.

Figure 12. Gradients in isotope ratio (*I*) perpendicular to the strike of the ridge axis for elements with bulk partition coefficients of D = 0.01 (black), D = 0.1 (blue), D = 1.0 (green) and D = 10.0 (red) for synthetic melts. Experiments shown here assume temperature model T₁ and a plume enrichment factor of N = 5. Distances are given relative to the ridge axis, and the location of the plume conduit is shown in gray. a)

Without dehydration related viscosity increases, i.e. $\eta(T)$. b) With dehydration related viscosity increases, i.e. $\eta(T,F)$.

Figure 13. Gradients in synthetic melt properties perpendicular to the strike of the ridge axis for cases with (blue) and without (red) dehydration related increases in viscosity for experiments with temperature model T_1 . Distances are given relative to the ridge axis, and the location of the plume conduit is shown in gray. a) Percentage of total volume of melt derived from plume material. b) Mean degree of depletion of material from which melt is generated. c) Volume weighted mean depth of melting.

Figure 14. Gradients in isotope ratio (*I*) perpendicular to the strike of the ridge axis for elements with bulk partition coefficients of D = 0.01 (black), D = 0.1 (blue), D = 1.0 (green) and D = 10.0 (red) for synthetic melts. Experiments shown here assume temperature model T₄ and a plume enrichment factor of N = 1. Distances are given relative to the ridge axis, and the location of the plume conduit is shown in gray. a) Without dehydration related viscosity increases, i.e. $\eta(T,F)$.

Figure 15. Gradients in isotope ratio (*I*) perpendicular to the strike of the ridge axis for elements with bulk partition coefficients of D = 0.01 (black), D = 0.1 (blue), D = 1.0 (green) and D = 10.0 (red) for synthetic melts. Experiments shown here assume temperature model T₄ and a plume enrichment factor of N = 5. Distances are given relative to the ridge axis, and the location of the plume conduit is shown in gray. a)

Without dehydration related viscosity increases, i.e. $\eta(T)$. b) With dehydration related viscosity increases, i.e. $\eta(T,F)$.

Figure 16. Longitudinal gradient of ²⁰⁸Pb/²⁰⁴Pb isotope ratio in basalts from the Easter – Salas y Gomez Seamount Chain (ESC) and the East Pacific Rise (EPR) along the eastern side of the Easter Microplate (EMP). Samples from the East Rift of the Easter Microplate, Easter Island and Salas y Gomez are highlighted in gray. Trends interpreting the data to show the location of purely plume-derived melts and melts formed by mixing of plume- and ambient mantle-derived melts are drawn in. A region interpreted here as melting of the heated ambient mantle adjacent to the plume is circled. Data are from Hanan and Schilling [1989] (\blacksquare , \blacktriangle , \triangle) and Kingsley and Schilling [1998] (\blacksquare).

Figure 17. Cartoon illustration of the spatial variations in melt chemistry resulting from mantle flow in an off-axis plume-ridge system (a). Viscosity increases associated with dehydration during melting can significantly alter flow in the system, resulting in distinct patterns in melt chemistry. b) In the absence of dehydration related viscosity increases [i.e., $\eta(T)$] flow between the plume and the ridge is subhorizontal and both plume and adjacent ambient mantle material undergoes continuous decompression (and therefore melting) en route to the ridge. This results in a small dip in isotope ratios near the plume due to melting of the hot ambient mantle adjacent to the plume followed by a continuous gradient in isotope ratio to the ridge. c) When the effect of dehydration on the viscosity of the residual mantle is considered [i.e., $\eta(T,F)$], a viscous plug is created in the region above the plume which forces the upwelling plume and adjacent ambient mantle material

to travel essentially horizontally to the ridge. Small amounts of plume material melt between the plume conduit and the ridge, but the high viscosity residual is immediately incorporated into the viscous plug. The heated ambient mantle adjacent to the plume is prevented from melting until it reaches the end of the viscous plug at the ridge axis. Consequently, the transition from plume-derived to ambient mantle-derived melts is very abrupt and the variation in melt chemistry is limited to the region immediately adjacent to the ridge.



b)

























Distance From Ridge (km)







Distance From Ridge (km)









c)

