The origin of the asymmetry in the Iceland hotspot along the Mid-Atlantic Ridge from continental breakup to present-day

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Article history:
Received 14 June 2013
Received in revised form 20 December 2013
Accepted 6 February 2014
Available online xxxx
Editor: Y. Ricard

Keywords:
North Atlantic mantle plumes mid-ocean ridges continental rifting hotspots dehydration

Abstract
The Iceland hotspot has profoundly influenced the creation of oceanic crust throughout the North Atlantic basin. Enigmatically, the geographic extent of the hotspot influence along the Mid-Atlantic Ridge has been asymmetric for most of the spreading history. This asymmetry is evident in crustal thickness along the present-day ridge system and anomalously shallow seafloor of ages ~49–25 Ma created at the Reykjanes Ridge (RR), SSW of the hotspot center, compared to deeper seafloor created by the now-extinct Aegir Ridge (AR) the same distance NE of the hotspot center. The cause of this asymmetry is explored with 3-D numerical models that simulate a mantle plume interacting with the ridge system using realistic ridge geometries and spreading rates that evolve from continental breakup to present-day. The models predict plume-influence to be symmetric at continental breakup, then to rapidly contract along the ridges, resulting in widely influenced margins next to uninfluenced oceanic crust. After this initial stage, varying degrees of asymmetry along the mature ridge segments are predicted. Models in which the lithosphere is created by the stiffening of the mantle due to the extraction of water near the base of the melting zone predict a moderate amount of asymmetry; the plume expands NE along the AR ~70–80% as far as it expands SSW along the RR. Without dehydration stiffening, the lithosphere corresponds to the near-surface, cool, thermal boundary layer; in these cases, the plume is predicted to be even more asymmetric, expanding only 40–50% as far along the AR as it does along the RR. Estimates of asymmetry and seismically measured crustal thicknesses are best explained by model predictions of an Iceland plume volume flux of ~100–200 m³/s, and a lithosphere controlled by a rheology in which dehydration stiffens the mantle, but to a lesser degree than simulated here. The asymmetry of influence along the present-day ridge system is predicted to be a transient configuration in which plume influence along the Reykjanes Ridge is steady, but is still widening along the Kolbeinsey Ridge, as it has been since this ridge formed at ~25 Ma.

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1. Introduction
The North Atlantic region has been influenced by anomalously profuse magmatism associated with the Iceland hotspot to varying degrees from before the time of continental breakup until present-day. For example, residual basement depth (bathymetry corrected for sediment loading and subsidence with crustal age), which commonly correlates with crustal thickness, is anomalously shallow for >2000 km along the margins of Greenland and Norway, as well as most of the basin surrounding Iceland (Fig. 1, Ito and van Keken, 2007). This shallow seafloor comprises most of the North Atlantic Igneous Province (e.g. Coffin and Eldholm, 1994; Holbrook et al., 2001; White, 1997). Northeast of Iceland, shallow topography surrounds the basin created by the now-extinct Aegir Ridge (AR). Conspicuously however, most of the AR basin (Norway Basin) itself is relatively deep (e.g. Vogt et al., 1981, 1982). Apparently, the
hotspot heavily influenced the areas west, east, and south of the basin, but had much less influence on the AR basin itself. Also peculiarly, the Iceland hotspot influence appears to extend less far north along the Kolbeinsey Ridge (KR) than south along the Reykjanes Ridge (RR) relative to Vatnajökull (e.g. Hooft et al., 2006; Holbrook et al., 2001; Mjelde et al., 2008; Smallwood et al., 2009). Shortly after breakup, the relative location of the hotspot center was likely near the margin of east Greenland (Fig. 2), although the lack of a documented age progression along the presumed hotspot track leads to large uncertainties in the relative location of the hotspot through time (e.g. Lawver and Müller, 1994; Mihalffy et al., 2008; Steinberger, 2000). In pre- and early-breakup history, hotspot influence was widespread, with no clear asymmetry.

During 52–43 Ma, the average seafloor half-spreading rate along the RR, KR, and AR slowed to ~12 km/Myr, and the influence of the hotspot on the AR, evident in crustal thickness, decreased significantly (Fig. 3). During 43–28 Ma, seafloor spreading at the AR was probably slower than at the RR and MR by as much as 30% (Breivik et al., 2006; Mosar et al., 2002; Smallwood and White, 2002; Voss et al., 2009), related likely to lithospheric stretching or the very earliest stages of rifting at the KR. Crustal thickness generated from 43 to 28 Ma along the middle and northern portions of the AR was only 3.5–5.5 km (Breivik et al., 2006), similar to that of normal (not hotspot influenced) oceanic crust at the same ultra-slow spreading rate of ~7 km/Myr (Dick et al., 2003; White et al., 2001). Along the 33 Ma isochron, crustal thickness is ~4 km in the northern part of the AR and thickens to ~7 km in the southernmost ~250–300 km of the AR (Rai et al., 2012). Thicker crust with the slightly slower spreading to the south is opposite the correlation for normal ridges (Dick et al., 2003; White et al., 2001), and therefore suggests a modest degree of hotspot influence, restricted to the southern portion of AR.

By 30–26 Ma, seafloor spreading had begun migrating from south to north along the KR, separating the Jan Mayen microcontinent (JMMC) from Greenland (Fig. 2); by ~25 Ma the AR was extinct and spreading was completely transferred to the KR (Nunns, 1983; Vogt et al., 1980). Plume influence along the RR at this time is inferred from smooth basement topography created by the part of the RR spreading obliquely...
When considering the tectonic evolution, two hypotheses can be formulated as to the cause of the long-term asymmetry in the Iceland hotspot. (1) The asymmetric geometry of the ridges relative to each other and to the hotspot center leads to asymmetric hotspot influence. (2) Variations in lithospheric thickness, including the conduit-like, “inverted troughs” which form beneath the ridge axes, and thick lithosphere of the JMMC, promote plume expansion SW along the RR and impede plume expansion NE to the AR.

To test the above hypotheses about the comparatively restricted hotspot influence in the AR basin and to address the cause of asymmetric Iceland hotspot influence overall, we use 3-D numerical models that simulate a plume interacting with rifting continents and spreading ridges. The models simulate ridge geometries and spreading rates based on geological estimates from the time of continental breakup until present-day. Varied model parameters are plume volume flux, mantle viscosity, and rheology of the lithosphere, which controls the structure of the lithosphere. In one set of models, the lithosphere corresponds to the cool thermal boundary layer near the surface. In another set of models, the rheology is controlled by water content, and partial melting removes water from the solid leaving a stiff, dehydrated lithosphere, independent of the thermal boundary layer. We quantify the effects of the above variables on the asymmetry of a plume interacting with the ridge. Finally, we compare model predictions with observations to infer the volume flux of the Iceland plume and rheology of the lithosphere.

2. Methods

2.1. Model setup

We employ Citcom, a finite element code widely used to simulate mantle convection (e.g. Moresi and Gurnis, 1996; Zhong et al., 2000). Citcom solves the equations describing conservation of mass, conservation of momentum, and conservation of energy in a Cartesian coordinate system for a fluid with zero-Prandtl number (see supplementary material). The extended Boussinesq approximation is used to simulate the adiabatic temperature gradient and latent heat loss due to melting (Bianco et al., 2011). Model dimensions are $2400 \times 2800 \times 400$ km, with $289 \times 257 \times 65$ elements of size $8 \times 11 \times 6$ km in the $x$, $y$, and $z$ directions, respectively (Fig. 4).

The structure of the stiff part of the plate, or lithosphere, is controlled by the rheology. One set of models simulates a “thermal lithosphere”, which develops because viscosity varies as a standard Arrhenius function of temperature and pressure.
A study investigating the effects of dehydrated lithosphere on the evolution of the Mid-Atlantic Ridge. The model setup and diagrams show the evolving mantle plume and the effects on the thermal and dehydration layers. The initial conditions simulate the pre-rifted, continental lithosphere spreading like a “pancake” beneath the lithosphere. The surface is held motionless to allow the plume to rise from the base to the top of the model, and for it to begin spreading like a “pancake” beneath the lithosphere. Once the pancake expands to a diameter of ~2400 km—the approximate extent of influence along the Greenland continental margin (Holbrook et al., 2001)—continental rifting and the seafloor spreading sequence initiates.

### 2.2. Mantle melting and crustal accretion

To investigate how the evolving mantle plume affects igneous crustal thickness, we solve for melt production and compute crustal thickness. Melting rate is calculated as the time rate of change of extent of melt depletion, \( F \), using the parameterization of Katz et al. (2003) and by advecting \( F \) with passive tracers (see Bianco et al., 2011 for details). The melt produced is assumed to instantaneously migrate directly opposite the spreading direction to the nearest ridge segment, where it is incorporated into the crustal accretion zone, which is 30 km wide across the ridge axis, for numerical stability. Crustal thickness, \( T_c \), is computed at each point by solving the time-dependent advection equation in the Lagrangian reference of each spreading plates, using explicit forward differencing in time.

\[
\frac{DT_c}{Dt} = q_c. \tag{1}
\]
The left hand side is the material time derivative of $T_c$, and $q_c$ is the volume flux of melt delivered from the mantle per unit area within the crustal accretion zone.

### 2.3. Tracking plume material

For measurements of the lateral extent of plume influence, we use passive markers to track the advecton of plume material. The markers were introduced at a depth of 200 km wherever excess mantle temperature is $> \Delta T/e$, then advected with the mantle flow. We use “width” to describe the extent of the plume pancake along the ridge axis (e.g., Ribe et al., 1995). This width is formally defined as the along-axis distance from the plume center to which the plume material contributes $>50\%$ to the model crust. The widths along the Reykjanes and Aegir Ridges ($W_{RR}$ and $W_{AR}$, respectively) are measured at $\sim 30$ Ma, which is near the time the AR became extinct and close to the isochron along which the Rai et al. (2012) seismic refraction profile ran. In addition, the total radial distances of plume influence at 30 Ma, $R_{RR}$ and $R_{AR}$, are the distance from the plume center to the most distal extent of plume influence along the RR and AR, respectively. The ratios $W_{AR}/W_{RR}$ and $R_{AR}/R_{RR}$ measure the asymmetry of plume influence along the AR compared to the RR. Ratios of unity represent perfect symmetry; lower values represent greater asymmetry. The ratio of radial extents $R_{AR}/R_{RR}$ characterizes the asymmetry of the plume pancake, whereas $W_{AR}/W_{RR}$ addresses the apparent asymmetry in width along these ridges and does not include the offset between the plume center and the AR as part of the measurement.

### 2.4. Model parameters

Several properties are likely to influence along-axis widths. Plume volume flux $Q$ is known to be one primary control on the steady-state (symmetric) width $W$ to which a plume expands along a straight ridge, spreading at a rate of $U$; $W \propto (Q/U)^{1/2}$ (Ribe et al., 1995). Plume volume flux $Q$ may also modulate the asymmetry of the plume pancake by influencing the strength of the part of mantle flow that is driven by plume buoyancy, which alone should be radially symmetric, relative to the part of the flow driven by the spreading plates, which, due to the asymmetric ridge geometry, should be asymmetric. Finally, variations in $Q$, as well as viscosity $\eta$ change the characteristic thickness of the hot plume pancake beneath the lithosphere $S$ (Ribe et al., 1995), where

$$ S = \left( \frac{4\eta Q}{g \Delta \rho} \right)^{\frac{1}{2}}, \tag{2} $$

in which $g$ is gravitational acceleration, and $\Delta \rho$ is the density contrast between the plume and the ambient mantle. When calculating $S$, we defined $\eta$ to be the lowest viscosity in the ponding plume pancake. The ratio of $S$ to the characteristic amount that the lithosphere thickens off-axis, $\Delta h$, is predicted to control the degree to which lithosphere structure influences the lateral expansion of the plume pancake (Ribe et al., 1995). If $S/\Delta h \gg 1$, then the plume expands much like it would against a flat lithospheric base, whereas if $S/\Delta h \sim 1$, the expansion can be perturbed by a sloping base of the lithosphere (Ribe et al., 1995). In models in which the lithosphere is controlled by dehydration, the lithosphere does not thicken systematically away from the ridge axis, $S/\Delta h$ is always very large ($\gg 1$), and therefore the asymmetric ridge geometry should have a smaller influence on making the plume asymmetric. If the lithosphere is thermally controlled, then $S/\Delta h$ is variable and can approach unity, in which case the asymmetric ridge geometry can have a larger influence on the shape of the plume pancake.

To modulate $Q$, $\eta$, and $S/\Delta h$, we vary three model input parameters: plume radius, $r$, Rayleigh number, $Ra$ (higher $Ra$ simulates lower plume viscosities), and water-independent versus water-dependent rheology (details given in Table 1). Ambient mantle potential temperature ($1325^\circ C$–$1338^\circ C$) is varied with Rayleigh number to produce reasonable ($5.5$–$6.5$ km) crustal thicknesses for non-plume influenced, slow-spreadng ridges (Dick et al., 2003; White et al., 2001). A range of plume volume fluxes are investigated ($95$–$446$ m$^3$/s) by varying plume radius ($65$–$180$ km) at four Rayleigh numbers ($5 \times 10^{-2}$–$2 \times 10^6$). About half of the calculations simulate a thermal lithosphere without the effects of dehydration stiffening, while the other half consider a dehydrated lithosphere that does include these effects. Model outputs are presented as maps of crustal thickness, volume fraction of plume-contributed crust and model seafloor ages, along with the widths ($W_{RR}$ and $W_{AR}$) and radial distances ($R_{RR}$ and $R_{AR}$) of plume influence along the Aegir and Reykjanes Ridges.

### 3. Model results

#### 3.1. General temporal behavior of the plume

The evolution of the plume in an example model (Model 3a, Table 1) is shown in Fig. 5. Again, the plume is first allowed to expand beneath a stationary, thick continental plate; once it spans a diameter of $2400$ km, continental rifting begins. Right after continental breakup (54 Ma), the initially wide plume pancake quickly contracts as plume material fills the inverted trough (pseudo-triangular conduit) created in the rifted, thick continental lithosphere, and plate motion draws plume material away from the ridge axis. In the case shown, the pancake is nearly half its original radius at $\sim 47$ Ma. The pancake is also nearly asymmetric; it extends further along the RR than along the AR, and has withdrawn completely from beneath the MR (Fig. 5).

From just after the model time of $\sim 47$ Ma until $\sim 30$ Ma, the plume pancake widens slightly along the ridges (Fig. 5), largely due to a factor of $\sim 3$ reduction in spreading rate (Fig. 3). By 30 Ma, the pancake in this model is more than twice as wide along the RR as it is along the AR. The slow widening along the ridges continues in this model to $\sim 27$ Ma (not shown).

From $28$–$25$ Ma, rifting at the KR begins in the south and propagates north at the expense of spreading at the AR. At 25 Ma (not shown), the AR is fully extinct. The widening of the plume along the RR stagnates as plume material that would otherwise feed the RR now flows toward the KR (see 23 Ma, Fig. 5). From $25$–$15$ Ma, the plume contracts along the KR in response to continental rifting, much like the initial plume contraction event at $54$ Ma. Starting $\sim 10$ Ma, the plume widens slightly along the KR. At the model time representing present-day, the plume pancake is still widening along the KR, but has reached a minimum in width along the AR.

#### 3.2. Record of plume influence on the seafloor

The predicted evolution is recorded in maps of crustal thickness and fractional contribution of the plume to the crust for models with two different plume fluxes, for both rheologies (Fig. 6). The model of high plume flux and thermal lithosphere is the same model presented in Fig. 5 (Model 3a, Fig. 6(a), (c)]. The initial contraction of the pancake immediately following continental breakup results in long (tapered) bands of plume-influenced crust along the continental margins adjacent to uninfluenced crust (Fig. 6(a)). From the minimum plume width after the initial contraction, near seafloor age of $\sim 49$ Ma, the extent of plume influence increases toward the $25$ Ma isochron along both ridges, although more extensively southward along the model RR than north along the AR.
The slight retraction in influence in the model KR basin near 23 Ma is seen as narrow bands of plume influenced crust along the margins at the northern end of the basin next to small patches of uninfluenced seafloor. After this retraction, plume influence widens toward the present-day KR and recedes along the RR.

A lower plume flux (Model 8a, Fig. 6(b), (d)) yields a width of influence on the seafloor that is overall less than in the high flux case (Model 3a) after the initial contraction. Between the 47 and 25 Ma isochrons, plume influence is seen to widen along RR while receding slightly (rather than widening as in Model 3a) along AR. The KR basin shows streaks of wide plume influence near the rifted margins, which are less pronounced than the solid bands of influence in Model 3a. Plume influence has widened along the KR from the minimum width near the continental margin to its present-day width, which is still increasing. In the RR basin, the width of influence decreases between the 25 Ma isochron and present-day, similar to Model 3a.

In both of the models shown with a thermal lithosphere, crustal thicknesses (Fig. 6(c), (d)) is slightly enhanced near the continental margins (7–9 km) and greatest (90–140 km) along the volcanic ridge east and west of the plume center. However, the predicted crustal thickness at the continental margins is not overly thick (i.e., prior to ~50 Ma), primarily because there is a predicted time lag between when rifting is first imposed and when the lithosphere is thin enough to allow for substantial decompression melting. This effect was shown to be overcome in previous numerical models by imposing the lithosphere to be (~50%) thinner beneath the rift zones than elsewhere in order to simulate rifting prior to the main continental breakup event (Nielsen and Hopper, 2004). On younger seafloor, shorter-wavelength variations in crustal thickness, 2–5 km in amplitude, are evident and extend 2–3 times further along RR in the high flux, compared to the low-flux case. These variations are caused by spatio-temporal variations in buoyancy-driven plume flow in the melting zone. Crust at the southern AR and KR is thickened by plume influence (11–14 km). Plume-thickened crust is present for about half the length of AR in the high-flux case (Model 3a), but is restricted to the southern quarter of the ridge in the low-flux case (Model 8a).

Relative to the above models with a thermal lithosphere (Models 3a, 8a), models with a dehydrated lithosphere and comparable plume fluxes (Models 4, 8b) predict a more dramatic initial contraction in plume influence during continental break-up, resulting in longer bands of plume-influenced margins adjacent to uninfluenced seafloor (Fig. 6(e), (f)). Between the 47 Ma isochrons, the overall width of plume influence is less with dehydrated lithosphere than with thermal lithosphere, with the largest difference occurring at the RR. The widths at the RR are more comparable to those at the AR indicating that the relatively flat base of the dehydrated lithosphere leads to a more symmetric plume pancake.

Models with a dehydrated lithosphere produce crustal thicknesses (Fig. 6(g), (h)) slightly thinner at the continental margins (<8 km) and much thinner along the east-west trending volcanic ridges (17–21 km), and lack the short-wavelength variations in crustal thickness seen in the thermal lithosphere cases, as buoyancy-driven flow in the dehydrated melting zone is suppressed by its high viscosity. Thickened crust extends a similar

<table>
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<th>Parameter</th>
<th>Ra</th>
<th>$T_p$</th>
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<td>(km)</td>
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Table 1
Model parameters varied (all other parameters were kept constant).

The slight retraction in influence in the model KR basin near 23 Ma is seen as narrow bands of plume influenced crust along the margins at the northern end of the basin next to small patches of uninfluenced seafloor. After this retraction, plume influence widens toward the present-day KR and recedes along the RR.

![Fig. 5. Snap shots at different times of Model 3a (Table 1), which has a relatively high flux ($Q = 232 \text{ m}^3/\text{s}$), low Rayleigh number ($0.5 \times 10^6$), and the lithosphere is thermally controlled (no dehydration rheology), illustrating the evolution of a typical model plume pancake of a hotspot centered beneath the yellow circles. Red isosurface envelops mantle with excess temperature $\geq 55^\circ\text{C}$; yellow isosurface marks melt production; gray isosurface marks material melting that originated in the plume stem. Active spreading centers are marked with black lines. To show how the plume pancake changes between panels, the dashed black line outlines the plume pancake from the previous panel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

![Image 42x317 to 292x502]
distance along the AR and KR for the two rheologies, but the models with a dehydrated lithosphere yield a smaller maximum crustal thickness (<9 km) at the AR.

3.3. Dependence of plume asymmetry on plume volume flux, viscosity, and rheology

The radial asymmetry of the plume pancake, measured by the ratio of radial distances of influence along the two ridges, $R_{AR}/R_{RR}$, does not appear to change with plume flux, $Q$, and Rayleigh number, which is inversely proportional to plume viscosity (Fig. 7). Thus, the radial asymmetry does not seem to be influenced by the characteristic thickness, $S$, of the pancake (Eq. (2))—which again varies with $Q$ and/or $\eta$—over the range of thicknesses tested (80–180 km). The biggest difference in $R_{AR}/R_{RR}$ occurs between cases with and without dehydration. With a dehydrated lithosphere, the radial extent of influence along the AR is 70–80% that of the RR ($R_{AR}/R_{RR}$ is $\sim$0.7–0.8). Thus, even when the lithosphere is relatively flat, models show asymmetry in the radial extents of the plume pancake. This result is likely due to westward shear from the model North American Plate inhibiting NE plume flow to the AR, with no such inhibition SSW along the RR. This result strongly supports that the asymmetric geometry of the ridges, alone, leads to asymmetric hotspot influence (Hypothesis 1). With a thermal lithosphere, $R_{AR}/R_{RR}$ is $\sim$0.4–0.5, indicating even greater asymmetry. In these cases, plume influence to the AR is inhibited not only by plate shear, but also by the large difference in lithospheric thickness across the transform between the RR and AR and the relatively thick thermal lithosphere of the JMMC, which has long been predicted to inhibit mantle flow between ridges (e.g. Vogt and Johnson, 1975). These results strongly support Hypothesis 2, that variations in lithospheric thickness can enhance the asymmetry of plume influence.

In contrast to the apparent insensitivity of $R_{AR}/R_{RR}$ to changes in $Q$, the ratio of widths along the ridges, $W_{AR}/W_{RR}$ changes appreciably with plume volume flux, $Q$ (Fig. 7(b)). $W_{AR}/W_{RR}$ increases with $Q$ due to the geometric effects of the gap between the plume center and the southern boundary of the Aegir Ridge. In a hypothetical case in which $Q$ is low enough that $R_{AR}$ is equal to the gap, $W_{AR}$ and $W_{AR}/W_{RR}$ would be zero. The proportional increase in $W_{AR}$ from zero with $Q$ is more rapid than the proportional increase in $W_{RR}$. The rate that $W_{AR}/W_{RR}$ increases with $Q$ is less in models with a thermal lithosphere than in models with a dehydrated lithosphere, reflecting a tendency of the former to promote a more asymmetric plume pancake. Rayleigh number (or viscosity) still has little, or no, effect on the asymmetry as measured by $W_{AR}/W_{RR}$.

4. Discussion: Comparison of model predictions with observations

4.1. Asymmetry and plume influence

Several aspects about the extents of plume influence as inferred from residual bathymetry in the North Atlantic (Fig. 1) can be interpreted based on our model predictions of plume-contributed crust. The residual bathymetry shows shallow continental margins, and thus plume-influenced thick igneous crust, which transitions to deeper seafloor, and thinner crust, over short seaward distances of ~100 km. We predict this transition to occur due to the rapid reduction in width of plume influence during continental rifting (Fig. 6). An observed minimum width of inferred plume influence is evident seaward of the continental margins in contours of residual bathymetry in the North Atlantic (Fig. 1) and in the RR basin, by the appearance of rough basement topography created by orthogonal spreading of a segmented RR (White, 1997). From this minimum width, the influ-
ences of the plume appears to have extended farther south along the RR from \(\sim 47-25\) Ma, which is seen as the southward propagation along-axis of the rough–smooth boundary (Fig. 1). This southward plume expansion is another behavior predicted by the models (Fig. 6).

Near 25 Ma, which corresponds to the time that the AR becomes extinct and the KR is fully active, the rough–smooth axial topographic transition began to propagate SW along the RR. In contrast, the models predict the plume influence to retract back north along the RR as more plume material is drawn toward the RR, shown by the AR spreading (Fig. 6(f)). As noted earlier, the models do not predict the large crustal thickness near the onset of rifting due to initially thick continental lithosphere inhibiting melting. From \(\sim 50\) Ma onward, however, the models generally match the overall trend of the observed decreasing crustal thickness with time. Cases with higher versus lower Rayleigh numbers (lower versus higher average viscosity) produce thicker versus thinner crust at a similar plume volume flux. The models with a dehydrated lithosphere produce thinner crust and a more subtle decrease in crustal thickness over time compared to models with a thermal lithosphere. Cases with higher plume volume flux predict a wider plume pancake and thus produce thicker crust than those with lower flux. For both types of rheologies, models with a lower plume flux (114–146 m\(^3\)/s) predict crustal thicknesses qualitatively similar to those observed. This result supports those based on \(W_{AR}/W_{RR}\) for plume fluxes of 100–200 m\(^3\)/s (Fig. 7).

Fig. 8(c)–(d) shows model predictions of seismically derived crustal thickness (Rai et al., 2012) from south to north along the \(\sim 30\) Myr isochron on the SE side of AR (location marked in Fig. 1). The seismic profile shows crustal thickness increasing southward in the southern half of AR, where spreading was slowest, and a more-or-less uniform crustal thickness in the northern half of the AR. Model calculations without a plume show no long-wavelength change in crustal thickness along the AR (black curves, Fig. 8(c)–(d)), in contrast to what is observed, which is further evidence for plume influence in the southern portion of the AR. Models with a dehydrated lithosphere produce thinner crust and a smaller southward increase in crustal thickness than the models with a thermal lithosphere. For both rheologies, models with the highest plume flux predict the plume to influence the whole AR and crust that is much thicker than observed. Models with

in oceanic basement topography, and along the AR are based on where the seismically measured crustal thickness (Rai et al., 2012) is seen to abruptly increase. Uncertainties in the widths (\(W_{AR}, W_{RR}\)) and radial distances (\(R_{AR}, R_{RR}\)) include the uncertainty in the location of the center of the plume using the possible locations shown in Fig. 2. An additional uncertainty of \(\sim 150\) km in the width along the AR (marked in Fig. 8) arises from two locations where seismically determined crustal thickness increases abruptly from NE to SW.

Our estimates of \(R_{AR}/R_{RR}\) and \(W_{AR}/W_{RR}\) for the Iceland hotspot at 30 Ma are 0.54–0.67 and 0.18–0.40, respectively (Fig. 7). When considering the model predictions for how \(W_{AR}/W_{RR}\) changes with volume flux, \(Q\), the estimated \(W_{AR}/W_{RR}\) of the Iceland hotspot suggests a plume flux between \(\sim 100–420\) m\(^3\)/s for a thermally controlled lithosphere, and \(\sim 100–200\) m\(^3\)/s for a dehydron-controlled lithosphere. Both flux ranges are consistent with the flux (200 m\(^3\)/s) simulated by Ito et al. (1999) and the preferred flux (193 m\(^3\)/s) simulated by Ribe et al. (1995) for a ridge-centered Iceland plume, which were based on predictions of the along-axis width (1400–1600 km) of the anomalously shallow topography and thick crust. The current flux estimates are greater than the published estimates (30–45 m\(^3\)/s) based on the narrower width of the geochemical anomaly of \(\sim 920\) km (Ribe and Delattre, 1998; Schilling, 1991). Our estimates of \(R_{AR}/R_{RR}\) for the North Atlantic fall between model predictions for cases with and without dehydration stiffening (Fig. 7). This finding suggests that the rheology of the mantle is intermediate between the temperature- and dehydration- (plus temperature) dependent rheology simulated.

4.2. Crustal thickness

Seismically measured crustal thickness near the AR is compared with model predictions in Fig. 8. The first comparison is along the SE to NW seismic refraction transect from the Norwegian margin to the central portion of the AR (Fig. 3, Breivik et al., 2006, location marked in Fig. 1). As noted earlier, the models do not predict the large crustal thickness near the onset of rifting due to initially thick continental lithosphere inhibiting melting. From \(\sim 50\) Ma onward, however, the models generally match the overall trend of the observed decreasing crustal thickness with time. Cases with higher versus lower Rayleigh numbers (lower versus higher average viscosity) produce thicker versus thinner crust at a similar plume volume flux. The models with a dehydrated lithosphere produce thinner crust and a more subtle decrease in crustal thickness over time compared to models with a thermal lithosphere. Cases with higher plume volume flux predict a wider plume pancake and thus produce thicker crust than those with lower flux. For both types of rheologies, models with a lower plume flux (114–146 m\(^3\)/s) predict crustal thicknesses qualitatively similar to those observed. This result supports those based on \(W_{AR}/W_{RR}\) for plume fluxes of 100–200 m\(^3\)/s (Fig. 7).

Fig. 8(c)–(d) shows model predictions of seismically derived crustal thickness (Rai et al., 2012) from south to north along the \(\sim 30\) Myr isochron on the SE side of AR (location marked in Fig. 1). The seismic profile shows crustal thickness increasing southward in the southern half of AR, where spreading was slowest, and a more-or-less uniform crustal thickness in the northern half of the AR. Model calculations without a plume show no long-wavelength change in crustal thickness along the AR (black curves, Fig. 8(c)–(d)), in contrast to what is observed, which is further evidence for plume influence in the southern portion of the AR. Models with a dehydrated lithosphere produce thinner crust and a smaller southward increase in crustal thickness than the models with a thermal lithosphere. For both rheologies, models with the highest plume flux predict the plume to influence the whole AR and crust that is much thicker than observed. Models with
lower plume flux predict the plume to influence only the southern part of the AR and crustal thicknesses similar to those observed. These results further support a plume with relatively low flux (95–128 m³/s).

Crustal thickness measurements along the present-day Mid-Atlantic Ridge, starting at the KR in the north, extending south across Iceland and then along the RR, as presented by Hooft et al. (2006), are compared with model predictions in Fig. 9. In agreement with the seismic results, models show peaks in crustal thickness over the center of the plume on Iceland, a sharp decrease ~200 km north and south of the peak, and gradual decreases in crustal thickness further from the plume center. Hooft et al. (2006) noted an asymmetry in the observed crustal thickness, with the crust along the KR, 200–500 km north of the plume center being 1–2 km thinner than that at the same distances south along the RR. The models with a dehydrated lithosphere predict the same sense of asymmetry, although slighter greater asymmetry than observed: the model crust is thinner by ~2 km along the KR 200–350 km north of the plume center than the same distance south along the RR. The models with a thermal lithosphere do not predict this sense of asymmetry. In terms of maximum crustal thickness, the models with a dehydrated lithosphere predict thinner crust than observed, whereas the models with a thermal lithosphere predict significantly thicker crust than observed.

Our model predictions for the peak crustal thickness on Iceland, the asymmetry in crustal thickness along the present-day Mid-Atlantic Ridge, as well as the degree of radial asymmetry, measured by $R_{AR}/R_{RR}$, at 30 Ma all suggest the actual rheology is intermediate between the two rheologies simulated. This result supports those of Reudas et al. (2004) whose models included a higher average viscosity than in our models without dehydration.

Fig. 8. Comparison of seismically measured and modeled crustal thickness along and across the AR axis, for different rheologies and plume fluxes. (a), (b) Profile of crustal thickness vs. age (gray) along a SE-to-NW profile starting at the Møre Margin and extending towards the Aegir Ridge, after Breivik et al. (2006). Colored curves show prediction for models with a (a) thermal lithosphere and (b) dehydrated lithosphere. (c), (d) Profile of crustal thickness vs. distance along the Aegir Ridge (gray) along the south-to-north profile of Rai et al. (2012) for cases with a (c) thermal lithosphere and (d) dehydrated lithosphere. In (c), (d) large arrows show the predicted extent of model plume influence on the ridges. The gray box shows the range of plausible observed plume influence inferred from the seismically measured crustal thickness variations. Models and their key parameters are labeled in the legend. Black solid and dashed lines are predictions of models without a plume.

Fig. 9. A comparison of model predictions and observations along the present-day Mid-Atlantic Ridge. Curves are for the same models as in Fig. 8; solid and dashed lines depict models with and without dehydration stiffening, respectively. Filled circles represent seismic measurements presented by Hooft et al. (2006); colored curves show crustal thickness of model predictions versus distance from the center of the plume along the ridges. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
and produced better fits to Iceland's crustal thicknesses. We suggest that a viscous, dehydrated lithosphere is present at the Iceland hotspot, but is less viscous than we have simulated. An intermediate behavior may arise if the ambient viscosity of the North Atlantic upper mantle is even lower than that modeled, so that the dehydrated material too is less viscous. Alternatively, it is possible that non-Newtonian rheology leads to lower viscosities in the dehydrated layer, where strain rates are higher, such as above the plume or near the ridge axis (Ito et al., 2010). Another possibility is that the presence of even a small amount of melt in the mantle substantially reduces viscosity to partially negate the effects of dehydration strengthening (Takei and Holtzman, 2009).

5. Conclusions

Numerical models of plume–ridge interaction are used to study the cause of variations in the influence of the Iceland hotspot along the Mid-Atlantic Ridge and determine the origin of the NE–SW asymmetry evident in the residual topography and crustal thickness. Models initially simulate a plume pancake that spans the full width of the Greenland margin at the time of continental breakup. The pancake is then predicted to contract rapidly as some material is advected away from the newly formed ridge axis and the rest draws into the axial, sublithospheric trough, providing a simple explanation for the observed rapid narrowing of Iceland plume influence near the continental margins. Following this initial contraction, the plume pancake is predicted to widen southward along the Reykjanes Ridge (RR), resembling the observed southward-trending, rough–smooth boundary east and west of the RR. To the northeast, the models with a lower plume flux predict the plume pancake to extend along only the southern part of the Aegir Ridge (AR), which is consistent with seismic measurements of crustal thickness along the AR. The observed southward convergence (east and west towards the RR axis) of the two rough–smooth boundaries in basement topography on crust younger than 25 Ma, after spreading shifted from the AR to RR, is not predicted by the models and could signal an increase in the Iceland plume flux since this time.

All models predict the plume pancake to spread less far along the AR than along the RR. The ratio of radial extents of plume influence along the AR and RR ($R_{AR}/R_{RR}$) is predicted to be insensitive to changes in plume volume flux and viscosity, and varies primarily with changes in rheology. When the lithosphere is controlled by dehydration, the plume expands 70–80% as far along the AR as it does along the RR ($R_{AR}/R_{RR} = 0.7–0.8$). This result indicates that the asymmetry is caused partly by the asymmetric configuration of the ridges relative to the plume center (ridge geometry control, hypothesis 1). In models with a thermal lithosphere, $R_{AR}/R_{RR} = 0.4–0.5$. This enhanced asymmetry is associated with the topography of the base of a thermal lithosphere (lithosphere thickness variation, hypotheses 2) that is not present with a dehydrated lithosphere.

Models with Iceland plume volume fluxes of 100–200 m$^3$/s best explain observed ratios of the widths of plume influence along the AR and RR ($W_{AR}/W_{RR}$), as well as crustal thickness along the RR and AR at ∼30 Ma. Comparisons of observed and modeled asymmetry in radial distance of plume influence ($R_{AR}/R_{RR}$) at 30 Ma and crustal thickness along the present-day Mid-Atlantic ridge suggest that a there is a dehydrated lithosphere, but one that is less viscous than simulated in models. The observed asymmetry in crustal thickness along the present-day ridge is predicted to be the result of the plume approaching a steady width along the RR, while still widening (since rifting began ∼25 Ma) along the Kolbeinsey Ridge.

Acknowledgements

We owe our gratitude to the captain and crew of the R/V Håkon Mosby for their invaluable contributions to the ARGGH2010 cruise, and to the University of Bergen for travel support. We extend our appreciation to the editor Dr. Yanick Ricard and two anonymous reviewers for offering critical, thorough reviews of this paper. This research was supported by NSF grants EAR-0855814 and OCE-0852115.

Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.epsl.2014.02.020.

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Acknowledgements

We owe our gratitude to the captain and crew of the R/V Håkon Mosby for their invaluable contributions to the ARGGH2010 cruise, and to the University of Bergen for travel support. We extend our appreciation to the editor Dr. Yanick Ricard and two anonymous reviewers for offering critical, thorough reviews of this paper. This research was supported by NSF grants EAR-0855814 and OCE-0852115.


