Iceland & the North Atlantic Igneous Province

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Abstract

It is almost universally assumed that Iceland is underlain by a hot plume rising from deep within the mantle. Nevertheless, this hypothesis is inconsistent with many first-order observations at Iceland, which is the best-studied ridge-centred hotspot on Earth. There is essentially no evidence for very high mantle temperatures, a time-progressive volcanic track, a seismic anomaly in the lower mantle, or radial symmetry in the pattern of geochemical anomalies on land. Iceland is basically a melting anomaly underlain by an upper-mantle seismic low-wave-speed anomaly. Temperatures are only moderately, if at all, elevated above normal mid-ocean ridge temperatures, the geochemistry is spatially and temporally heterogeneous and it differs only subtly from MORB.

Iceland lies where the mid-Atlantic ridge crosses the Caledonian suture, which marks the site of a ~ 400 Myr-old subduction zone. The great melt production there may be explained by enhanced fertility inherited from ancient subducted slabs that still remain in the shallow mantle. This model is consistent with the persistent locus of melt production on the ridge, the lack of geophysical indicators of a plume and the spatial and temporal geochemical heterogeneity of Icelandic basalts.

In this way, Iceland and the associated North Atlantic Igneous Province are explained as natural consequences of relatively shallow processes related to plate tectonics. This contrasts with the plume model, where they are explained by a process entirely independent of plate tectonics – a narrow diapiric upwelling driven by heating at the surface of a deep, hot body such as the Earth's core.

Problems with the plume model at Iceland

Few Earth science data from Iceland and the North Atlantic Igneous Province agree with the predictions of the plume hypothesis [*Foulger*, 2002]:

1. There is no evidence for the 250-600°C mantle temperature anomaly required for a plume. Marine heat flow measurements around Iceland provide no evidence for high temperatures [*Stein & Stein*, 2003]. The geochemical compositional range of Icelandic basalts overlaps that of normal mid-ocean ridge basalt (N-MORB), and geothermometers yield estimates of potential temperature (T_p) that range from temperatures similar to those inferred to exist beneath mid-ocean ridges to being ~ 100 K higher. Even in central Iceland, primitive lavas have eruptive temperatures of only ~ 1,240°C [*Breddam*, 2002], close to those of similarly magnesian N-MORB [*Ford et al*., 1983]. Picrite glass, an indicator of high temperatures, is absent from Iceland (see also Temperature and Mantle Temperature pages).

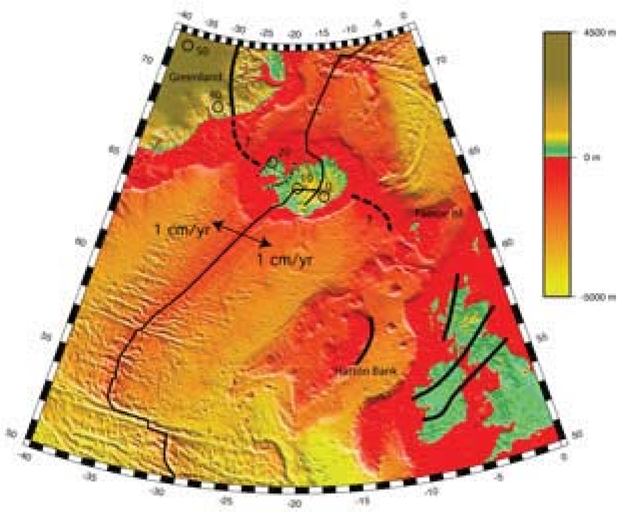


Figure 1: Bathymetry of the north Atlantic. Thick lines indicate the Caledonian suture. Circles indicate hypothesised locations of an Icelandic mantle plume at the times indicated in Ma.

2. For a plume at the latitude of Iceland to have remained fixed with respect to other Atlantic “hot spots”, it is required to have migrated southeast from a location beneath central Greenland at ~ 60 Ma to underlie southeast Iceland at present [*Lawver & Muller*, 1994]. However, no time-progressive volcanic track such as occurs at Hawaii is observed. Volcanism has been focused at the mid-Atlantic ridge since the opening of the Atlantic at ~ 54 Ma (Figure 1; see also Iceland2 page). The proposed migration, which is widely assumed and repeatedly asserted to have occurred, is unsupported by data.

   It is often asserted that the locus of spreading within Iceland itself has migrated east since 15 Ma. However, the ages of surface lavas are more consistent with a parallel pair of ridges having existed in Iceland for much of the last 15 Myr, and perhaps the last 26 Myr. Spreading in the approximate location of the present-day Northern Volcanic Zone (Figure 2: NVZ) has persisted, but spreading about a subsidiary ridge in western Iceland has repeatedly succumbed to transport off axis to the west, and been replaced by new axes more colinear with the Kolbeinsey and Reykjanes ridges (Figure 2). Simultaneous spreading about more than one ridge is also supported by geochemistry. Dated samples with ages of 7–2 Ma show that in eastern Iceland La/Sm and $^{87}Sr/^{86}Sr$ decreased with age but in western Iceland they increased, suggesting that the same mantle was not tapped in the two areas [*Schilling et al.*, 1982]. The Iceland region classifies as a “diffuse oceanic spreading plate boundary” [*Zatman et al.*, 2001].

   The resulting “leaky microplate” tectonics gives rise to local complexities within Iceland itself. These include variable rates and directions of extension, which may explain the spatial and temporal variations in magma production rate, and the predicted existence of a captured oceanic microplate with crust as old as ~ 30 Ma [Foulger & Anderson, 2005]. These complexities may result from residual structure inherited from the Caledonian suture, within which Iceland and the Greenland-Iceland and Iceland-Faroe ridges formed.

   The primary locus of spreading in Iceland, the Northern Volcanic Zone (Figure 2: NVZ) has thus not migrated east relative to the Kolbeinsey ridge as is often claimed. It has, on the contrary, remained relatively fixed since ~ 15 Ma and perhaps since ~ 26 Ma.

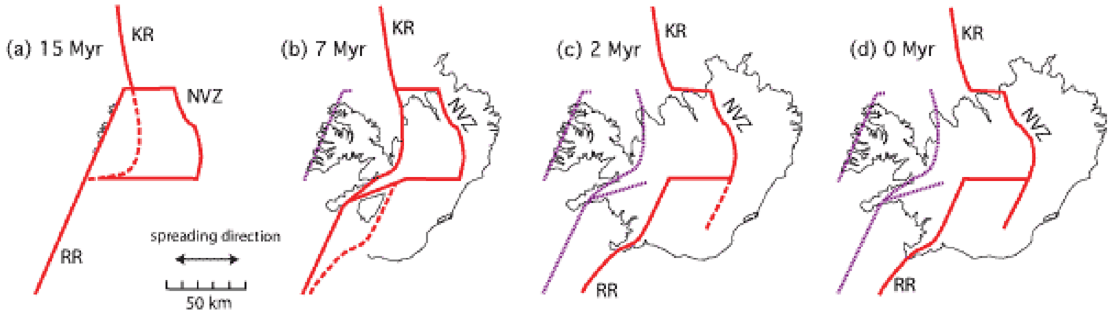


Figure 2: Tectonic evolution of Iceland during the last 15 Myr. Red lines: active plate boundaries (simplified), dashed red lines: imminent plate boundaries, dashed mauve lines: extinct plate boundaries rafted away in the westward-drifting North American plate, KR, RR: Kolbeinsey and Reykjanes ridges, NVZ: Northern Volcanic Zone [from Foulger, 2002].

3. Seismic tomography yields no evidence for a plume-like structure in the lower mantle. Iceland is underlain by a low-wave-speed anomaly that all seismic tomography studies with good upper-mantle resolution agree extends only down to the mantle transition zone [*e.g.*, *Ritsema et al.*, 1999; Figure 3].

   Teleseismic tomography in Iceland itself reveals that at depths greater than ~ 250 km the anomaly becomes elongated in a direction parallel to the mid-Atlantic ridge. This is consistent with an origin that is not very much deeper [Figure 4; *Foulger et al.*, 2000; *Foulger et al.*, 2001].

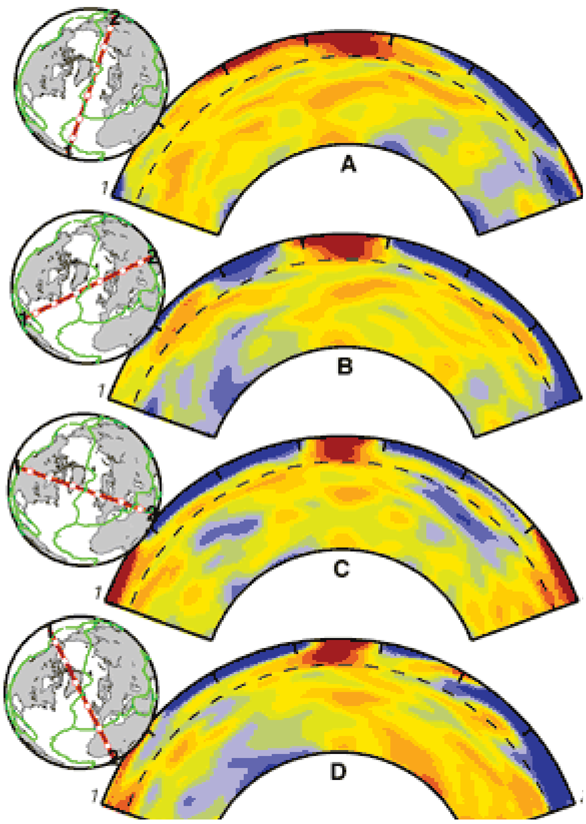


Figure 3: Tomographic cross sections through Iceland [from Ritsema et al., 1999].

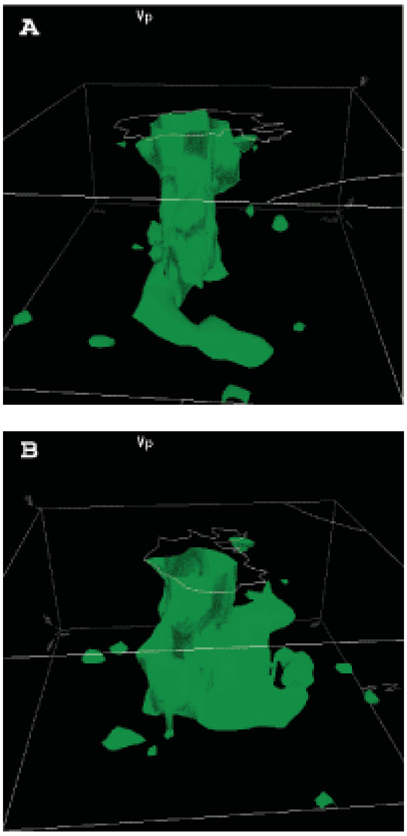


Figure 4: Three-dimensional solid-body image of the delta-Vp > 0.3% low-wave-speed anomaly beneath Iceland from the surface to 400 km depth. Map of Iceland on the surface provides orientation: A) view from the north, B) view from the east. From the model of Foulger et al. [2000] and Foulger et al., [2001].

Tomographic cross sections illustrating a continuous, low-wave-speed body extending from the surface to the core-mantle boundary beneath Iceland have been produced [*Bijwaard & Spakman*, 1999] by:

a. Over-saturating the colour scale, which imparts the visual impression of continuity of strong anomalies in the upper mantle and weak anomalies in the lower mantle. The latter may be at the noise level and not confirmed by other studies (*e.g.,* compare Figures 3 & 5).

b. Cross sections are truncated to remove similar bodies beneath the Canadian shield and Scandinavia, where plumes are not expected [*Bijwaard & Spakman*, 1999].

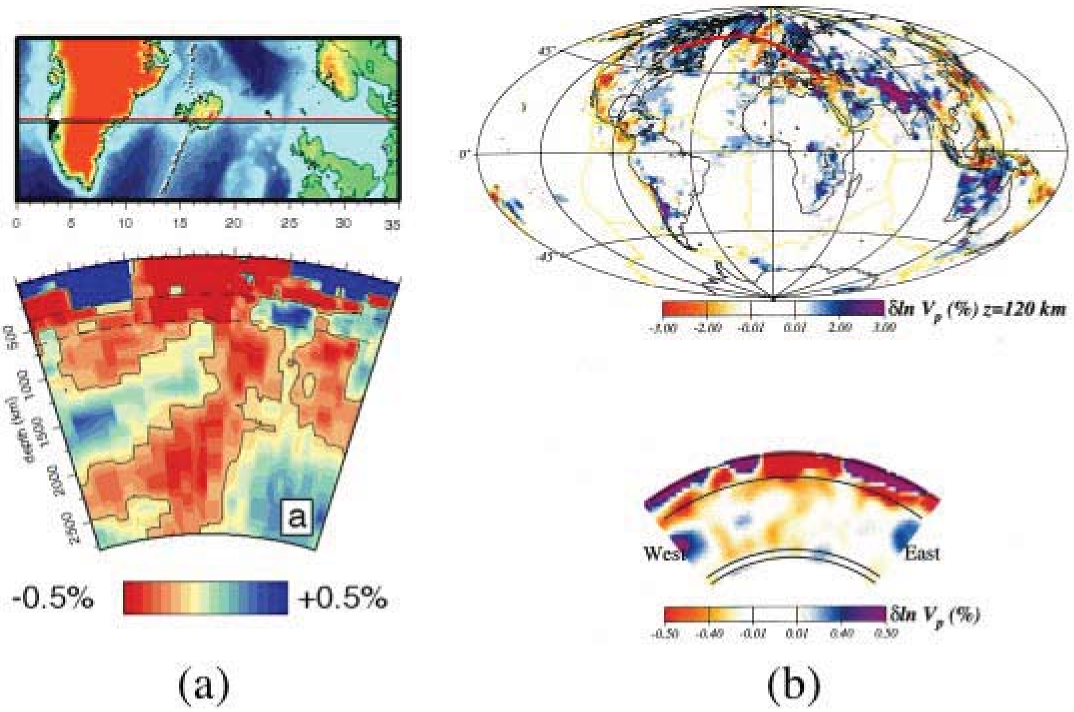


Figure 5: (a) Cross section showing a low-wave-speed anomaly beneath Iceland that is apparently continuous from the surface to the core-mantle boundary (from Bijwaard & Spakman, 1999). The colour scale is saturated at an anomaly strength of Vp = 0.5%. (b) the same line of section, but longer, through the same model, plotted using a colour scale saturated at a higher value. The anomaly beneath Iceland is clearly much weaker in the lower mantle, and similar lower-mantle anomalies are also observed beneath Hudson Bay, Canada, and Scandinavia. The downward-continuous anomaly beneath Iceland is not confirmed in other studies e.g., that of [Ritsema et al. [1999]] (Figure 3).

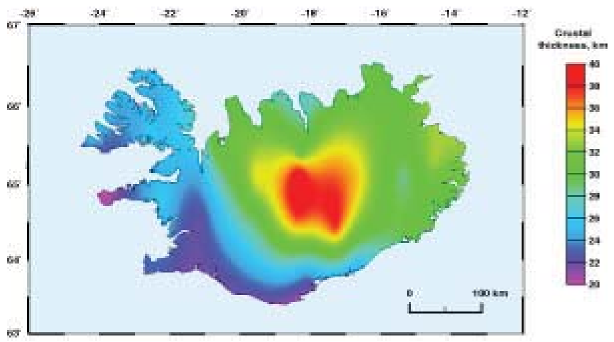


Figure 6a: Map showing the depth to the base of the lower crust (defined as the depth to the Vs = 4.2 km/s horizon), from receiver functions [from [Foulger et al., 2003]]. Click on figure for enlargement.

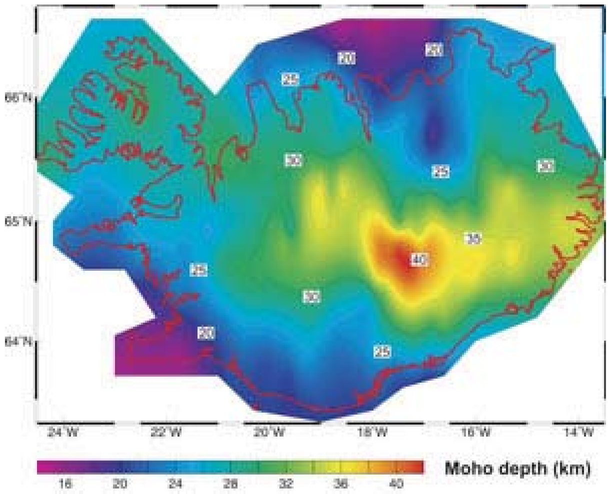


Figure 6b: Map of total crustal thickness determined using a combination of explosion seismology profiles and gravity [from Darbyshire et al., 2000]. Click on figure for enlargement.

4. Crustal structure in Iceland is not what is predicted by the plume hypothesis. Maps of crustal thickness show that the crust is thickest, ~ 40 km, beneath central Iceland and thins to 20-30 km toward the coasts (Figure 6). This is not what is expected for a plume over which the lithosphere is moving. The crust is thinner beneath western Iceland than eastern Iceland, the opposite of what is expected for an eastward-migrating plume. The local gravity field can probably be explained by crustal structure alone, without the need for density anomalies in the mantle. The block of thick crust beneath central Iceland may be a submerged, captured oceanic microplate (compare Figures 2 & 6a) [*Foulger & Anderson*, 2005].

   Historically, crustal seismic data from Iceland have been interpreted both as indicating that the crust is thin and the mantle beneath hot (the “thin, hot” model), and that the crust is thick and the mantle beneath cool (the “thick, cold” model). Both of these models have been considered to be consistent with the plume hypothesis, illustrating well that the model of a plume beneath Iceland is a data-independent *a-priori* assumption, and not an hypothesis [*Foulger et al.*, 2003]. Current interpretations of crustal seismic data suggest that the crust beneath Iceland is cooler than at similar depths beneath the East-Pacific Rise [*Menke & Levin*, 1994].

5. There is no evidence in seismic anisotropy for the pattern of radial flow expected from a plume beneath central or south-central Iceland [*Li & Detrick*, 2003] (Figures 7 & 8). The results are, instead, consistent with flow parallel to the rift zones in Iceland at depths < 100 km, and in a general NS direction or parallel to the mid-Atlantic ridge at depths > 100 km [*Li & Detrick*, 2003].

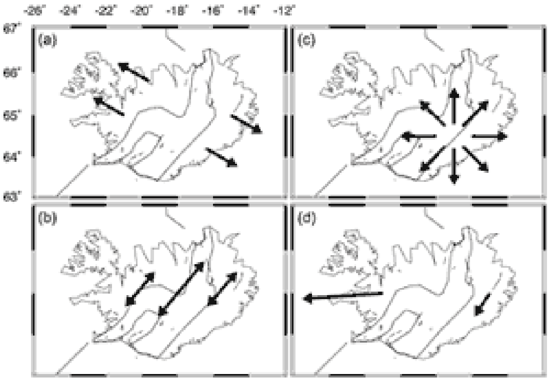


Figure 7: Possible mantle flow components beneath Iceland, (a) in plate spreading direction. (b) channeled along the ridge, (c) Radial from a plume centre, (d) from absolute plate movement [from Li & Detrick, 2003].

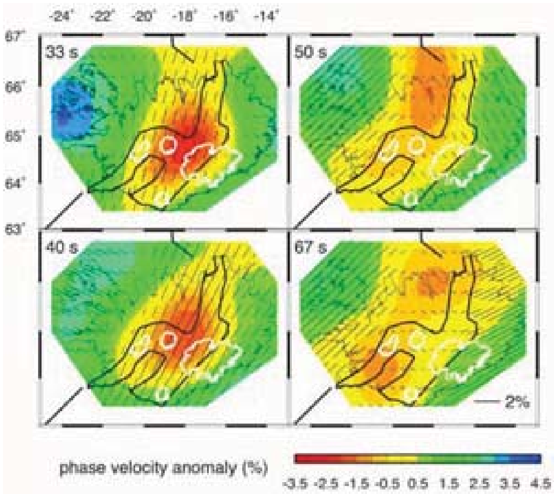


Figure 8: Maps of Rayleigh-wave phase velocity and azimuthal anisotropy at four periods (33, 40, 50 and 67 s). Colour contours are isotropic phase velocity perturbations relative to the average values for Iceland. As a rule of thumb, for these depths and periods, the depths sensed in km are approximately equal to the period in seconds (given at top left in each panel). Strikes of lines show orientations of fast directions, which may indicate flow direction. Line lengths are proportional to the magnitude of anisotropy [from Li & Detrick, 2003].

6. There is no geochemical evidence for a localised magma source beneath SE-central Iceland (Figure 1) or radial flow from this location:

    - The geochemistry of Icelandic rocks cannot be explained simply by mixing of an "enriched" plume component and a "depleted" MORB component, but additional components must be invoked, *e.g.*, to explain the helium isotope ratios (see also Helium Fundamentals page). It has been proposed that as many as five components are required to explain the geochemistry, and that the "Icelandic plume" is heterogeneous. The spatial pattern of heterogeneities does not reveal a radial pattern.

    - Pb isotope ratios do not increase towards the proposed plume location beneath SE-central Iceland (Figure 1). The lowest Pb isotopic compositions are not restricted to samples located on the edge of Iceland [*Chauvel & Hemond*, 2000], and some highly unradiogenic Pb values are found in central Iceland. Furthermore, Pb isotope values correlate with rock type and not location.

- Immediately north of the proposed plume centre, Pb is relatively unradiogenic ($^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ are low) in the Northern Volcanic Zone and along the Kolbeinsey ridge, suggesting depleted mantle sources for each [*Mertz et al.*, 1991]. $^{87}Sr/^{86}Sr$, also postulated to be a plume tracer, *decreases* towards SE-central Iceland from the Icelandic shelf edge [*Schilling et al.*, 1983], the opposite of what is expected. $^{3}He/^{4}He$ is lower in the Northern Volcanic Zone than on the more distant and indirectly linked Reykjanes peninsula. La/Sm ratios, also expected to increase towards a plume centre, *decrease* southward along the Kolbeinsey ridge whereas they *increase* northward along the Reykjanes ridge towards Iceland [*Mertz et al.*, 1991]. There is thus no geochemical evidence for northward flow of "plume" material from Iceland along the Kolbeinsey ridge [*Mertz et al.*, 1991]. In addition to being inconsistent with the plume model, this also casts doubt that the poorly developed chevron ("V-shaped") ridges about the Kolbeinsey ridge formed by the northward flow of pulses of hot "plume" material from SE-central Iceland.

- There is a discontinuity in many chemical species across central Iceland, *e.g.*, La/Sm and $^{87}Sr/^{86}Sr$ between the Western Volcanic Zone and the Skagi Zone [*Schilling et al.*, 1982].

7. Other geochemical problems associated with the plume model at Iceland include:

   - $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ are not correlated with $^{3}He/^{4}He$ [*Condomines et al.*, 1983].

   - The Kolbeinsey ridge, like the Reykjanes ridge, is shallow. However, it appears to bear little geochemical evidence that it is supported by "plume" material, which suggests that such an explanation for the shallow bathymetry of the Reykjanes ridge is not unique [*Mertz et al.*, 1991].

   - It is commonly assumed that plumes are HIMU, *i.e.*, they are enriched in $^{238}U/^{204}Pb$. However, such rocks comprise only the alkaline basalts in Iceland, that represent a small percentage of all the lavas. The majority are tholeiites that are low in $^{206}Pb/^{204}Pb$ [*Chauvel & Hemond*, 2000].

   - Different "plume tracers" do not agree, *e.g.*, elevated $^{87}Sr/^{86}Sr$ and delta-Nb extend only as far south as 61°N [*e.g., Fitton et al.*, 1997], but $^{3}He/^{4}He$ is elevated as far south as the Charlie Gibbs Fracture Zone at 53°N.

   - Shorter crustal residence times, concluded to be a response to glacial unloading, are observed to make erupted lavas more depleted [*Gee et al.*, 1998], illustrating that crustal processes influence lava characteristics that might otherwise be interpreted in terms of a plume model.

What exactly needs to be explained at Iceland?

In order to explain Iceland and the associated volcanic province, a model is required that can account for:

- the production of 2-3 times more melt at the mid-Atlantic ridge between ~ 63°30' and ~ 66°30' than elsewhere, at temperatures at most relatively mildly elevated,

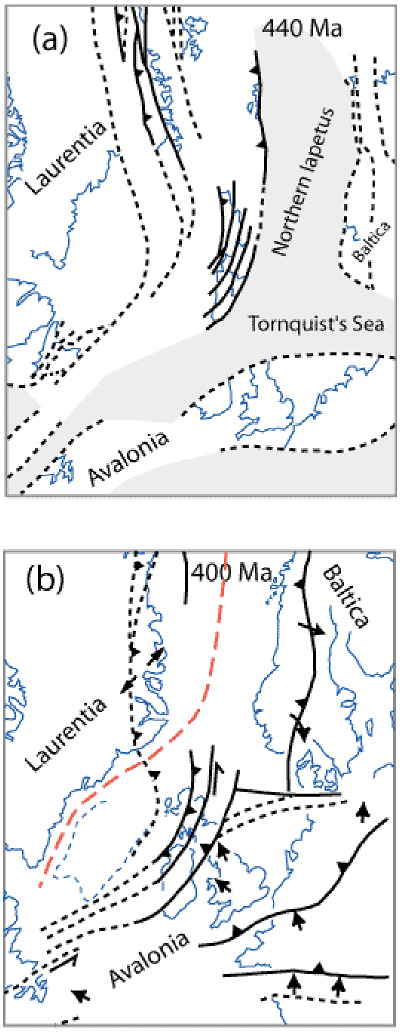
- a regional mantle seismic anomaly that extends down to the transition zone, in contrast with the ~ 250-km depth extent of low-wave speeds beneath marine parts of the spreading ridge system, and

- the ocean-island-basalt (OIB)-like geochemistry of some of the lavas.

A shallow model involving processes related to plate tectonics

In the absence of high temperatures, mantle composition that is more fusible than normal peridotite is probably the only option. Iceland and the North Atlantic Volcanic Province formed in the Caledonian suture, which was created at ~ 400 Ma when what is now Greenland and Scandinavia collided as the Iapetus ocean closed (Figure 9). In particular, the province formed where the new mid-Atlantic ridge crossed the western frontal thrust where it traverses the north Atlantic from Greenland to Britain. Because the Caledonian suture is the site of earlier subduction, abundant eclogite is expected. Eclogite is the high-pressure form of basalt, and is created when oceanic crust is carried deep into the Earth at subduction zones.

Figure 9: Closure of the Iapetus ocean at (a) 440 Ma, and (b) 400 Ma, by convergence of Laurentia, Baltica and Avalonia. Arrows: convergence directions; thick lines: faults and orogenic fronts. Black triangles indicate the sense of thrust faults. Slabs were subducted beneath Greenland, Baltica and Britain. Dashed red line indicates the position of the mid-Atlantic ridge that formed at ~ 54 Ma [from Foulger & Anderson,2005].



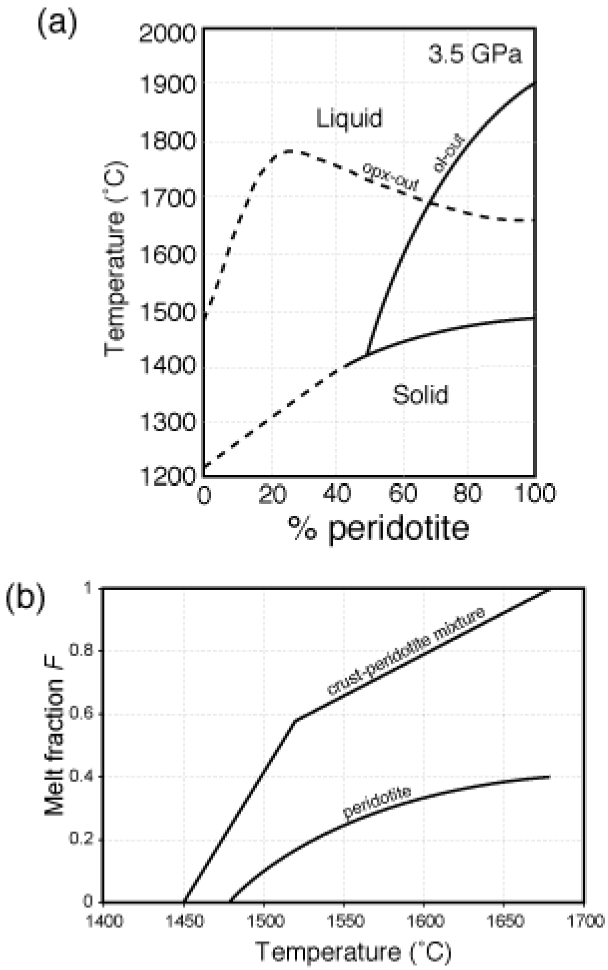


Figure 10: (a) Solidus and liquidus for fertile peridotite containing varying percentages of average altered oceanic crust. opx: orthopyroxene, ol: olivine [adapted from Yaxley, 2000], (b) Relationship between melt fraction F and temperature for fertile peridotite and a mixture of 30% average altered oceanic crust and 70% fertile peridotite. The peridotite line is the parameterisation of McKenzie & Bickle [1988] for normal fertile peridotite, and the crust-peridotite line is an approximate estimate for the bulk composition corresponding to the liquidus minimum of (a). The higher average dF/dT and lower solidus temperature for the mixture results in enhanced melt productivity at a given temperature [derived from data in Yaxley, 2000].

Eclogite, and eclogite-peridotite mixtures, have lower liquidi and solidi and a narrower melting interval than peridotite [*Yaxley*, 2000] (Figure 10a). At typical mantle temperatures, where peridotite melts to the extent of just a few percent, eclogite may be almost completely molten. In the case of eclogite-peridotite mixtures, up to several times the amount of melt is expected than from pure peridotite (Figure 10b). Thus it may be possible to explain the volume of melt at Iceland by processes the same as elsewhere along the mid-Atlantic ridge, but occurring where the mantle is fertilised by eclogite in the ancient subduction zone within which it lies. This model suggests that Iceland can be explained by passive upwelling of unusually fertile mantle. It predicts that that isentropic decompression melting of an eclogite-rich source at the mildly elevated temperatures of the north Atlantic can produce 2 – 3 times as much melt volume as the same process involving peridotite only.

There is plentiful geochemical evidence for remelted crust of Caledonian age in the basalts of east Greenland, Iceland and Britain from calculated compositions of parental melts, trace- and rare-earth elements and radiogenic isotope ratios [*Breddam*, 2002; *Chauvel & Hemond*, 2000; *Fitton et al.*, 1997; *Korenaga & Kelemen*, 2000; *Lesher et al.*, 2002].

Na_8 and TiO_2 are much higher in Iceland than on the adjoining ridges, the opposite of what is expected [*Klein & Langmuir*, 1987] for the greater extent of melting and depth range of melting required to explain the thicker crust, assuming a peridotite source (Figure 11). A peridotite/eclogite mixture is expected to have high Na_8 and TiO_2.

A source in extensively melted subducted Iapetus crust can explain the subtle differences in geochemistry between Icelandic basalts and MORB, including rare-earth elements, trace element ratios such as Zr/La, Nb-Y-Zr systematics, isotopic and noble-gas data [*Foulger et al.*, 2005]. Oceanic crust comprises a variety of lithologies, including troctolite, olivine gabbro, gabbronorite, oxide gabbro and minor residual granitic material. Remelting these produces basalts that reflect subtle variations in geochemistry inherited from the fractionation history of the corresponding mineralogy.

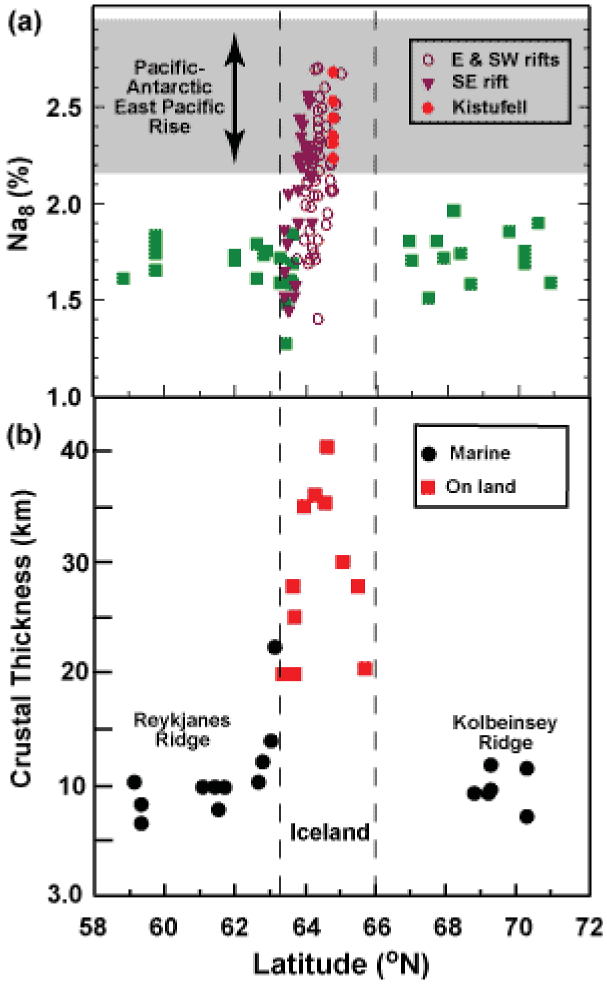


Figure 11: (a) Parental soda (Na_8) in basalt glass v. latitude. (b) Crustal thickness vs. latitude, from a compilation of seismic experiments in Iceland and the North Atlantic [from Foulger et al., 2003].

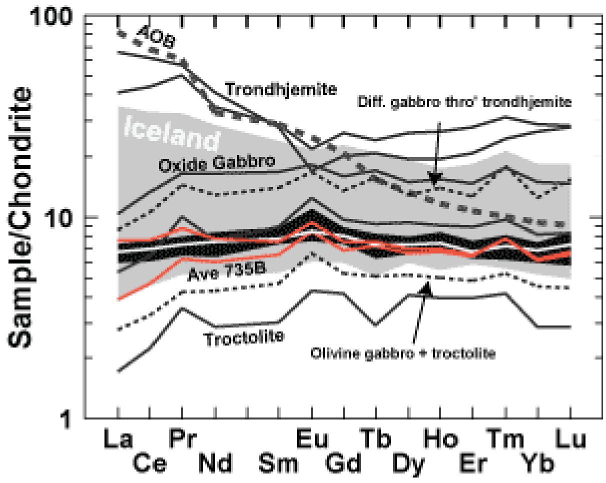


Figure 12: Comparison of the rare-earth-element patterns of average Hole 735B gabbro lithologies with and without the addition of alkali olivine basalt (AOB), with those of Icelandic basalts [from Foulger et al.,2005].

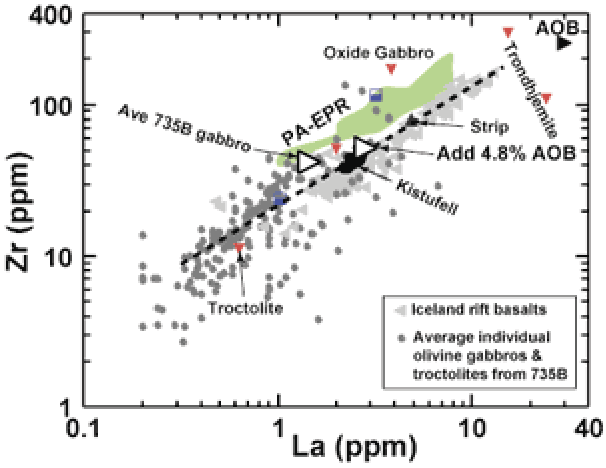


Figure 13: Icelandic basalts can be well modelled as average gabbro from DSDP hole 735B plus 4.8% alkali olivine basalt [Foulger et al.,2005].

What has been termed the "depleted plume component" in Icelandic basalts may be derived from remelted abyssal olivine gabbro [*Chauvel & Hemond*, 2000; *Kempton et al., 2000; Breddam*, 2002]. Icelandic ferrobasalts are similar to abyssal oxide gabbros. The "enriched plume component" may be derived from remelting axial or seamount E-MORB, alkalic olivine basalt, associated intrusive rocks and sedimentary materials of the subducted crust, or possibly small amounts of ancient continental crust that may, as at Jan Mayen, still underlie portions of Iceland [*Foulger et al.*, 2005; *Amundsen et al.*, 2002].

ODP Hole 735B cored a very long section of gabbroic oceanic crust on the southwest Indian ridge, and may be used to estimate the composition of subducted oceanic crust. The chondrite-normalized rare-earth-element patterns of primitive basalts from Kistufell in central Iceland [*Breddam*, 2002] may be modelled using the Hole 735B data.

In Figure 12, average Hole 735B gabbro lithologies (solid black lines) are compared with the range (black band) and average (white line) of basalts from Kistufell [*Breddam*, 2002]. The range of basalts from Icelandic rifts [*MacLennan et al.*, 2002] is shown as the gray field. The bold dashed line shows the average of two Ne-normative alkali-olivine basalts

(AOB) from seamounts near the East Pacific rise. The two red lines show the weighted average of all samples analyzed for rare-earth elements from Hole 735B (lower red line), and the same composition plus 4.8% AOB (upper red line). The latter closely matches average Kistufell olivine tholeiite. In general, the flat-to-enriched REE patterns of Icelandic basalts can be produced by mixing melt derived from abyssal gabbro and either an enriched material such as AOB, or silicic material, such as trondhjemite.

Figure 13 illustrates how Zr and La can be modelled in a similar way.
The high $^3He/^4He$ observed in Iceland is probably of Caledonian age, and preserved in olivine crystals in the subducted slabs. Olivine traps helium in gas bubbles, and since U+Th is essentially absent from olivine crystals, old, high $^3He/^4He$ ratios are preserved until such time as the olivine is remelted (see Helium fundamentals page) [*Anderson*, 1998; *Natland*, 2003].

Physical models for melting subducted crust

The extent to which subducted crust trapped at shallow levels in the mantle re-homogenizes with its peridotite host is not known. The retention of essentially pristine blocks of crust that are of the order of kilometres in thickness, and complete homogenization with mantle peridotite, represent end-member scenarios. For the case of extensive melting of pristine blocks of crust, the experiments of *Ito & Kennedy* [1974] and the compositions of natural gabbros suggest that 60-80% melting of the original bulk gabbroic assemblage is required to reproduce the compositions of Icelandic tholeiites.

Eclogite upwelling beneath the mid-Atlantic ridge in the Iceland region will be much closer to its solidus than peridotite, or it may even be partially molten. Experimental work shows that the crystallization/melting interval for eclogite (80 – 90 K) is smaller than for gabbro (> 200 K), and much smaller than for peridotite (~ 400 K) [*Yoder & Tilley*, 1962; *Ito & Kennedy*, 1974]. A melt equivalent to a moderately differentiated abyssal tholeiite can thus probably be generated from an average eclogitic abyssal gabbro, and partial melting beyond a few tens of percent will not greatly affect the generally basaltic composition.

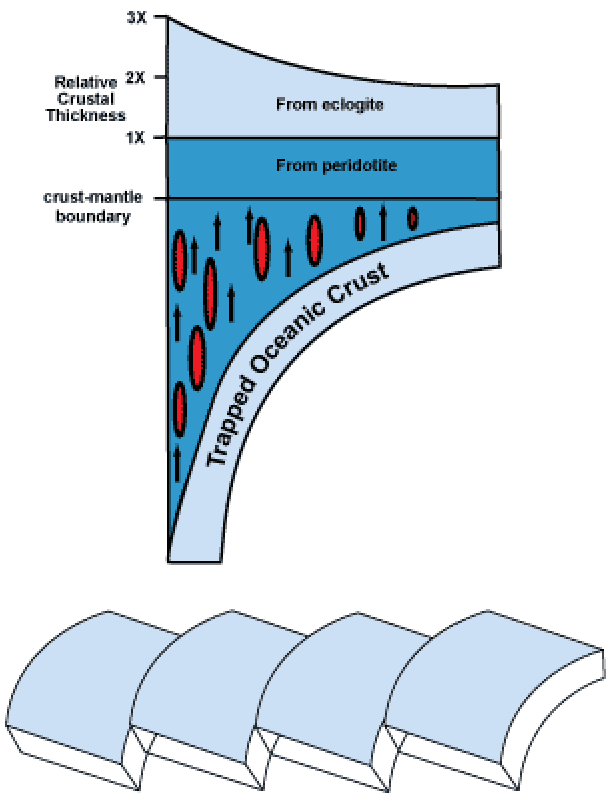


Figure 14 (Previous page): Schematic diagram illustrating how anomalously large amounts of melt may be obtained from remelting a subducted crustal slab of normal thickness. The slab may be emplaced at a high angle in the mantle (top) or thickened by imbrication (bottom).

Melt extraction from partially molten rock can begin at degrees of melting of less than one percent, and consequently, progressively extracted melt increments derived from eclogite must pond and re-homogenize in some reservoir prior to eruption. A similar process of fractional melting, aggregation, and homogenization is also required beneath normal spreading ridges since MORB is thought to be formed by up to ~ 20% partial melting of peridotite integrated over the melt column.

In order to consistently produce 2 – 3 times the normal thickness of crust in the north Atlantic (~ 10 km), more than one "normal thickness" of subducted oceanic crust is required. This could be available if the recycled crustal slabs are emplaced at a steep angle in the mantle, or imbricated (Figure 14). In the case of eclogite dispersed in a host of peridotite, the amount of fusible material available would depend on the degree of refertilisation that took place and the depth extent of the melt source region.

Plate tectonics beginning and end games

The opening and closing stages of oceans and the formation of collisional sutures are probably radically different processes from steady-state plate tectonics. The final stages of ridge-trench collision introduces sediments, water, back-arc basins and young, thin, hot oceanic crust into the shallow mantle. Such lithosphere is buoyant, and thermal modelling suggests that if younger than ~ 50 Myr, it does not sink deeper than a few hundred km [*Oxburgh & Parmentier*, 1977]. At a half-spreading rate of 1 cm/a, this would amount to 500 km of plate. A length of the final subducting lithosphere equivalent to the thickness of the colliding cratons, or up to ~ 200 km would be trapped in the continental lithosphere. The remainder of the late-subducting, buoyant oceanic lithosphere, perhaps up to several hundred km in length, might be retained in the asthenosphere beneath the sutured cratons.

When continental break-up occurs along old sutures, magmatism may be enhanced by mantle made unusually fertile by eclogitised subducted oceanic crust trapped in the rifting lithosphere, and this may contribute to the formation of volcanic margins. Delamination of the continental mantle lithosphere at the time of break-up may also recycle fertile material into the mantle beneath the new ocean. Enhanced magmatism may continue longer than the initial break-up stage if subducted material lies in belts transverse to the new ridge, and continues to be recycled into the melt extraction zone beneath the ridge despite lateral ridge migration. That lateral ridge migration with respect to underlying mantle occurs is shown by the fact that globally ridges migrate with respect to one another. A model involving a transverse belt of fertility may also explain magmatism in the Tristan da Cunha region in the south Atlantic, and elsewhere.

New questions and problems

The model described above does not suffer from many of the problems of the plume hypothesis, but it nevertheless raises several new questions and problems. Some of these are:

- Can isentropic upwelling provide enough thermal energy to produce the large melt volumes observed from eclogite, or peridotite refertilised with recycled eclogite?
- Can large melt fractions, perhaps up to 60–80%, be ponded and homogenised above the melting column, and at what depth might this occur?

- Eurasia drifted through several tens of degrees of latitude between 400 and 50 Ma. Down to what depth did the upper mantle drift with it?
- Why are large quantities of ecolgite not observed in exhumed orogenic belts?

A model such as is described here, which is radically different from the plume model, may require us to rethink related assumptions about structure and processes inside the Earth.

Concluding remarks

A model whereby the Iceland melting anomaly is derived from shallow sources in the mantle and processes consequential to plate tectonics (see also *Anderson* [2001] and PT Processes page) is consistent with the absence of very high temperatures, the persistence of the melting anomaly on the mid-Atlantic ridge, the seismic tomography, crustal structure and geochemistry. It is also consistent with the north-south tectonic and geochemical asymmetry, which is expected if rifting occurs above a heterogeneous mantle harbouring north-south asymmetry inherited from an embedded dipping slab that has variable melt fertility. Above such a heterogeneous mantle, small structures, *e.g.*, the Tjornes Fracture Zone in north Iceland, are expected to be marked by abrupt changes in geochemistry, and this is indeed observed. In the model proposed here, the location of the Iceland volcanic province over an easterly trending branch of the Caledonian suture is not a coincidence.

News & Discussion

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