An alternative model for Iceland & the North Atlantic Igneous Province

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Summary

It is almost universally assumed that Iceland is underlain by a hot plume rising from deep within the mantle. At Iceland, probably the best-studied hotspot on Earth, this hypothesis is inconsistent with many first-order observations, such as the lack of evidence for high mantle temperatures, a time-progressive volcanic track or a seismic anomaly in the lower mantle. Iceland is essentially a melt anomaly with normal, ridge-like mantle temperatures.

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 at Iceland is explained well by enhanced fertility there resulting from ancient subducted slabs that still remain in the shallow mantle. This model is consistent with the historical locus of melt production, and the lack of geophysical indicators of a plume [*Foulger et al.*, 2003a]. It is also consistent with the geochemistry of Icelandic basalts, which differs only subtly from mid-ocean ridge basalt (MORB) [*Foulger et al.*, 2003b]. In this way, Iceland is explained as a natural consequence of relatively shallow processes related to plate tectonics. Unlike the hot, thermal plume model, this model can account for all the major geophysical, geological, petrological and geochemical observations at Iceland without special pleading, paradoxes, or invoking coincidences.

A plume model is inconsistent with many observations

Virtually none of the results of Earth science research in Iceland agree with the predictions of the plume hypothesis [*Foulger*, 2002]. Evidence for the 200-600°C mantle temperature anomaly required for a plume is absent. Marine heat flow measurements around Iceland provide no evidence for high temperatures [*Stein & Stein*, 2003]. The petrology of Icelandic basalts is similar to MORB, and geothermometers involving Mg# and MgO indicate temperatures no more than approximately 70°C higher than the average beneath mid-ocean ridges (e.g., http://www.mantleplumes.org/HawaiiFocusGroup/Sisson_abs.html). Even in central Iceland, primitive lavas have eruptive temperatures of only ~ 1240°C [*Breddam*, 2002], close to those of similarly magnesian N-MORB [*Ford et al.*, 1983]. Picrite glass, an indicator of high temperatures, is not found.

A plume is postulated to have migrated southeast from beneath the Greenland craton at ~ 60 Ma to underlie southeast Iceland at present [*Lawver & Muller*, 1994] (Figure 1). However, no time-progressive volcanic track is observed, such as occurs at Hawaii. Volcanism has been focused at the mid-Atlantic ridge (MAR) since the opening of the Atlantic at ~ 54 Ma.

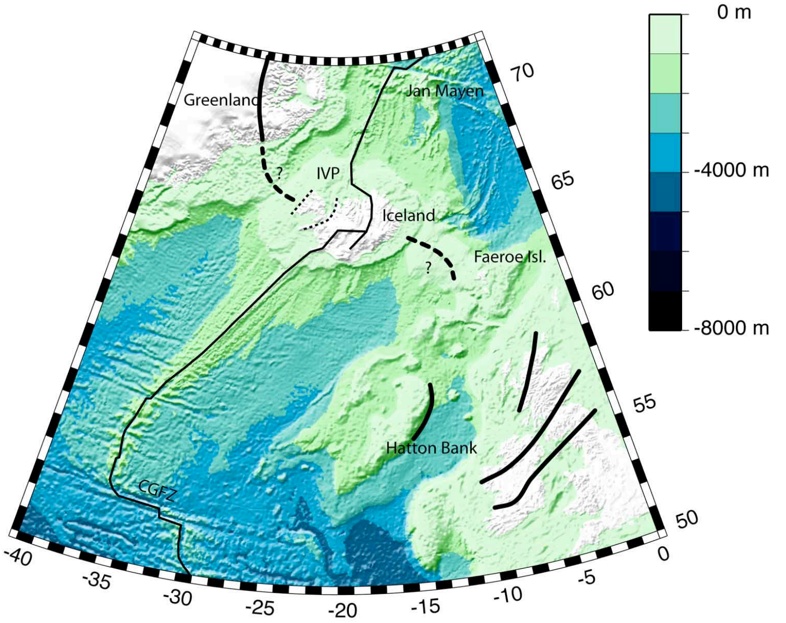

Figure 1: Present-day bathymetry of the north Atlantic, showing the Greenland-Iceland-Faeroe bathymetric ridge which is underlain by crust ~ 30 km thick. Other shallow areas are blocks of stretched continental crust. Thin black line: MAR; thin dashed black lines: extinct ridges; thick lines: faults of the Caledonian suture [Soper et al., 1992]; thick dashed line: inferred trend of suture crossing the Atlantic Ocean [Bott, 1987], IVP: Iceland volcanic plateau, CGFZ: Charlie Gibbs fracture zone.

Seismic tomography yields no evidence for a plume-like structure in the lower mantle [*Ritsema et al.*, 1999], which is predicted by the plume hypothesis. Instead, both the strength and the non-cylindrical morphology of the upper-mantle seismic anomaly show that it extends only down to the mantle transition zone (Figure 2) [*Foulger et al.*, 2000; *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 by over-saturating the colour scale, which imparts the visual impression of significance to weak bodies in the lower mantle that are at the noise level and have not been confirmed by other studies [*Bijwaard & Spakman*, 1999]. Cross sections are also truncated to remove similar bodies beneath the Canadian shield and Scandinavia, where plumes are not expected.

Crustal structure in Iceland provides no support for the plume hypothesis. The crust is thinner beneath western Iceland than eastern Iceland, the opposite of what is expected for an eastwardmigrating plume (Figure 3). The local gravity field can probably be explained by crustal structure alone, without need for large density anomalies in the mantle. Historically, crustal seismic data from Iceland have been interpreted both as indicating that the crust is thin and the mantle beneath hot, and that the crust is thick and the mantle beneath cool. 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 an *a-priori* assumption, and not an hypothesis [*Foulger et al.*, 2003c]. 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].

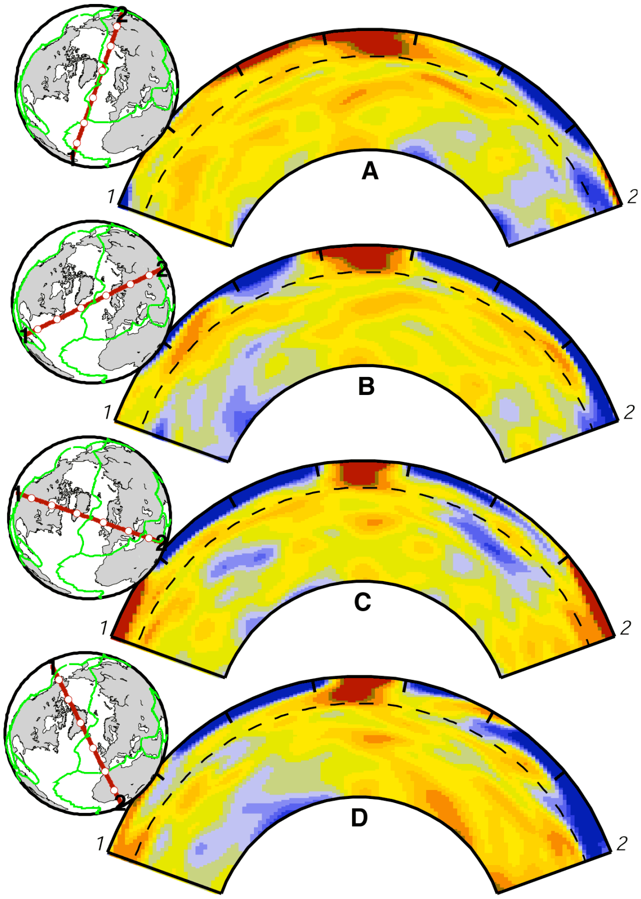

Figure 2: Tomographic cross sections through Iceland [Ritsema et al., 1999]. Courtesy of J. Ritsema.

Although the geochemistry of Iceland is somewhat different from that of the adjoining Reykjanes ridge, interpretation in terms of mixture of a plume component and MORB is problematic. The geochemistry cannot be explained by mixing two components, but "depleted" and "enriched" plume components must be invoked, and perhaps an additional component to explain the helium isotope data. $^{87}Sr/^{86}Sr$, postuated to be a plume tracer, increases away from the presumed centre of the plume to the Icelandic shelf edge [*Schilling et al.*, 1983] – the opposite of what is expected. Na_8 and TiO_2 are much higher in Iceland than on the adjoining ridges, again the opposite of what is expected for the greater extent of melting and depth range of melting required to explain the thicker crust [*Klein & Langmuir*, 1987].

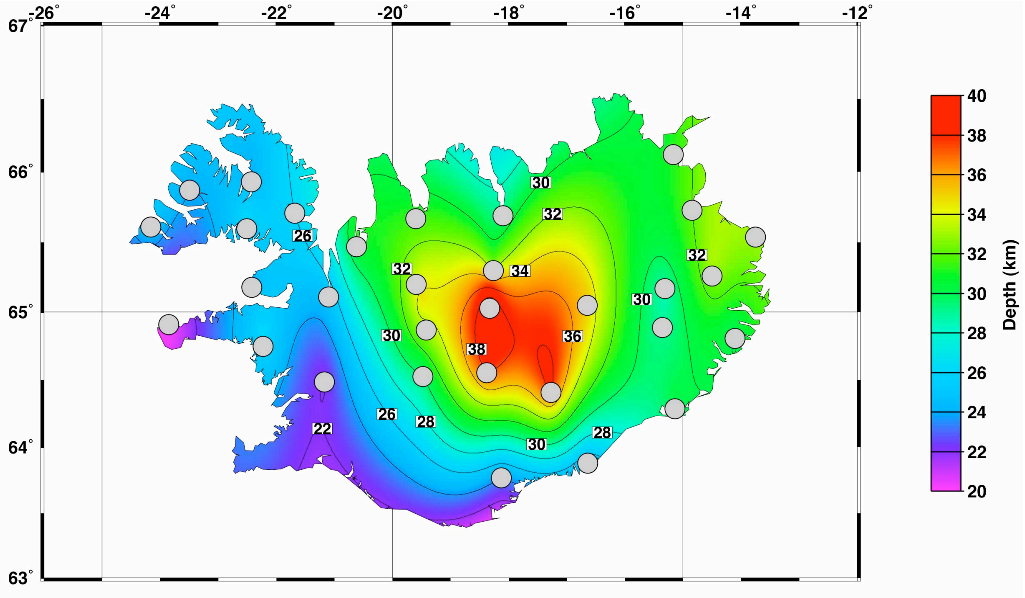

Figure 3: Contour map of the depth to the base of the lower crust (defined as the depth to the V_s *= 4.2 km/s horizon) (from Foulger et al., 2003c).*

What must be explained?

In order to explain Iceland, a model is required that can account for the production of 2-3 times more melt at the MAR between ~ 63˚30' and ~ 66˚30' than elsewhere on the ridge, at similar temperatures. A 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 are now Greenland and Scandinavia collided as the Iapetus ocean closed (Figure 4). This suture is thus the site of earlier subduction, and abundant eclogite is expected. Eclogite is the high-pressure form of basalt, and is created when oceanic crust is transported into the Earth at subduction zones. The latest-subducting crust would probably have been fairly young and hot. It would thus not have been dense enough to sink deep into the mantle, but would have remained, abandoned, in the upper mantle.

A shallow model involving plate tectonic processes

Eclogite, and eclogite-peridotite mixtures, have lower liquidi and solidi and a narrower melting interval than peridotite [*Yaxley*, 2000]. At typical mantle temperatures, where peridotite melts to the extent of just a few percent, eclogite is almost completely molten. In the case of eclogite-peridotite mixtures, up to several times the amount of melt is expected than from pure peridotite. Thus the volume of melt at Iceland can be explained by processes the same as elsewhere along the MAR, 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 only, and it predicts that isentropic decompression melting of an eclogite-rich source can produce 2 – 3 times as much melt volume than the same process involving peridotite only.

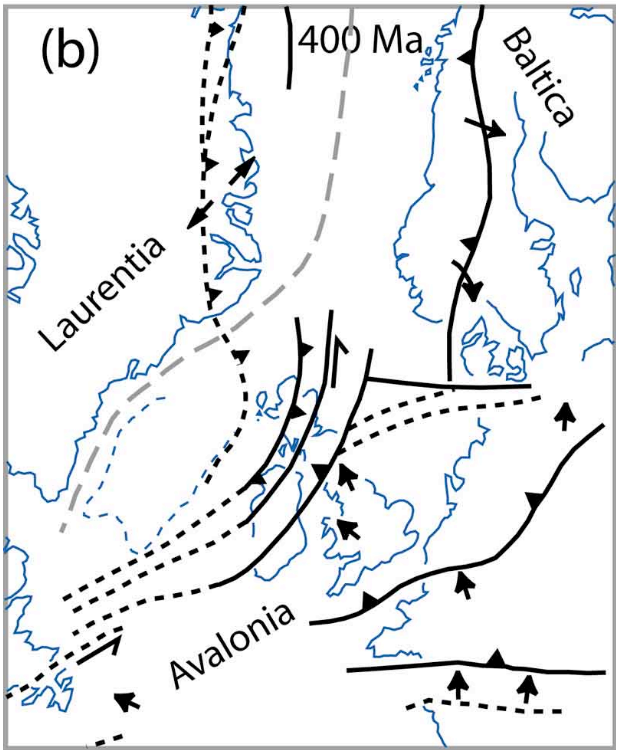

Figure 4: Closure of the Iapetus ocean at 400 Ma. Arrows: convergence directions; thick lines: faults and orogenic fronts. Black triangles indicate sense of thrust faults. Slabs were subducted beneath Greenland, Baltica and Britain [after Soper et al., 1992]. Dashed grey line indicates position of MAR that formed at ~ 54 Ma.

There is 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 (REE) and radiogenic isotope ratios [*Breddam*, 2002; *Chauvel & Hemond*, 2000; *Korenaga & Kelemen*, 2000; *Lesher et al.*, 2002]. A source in extensively melted subducted Iapetus crust can explain the subtle differences in geochemistry between Icelandic basalts and MORB, including REE, trace elements such as Zr/La, Nb-Y-Zr systematics, isotopic and noble-gas data (Figure 5, *Foulger et al.*, 2003c).

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. What has been termed the "depleted plume component" [*Kempton et al.*, 2000] in Icelandic basalts may be derived solely from abyssal gabbro, and the "enriched plume" component may be derived from remelting axial or seamount E-MORB, AOB, and associated intrusive rocks.

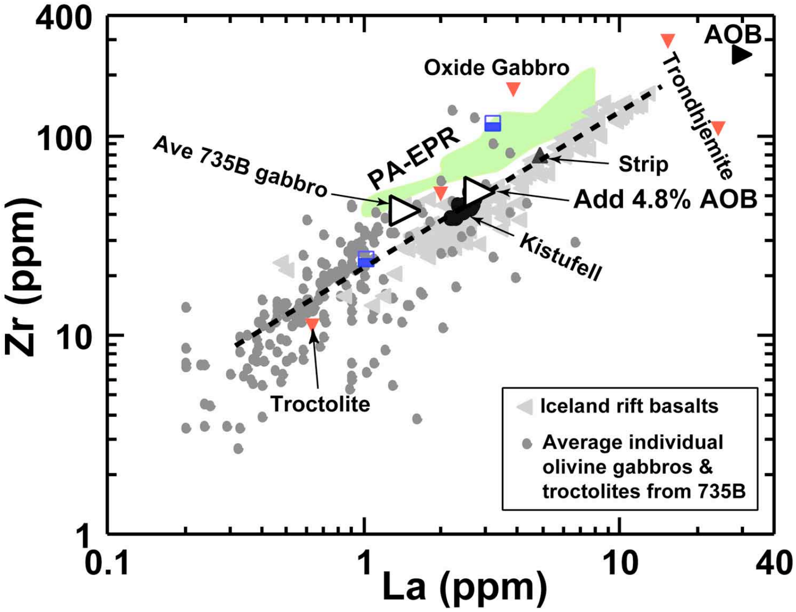

Figure 5: Icelandic basalts can be well modelled as average gabbro from DSDP hole 735B plus 4.8% alkali olivine basalt.

The high ^{3}He/^{4}He 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-^{3}He/^{4}He ratios are preserved until such time as the olivine is remelted [*Anderson*, 1998; *Natland*, 2003].

Summary

This model for the Iceland melt extraction anomaly, which involves shallow plate tectonic processes only, can explain the melt distribution, temperature, seismology, petrology and geochemistry of the region more plausibly and with less special pleading and fewer appeals to coincidence than models involving a hot plume.

The Iceland region serendipitously offers many clues to its genesis, and has been unusually well studied. The lessons learned there may give clues to the origin of other "hotspot" melt anomalies. The essential ingredients are mantle fertility arising from crust subducted when it was still relatively hot and young, or from some other source such as the continental lithosphere, and lithospheric extension. In this context it would seem no coincidence that many "hotspots" occur on or near ridges, triple junctions, faults and sutures. This kind of model attributes melt anomalies to the by products of plate tectonics, and may provide a generic alternative to the plume model.

References

Anderson, D.L., A model to explain the various paradoxes associated with mantle noble gas geochemistry, *Proc. Nat. Acad. Sci.*, **95**, 9087-9092, 1998.

Bijwaard, H., and W. Spakman, Tomographic evidence for a narrow whole mantle plume below Iceland, *Earth planet. Sci. Lett.*, **166**, 121-126, 1999.

Bott, M.H.P., Plate tectonic evolution of the Icelandic transverse ridge and adjacent regions, *J. geophys. Res.*, **90**, 9953-9960, 1985.

Breddam, K., Kistufell: Primitive melt from the Iceland mantle plume, *J. Pet.*, **43**, 345-373, 2002.

Chauvel, C., and C. Hemond, Melting of a complete section of recycled oceanic crust: Trace element and Pb isotopic evidence from Iceland, *Geochem. Geophys. Geosys.*, **1**, 1999GC000002, 2000.

Ford, C.E., D.G. Russell, J.A. Craven, and M.R. Fisk, Olivine-liquid equilibria: temperature, pressure and composition dependence of the crystal/liquid cation partition coefficients for Mg, Fe2+, Ca, and Mn, *J. Pet.*, **24**, 256-265, 1983.

Foulger, G.R. and D.L. Anderson, Iceland is cool: A reinterpretation of the tectonics and melt anomaly as shallow, low-temperature processes, submitted to *J. Volc. Geoth. Res.*, 2003a.

Foulger, G.R., J.H. Natland and D.L. Anderson, Iceland is fertile: The melt anomaly results from extensive melting of subducted crust in the Caledonian suture, not from a plume, submitted to *J. Volc. Geoth. Res.*, 2003b.

Foulger, G.R., Z. Du, and B.R. Julian, Icelandic type crust, *Geophys. J. Int.*, in press, 2003c.

Foulger, G.R., Plumes, or plate tectonic processes?, *Astron. Geophys.*, **43**, 6.19-6.23, 2002.

Foulger, G.R., M.J. Pritchard, B.R. Julian, J.R. Evans, R.M. Allen, G. Nolet, W.J. Morgan, B.H. Bergsson, P. Erlendsson, S. Jakobsdottir, S. Ragnarsson, R. Stefansson, and K. Vogfjord, Seismic tomography shows that upwelling beneath Iceland is confined to the upper mantle, *Geophys. J. Int.*, **146**, 504-530, 2001.

Foulger, G.R., M.J. Pritchard, B.R. Julian, J.R. Evans, R.M. Allen, G. Nolet, W.J. Morgan, B.H. Bergsson, P. Erlendsson, S. Jakobsdottir, S. Ragnarsson, R. Stefansson, and K. Vogfjord, The seismic anomaly beneath Iceland extends down to the mantle transition zone and no deeper, *Geophys. J. Int.*, **142**, F1-F5, 2000.

Kempton, P.D., J.G. Fitton, A.D. Saunders, G.M. Nowell, R.N. Taylor, B.S. Hardarson, and G. Pearson, The Iceland plume in space and time: a Sr-Nd-Pb-Hf study of the north Atlantic rifted margin, *Earth planet. Sci. Lett.*, **177**, 273-285, 2000.

Klein, E.M., and C.H. Langmuir, Ocean ridge basalt chemistry, axial depth, crustal thickness and temperature variations in the mantle, *J. geophys. Res.*, **92**, 8089-8115, 1987.

Korenaga, J. and P.B. Kelemen, Major element heterogeneity in the mantle source of the north Atlantic igneous province, *Earth planet. Sci. Lett.*, **184**, 251-268, 2000.

Lawver, L.A., and R.D. Muller, Iceland hotspot track, *Geology*, **22**, 311-314, 1994.

Lesher, C.E., J. Blichert-Toft, and O. Stecher, Mantle sources and contamination of the basalts of the North Atlantic Igneous Province, *J. Pet.*, submitted, 2002.

Menke, W., and V. Levin, Cold crust in a hot spot, *Geophys. Res. Lett.*, **21**, 1967-1970, 1994.

Natland, J.H., Capture of mantle helium by growing olivine phenocrysts in picritic basalts from the Juan Fernandez Islands, SE Pacific, *J. Pet.*, in press, 2003.

Ritsema, J., H.J. van Heijst, and J.H. Woodhouse, Complex shear wave velocity structure imaged beneath Africa and Iceland, *Science*, **286**, 1925-1928, 1999.

Schilling, J.-G., M. Zajac, R. Evans, T. Johnston, W. White, J.D. Devine, and R. Kingsley, Petrologic and geochemical variations along the mid-Atlantic ridge from 29°N to 73°N, *Am. J. Sci.*, **283**, 510-586, 1983.

Soper, N.J., R.A. Strachan, R.E. Holdsworth, R.A. Gayer, and R.O. Greiling, Sinistral transpression and the Silurian closure of Iapetus, *J. geol. Soc. Lon.*, **149**, 871-880, 1992.

Stein, C., and S. Stein, Sea floor heat flow near Iceland and implications for a mantle plume, *Astron. Geophys.*, **44**, 1.8-1.10, 2003.

Yaxley, G.M., Experimental study of the phase and melting relations of homogeneous basalt + peridotite mixtures and implication for the petrogenesis of flood basalts, *Cont. Min. Pet.*, **139**, 326-338, 2000.