

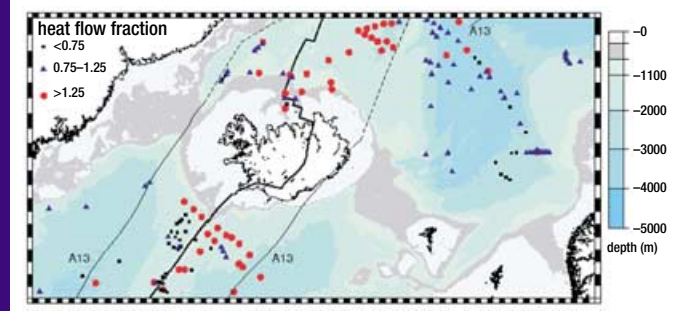
Mantle plumes: heat-flow near Iceland

In the first of four pieces arising from Gill Foulger's challenge to the mantle plume hypothesis (last issue), Carol Stein and Seth Stein join the debate with some data and comment on heat-flow around Iceland.

Abstract

Seafloor heat-flow near Iceland on the North American side of the Mid-Atlantic Ridge is comparable to that for oceanic lithosphere elsewhere, and thus shows no evidence for significantly higher temperatures associated with a mantle plume. Heat-flow is higher on the Eurasian plate than on the North American plate, an intriguing asymmetry opposite to that expected from models in which Iceland formed over a mantle plume.

1: Bathymetry and heat-flow for the Iceland region. Heat-flow shown as heat-flow fraction, observed values normalized by global average values for that lithospheric age (figure 2). Lithosphere younger than about 35 Myr indicated by the positions of magnetic anomaly 13 (solid line) after Mueller *et al.* (1997) or approximated by dashed line.



Foulger's (2002) paper in the last issue of *Astronomy & Geophysics* (A&G 43 6.19) illustrates the debate over whether hotspots – regions of long-lived excess volcanism such as Iceland, Hawaii or Yellowstone – result from plumes of hot material upwelling from great depth in the mantle (Morgan 1971). In the plume model, plate motion over fixed or slow-moving plumes causes age-progressive linear volcanic chains and topographic swells that identify plumes and yield inferences about their properties. This model has been widely accepted because it gives an elegant explanation of how diverse volcanic regions have similar origins, and an absolute reference frame describing plate motions relative to the deep mantle.

However, many hotspots deviate from the expected behaviour. Some hotspots move significantly relative to each other and the spin axis (Tarduno and Cottrell 1997), changes in some volcanic chain orientations do not correspond to the expected plate motion changes (Norton 1995), and some chains show no clear age progression (Schlanger *et al.* 1984). A view is emerging that at least some hotspots, notably Yellowstone, are not due to deep mantle plumes (Humphreys *et al.* 2000, Christiansen *et al.* 2002), and the entire plume model is being challenged (Anderson 2000, Hamilton 2002).

Iceland is a focus of these discussions, as the type example of a hotspot on a mid-ocean ridge. In the plume model, the elevation and thick crust relative to typical mid-ocean ridges result from melting by a hot plume (White 1999),

whereas in Foulger's (2002) non-plume model, temperatures are not unusually high but excess melting of more fertile material occurs, consistent with petrologic arguments (Korenaga and Kelemen 2000). Seismological results for the maximum depth of the low velocity anomaly, the strongest discriminant between a deep mantle plume and an upper mantle melting anomaly, are discordant (Foulger *et al.* 2001, Shen *et al.* 2002) because seismometers on Iceland have limited resolution for structure at depth owing to the island's small size.

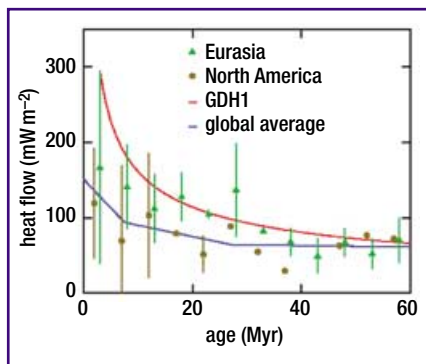
Seafloor heatflow

Given this interest, we examined seafloor heat-flow data from the Iceland region. The small or absent heat-flow anomalies at other hotspots play a role similar to that of the dog whose failure to bark helped Sherlock Holmes locate the missing racehorse Silver Blaze. Originally, the uplift at Hawaii and similar midplate hotspots was thought to reflect a hot plume causing heating to about 50 km of the surface (Crough 1983, McNutt and Judge 1990). Such heating predicts heat-flow significantly higher than from the usual cooling of oceanic lithosphere as it spreads away from the mid-ocean ridges where it formed. Although anomalously high heat-flow was initially reported, subsequent analysis showed that most, if not all, of the apparent anomalies resulted from comparing data to thermal models that underestimated heat-flow elsewhere (Von Herzen *et al.* 1989, Stein and Abbott 1991, Stein and Stein 1993).

Hence subsequent models generally assume that the uplift results from the dynamic effects of rising plumes (Liu and Chase 1989, Sleep 1994) and the associated compositional buoyancy, whose thermal effects are concentrated at the base of the lithosphere and raise surface heat-flow at most slightly, because conduction to the surface takes tens of millions of years.

Heat-flow has played little role in the debate about hotspots like Iceland, which are on or near mid-ocean ridges, for two reasons. The first is that predictions for heat-flow have not been offered, because such hotspots are thought to reflect an interaction between upwelling plumes and nearby spreading centers (Ito *et al.* 1996) more complex than at mid-plate hotspots which are generally attributed to a simpler (albeit not yet understood) interaction of a plume with a plate interior. Second, seafloor near on-ridge hotspots is young, less than 40 Myr old. In young seafloor, measured heat-flow is significantly lower than expected purely from conductive cooling of the lithosphere, because some heat is transported by hydrothermal circulation of sea water through the crust (e.g. Stein and Stein 1994). Hence it was unclear how to characterize "normal" heat flow and assess possible perturbations.

Plume models imply that heat-flow should be above the "normal" in several ways. The most important is likely to be an indirect effect of plume material migrating along the Mid-Atlantic Ridge (White 1999). This should raise temperatures along the ridge by up to several



2: Heat-flow data (figure 1) grouped in Myr bins for the Eurasian and North American plates, compared to the predictions of the GDH1 thermal model which does not include the effect of hydrothermal circulation, and a linear fit to the global average values.

hundred degrees, depending on distance from the plume, so that lithosphere formed on either plate would have higher heat-flow.

The plume should also have direct effects on heat flow. First, outward-flowing plume material should heat the base of already-formed lithosphere. This effect would be similar to that at Hawaii, but larger because heat is added at the base of the lithosphere, which is thinner near Iceland because of its relative youth. Hence increased heat-flow should occur on both sides of the Mid-Atlantic Ridge.

A second direct effect could result from the history of relative motion between the plume, Mid-Atlantic Ridge, and the two plates. Modelling this history is more complex than along the Hawaiian–Emperor seamount chain, where the history of volcanism is used to infer the history of the plume. In contrast, the Iceland plume’s history cannot be inferred directly from the elevated Iceland–Greenland and Iceland–Faroe plateaus extending westward and eastward from Iceland (figure 1), because models assuming various hotspot sizes and motions “offer non-unique solutions that could be used to explain a plateau of any location, origin, and age progression” (Vink 1984).

To address this ambiguity, Vink (1984) used plate reconstructions assuming that plumes are fixed to predict that the plume presently under Iceland was under Greenland 45 Myr ago. Since then, westward motion of the Mid-Atlantic Ridge relative to the plume has brought Iceland over the plume. During this time, plume material flowed laterally beneath the North American plate to the Mid-Atlantic Ridge. Assuming that plume material flowed to the closest point on the Mid-Atlantic Ridge, where plateaus formed by excess volcanism and were transported away in opposite directions as the two plates spread, this matches the observed trends of the plateaus. Alternatively, White and McKenzie (1989) argued that such lateral flow was not possible. Instead, they proposed that a

newly formed plume initiated the rifting of the Greenland margin and the opening of the North Atlantic, such that the paired plateaus formed directly above, via ridge jumps that kept the Mid-Atlantic Ridge above the plume’s core (White 1999). Although these plume history models differ, and only the first reflects detailed kinematic modelling, we expect that both predict heat-flow near Iceland higher on the North American (west) plate than for lithosphere of the same age on the Eurasian (east) plate.

We thus examined heat-flow data for sites within 500 km of Iceland to see if they showed either expected effect – abnormally high heat-flow on either side of the ridge, and higher heat-flow to the west. Only good-quality data, by the criteria of Stein and Abbott 1991, were used. As shown in figure 2, we find no evidence for either effect. The North American values, where a plume should raise heat flow, are consistent with the global average for lithosphere of that age including the effect of hydrothermal circulation (Stein *et al.* 1994). We do observe an asymmetry, but in the opposite sense. Out to an age of about 35 Myr, European values are generally about 40% higher than for North America, approaching those of a lithospheric cooling model (Stein and Stein 1992) that does not include hydrothermal effects.

Asymmetry

Such striking asymmetry between ridge flanks is unusual. Although significantly more data will be needed to fully understand it, we can ask three questions with what we have:

- Is it real? Heat-flow data in the region are sparse, as are such data elsewhere in the oceans, owing to the cost and difficulty of collection. We lack the ideal distribution of data on opposite sides of the ridge, especially near the plateaus, and so have only a regional comparison. Even so, the asymmetry seems real.

- Is it due to sediments? For a given age, sediments tend to be thicker on the Eurasian side (Talwani *et al.* 1971). The higher heat-flow may thus reflect impermeable sediment suppressing hydrothermal circulation, as observed near the Juan de Fuca ridge (Davis *et al.* 1992). However, this mechanism is thought to require that almost all igneous basement rock be covered, which is not the case here, especially within 10 Myr of the axis. Moreover, on a global basis, sediment thickness rarely has a significant effect on heat-flow (Stein *et al.* 1995). Hence, although sediment effects may contribute, our sense is that they are not the prime cause of the asymmetry.

- If not, what causes it? Because the asymmetry is opposite to that expected from the proposed history of the plume, non-sediment-related effects also seem worth considering.

First, the asymmetry might somehow reflect differences only in mantle temperature between

the plates. However, in such a case we expect comparable variations in subsidence, with the hotter Eurasian plate subsiding faster and hence being deeper for a given age. Such an effect has been reported, but the 5% subsidence-rate asymmetry (Johansen *et al.* 1984) is significantly less than that in heat-flow. Second, the asymmetry might somehow reflect westward migration (absolute motion) of the Mid-Atlantic Ridge, which may affect spreading processes (Stein *et al.* 1977, Small and Danyushevsky 2003). However, initial inspection of data suggests that the asymmetry dies off to the north and south. Third, the asymmetry might reflect ridge migration over an unusual part of the mantle, similar to Foulger’s (2002) proposal that Iceland results from excess magmatism as the ridge migrates over the Caledonian suture. Such a mechanism needs a process that generates both higher-than-normal heat-flow and much-less-anomalous depths.

In summary, heat-flow data near Iceland show no evidence for either of the regional thermal anomalies that might be expected near a mantle plume – higher overall heat-flow and asymmetry with higher heat-flow on the North American plate. Hence if a plume exists, it is not significantly hotter than typical mid-ocean ridges. Moreover, the heat-flow asymmetry opposite to that expected implies either significant sediment perturbations or other tectonic processes. Hence, whatever the outcome of the debate over the depth of the low velocity anomaly near Iceland, heat-flow should provide useful constraints on models for what is occurring. ●

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