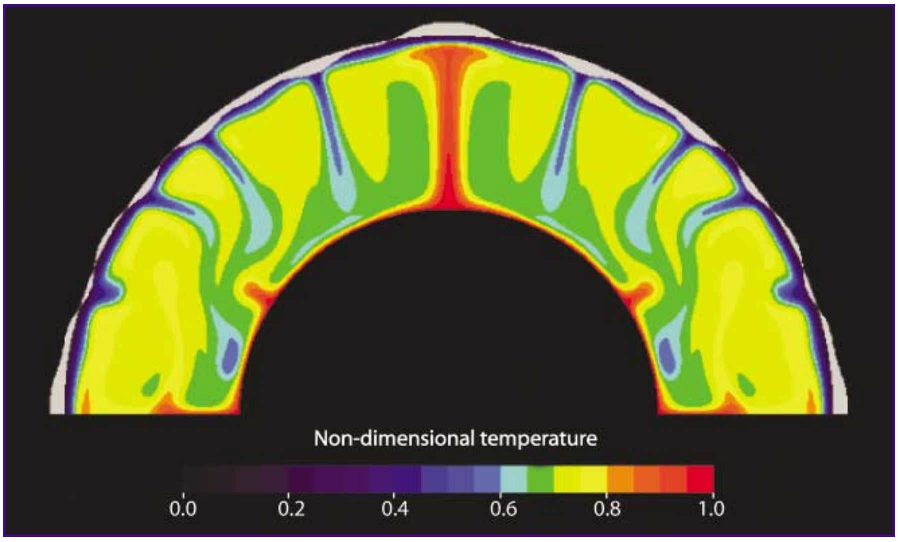
Plumes, or plate tectonic processes?

A mantle plume under Iceland is taken for granted as the cause of the volcanism there. But **Gill Foulger** argues that the evidence does not stand up.

Abstract

Hotspots – large volcanic provinces – such as Iceland, Hawaii and Yellowstone, are almost universally assumed to come from plumes of hot mantle rising from deep within the Earth. At Iceland, perhaps the best-studied hotspot on Earth, this hypothesis is inconsistent with many first-order observations, such as the lack of high temperatures, a volcanic track or a seismic anomaly in the lower mantle. The great melt production there is explained better by enhanced fertility in the mantle where the mid-Atlantic spreading ridge crosses the Caledonian suture zone. The thick crust built by the excessive melt production encourages complex, unstable, leaky microplate tectonics, which provides positive feedback by enhancing volcanism further. Such a model explains Iceland as a natural consequence of relatively shallow processes related to plate tectonics, and accounts for all the first- and second-order geophysical, geological and geochemical observations at Iceland without special pleading or invoking coincidences.

We know little about the deep interior of Earth, but because it is the key to understanding surface geology, volcanism and earthquakes, there is much speculation about its composition and the processes that occur within it. Perhaps the most fundamental question is the depth extent of those structures and processes that influence the surface. Opinion is divided regarding whether the mantle, at depths exceeding ~1000 km, has little to do with surface processes, or whether it is actively involved, down to the outermost core at ~3000 km depth, in the mass transport system associated with plate tectonics. The latter view would imply that material from the deepest mantle can be sampled at volcanic provinces on Earth's surface. The former would imply that it cannot.

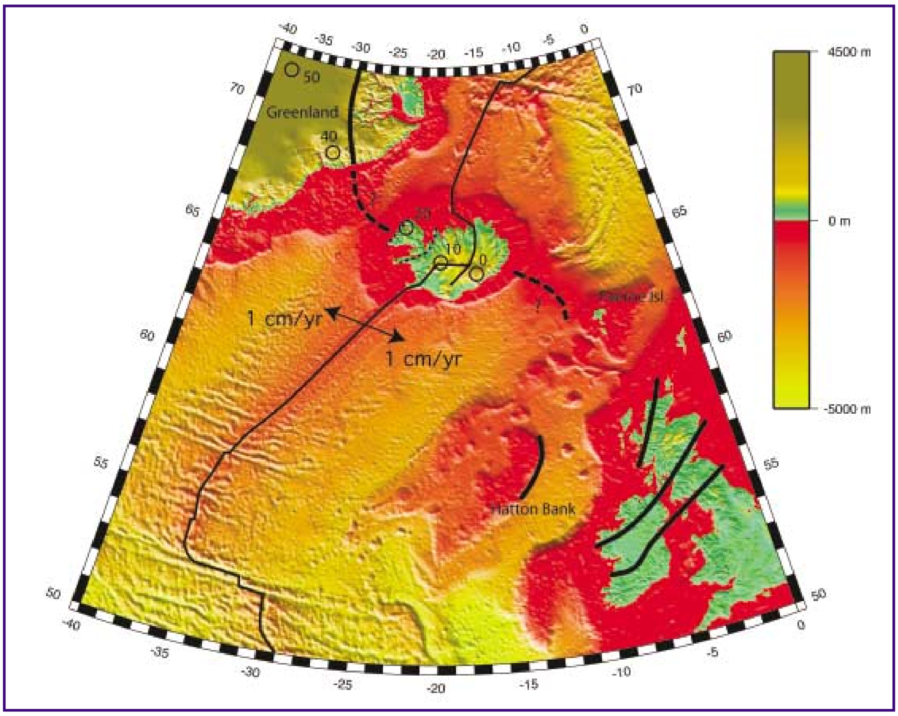


1: Numerical simulation of a deep mantle plume. The red, mushroom-like feature represents a hot upwelling from the core–mantle boundary. Blue, linear features are cold downwellings. (From Kiefer and Kellogg 1998.)

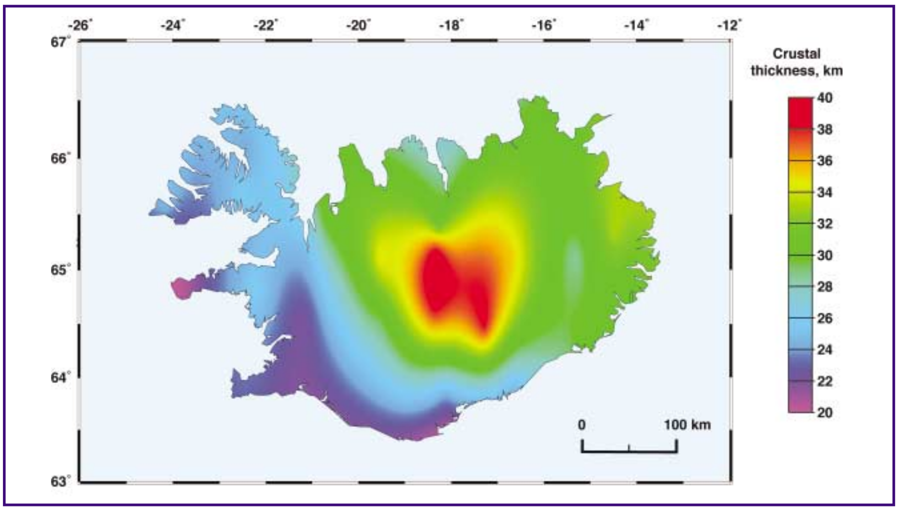
An important contribution to this debate came hot on the heels of the newly accepted plate tectonic theory. Morgan (1971) suggested that "hotspots", i.e. areas of exceptionally intense volcanism such as Hawaii, Yellowstone and Iceland, are fuelled by plumes of buoyant, hot material that arise in the deep mantle and punch through the mobile, convecting, shallow mantle to reach the surface (figure 1). This theory was developed in order to explain the time-progressive volcanic trails associated with some hotspots, and their apparent fixity relative to one another. If the sources of the volcanism are rooted in a relatively immobile deep mantle, they will not move relative to one another and the plates at the surface will drift passively above them, bearing away trails of volcanism. Hot plumes are unlikely to form spontaneously in a gradational layer, but would rise from a thermal boundary layer. This implies that their source would have to be the core–mantle boundary, which is the largest thermal boundary layer in the Earth apart from the surface itself.

Morgan's plume hypothesis was initially received sceptically (e.g. O'Hara 1975, Tozer 1973), but criticism and debate waned quickly. This uncharacteristic reluctance to engage in debate was noted, and some felt that Earth scientists were afraid to question this radical new hypothesis because of their recent humiliation over their vigorous opposition to Wegener's theory of continental drift. Within a few years the hypothesis attained the status of an unchallenged basic premise, and the alternative theories initially suggested, including local convection, fracture control mechanisms, and propagating cracks, are little tested and rarely discussed today. As a result, few students since the mid-1970s have been introduced to the concept that plumes might not exist.

However, few, if any, of the original predictions of the plume hypothesis have been confirmed. Observations show that hotspots are not hot (Anderson 2000, Stein and Stein 1993), do not have time-progressive volcanic trails (Turner and Jarrard 1982), are not relatively fixed (Molnar and Atwater 1973, Molnar and Stock 1987, Tarduno and Gee 1995), and do not have detectable seismic wave speed anomalies extending into the lower mantle (Montagner and Ritsema 2001). *Ad hoc* adjustments to the model, or arguments that the signal is too weak to be observed, are invoked to account for



2: Bathymetry of the north Atlantic region. The shallow bathymetric ridge that traverses the Atlantic ocean from Greenland to the Faeroe Islands, and marks the location of thick crust, can be seen clearly. Other shallow bathymetric areas, e.g. the Hatton Bank, are blocks of stretched, thinned continental crust. The thin black line indicates the currently active spreading plate boundary, and thin dashed lines indicate the locations of extinct ridges in Iceland. The thick lines indicate faults of the Caledonian suture (Soper *et al.* 1992). The dominant strike of faults in the suture is northerly. The thick dashed line indicates the inferred overall trend of the suture where it crosses the Atlantic ocean (Bott 1987). Circles indicate the hypothesized locations of an Icelandic mantle plume at the times indicated, which are in millions of years (Lawver and Muller 1994).



3: Map showing crustal thickness across Iceland. (From Foulger *et al.* 2002.)

such observations. The plume hypothesis has little predictive capability and is largely data-independent (Smith and Lewis 1999).

An Icelandic plume…?

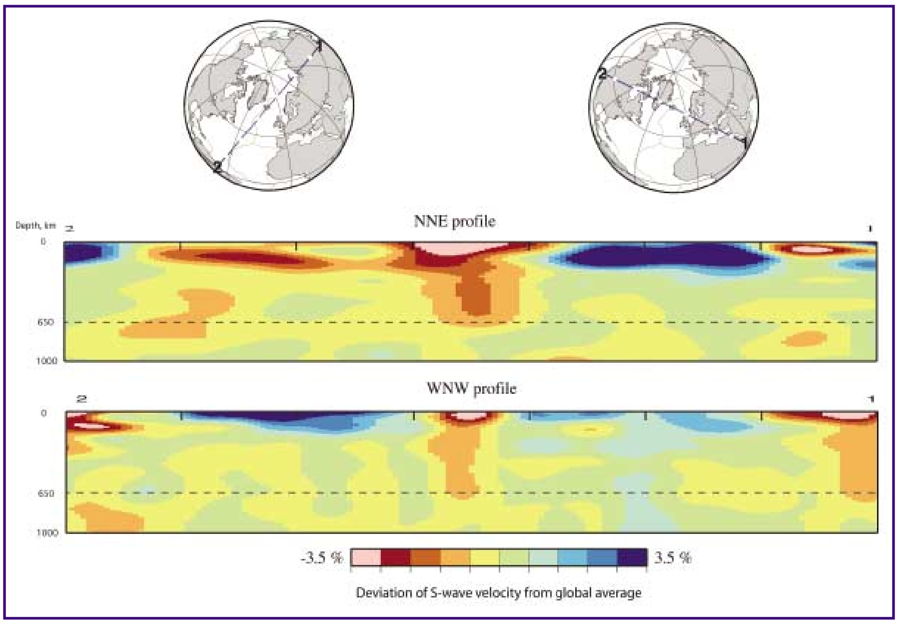
Iceland is one of Morgan's type example plumes – an on-ridge plume. It is probably the best-studied hotspot in the world because the extensive landmass of Iceland allows large-scale, detailed land experiments to be conducted (figure 2). It lies astride the mid-Atlantic ridge, and is the only large exposure of spreading ridge on Earth. Many seismic experiments have imaged both the crust and mantle there, the bathymetry of the surrounding ocean is well-mapped, and the gravity and magnetic fields are known from both satellite and ground-based surveying. Isotopic dating has established a clear picture of the ages of rocks in Iceland, and most aspects of the geology are well understood as a result of extensive mapping, sampling and analysis. This body of knowledge makes Iceland perhaps the best place on Earth to test the plume hypothesis.

The north Atlantic region has had a long history of geological complexity. Over 400 million years ago an earlier ocean existed – the Iapetus ocean – that was consumed by subduction, causing the flanking continents to collide and form a supercontinent. The collision belt, known as the Caledonian suture, is a highly complex zone that includes major faults and diverse rock types (Soper *et al.* 1992). It runs down the coast of northeast Greenland and passes through northern Britain (figure 2). After a long quiescence, the supercontinent split apart again, and about 54 million years ago the north Atlantic ocean began to open. Greenland separated from Scandinavia, and the Iceland volcanic province formed where the new spreading ridge crossed the old suture. Today, the north Atlantic is widening at a rate of about 2 cm/year.

The crust beneath oceanic areas is thought to comprise rock that rose from the mantle as melt and cooled and solidified at or near the Earth's surface. It is distinguished from the mantle by seismic wave speed, from which its density and petrology are inferred. The thickness of the crust is considered to indicate the amount of melt produced at a given locality. The average crustal thickness beneath most of the north Atlantic is about 10 km, but at the present latitude of Iceland the crust produced as the ocean widened was always exceptionally thick – typically about 30 km (figure 3) (Foulger *et al.* 2002). This band of thick crust manifests itself in the bathymetry as an elevated ridge that traverses the ocean from Greenland to the Faeroe Islands, and rises above sea level at Iceland (figure 2).

A fundamental prediction of the plume hypothesis is high temperatures, perhaps 200–600 °C higher than ambient mantle. Above a plume, the crust would be expected to be hot. The temperature of the Earth's crust and mantle can be studied using heat flow, petrology and seismology, but to date there is no evidence for high temperatures. Heat flow in Iceland and the surrounding sea is no higher than elsewhere for lithosphere of the same age (Stein and Stein 2002, Von Herzen 2001). Picrite glasses, which are rocks diagnostic of high temperatures, are absent in Iceland, as are geochemical tracers of high temperature (Korenaga and Kelemen 2000). The attenuation of seismic waves in the crust suggests that temperatures beneath Iceland are lower than beneath spreading ridges in the Pacific Ocean (Menke and Levin 1994), and 3-D tomographic seismic wave speed anomalies in the mantle, which are sensitive to temperature, are similar in strength to anomalies detected beneath ridges and non-hotspot regions elsewhere. Such evidence for normal temperatures alone should be enough to rule out the plume hypothesis at Iceland. In order to explain the thick crust, a mechanism is required for generating excessive melt without excessive temperatures.

Another fundamental requirement of the original plume hypothesis is that they are fixed relative to one another. Such fixity requires that a plume now beneath southeast Iceland must



4: Cross sections through a whole-mantle tomography model (Ritsema *et al.* 1999) showing structure in the top 1000 km of the mantle at Iceland. (Courtesy of J Ritsema.)

have underlain central Greenland when the north Atlantic began to open, and migrated east at ~2 cm/year relative to Greenland subsequently (Lawver and Muller 1994) (figure 2). Thus, in the plume model, the ridge of thick crust southeast of Iceland must be explained by lateral flow from the then-distant plume (Vink 1984), and the current location of the plume on the spreading ridge where it crosses the Caledonian suture is a coincidence. The lack of lateral flow forming thick crust elsewhere beneath the north Atlantic is unexplained. The observations are, however, more consistent with a model whereby the melt production anomaly has always been centred on the spreading ridge. It has been suggested recently that plumes can wander (e.g. Koppers *et al.* 2001), despite the fact that the hypothesis was originally proposed to explain the relative hotspot fixity that was then believed to be the case (e.g. Hamilton 2002). However, in the case of Iceland it is difficult to understand why a plume should migrate in such a way as to be perpetually centred on a spreading ridge.

Many aspects of crustal and mantle structure require further *ad hoc* adaptions of the plume model. Several independent seismic experiments all agree that the crustal thickness varies from ~40 km beneath central Iceland to ~20 km towards the coasts (figure 3 and see Foulger *et al.* 2002 for a summary). At first glance, this appears to be exactly what is expected if a plume underlies central Iceland. However, a little reflection reminds us that a spreading ridge passes through Iceland, about which the flanking plates are transported to west and east. If 40 km of melt were produced by a plume beneath central Iceland, a band of thick crust 40 km thick would be expected to traverse the entire island from west to east. This is not seen. Furthermore, the requirement that a plume migrated from west to east and now underlies southeast Iceland (figure 2) is at odds with the observation that the crust beneath western Iceland, in the wake of the supposed plume, is thinner than beneath eastern Iceland, where the plume supposedly has yet to arrive.

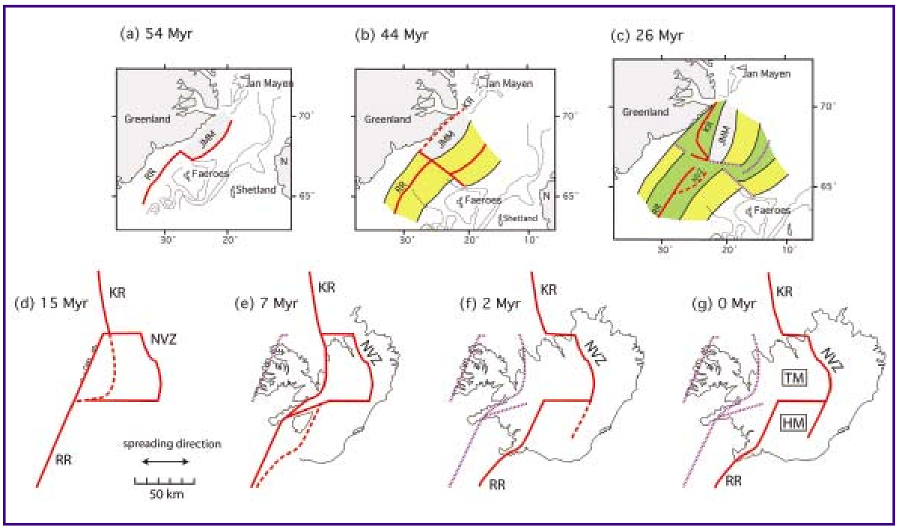
Numerous independent seismic tomography experiments have yielded consistent images of the 3-D structure of the mantle beneath Iceland (see Foulger *et al.* 2001 for summary). A low-wave-speed anomaly occupies the upper mantle beneath much of the north Atlantic and extends to greater depths than beneath the submarine spreading ridges in the central Atlantic (figure 4). The anomaly is strong near the surface, wanes in strength with depth, and is relatively weak below ~300 km. Beneath Iceland, the true depth extent of the anomaly is poorly known, because seismic tomography experiments that use upward-travelling rays smear anomalies vertically. This happens because of the problem of parallax when estimating distance using quasi-parallel rays (Keller *et al.* 2000). The tomographic observations at Iceland could be fit by an anomaly that bottoms somewhere in the depth range 350–650 km, and peaks in amplitude at ~100–150 km depth (Du and Foulger 2002).

However, a robust result on which all studies agree is that the strong, upper-mantle anomaly does not continue down into the lower mantle (Foulger *et al.* 2001). The extraction of quantities of lower mantle too small to see seismically has been advocated on the basis of high ^{3}He/^{4}He ratios measured in some rocks in Iceland. This argument is based on the assumption that high ^{3}He/^{4}He ratios result from an excess of ^{3}He that resides in the lower mantle. However, this argument is flawed because it predicts lower mantle concentrations of ^{3}He as high as those found in gas-rich chondritic meteorites, an inference that is at odds with models of high-temperature planetary accretion and the observed depletion of Earth in chemical species much less voltile than helium. An alternative interpretation would be that high ^{3}He/^{4}He ratios arise from a deficiency of ^{4}He and come from low U+Th domains in the upper mantle, where they have been preserved since earlier in Earth history by a low rate of addition of radiogenic ^{4}He (Anderson 1988, 1989, Foulger and Pearson 2001). It has also been suggested that plumes rise from the base of the upper mantle, at a depth of 650 km. However, this is a mineralogical phase-change boundary (Anderson 1967), there is no evidence that it is a thermal boundary layer or a chemical boundary, and the continuity of structures across it in many regions suggests that it is not.

... or the results of plate tectonics?

As so eloquently stated by Tozer in his letter to *Nature* in 1973, "something is clearly going on" at Iceland, nonetheless. What alternative hypothesis can be offered? The Iceland region persistently produces up to three times the amount of melt produced on the north Atlantic spreading ridge without greatly elevated temperatures, and rock compositions are similar to those observed at "normal" submarine spreading ridges. An explanation may be found by abandoning the assumption that the mantle is essentially homogenous (Foulger and Anderson 2002). It is generally assumed that virtually all material erupted at spreading ridges comes from partially melting peridotite, which is thought to comprise the bulk of the mantle. Basalt, the stuff erupted at spreading ridges and of which Iceland is made, is produced when peridotite melts to a degree of up to about 20%. This process is thought to occur as the plates separate and mantle rises passively to fill the void. The rising mantle passes through a pressure interval where melting can occur, thought to correspond to a depth interval from a few tens of km to possibly ~100 km beneath ridges. The production of several times as much melt as normal would require the fluxing of several times as much mantle through this melt zone, and thus the widespread assumption that a plume is needed. However, the remelting of oceanic lithosphere, thrust down into the mantle when the old Iapetus ocean closed 400 million years ago, can produce far more melt than peridotite at the same temperature.

The Caledonian suture zone, which formed when Greenland, Scandinavia and Europe collided, is expected to be underlain by subducted Iapetus crust and lithospheric mantle. This would result in mantle of exotic composition, metasomatized by fluids from above and below, containing old oceanic crust, mantle lithosphere,



5: Tectonic evolution of the Iceland region during the past 54 million years. Grey: continental crust. Yellow: sea floor that formed 44–54 million years ago. Green: sea floor that formed 26–44 million years ago. Red lines: active plate boundaries. Dashed red lines: imminent plate boundaries. Dashed mauve lines: extinct plate boundaries. Thin lines: bathymetric contours. KR, RR: Kolbeinsey and Reykjanes ridges. NVZ: Northern volcanic zone. JMM: Jan Mayen microcontinent. TM: Trollaskagi microplate. HM: Hreppar microplate. N: Norway. (a)–(c) are redrawn from Bott (1985), (d)–(g) are simplified from Foulger and Anderson (2002).

eclogite, accreted ocean trench and subduction-zone material and possibly sediments. This medley may be mixed with "normal" peridotite mantle, and homogenized well, poorly or variably. Subducted oceanic crust, or a mixture of crust and peridotite mantle, can produce several times more melt at a given temperature than peridotite alone (Yaxley 2000). The depth interval throughout which melting occurs is greater for such a mixture, and it can even produce substantial melt at temperatures lower than that at which peridotite begins to melt. In other words, where there is subducted oceanic crust, volcanism may even occur over coldspots in the mantle – elevated temperatures are not required.

Evidence for a component of recycled crust in the rocks erupted at Iceland is to be found in the chemistry of the basalts there. The estimated compositions of parent melts (Korenaga and Kelemen 2000), trace-element, isotopic and noble-gas data (Breddam 2002, Chauvel and Hemond 2000, Lesher *et al.* 2002) all indicate remelted Iapetus and perhaps also older crust. An expected by-product is enrichment in the lighter elements of the Lanthanide series, and this is also observed in Icelandic basalts. This explanation for the origin of the excessive melt, that it is produced at an unusually fecund part of the mid-Atlantic ridge, implies that the source has always been centred on the ridge and has not migrated east from beneath Greenland. It thus explains the symmetry about the ridge of the thick crust that traverses the north Atlantic, which the plume hypothesis cannot without invoking special explanations (e.g. Vink 1984).

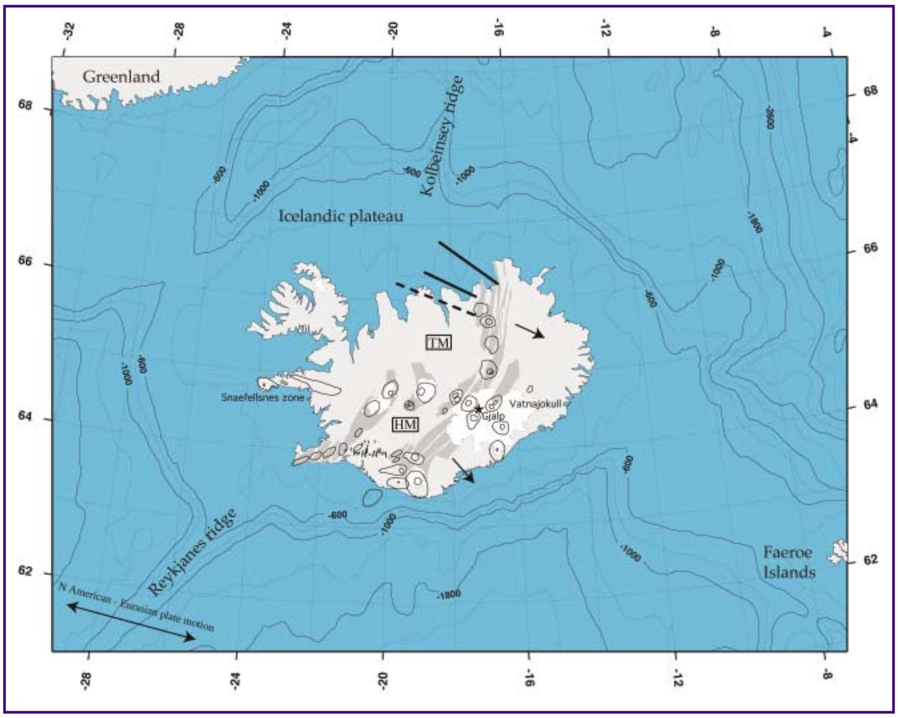
The coincidence of a spreading ridge, a suture zone and resultant exceptionally thick crust would be expected to result in tectonic complexity, in contrast to the relative simplicity of normal spreading ridge tectonics. Such complexity is a striking feature of the Iceland region (Foulger and Anderson 2002). Instead of simple spreading about a single axis, extension has occurred about a complex of multiple, unstable, ephemeral spreading ridge segments that have been connected by transverse eruptive zones and have trapped microplates between them (figure 5). This zone of complexity has migrated progressively south, parallel to the dominant trend of faulting in the Caledonian suture (figure 2).

When the north Atlantic began to open, about 54 million years ago (figure 5a), spreading proceeded relatively simply for the first ~10 million years. A major reorganization then occurred in the Iceland region. A second spreading centre formed within the Greenland craton, splitting off a fragment of continental crust known as the Jan Mayen microcontinent (figure 5b). For the next 20 million years or so, complementary fan-shaped opening occurred about both ridges (Bott 1985). The Jan Mayen microcontinent was rafted east and rotated ~30° counterclockwise (figure 5c), resulting in ~60 km of fan-shaped opening across its southern boundary fault. Massive volcanism would have occurred as a result, and this coincides with the time of formation of the Iceland plateau – a volcanic pile up to 600 km in north–south extent (figure 6).

About 26 million years ago, the easternmost spreading ridge north of the Iceland region became extinct, and a parallel pair of spreading ridges formed further south (figure 5c). The easternmost of these is still active in Iceland. This ridge maintained its position relative to the Kolbeiney ridge and thus, as it spread, the western ridge was progressively transported west relative to the oceanic spreading-ridge axis. The western ridge responded by repeated extinctions, accompanied by the opening of new, more colinear rifts about 15 and 7 million years ago (figures 5d, e). Spreading about a pair of parallel ridges ceased in north Iceland ~7 million years ago, and ~2 million years ago a second parallel ridge formed in south Iceland (Saemundsson 1979) (figure 5f). The progressive easterly migration of the westernmost rift relative to the Kolbeinsey ridge is often quoted as evidence for an easterly migrating plume, but such migration was required to maintain approximate ridge colinearity. Furthermore, the eastern zone offers no evidence for plume-related easterly migration. On the contrary, it has been relatively stationary relative to the Kolbeinsey ridge for the last 26 million years (Bott 1985), with minor westerly migrations. The north–south tectonic asymmetry of Iceland is accompanied by north–south geochemical asymmetry. These are paradoxes in the plume hypothesis, which predicts radial symmetry, but readily explained as the results of thick crust, northerly tectonic fabric, and compositional heterogeneity in the Caledonian suture.

Three microplates have been trapped between the parallel pairs of spreading ridges. The first, the Jan Mayen microcontinent, currently lies below sea level northeast of Iceland. Part of it (not shown in figure 5) is thought to continue under eastern Iceland, submerged beneath later lavas that erupted on to the surface (Schaltegger *et al.* 2002). The second microplate was captured between the pair of ridges that formed ~26 million years ago, and contains oceanic crust up to ~30 Myr old (figure 5d). This crust is currently trapped beneath central Iceland (figure 5g). The continued piling of additional surface lavas on to this microplate probably accounts for the exceptionally large thickness of crust – up to 40 km – beneath central Iceland (figure 3). A third microplate is in the process of formation between the currently active pair of spreading ridges in south Iceland (figure 5g).

The unstable plate boundary configuration has resulted in minor local variations in the direction of motion, which explain the variation in volcanism in Iceland. Evidence for this may be seen in the variable trends of extinct dykes (Saemundsson 1979) and the present-day volcanic zones of Iceland (figure 6), the direction of motion measured using satellite surveying (Hofton and Foulger 1996) and the mechanisms of large earthquakes (Einarsson 1991). Southeast Iceland currently moves in a slightly more southerly direction than northeast Iceland, resulting in fan-shaped extension, widening to the east, across a west–east zone passing through central Iceland (figure 6). This has resulted in an eruptive zone that traverses Iceland from the relatively inactive Snaefellnes zone in the west to the cluster of highly active volcanoes beneath the Vatnajokull icecap in the east, where up to a few kilometres of north–south extension may have occurred during the last 2 million years. The



6: Present-day tectonics of Iceland. TM: Trollaskagi microplate. HM: Hreppar microplate. Thick lines in north and thin lines in south: faults of fracture zones. Grey zones in Iceland: segments of active spreading ridge. White: icecaps. Black outlines: active central volcanoes/calderas. Arrows in Iceland indicate local direction of motion. Star indicates location of recent subglacial Gjalp eruption.

power of this volcano cluster was recently demonstrated by the spectacular Gjalp subglacial eruption (Gudmundsson *et al.* 1997). The intense volcanism and locally great crustal thickness there is traditionally interpreted as marking the centre of a plume. However, major volcanism at this location is required by the tectonic structure and present-day deformation of Iceland – a plume is not needed. A new, west–east volcanic microplate boundary is currently developing in south Iceland, along the southern boundary of the Hreppar microplate (figure 6) as is indicated by large earthquakes and volcanic activity there (Einarsson 1991).

The remarkable tectonic disequilibrium of the Iceland region may be a consequence of the extremely thick crust. At normal mid-ocean spreading ridges the processes of upward melt-transport from the mantle and crustal construction proceed in and beneath crust that is only a few kilometres thick. At Iceland the crust is typically 30 km thick and relatively cold. It presents a more formidable barrier to upward-migrating mantle melt and established ridges may be more difficult to sustain. In addition to occurring in response to the thick crust, tectonic disequilibrium also influences magmatic rate, providing a positive feedback process. Diachronous bathymetric ridges, presumed to indicate slightly thickened crust (the so-called "V-shaped ridges"), flank the Reykjanes ridge south of Iceland (Vogt and Johnson 1975). These appear to indicate short-lived, local enhancements in magma production that propagate south along the ridge. The onset close to Iceland of these apparent changes in productivity correlate with ridge reorganizations in Iceland and are probably caused by them.

Summary

The excessive melt production at the Iceland volcanic province can be explained by high mantle fertility associated with an ancient subduction zone – the Caledonian suture, where it is crossed by a spreading ridge. This has given rise to locally excessive melting and consequential thick crust and complex, unstable tectonics. This interpretation of Iceland attributes its existence to relatively shallow processes and structures associated with plate tectonics, for which there is direct evidence (Anderson 2001). It provides an alternative to the plume model, which attributes Iceland to an *ad hoc*, cylindrical column of hot mantle rising from the deep mantle. That model cannot be reconciled with the absence of a substantial temperature anomaly, and cannot account for many first-order observations from Iceland without special pleading or appeals to coincidence.

It will be exciting to see if analogous interpretations can explain other large volcanic provinces, many of which also formed where ancient sutures reopened (Smith 1993). If it transpires that processes associated with plate tectonics can explain observations elsewhere with fewer forced explanations and fewer contradictions than the plume model, then a long-overdue alternative working hypothesis for the origin of large volcanic provinces may at last be to hand. ●

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