There is No Plume under Iceland

an address to the Royal Astronomical Society

London, 10th May, 2002

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The plume hypothesis was first proposed by Jason Morgan in 1971 in a letter to Nature where he suggested that major volcanic areas on Earth such as Iceland, Yellowstone and Hawaii, which are termed "hot spots", were fuelled by plumes of hot material rising like diapirs from the lower mantle. Such diapirs would have to arise from a thermal boundary layer, and this implies their source would have to be the core-mantle boundary, which is at a depth of about 3,000 km.

This model was received with some scepticism to begin with, and a very amusing sequence of discussion letters was published in Nature in the early seventies, but criticism soon waned, and the plume hypothesis was enthusiastically embraced by almost all Earth scientists. It was applied to ever-increasing numbers of volcanic areas, and adapted to fit the observations where its predictions were not fulfilled. It became all things to all men. In my talk I am going to challenge the plume hypothesis in the case of Iceland, which is probably the best-studied hot spot in the world because the extensive landmass of Iceland allows detailed land experiments to be conducted.

The Iceland hotspot lies at the culmination of a very broad, regional bathymetric anomaly that extends throughout most of the north Atlantic and has a north-south extent of about 3,000 km. This is an important point, because this kind of association can only be interpreted as a coincidence in the plume context. I shall be showing you this evening that there are many such coincidences associated with the so-called Iceland plume!

Several experiments have been performed to determine three-dimensional seismic images of the structure of the mantle beneath Iceland with the objective of imaging the mantle plume assumed by many to underly the island. These experiments all agree that a strong low-wave-speed seismic anomaly lies beneath Iceland in the upper mantle, extending down to depths of 400 - 600 km, but that this anomaly does not continue down into the lower mantle. This result is robust, and is shown by several independent studies. Furthermore, the shape of the anomaly in the upper mantle is elongated parallel to the spreading ridge, which runs the entire north-south length of the Atlantic, and passes through Iceland. We can conclude from these findings that there is no plume under Iceland if a plume is defined as a vertical, cylindrical upwelling from the lower mantle. As I mentioned before, we can always change the definition of a plume to fit our observations, but if we do that it essentially becomes worthless as a scientific hypothesis because it has no predictive capabilities and at the end of the day it can be anything anyone wants.

Now lets turn our attention to the crust. The crust in oceanic areas is considered to be the surface layer that has been made up of molten rock that has risen from the mantle and cooled and solidified on reaching the Earth's surface. The thickness of the crust is considered to be an approximate proxy for the amount of melt produced at a given locality. The average thickness of the crust beneath the ocean floor is 7 km.

A large number of seismic experiments have been conducted at Iceland to study the thickness of the crust and how this varies across the island. Three independent experiments, using receiver functions, explosion seismology and seismic surface waves, all agree that the shallow layer with crustal seismic velocities is about 40 km thick beneath central Iceland, thinning to about 20 km towards the coasts. At first sight, this would appear to be exactly what is expected if a plume underlay central Iceland. However, if one thinks a little more carefully it becomes clear that things are not quite so straightforward. A spreading ridge passes through Iceland, about which the flanking plates are transported to the west and east. Thus, if there is a patch along the spreading plate boundary where a particularly large amount of melt is produced then it would be expected that a band of thick crust would traverse the whole island from west to east. This is clearly not seen.

There are several possible explanations for the patch of apparently thick crust beneath central Iceland. The temperature there might be exceptionally high, and as the crust is transported away and cools, thickened crust might acquire mantle-like seismic wave speeds and be mistaken for mantle by seismologists. Alternatively, if the lower part of the thick "crust" is, instead, exceptionally hot mantle, it might cool and acquire normal mantle-like seismic wave speeds. Another, alternative explanation is that it is an old, foundered block of crust. That such a block exists is, in fact, predicted by reconstructions of the history of formation of Iceland.

Finally, this area of thick crust might represent a recent increase in magma production. Such an increase is not consistent with the classical plume model, which predicts that volcanism should wane with time, not wax. Nevertheless, "pulses" of enhanced melt production have been suggested for the Iceland "plume" to explain the so-called "V-shaped ridges" that flank the Reykjanes ridge. These ridges are diachronous bathymetric features a few hundred metres high that have been interpreted as forming from pulses of enhanced magmatism that have propagated from central Iceland southward along the Reykjanes ridge. However, there is no evidence in the variation in crustal thickness beneath Iceland for preferential channeling of melt beneath the ridges there. On the contrary, some determinations of crustal thickness show relatively thin crust beneath the ridges in Iceland, despite the fact that the "plume" is supposed to be at a production high at the moment.

There is another important aspect of the specially adapted plume model used to explain Iceland that is not supported by observed crustal thicknesses. It is hypothesised that the

Iceland plume has migrated east at 2 cm/year with respect to Greenland for at least the last 70 million years. Such a migration is required if the Iceland plume has remained fixed relative to other hotspots in the world, and such mutual fixity is a fundamental requirement of the plume hypothesis. The Iceland plume is thus predicted to have passed beneath west Iceland and to currently underlie southeast Iceland. It is thus to be expected that the crust beneath west Iceland would be thicker than the crust beneath east Iceland, where the plume has yet to bring its influence to bear. However, the opposite is observed. The crust beneath west Iceland is typically 20-25 km thick whereas beneath east Iceland it is typically 30-35 km thick.

Over the past three decades or so, the preferred model for the crust beneath Iceland has changed radically. In the seventies and eighties the model preferred by seismologists was one of a thin crust, only about ten kilometers thick, underlain by very hot, partially molten mantle. This model was thought to be consistent with the plume hypothesis, which required excessive amounts of volcanism and magma. The source of this excess magma was then the hot, partially molten upper mantle that lay at shallow depth beneath Iceland. In the nineties, however, more sophisticated seismic experiments were performed, and seismologists adopted instead a model involving a very thick crust, up to about 40 km thick, underlain by relatively cold mantle containing no partial melt. This model is also thought to be consistent with the plume hypothesis, which predicts excessive melt production and thus a thick crust. The low temperatures in the upper mantle are attributed in an ad-hoc fashion to a cold "lid", the role of which is not clear. Thus, both thin, hot and thick, cold crust models have been counted as being fully consistent with the plume hypothesis. These are diametrically opposite models, and it is clear from this that no conceivable observations concerning crustal structure would be considered inconsistent with the plume hypothesis. This hypothesis is therefore not disprovable, and therefore is not scientific. Whatever is observed is considered consistent with it and if generic predictions are not confirmed, as is usually the case, ad hoc, special-case plumes are contrived.

However, as eloquently stated by Tozer in a letter to Nature in 1973, "something is clearly going on". So lets step back and attempt to reassess the observations, free of prejudice and preconceptions about plumes. Iceland is basically a melt extraction anomaly. It lies at the centre of one of the largest regional gravity and bathymetric highs on Earth, it has a long history of very complex tectonics, including double, migrating spreading centres, fan-shaped opening about ridges and opening, leaking transform zones. It formed along a major transform zone which itself formed along the ancient Caledonian suture zone, which separates rocks of the Caledonian orogeny to the north from Archaean cratonic rocks to the south. Although the layer with seismic wave speeds characteristic of the crust is up to an astonishing 40 km thick, Iceland has a relatively low elevation, and this suggests that what appears to be crust may in fact be some form of anomalous mantle, and the amount of melt at Iceland may be less dramatic than appears at first sight. Lastly, the anomalous appearance of Iceland is in part a result of its poking up above sea level. Nowhere else does a mid-ocean ridge do this, and thus Iceland has been shaped by glaciation and subaerial volcanic processes, unlike any other part of the mid-ocean spreading plate boundary. I suggest that it is in this multitude of unusual factors that an explanation for the origin of Iceland is to be found, rather than in a diapiric upwelling from the core-mantle boundary that just happens coincidentally to currently underlie this unique and extraordinary region where so many unusual structures and processes coincide.

I could do worse than to finish my talk by quoting the modest words of Lavoisier to the French Academy of Science in 1775. In laying to rest the theory of phlogiston, a conceptual substance that was thought to be lost when material burnt, Lavoisier said "my object is not to substitute a rigorously demonstrated theory but solely an hypothesis ... which appears to me to contain fewer forced explanations and fewer contradictions". I suggest that plumes are the modern geophysical equivalent of phlogiston, and that, instead of seeking increasingly more contrived ways of forcing diverse observations to fit a pre-conceived theory that is assumed to be unquestionable, we should seek explanations for the more spectacular volcanic areas of Earth that are consistent with the observations, have predictive powers, and fewer contradictions.