DO MANTLE PLUMES EXIST?

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Introduction

This question is a subject of recent, sometimes heated debate amongst the geological community, and is unlikely to be resolved in the near future. The only way to determine the answer is to examine the evidence as objectively as possible. Continuing research to try and understand these deep earth processes, must avoid the trap of giving interpretation and theory the status of fact.

Early models

Wegner in 1924 was the first person to propose that the earth was in fact dynamic. As a result of his work, and the efforts of Hess and others in the 1960's the theory of plate tectonics was born. This model explains the presence of volcanic activity at both spreading centres and at subducting plate boundaries. Both seismic and geochemical evidence have subsequently strengthened this model. Subduction and spreading however do not account for all forms of magmatic activity on earth. Volcanic activity not explained by plate tectonics occurs at ocean islands, centres on some mid ocean ridges, oceanic plateaux, sea mounts, in large igneous provinces (LIPs), and at intra plate supervolcanoes. It is this volcanic activity, which has been more problematic to explain.

Wilson (1963) was the first person to propose a mechanism for this unexplained magmatism. At the time of this first paper there was still argument about the basic dynamics of the mantle and lithosphere. Jeffreys and others believed in a rigid contracting cooling earth. Heezen and others supported the idea of a rigid but expanding earth. Wegner's hypothesis was that the earth was mobile and continents drifted on it. Wilson with Hess and others believed that the mantle was convecting, Wilson dismissed the proposal that transcurrent faults in the Pacific ocean were a cause of Hawaiian volcanism, because seismic activity was either intimately associated with eruptions or was shallow and could be attributed to isostatic readjustment. He was not able to support the notion that a transcurrent fault could exist for millions of years and be active at its SE margin while it had ceased to be active at its NW margin. Wilson proposed a two layer convection model. Using Rayleigh's theory Wilson proposed a jet stream type of convection within the mantle, which was driven by the large density contrasts. He proposed that the drift apparent in the heat source could be explained if it originated in the deeper more slowly convecting mantle.

A second model was proposed by Jackson and Shaw (Raymond. L.A. 1995). They suggested that shear melting at the base of the lithosphere generated melt and a thermal feedback system produced more melting. However it was Wilson's proposals that became widely accepted and established as the plume model. This was elaborated and developed by Morgan (1971) who suggested a model of 20 deep mantle plumes rising in 'unique' positions which flowed away from their centres horizontally through the asthenosphere and that this movement contributed to plate motion.

Plume model

- Plumes are proposed as hot narrow regions of upwelling mantle. The increase in temperature between the plume and surrounding mantle may only be in the order of $50^{o} – 100\,^{o}$ C. The origin of the plume is unclear but it probably originates at the core mantle boundary where there is a variation in topography of a few hundred meters, and where the convecting liquid core is losing heat by conduction. It is proposed that this heat source can produce a few percent partial melt, which could be the source of the plume.

- Plumes are thought to be long lived, surviving for 10's of millions of years. During their ascent they are able to cross the endothermic 670 km discontinuity. There is however a recent suggestion by Courtillot *et al.* (2003) that plumes may arise from at least three different sources in the mantle. (Fig.1) One type originate in the lower mantle based on a chemical heterogeneity in the D" layer. Another type originates at the base of the transition zones which correspond to superswells. A third type originates in the upper mantle. Courtillot's model goes some way towards explaining the diverse morphologies exhibited by plume related volcanism.

- At the base of the lithosphere the plume can no longer ascend and the transfer of heat is inhibited. This causes thermal erosion of the lithosphere, which is consequently thinned above a hot spot. The excess heat has been predicted to cause uplift of 1 to 2 kilometres prior to volcanism.

- A plume head is formed at the base of the lithosphere in the initial phase of contact. This 'stoping' effect at the base of the lithosphere raises the temperature sufficiently to produce partial melting. This melt originating in the more primitive mantle then rises through the lithosphere undergoing variable interactions with the surrounding rock and eventually erupts as plume induced volcanism, with geochemistry suggestive of a deep mantle source.

- Plumes are thought to be the initiating mechanism for the early stages of continental break up.

- The very large volumes of magma characteristically erupted at the start of development of a LIP, are attributed to the excess heat from the plume head.

Evidence of plumes

Saunders *et al* (2003) cite Hawaii, Iceland and Large Igneous Provinces (LIP's) in support of the model.

- In Hawaii the plume heat source has been able to produce melting despite the very high lithostatic pressures found at 70 – 80 km. The rate of basalt production at Hawaii is currently 0.13 km^3a^{-1}. This value is higher than average production during the lifetime of the island chain which is lower at 0.013 km^3a^{-1}. Saunders points out that at a modern mid ocean ridge where the asthenosphere is within a few kilometres of the earths surface melting rates on a 104 km long, 1 km wide and 1 cm a^{-1} spreading ridge produce magma at an average rate of 1.2 km^3 a^{-1} (Mc Lean. M.D. 1996). The lower average volumes of melt reaching the surface of Hawaii from such high lithostatic pressures must be evidence of a powerful heat source.

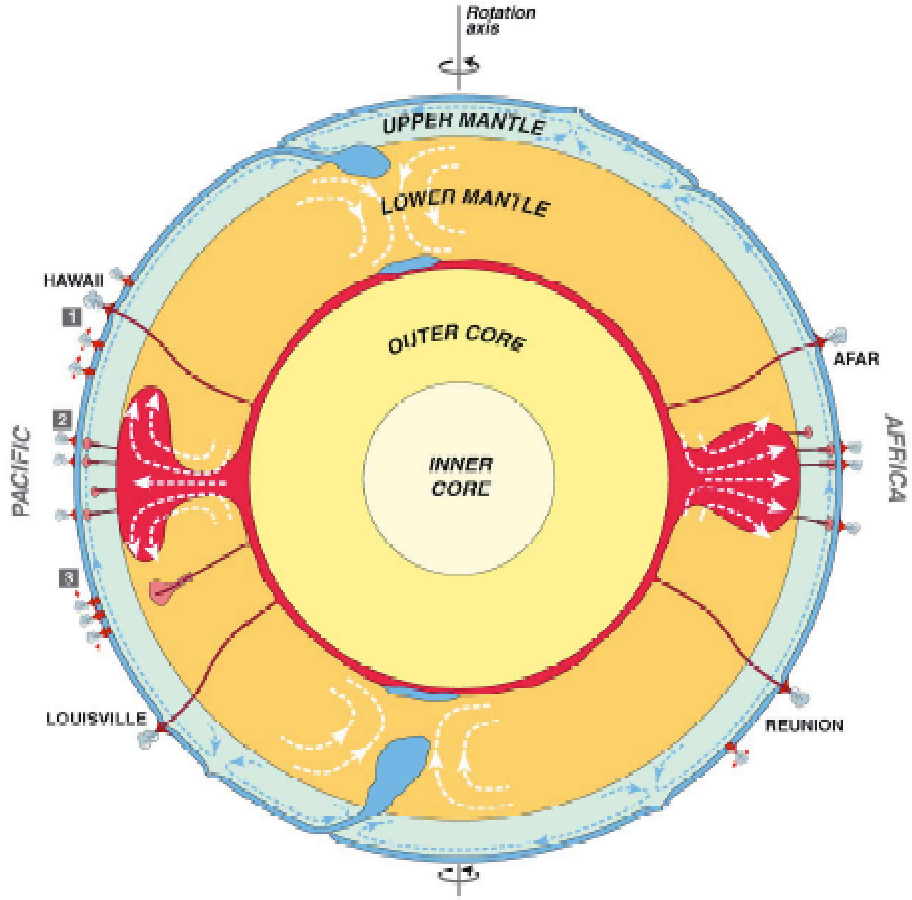

Fig.1 A schematic cross section of the earth showing three sources of plumes. 1. Plumes originating at the lower mantle boundary layer D". 2. Plumes originating from the tops of domes near the transition zone. 3. Plumes with a superficial source. At present only plume tails, and no plume heads are active. Adapted from: Courtillot, V., Davaille, A., Besse, J., Stock, J., 2003. *Three distinct types of hotspots in the Earth's mantle.* Earth and Planetary Science Letters. **205,** 295-308.

- The Hawaiian plume is credited with having being the mode of formation of the entire Hawaiian Emperor chain. The chain extends for > 5000 km and has formed over a period of > 90 Ma. The bend in the chain is thought to indicate a change in direction of the plate over the plume and the lack of a plume head is because it has now been subducted, possibly at the Kurile trench.

- The Hawaiian Emperor chain is a time progressive system representing the existence of a long lived plume.

- Saunders also cites the evidence of the Hawaiian swell. This is a circular region of the oceanic crust surrounding Hawaii. It has a radius of ~ 700 km and an elevation of ~ 1500 m. Saunders suggests that the swell is not entirely related to thermal expansion, but could also have a dynamic component.

- Saunders suggests that the lack of excess heat flow is because the movement of the plate over the heat source means that by the time heat has migrated to the surface the ocean island created by that part of the plume is now at some distance from the top of the plume.

- Saunders also suggests that the existence of partial melt deep within the mantle is supported by the presence of a deep mantle seismic anomaly.

- The Hawaiian islands erupt both tholeitic and alkalic magma. With each group of magma showing stages with distinctive chemistry. They generally have high magnesium numbers, while CaO, K_20, Na_2O, FeO, Al_2O_3, show a wide range of values. Tholeitic gases erupted early are rich in Fe, Ca, Ti, Na, H_2O, CO_2, S, F and Cl. The basalts also have distinctive rare earth chemistry particularly in light elements such as La and Ce. $^{87}Sr/^{86}Sr$ is low and $^3He/^4He$ can be up to 4 times the values of that in MORBs. Raymond (1984) suggests that these features of rock chemistry together with phase equilibrium models mean that olivine-basalt magmas must rise from as deep as 80 km. Thus the source is deep within the mantle, the crust beneath Hawaii being about 30 km thick.

In Iceland Saunders suggests that:

- The plume here has been the cause of the large volumes of basalt and explains the thick oceanic crust (30 km) despite its presence on the MOR.

- Picrites which are found in other high temperature melts but have not been seen in Iceland. They have formed at depth, but may been have been prevented from reaching the surface because of their very high densities

For LIPs Saunders proposes that:

- They show time progressive volcanism. (Morgan, 1971. White, R.S, & McKenzie, D.P., 1989).

- The initial short bursts and high volumes of magmatism are caused by a sudden increase in mantle flux as the plume head is starting. They may also be the result of the initial decompression associated with the lithospheric extension in the overlying plate. The Réunion hotspot which was beneath India in the Late Cretaceous formed the Deccan traps in this way.

Problems with the plume model

There has never been complete agreement about the existence of mantle plumes. Don Anderson of the California Institute of Technology and most recently Gill Foulger of Durham and others have proposed that there is an inconsistency between the predictions of the plume model and what is observed. Foulger (2003) claims that at some sites of proposed plumes the tomography of the mantle only shows anomalies in the upper mantle (Fig. 2).

- In Iceland the evidence for a lower-mantle seismic anomaly has been discredited many times. Bijward and Spakman (1999) claimed to have demonstrated a bent plume < 500 km rising from a root zone > 1000 km at the core mantle boundary with a plume top of ~ 1200 km and excess temperatures of 200-300 K. However Montelli *et al.* (2003) have proposed that previous models were affected by an inappropriate modeling of finite-frequency effects. They claimed an enhanced capability for detecting Earth's internal structures, and unambiguous evidence for at least 5 hotspots originating deep in the lower mantle, but they also claim that the heat source below Iceland has a shallow origin.

- Heat flow which could be expected to be measurable beneath Iceland in the presence of a plume does not exist (Foulger 2003). In fact current data suggests that the lithosphere beneath Iceland is cooler that at the same depth below the East Pacific Rise.

- The plume model predicts that $^{87}Sr/^{86}Sr$ is a geochemical plume tracer. It should therefore occur in higher ratios near the centre of the plume. $^{87}Sr/^{86}Sr$ ratios however increase away from the presumed centre of the plume, towards the edge of the Icelandic shelf. (Foulger *et al.* 2003)

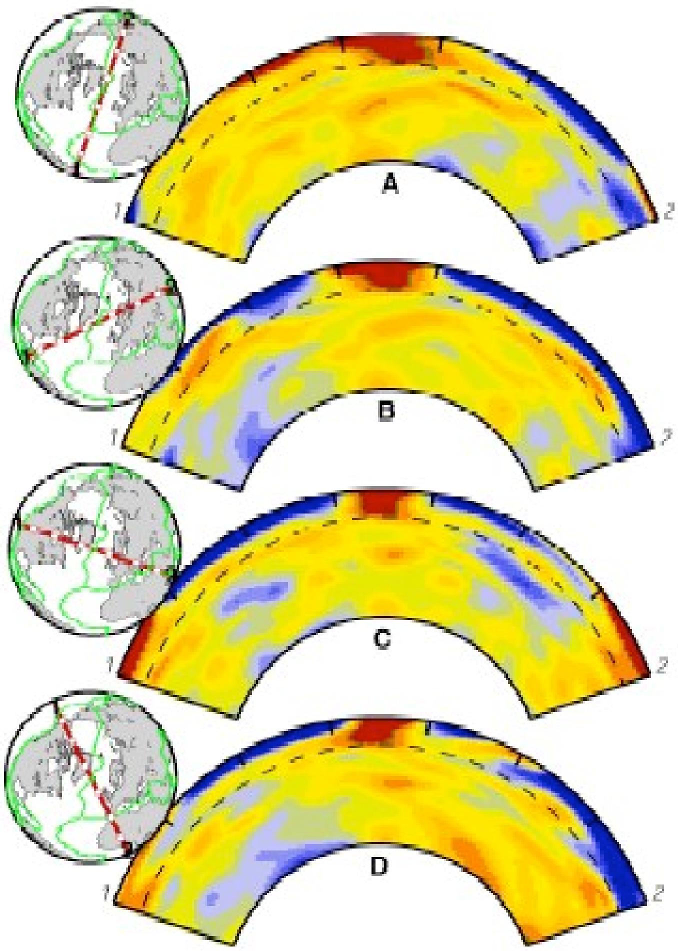

Fig 2. Tomographic cross section thorough the North Atlantic showing no evidence of a deep mantle seismic anomaly, but evidence of a shallow heat source. Adapted from Foulger, G.R., Anderson, D.L., & Natland, J.H., 2003. *An alternative model for Iceland & the North Atlantic Igneous Province.* Penrose Conference.

- Koppers *et al.* (2001) have questioned the presumed fixity of hot spots. They used $^{40}Ar/^{39}Ar$ age progressions for the last 140 Ma along the Pacific Seamount trail and compared these with Pacific Plate velocities, which they predicted from their Euler poles of rotation. They concluded that relative plate motion between hotspots was required to fulfil the observed age progressions. They suggest that the Pacific hot spots show motion of between 10-60 mm/y for the past 100 Ma.

- The plume model suggests that the bend in the Emperor Seamount chain demonstrates a change in direction of movement of the Pacific Plate. Seafloor spreading strike slip faults do not demonstrate this change in direction of movement.

- Iceland does not show a time progressive track. Lawver, L.A., and Muller, R.D. (1994) and others have proposed that the Iceland plume is migrating in an easterly direction. Crustal structure beneath Iceland however is in fact thicker below the eastern margin than below the western margin, which does not support the model of an easterly migrating plume (Fig. 3).

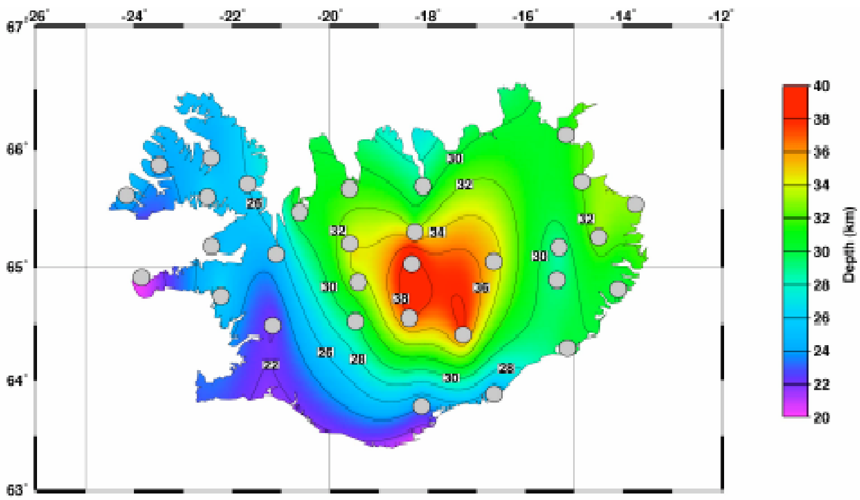

Fig 3. Contour map showing depth in km to the base of the Icelandic crust based on seismic speed of 4.2 km/s. The crust is thinnest in the SW and W. Foulger G.R., Anderson D.L., & Natland J.H., 2003. *An alternative model for Iceland & the North Atlantic Igneous Province.* Penrose Conference.

- Plume induced melting should be demonstrated by high temperature magmas and Foulger *et al.* (2003) point out that picrites are not found in Iceland, and that central Iceland lavas erupt at temperatures of ~1240°C. This temperature is close to melt temperatures in depleted N-MORB, so do not show a particularly high thermal anomaly.

- There is common agreement amongst plume proponents that the Deccan Traps were caused by the Réunion hotspot, which was beneath India in the late Cretaceous. Sheth, H. (2003) proposes an alternative source for the Deccan Traps. He argues that the duration of the event was 8-9 Ma not the 1 Ma commonly proposed, and that the large volumes of magma could be a result of the great lengths of the eruptive fissures.

- He sees no evidence of an age progression, which would need to be present if the plate was moving over a hot spot. Basalt from the Laccadives Ridge 1000 km south of Bombay have a predicted age of 60 Ma, but reliable ^{40}Ar-^{39}Ar dating of lava flows from Bombay show ages of ages of 60-61Ma (Sheth, H. 2003). Movement of this speed, cannot be supported by a plume model. Sheth concedes that there is age progression between Laccadive Ridge and Réunion but he explains this as a result of crack propagation through the lithosphere.

- He also argues that high $^4He/^3He$ ratios do not necessarily represent plume activity, but could reflect the components of a shallow enriched continental mantle source.

Alternative models

What are the proposals that can explain volcanism without the need for a plume?

1. The edge effect. Sheth, H. (2003) proposes that the Deccan Traps could have been caused by an Edge effect and that eclogite trapped in ancient sutures may have been a source of fertile material for the Deccan Traps. King, S.D., and Anderson. D.L., (1998) propose that changes in the thickness of the lithopshere produce instabilities. This can cause convection in the upper mantle particularly at the edge of thick cold Archaean cratons. Initially a small-scale convective instability results in down welling, that remains fixed in position at the boundary of the continental and oceanic lithosphere. This downwelling has a corresponding upwelling, about 600 km from the edge of the continent. In this model melting is a result of increased amounts of material passing through the area being melted. They predict that in this way 3 times more melt can be produced, than in a plume with 300°C temperature gradient. This process is potentially unsteady and can pulsate, however pulsation in eruptive rates are recognised features of LIP's.

2. **Inhomogeneity.** The plume model assumes that the upper mantle is vigorously stirred and is homogenous. It is proposed that inhomogeneity of the mantle could be the cause of melting rather than the anomalous heat of a plume. Many hot spots are also coincident with old sutures. Iceland lies on the line of the Iapetus suture and Yellowstone lies on the boundary, of two ancient cratons. It is suggested that delamination of the cold subducting slab can leave areas of fertile, volatile rich, crustal material in the mantle wedge and back arc basins. This could produce melt in two ways.

a. The cold slab material could provide a major thermal heat sink between itself and the much larger surrounding mantle. This would be sufficient to produce melt because the fertile material would have some partial melt anyway at thermal equilibrium.

b. Subducted slabs that get as deep as 650 km could be entrained in shallow mantle convection and become involved in upwelling. This would have a particularly powerful suction force where ancient thick cratons were under tension. This fertility could perhaps be the cause of LIP's.

3. Stress and extension. The large volumes of volcanic activity seen at Yellowstone and the Snake River plain, could be a result of lithospheric extension and stress. When the triple junction of the Pacific, Farallon Plate was subducted beneath the American Plate the direction of stress changed dramatically from compression to strike slip. This caused extension in the western United States. The extension caused thinning of the crust and the resulting upwelling produced melting in the Yellowstone area. Thermal instability caused by proximity to an Archaean craton and the presence therefore of fertile trapped crust produced enhanced melting. Volcanic activity has propagated to NW and NE following lines of previously existing weaknesses in the crust.

4. $^4He/^3He$ ratios. High $^4He/^3He$ ratios are quoted as being an indicator of deep plumes representing previously undegassed mantle material. However this assumption is questioned and there are suggestions that wide ranges of $^4He/^3He$ ratios could actually be produced in the shallow mantle, i.e. Olivine crystals trap helium in gas bubbles and these ratios can be preserved until the olivine is remelted. The elements thus claimed as deep mantle sources could have been in the shallow mantle when melted.

Conclusion:

It is recognised that the plume model is poorly constrained. The questions which need to be clarified by proponents of the deep mantle melting model are:

- Are hot spots hot?
- Are they fixed relative to one another or can they migrate?
- Does their excess heat flow cause uplift of the lithosphere, or is the uplift caused by a change in geochemistry?
- Are there low velocity zones at the heads of plumes?
- Are plumes required to produce the uplift and excess volcanism seen at the start of continental rifting and the creation of LIPs.
- Is an anomalous heat source of the magnitude suggested by a plume required to produce intra plate volcanism?
- Do the anomalous geochemical signatures of intra plate volcanism require a deep mantle source?
- Is there a geochemical signature which can be unequivocally linked to the deep mantle?
- Is the criticism by some groups, of claims that time progressive volcanism is not always shown, a valid argument?

Where do plumes originate and how do they propagate through the mantle?
Proponents who question the evidence of the plume model need to clarify the following questions.

- Can the excess heat required for melting come from the shallow mantle, and is the proposed temperature gradient of ~10°-20°C sufficient to produce melt in the volumes required?
- Is there evidence that the shallow mantle is heterogeneous enough to be the source for large melt volumes?
- Do eclogite and other fertile materials stripped in subducting slabs, remain trapped in the shallow mantle and become a fertile source for later melting?
- Can subducted slabs can be recycled in the shallow mantle?
- Can the anomalous geochemical signal seen in intraplate volcanism be produced from a shallow mantle source.
- How effective is the Edge effect?

To date most workers have concentrated their research efforts on already well studied areas. In order to validate or invalidate some of the hypotheses they need to be tested in less well known intraplate settings. The problems yet to be solved are enormous not least because this debate crosses the boundaries of all geological disciplines. Researchers need to have a detailed understanding of areas outside their own areas of expertise in order to critically assess the work of others and to be able to benefit from knowledge gained by other disciplines. It is interesting that lithospheric stress, for so long ignored, should now resurface as a proposed model. The work of the geochemists in constraining the parameters of melting particularly in relation to heat and the presence of volatiles will be vital in the next stage of this debate.

As an undergraduate it has been difficult to critically assess the detail of the claims and counter claims. My experience in researching this essay has been that the literature questioning the validity of the plume model has been coherent and logical in its presentation. The papers supporting the plume model have been less coherent and have tended to make more assumptions. I have failed to find any discussion on how two such diverse mechanisms as the large upwellings and downwellings seen on mantle tomography and the proposed very narrow plumes can coexist in the same environment. The jury is still out, but whatever the answer no harm will come from questioning of the various models, which is now underway.