Do deep mantle plumes exist?

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Since the acceptance of the theory of plate tectonics in the late 1960's, much of Earth's volcanism has been understood as an inherent by-product of the processes of plate tectonics. At convergent plate boundaries the subducting plate releases water (previously held in hydrous minerals: biotites, amphiboles) as it sinks deeper into the mantle and undergoes metamorphism. Introduction of H_20 lowers the melting temperature resulting in partial melting in the mantle wedge, generating buoyant magma which through a process of magmatic differentiation rises upwards to create and feed an overlying silicic volcanic structure. At divergent plate boundaries, characterised by mid-ocean ridges, the plates moving apart create an upwelling of basaltic magma as a consequence of adiabatic decompression, creating a topographical high of volcanic seamounts along the length of the plate boundary (DePaolo & Manga 2003).

However instances of volcanic activity, such as that in Hawaii, occur thousands of kilometres from the nearest plate boundary. Furthermore the proportional rate per unit area of basaltic lava produced at Hawaii is the most prolific in the world, averaging approximately 0.013 km^3 a^{-1} over the past 80 million years (Saunders 2003). Examples of intraplate volcanicity occur not only in oceanic island settings such as Hawaii. For example the Massif Central in France displays evidence of linear magmatic events and high basaltic flows coupled with extensional rifting. On the African cratonic plate, age-progressive volcanism trends northwards up the East African Rift Valley coupled with flood basalts.

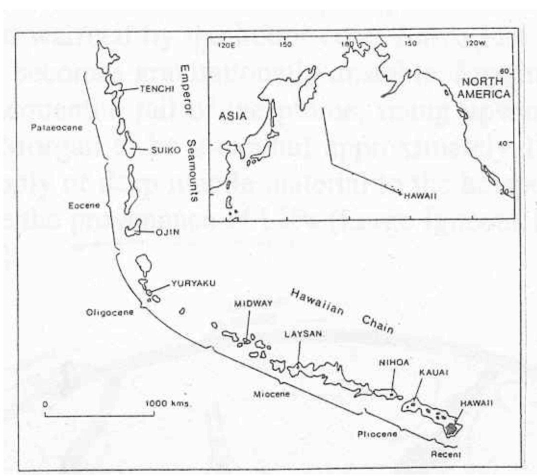

Figure 1: The Hawaiian Islands and Emperor seamounts (which lie beneath the surface of the ocean). The 6,000+ km volcanic chain youngs progressively towards the south-east (Hall 1996)

J.D. Dana, an American geologist of the nineteenth century, was the first scientist to identify the phenomenon of directional age increase along a chain of volcanic islands. He recognised a northwesterly trend of volcanoes ranging across the island of Hawaii, from the young and still active Kilauea and Mauna Loa at the southeastern end to the eroded volcanic remains on the neighbouring island of Nihoa at the northwest and suggested that the volcanoes were linked not only by direction but also by age (Cattermole 2000) (Figure 1).

Directional age variation was recognised in several other volcanic island chains, notably the Canary Islands, and in 1963 J. Tuzo Wilson published his radical paper in the Canadian Journal of Physics suggesting that time-progressive volcanic chains originated as a result of lithospheric plate movement across a slow-moving or stationary heat source in the deep mantle. The 'hotspot' hypothesis was further strengthened by W. Morgan in 1971 (Figure 2) who suggested "about twenty" upwelling plumes, fixed relative to one another, were responsible both for continental drift as a result of convection forces in the lower mantle and for a variety of sites of volcanic activity. These included the Hawaiian-Emperor island chain, the Galapagos and Réunion island chains, volcanics in Patagonia, the ring-dyke complex of South West Africa and the highly active volcanic island of Iceland, situated directly over the Mid Atlantic Ridge.

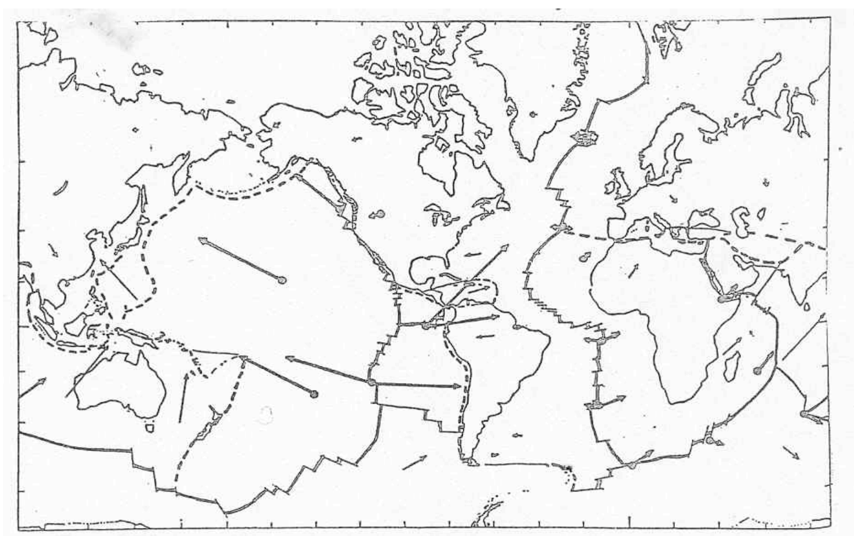

Figure 2: Diagram to illustrate the directional movements of tectonic plates over the mantle (bolder arrows indicate plate motion at hotspots) (adapted from Morgan 1971)

Recognition of tholeiitic basalt in Hawaii and parts of Iceland, at variance with the usual composition of MORB, coupled with evidence of gravity highs at these and other hotspots, led Morgan to the conclusion that the plumes were delivering primordial material from the deep mantle (Morgan 1971). Over the last thirty years the mantle plume hypothesis has become widely accepted as a model to explain most anomalous volcanism. It is thought that solid diapirs of material, made buoyant through heat flow from the core, dissociate from the D" level in the deep mantle (Figure 3), rising upwards relatively quickly through the mantle (Hager et al. 1999). Laboratory simulations of fluid behaviour predict that material directly above the core/mantle boundary and warmed by the hotter core, forms just such a thermal boundary. As this increases in depth, it becomes gravitationally unstable, forming a bulbous head (DePaolo & Manga 2003). The consequential tail of the plume, rising upwards behind the bulbous plume head, was estimated by Morgan to be a conduit approximately 100 km wide (Morgan 1972), ensuring a continuing supply of deep mantle material to the hotspot at the Earth's crust once the plume head, thought to be the provenance of LIPs (Large Igneous Provinces) becomes exhausted (DePaolo & Manga 2003).

A linear track of time-progressive volcanoes, associated with extensive provinces of flood basalts near the oldest region of the chain, has become recognised as a signature of deep plume-originating hotspot magmatism. Further characteristics include the topographic high anomaly noted by Morgan (suggesting the presence of a buoyant flux of material), a recognisably low seismic shear velocity at a depth of 500 km indicating less dense, hotter material, and high $^3He/^4He$ ratios, said to be characteristic of more primitive mantle material. However recent studies comparing forty-nine putative deep mantle plume hotspots with these criteria show that only seven, including Hawaii and Iceland, satisfy three or more criteria (due in some circumstances to lack of evidence) and can be regarded as potentially sourced from the deep mantle (Courtillot et al 2003).

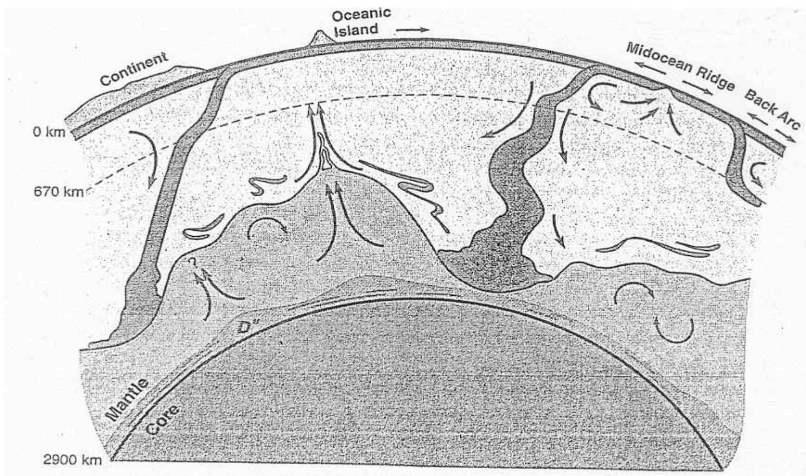

Figure 3: Schematic diagram of buoyant material dissociating from the denser D" level at the base of the CMB (adapted from Kellogg et al 1999)

Seismic tomography studies of Earth's interior have sought to identify and verify plumes of anomalously hot material, originating in the lower mantle. Imaging of the mantle directly beneath the Hawaiian Islands (Figure 4), appears to confirm *P*-wave velocity anomalies, indicating a heat source ascending from a depth near-equivalent to the CMB (DePaolo & Manga 2003). However data reduction techniques have been employed which enhance and accentuate the desired image. Present technology in seismic tomography does not yet allow accurate high-resolution imaging of anomalies less than 500 km in size (Julian 2003). Furthermore accurate imaging at depth is still technologically restricted.

A connection has been advanced between cool, high-velocity subducting material, causing downward convective flow (Figure 5) and the upwelling of low-velocity reheated ancient slab material creating a whole mantle convection cell (Silver et al. 1988). Such a hypothesis could be said to account for characteristics of mantle plumes (Ivanov 2003) including an excessively high increase in volcanism, giving rise to LIPs, commonly attributed to plume heads.

However it is thought that only exceptionally old and therefore extremely thick oceanic slabs generate sufficient negative buoyancy to punch through and descend rapidly beneath the 670 km discontinuity to the lower mantle and that younger, less thick subducting oceanic crust remains in the upper mantle. (Anderson 2003 (2)). Controversy exists as to whether the upper and lower mantles form one single or two separate convections cells, and whether material can be positively identified as rising up from the lower mantle through the Transition Zone (Hofmeister & Criss 2003). The deepest source recorded for material from the mantle is a depth of 670 km, noted in inclusions contained within diamonds (Gasparik 2000). Moreover it has been suggested that pressures in the deep mantle may be so great that atoms are super-compressed and when D" material becomes heated, the atoms are unable to expand and achieve the consequential buoyancy rates expected at normal pressure levels. High viscosity levels at the thermal boundary layer could therefore slow convection processes, encouraging subsequent heat loss by conduction and hampering the progress of upwelling material (Anderson 2003 (3)).

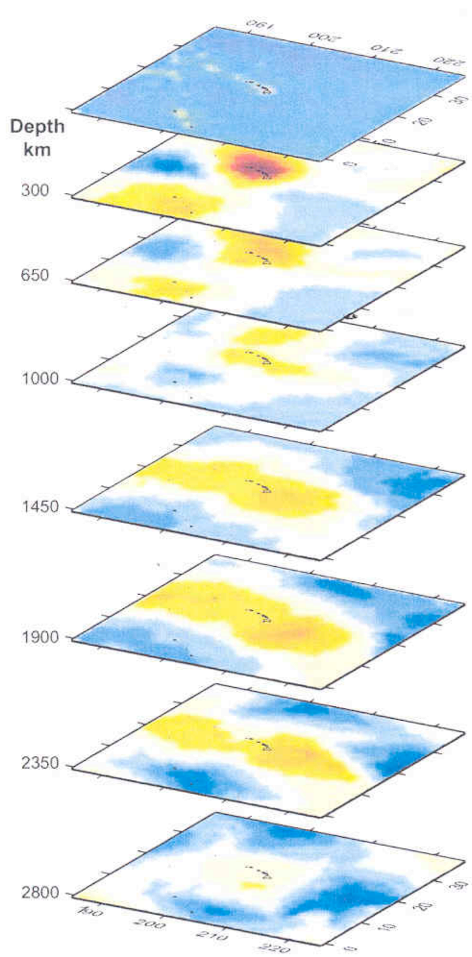

Figure 4: Seismic tomography images of P wave velocity anomalies beneath the Hawaiian islands. Data reduction techniques have been employed to enhance the images. Red areas indicate slower P waves, interpreted as less dense and therefore hotter areas, blue areas indicate faster P waves, interpreted as denser and therefore cooler areas (DePaolo & Manga 2003)

It is the content and character of the chemically heterogeneous material contributed to the upper mantle by the less thick subduction slabs which is suggested may be responsible for much of the hotspot volcanism previously attributed to deep mantle plumes. Dis-homogeneity in the upper mantle generates temperature variations, fluctuations probably sufficient to drive shallow convection cells. Chemical heterogeneity results in a reduction of localised melting temperatures, resulting in increased quantities of buoyant melt material (Anderson 2003 (1)). As subducting oceanic plates sink to depths > 3.5 km and pressures > 10 kbars, metamorphic processes cause recrystallisation to form eclogite, a sodium-rich pyroxene-garnet rock (Press & Siever 2001). Melting temperature of eclogite is considerably lower than that of mantle and at temperatures where peridotite is 20% molten, a 30%-eclogite/70%-peridotite mixture becomes 60% molten peridotite (Yaxley 2000).

This enhanced fertility within the mantle patently has implications for the production of excessive quantities of magma. Iceland overlies the ancient Caledonian suture zone, formed ~ 400 million years ago with the closure of the Iapetus ocean (Figure 6**).** Metamorphosed remnants of the oceanic crust, now preserved as eclogite, are therefore expected to underlie Iceland and generate the unusually large quantities of magma resulting in the localised topographical high. Furthermore, evidence in the basalts of east Greenland point to remelted Caledonian oceanic crust (Foulger et al. 2003). These Greenland basalts have been suggested as the flood basalt provinces of a deep mantle plume head (Courtillot et al. 2003).

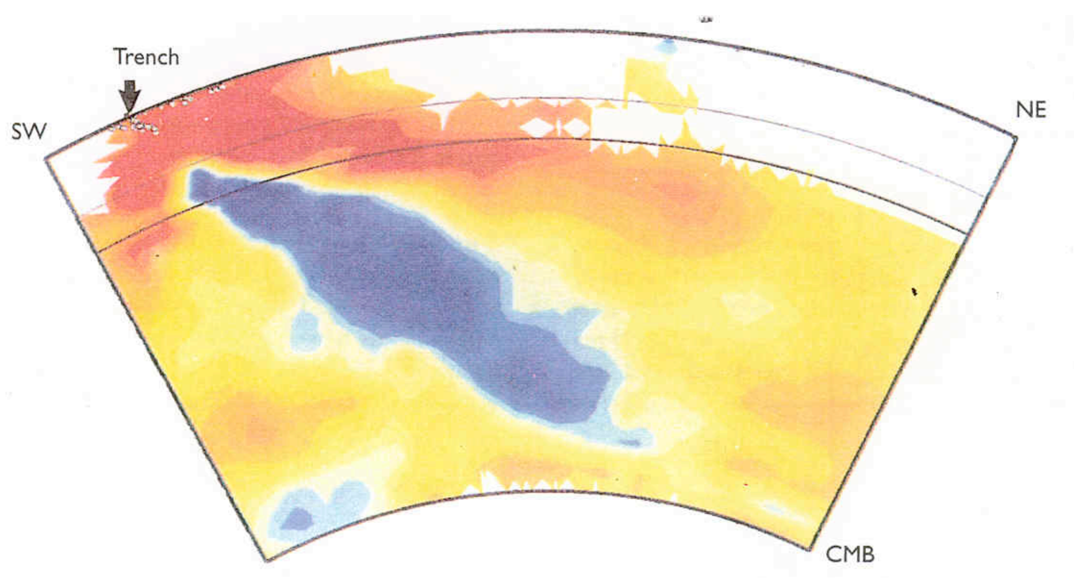

Figure 5: Seismic tomography image shows subduction of Farallon Plate (blue colouration illustrates high velocity P-waves, indicating cool material) towards the deep mantle. Red colouration indicates slower velocity P-waves, therefore hotter material. Adapted from Press & Siever 2001.

It is further proposed that high $^3He/^4He$ ratios noted in Icelandic basalts may be of Caledonian origin, trapped in gas bubbles in the olivine phenocrysts included in the subducting slabs (Foulger 2003). Furthermore, although these high helium ratios may suggest the considerable age of some elements of the mantle, they fail to inform upon the depth or the source of the material (Natland 2003). Helium ratios cannot therefore be held to prove definitively that the provenance of primordial material is a source from the deep mantle.

Chemical heterogeneity within the upper mantle could be responsible for the tholeiitic composition of ocean island basalts (OIBs), found for example in Hawaii and in areas of Iceland, at variance to MORB composition, indicating different degrees of melting interacting with the overlying crustal material, rather than representing primordial deeply sourced material. Moreover the oldest Emperor magmas of the Hawaiian island/Emperor seamount chain are more akin to MORB than tholeiitic composition, probably indicating that they erupted on a shallower lithosphere (Anderson 2003 (3)).

Furthermore, there is no evidence in the Hawaiian/Emperor chain for a flood basalt province, cited as a necessary precursor to ensuing deep mantle plume activity. It has been suggested (Courtillot et al. 2003) that this LIP might have undergone subduction, however this is an improbable suggestion as studies show oceanic plateaus as non-subductable (Abbot et al. 1997) and there is no obvious evidence in the area of obduction or accretion of such material (Foulger et al. 2003 (2)).

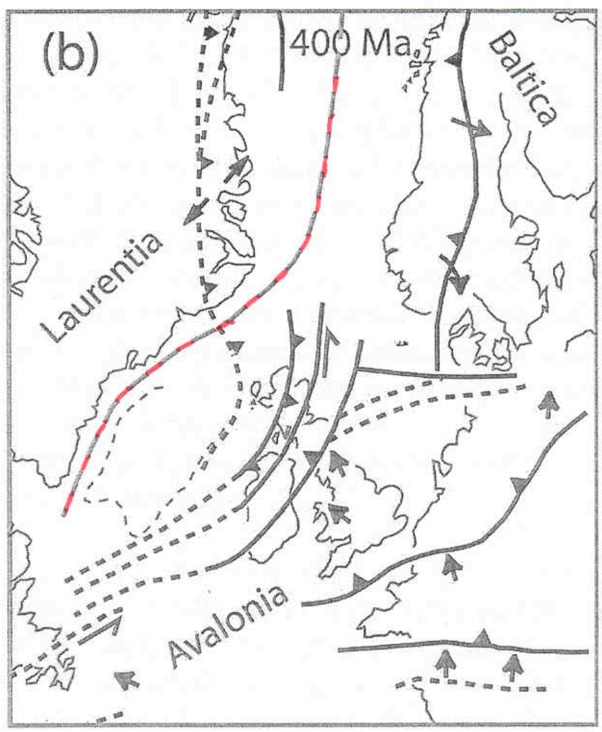

Figure 6: Diagram illustrating the closing of the Iapetus Ocean 400 Mya shows that oceanic slabs were subducted under Britain, Baltica and Greenland. Dashed black/red line shows position of the mid-Atlantic Ridge (adapted from Foulger et al. 2003 (1))

Time-progressive chains of magmatic activity are nevertheless an observable phenomenon in intraplate volcanism as can be clearly demonstrated along the islands and seamounts of the Hawaiian/Emperor chain, suggesting a concentrated, long-standing upwelling of melt material from the mantle causing volcanism along the direction of the overlying plate movement (Saunders 2003). Less readily explicable is time-progressive magmatism observed in the Oregon/Newbury chain, where time progressions occur in differing directions (Christiansen 2003) and in the Snake River Plain of Nevada where a silicic time-progressive chain is directionally fixed relative to the Hawaiian chain whilst basaltic magmatism is continuous. Furthermore, Icelandic magmatism is not fixed relative to the Hawaiian track and has been focused in the localised area of the mid-Atlantic ridge over the last ~ 54 million years, from the time of the opening of the Atlantic ocean (Foulger 2003). It has been suggested that intraplate magmatism may be the result of fracturing of the lithosphere, caused as a result of shallow stresses emitted from subduction boundaries and transmitted across tectonic plates (Natland 2003). Stress-induced fracturing propagates a directional pattern of fissures which could mirror the age-progressive volcanism of island chains. It could further account for the multi-directional magmatism of the Oregon/Newbury chain. Plate tectonic processes at plate boundaries would inevitably alter the geometrical alignment of stress patterns and could therefore account for dramatic directional alterations, such as that which occurs between the Hawaiian island/Emperor seamount chains (Natland 2003) (Figure 1).

Finally it is currently suggested that hot spots do not demonstrate the anomalous high temperatures which accounted originally both for the name and the necessity of a mechanism to bring extensive quantities of super-heated melt from areas of the deep mantle. Studies on previously reported analysis of localised high heat flow have been found to have been erroneously contrasted with areas of anomalously low heat flow. New analysis of areas of lithosphere to the west of Iceland demonstrate heat flow levels comparable to same-age lithosphere in other non-magmatic regions and consequently show no evidence of significantly raised temperatures which might be associated with a deep mantle plume anomaly (Stein & Stein 2003).

In conclusion it is evident that deep mantle plumes have been used as a convenient mechanism to explain many examples of anomalous magmatism without consistently rigorous examination of all features of the manifestations of such activity. Considerable advances in the science and technology of seismic tomography are essential for a further understanding of the dynamics of Earth's mantle. Without greatly ameliorated imaging of the lower mantle, definitive statements as to whether deep mantle plumes do or do not exist are spurious. By the same token, a more rigorous analysis to decipher the information gleaned by tomographic imaging needs to be undertaken to lessen the risk of ambiguous interpretations of the images. The future of careful research into a wide spectrum of sites of anomalous magmatism, coupled with technological advance in seismic tomography is vital to the advancement of understanding in this area.

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