

Do mantle plumes exist?

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“If plume hypothesis cannot be adapted to fit the observations, then the observations are commonly adapted to fit the hypothesis”

– Gillian Foulger; 14th August 2003

Not all of the volcanic activity on Earth can be related to present day active plate margins. A few of the 500-600 volcanoes on the Earth are located away from plate margins and are called mid-plate or intraplate volcanoes, or hotspots. They occur on continents and oceans and represent sites of melting anomalies in the mantle beneath them and this melt ascends through narrow plumes. Volcanoes at plate boundaries are caused as a result of subduction, which causes crustal melting of the upper mantle.

Isotopic dating of the lavas that make up the volcanic islands on the Pacific plate shows that in all cases, the age of the islands increases from SE to NW. The youngest islands in the chains are all volcanically active, but as the islands increase in age they become extinct. The islands are also much younger than the ocean crust that they are built on.

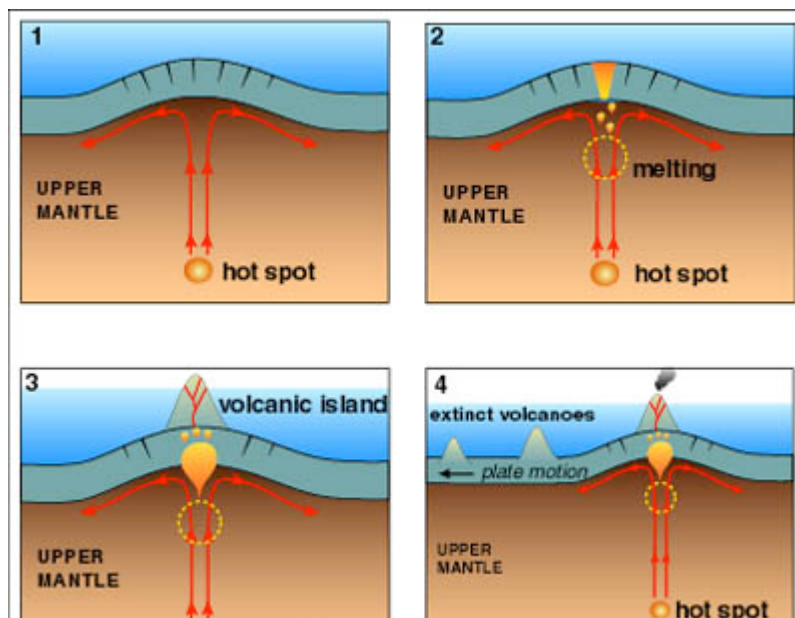


Figure 1: sequences in the formation of a volcanic island above a mantle plume – (courtesy of http://www.soc.soton.ac.uk/CHD/classroom@sea/carlsberg/images/plume_sequence.jpg - 2003)

The formation of these volcanic islands is related to the occurrence of long-lived, stationary hot spots within the mantle (see Figure 1 above). The hot spots create localised plumes of hot, rising mantle material. As the plume rises towards the base of the lithosphere, the reduction in pressure allows partial melting of the mantle material within the plume to form basaltic magma. The magma melts its way through the oceanic crust and erupts onto the ocean floor to build up an active volcanic island. As the plate carries on moving over the plume, the original island is carried away from the magma source and eventually becomes extinct.

The plate acts as a conveyor belt so as the old island is carried away, a new volcanic island is formed in its place above the hot spot. This process builds up a chain of islands, with the age of each increasing with distance away from the currently active island. As the old islands are carried away from the hot spot, they subside (sink down into the crust) and are eroded by the sea, so that many of the older islands are now under the sea surface and form guyots.

Some geologists consider that mantle plumes are generated in the lower levels of the asthenosphere by the decay of concentrations of radioactive isotopes. However, many believe that they are generated at much deeper levels in the lower mantle, at the core-mantle boundary, also known as the D'' layer. One of the reasons for this is that the plumes seem to have remained in the same position over very long periods of geological time (they appear to persist for periods of approximately 200 million years), whereas patterns of mantle convection currents seem to be a lot more erratic.

In excess of 70 hotspots have been identified on the Earth's surface and where they underlie continental crust, the crust becomes domed and extensive volcanic activity can occur. The huge volumes of flood basalts erupted in the Deccan Traps of India during the Tertiary period are thought to be caused by the eruption of a mantle plume head at the surface. During the Deccan Traps event, in excess of 50,000 km² of lavas were erupted over a period of only a few million years.

Experiments in fluid dynamics have shown that the hot, less dense, less viscous mantle layer becomes gravitationally unstable and buoyant, and moves upwards as a diapir or a voluminous plume head. A column of magma trails the latter and finally assumes a variety of shapes – domes, waves, mushrooms, teardrops or dykes.

In 1963, Tuzo Wilson suggested that there is a hotspot in the mantle which is forming the Hawaiian island chain as the Pacific sea floor moves over it (see Figure 2 below). In 1971, W. Jason Morgan took Wilson's theory a step further and proposed that hot material rises up from the core-mantle boundary in chimney-like plumes to feed hotspots on the surface. He said plumes explain excess volcanism, fixed hotspots and linear island chains. Plumes had to be sourced in the deep mantle as the upper mantle is convecting and diapiric upwelling can only come from a thermal boundary layer, the core-mantle boundary.

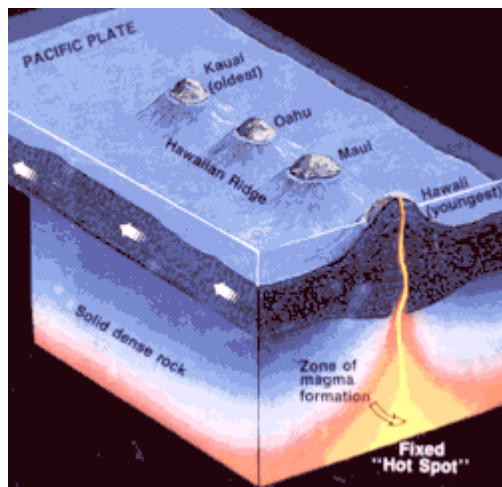


Figure 2: this textbook picture of the hotspot theory. (Courtesy of USGS: <http://geology.about.com/library/weekly/aa011401a.htm>)

Foulger has pointed out the problems associated with Morgan's theory. She says that hotspots are not, in fact, hot. Heat flow data from hotspots provide no evidence for their being hotter than lithosphere of the same age elsewhere. Originally, the uplift at Hawaii and similar mid-plate 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.

Hotspots are not fixed either - the so-called hotspots on the Mid-Atlantic Ridge are permanently there and chains have not formed. Many chains are not time-progressive e.g. Iceland and the Azores and seismic imaging does not detect the hotspots in the lower mantle.

Anomalies are found to be confined to the upper mantle where mantle tomography has imaged proposed mantle plume locations e.g. Yellowstone, Tristan da Cunha and the Azores. Heat flow measurements and petrology provide very little evidence of the high magma temperatures postulated for deep plumes e.g. Hawaii and Iceland.

Hotspots move relative to one another at rates of the order of centimetres per year, and many island chains originally assumed to be time-progressive are not. Physical models suggest that classical plumes may be impossible because the enormous pressure in the deep mantle suppresses the buoyancy of hot material.

The Hawaiian-Emperor chain is known as the best plume example based on 'plume facts', but Foulger disagrees with this. She has pointed out that the average basalt production rate is about the same as single mid-ocean ridge spreading centres a few tens of kilometres long, which are considered to be supplied by the shallow mantle. Seismic tomography, which can map the wave speed through rocks, shows that wave speed beneath Hawaii is quite high compared with the rest of the Pacific and it is therefore not melting.

Foulger argues the following:

- The great 'bend' is not a result of a change in direction of motion of the Pacific plate as no such change occurred. The Emperor and Hawaiian chains differ in trend by about 60° . The two trends intersect at about 30°N , near the Mendocino fracture zone (see Figure 3 below).
- The 'hotspot' migrated roughly 1000 km south while the Emperors were formed, but abruptly ceased this motion at the time the bend occurred.
- There is no reasonable candidate for a Hawaiian 'plume head'.
- The volume flux along the Hawaiian chain has increased by an order of magnitude during the last 5 Ma approx.
- There is no significant heat flow anomaly around the bathymetric swell.

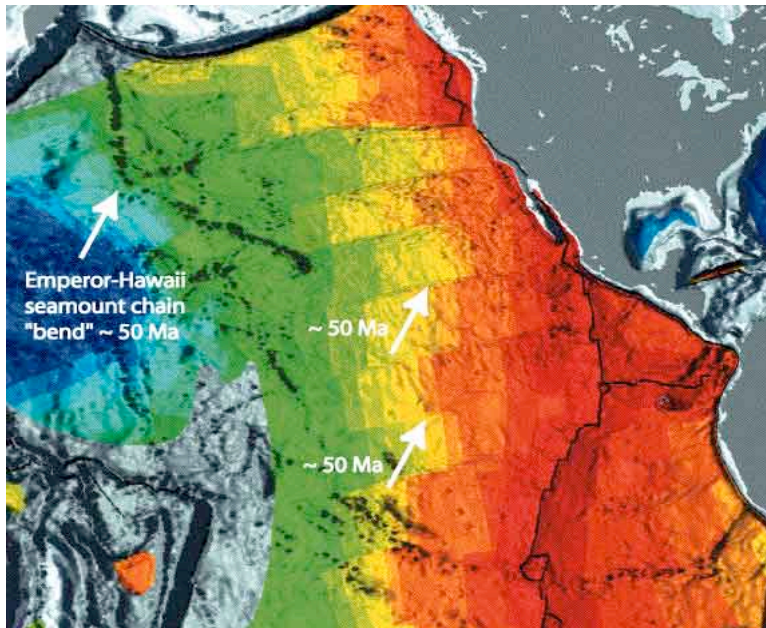


Figure 3: Map of the Pacific Ocean showing sea floor age as determined from magnetic lineations. It can be seen clearly from the continuity of fracture zones that no change in the direction of motion of the Pacific plate occurred at the time of the bend at about 50 Ma. (Courtesy of Anderson and Foulger: <http://www.mantleplumes.org/Hawaii> - 2003)

With reference to Iceland, Foulger says that a fraction of a percent of partial melt in the mantle beneath it can explain the seismic anomaly there better than high temperature, for which there is no evidence. The evidence for a lower-mantle seismic anomaly beneath Iceland has been discredited many times.

Large Igneous Provinces (LIPs) are claimed to require a plume model because of their huge volumes and eruption rates and associated volcanic chains.

What is often not pointed out is the following:

- In many cases, LIPs do not have associated volcanic chains nor the precursory uplift required by the plume hypothesis.
- Quantitative modelling of plumes has been unable to reproduce the large volumes and short eruption times specifically claimed to require a plume model.
- LIPs can be explained equally well by other models.

Don L. Anderson of Caltech believes that the mantle's physical properties preclude the formation of narrow, buoyant plumes in the lower mantle and seal off the mantle below around 1000 km. He argues that chains of volcanoes such as Hawaii could form along a crack in the plate that lets hot mantle rock at a few 100 km depth rise to the surface and melt. Foulger argues that it is incorrect to assert that propagating crack models

cannot explain the chain, because no-one has ever made a serious attempt to quantify such a model.

Scientists argue that plate tectonics can explain mid-plate island chains like Hawaii and The Canary Islands. They claim that there is no evidence of narrow columns piercing the whole mantle and emerging at the Earth's surface and that extremely high pressures in the mantle stop rock from rising.

Rex Pilger argues that nearly all of the Cenozoic hotspots of the Pacific plate owe their origin to lithospheric structure. Variations in plate thickness provide the context for the hotspots to emerge, possibly with the control of variable fertility of the underlying asthenosphere and mesosphere i.e. hotspots are shallow in origin. He says the only reason we can't include the two bigger, long-lived hotspots, Hawaii and Louisville, is because their oldest extents are hidden in subduction zones, along with the plate structure.

Andy Saunders, professor of geochemistry at Leicester University said, "Like the electron, which is never seen, but whose effects are predictable and observed, plumes are elusive, hidden, enigmatic, and important."

Saunders says that seismic tomography shows that the waves slow down beneath Hawaii, a so-called hotspot. This contradicts Foulger's point that seismic waves are higher below Hawaii compared to the rest of the Pacific.

He says that this suggests the existence of an upwelling of buoyant, most likely hot, rock beneath the island, which fits with his working definition of a plume. Foulger has suggested that the island may have resulted from a tear in the plate. Saunders argues that while it is possible, no puncture has been observed.

Bob Christiansen (2002) of the USGS thinks the Yellowstone hotspot is not related to a deeply fixed plume, but rather to upper-mantle convection related to the regional extension that affects the North Western United States. He points out that the hotspot track at Yellowstone runs along a major structural boundary in the lithosphere. The Eastern Snake River Plain records the former track of the Yellowstone hotspot, which has been active since the onset of basin and range extension in the region 15 to 17 Ma ago; the hotspot track marks the northern edge of large-scale regional extension. Christiansen says that there does not appear to be evidence for a deep mantle source.

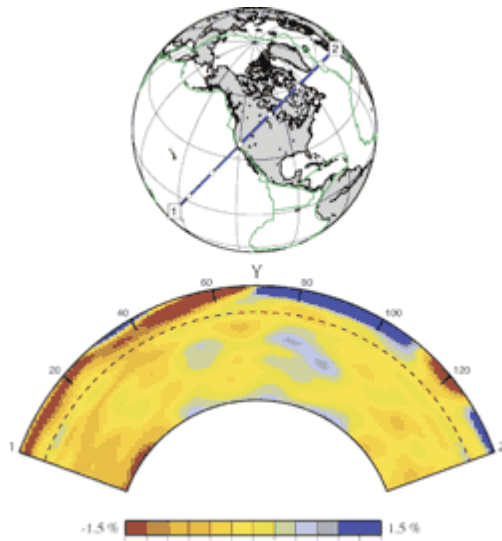


Figure 4: Whole-mantle cross-section through Yellowstone (courtesy of J. Ritsema)

Whole-mantle tomography shows that Yellowstone lies at a profound lithospheric structural discontinuity where the Basin & Range region to the southwest abuts the North American craton to the northeast. There is no significant low-wave-speed anomaly either in the lower mantle or the lower part of the upper mantle. In fact, wave-speeds are anomalously high in the lower half of the upper mantle (Foulger, 2003 - see Figure 4 above).

The most resolvable features of plumes (lithospheric and transition-zone thinning, plume heads, spreading out of hot material below the plate and at 650 km) are absent in seismological models (Bruce Julian, Gillian Foulger, 2003). Furthermore, Julian states that the vertical travel time of seismic waves beneath Hawaii is the same as the global average, thus contradicting Saunders and Foulger.

Although a high $^3\text{He}/^4\text{He}$ ratio indicates an approximate age of mantle components, it tells us nothing about their original depth or distribution (Meibom, 2003). A high ratio just means isolation of helium, captured with other volatiles in fluid inclusions in minerals, from U and Th, which are retained in melts that are generally excluded from such inclusions (James Natland, 2003). ^4He is thus low and remains invariant in old peridotitic or cumulate ultramafic protoliths (Anderson, 2003). We expect such material to be present in the upper mantle (Meibom, 2003) and the mantle beneath ancient continental crust, which often ends up in the middle of ocean basins and becomes involved in partial melting beneath ridges and at active ends of linear volcanic chains.

The alternative to hotspots is plate tectonics, which involve fertility and extension. The mantle is fertilised by eclogite from subducted slabs, which becomes trapped in the mantle wedge (behind subduction zones) and the continental lithosphere. Cordery et al (1997) pointed out that the solidus and liquidus of eclogite in the trapped slab is lower than mantle peridotite with eclogite being molten before peridotite. Hofmann and White (1982) deduced that ocean island basalt geochemistry is consistent with fractional melting of mid-ocean ridge basalts.

Extension can be observed in the East African Rift, in continental rifts and back arc extension, to name a few. The asthenosphere rises which causes more heat to accumulate higher up and the thinning causes extension. Extension + fertility = fecundity, this being the amount of melt that can be produced and hotspots on mid-ocean ridges are an obvious source of extension.

In Iceland, a hotspot track is not observed according to Foulger. There is no evidence for any high temperatures required for hotspots and the crustal structure is inconsistent. No picrite glass can be found, which is common in areas of high temperatures. The temperature of calculated primary melts is similar to mid-ocean ridges and there is no heat flow anomaly. The mantle seismic anomaly does not extend down to the lower mantle. Iceland is now found to be a 'thickspot' with a crust of about 30 km in thickness with normal temperatures and a cold crust.

The most convincing arguments for a "hotspot" or a plume would be high magma temperature, uplift, thick crust, high heat flow, thermal erosion of lithosphere, or a deep mantle tomographic signal. These are indicators of a thermal mechanism, as opposed to athermal mechanisms which have also been proposed for oceanic plateaus, swells and continental flood basalts.

Athermal mechanisms include focusing, fertility, ponding, EDGE and rift mechanisms, processes involving lithospheric stress and dykes, and a partially molten shallow mantle (Anderson, 1998). Melting of particularly fertile or volatile-rich mantle containing materials such as recycled oceanic crust, sediments, eclogite, piclogite or pyroxenite, also removes the need for high plume temperatures.

A small fraction of the total surface heat flow comes from the core and the plume hypothesis focuses on this core heat. The high pressure and low heat flow at the base of the mantle means that buoyant upwellings must be huge, long-lived and slow to develop. Even a small intrinsic

density contrast between the deep layers in the mantle will trap the upwellings, since pressure lowers the thermal expansivity of silicate rocks, and increases the viscosity and thermal conductivity.

In general, plume theorists believe the cause of mid-plate volcanism is unrelated to modern plate motions, coming instead from deeper convective disturbances within the Earth that are fuelled by heat from the core. The alternative is whether most mid-plate and linear-chain volcanism like that of ridges and arcs and is directly related to the plate-tectonic cycle in the shallow mantle.

Foulger states that the plume hypothesis, as it is applied today, requires that Earth dynamics be driven by plate tectonics and plumes. Plate tectonics is driven by forces at plate boundaries (ridge push and slab pull) and plumes are driven by heat from the Earth's core. The new theory suggests that only plate tectonics is needed.

If the existence of a plume is going to be accepted, then convincing evidence for high temperatures and deep upwelling must be found. Until this is achieved all the possibilities that are consistent with the observations should be entertained, including the possibility that the melt anomaly may arise from locally fusible mantle at normal mantle temperatures.

All of the arguments used in support of plumes and against alternative mechanisms have been widely discussed in all of the literature. There is little support for these arguments, but they are constantly repeated, and new papers often quote earlier ones containing undiscussed repetitions. In order to progress we must critically assess the original sources of ideas, not simply repeat assertions.

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