

Hot spots and the mantle plume controversy

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Before we can discuss whether or not mantle plumes exist, we have to first define what they are. The term “hot spot” was first coined by J. Tuzo Wilson in 1963. It was known that the Hawaiian islands age to the northwest along the archipelago and Wilson suggested that this resulted from the Pacific plate moving over a region of the mantle beneath that was unusually hot. He termed this a “hot spot”. The idea of mantle plumes came along 8 years later, when W. Jason Morgan suggested that this, and 18 other “hot spots”, were fuelled by the continual influx of hot material from thermal plumes rooted in the deep mantle.

The model quickly matured, and classical plumes were envisaged as bottom-heated convective upwellings that rise through their own thermal buoyancy. It is generally assumed that they must rise from a major thermal boundary layer, and the only one known to exist in the Earth is at the core-mantle boundary.

Plumes were originally proposed to explain the excess volcanism observed at places such as Hawaii and Iceland, relative fixity between “hot spots”, and the regular time-progression of volcanism along island chains, especially in the Pacific ocean. Laboratory experiments were performed that involved injecting coloured, buoyant material into fluid-filled tanks. These experiments produced vivid images of mushroom-shaped upwellings and were influential in popularising the model. Later, when powerful computers became available, numerical images and movies were produced.

Unfortunately, as is often the case, the observational evidence was less compliant. Despite a lot of searching, little evidence was found from petrology and other methods that “hot spots” are hot. Many proposed “hot spots” produce very small volumes of magma. Even Hawaii, the best candidate for a plume, has only produced an amount of magma corresponding to approximately one marine spreading segment for most of its ~ 80-million-year history. Only in the last five million years did it suddenly increase its output by an order of magnitude.

Many “hot spots” are not fixed relative to one another. The most spectacular example of this is Iceland, where volcanism has been centred on the mid-Atlantic ridge ever since its beginnings about 54 million years ago. This means that it has moved with respect to other Atlantic “hot spots”.

A lot of age dating of island chains has been done during the last three decades to look for the predicted time-progressions. However, many chains were found to be not time-progressive, e.g. the Line island chain south of Hawaii, and the Cameroon volcano line in west Africa. Lastly, despite over three decades of seismology of increasing sophistication, the pipe-like structures predicted to lie in the deep mantle have not been reliably imaged. Again, Iceland provides a good example of this, and there, multiple local and global seismic experiments essentially all agree that the anomaly is confined to the shallow mantle and does not extend deeper than about 650 km.

Despite these difficulties, the reaction of many Earth scientists has been one of bewilderment that the evidence for “what we know is out there” has not been found. Creativity has been applied in adapting the model to fit the observations. “Contemporary” plumes can come from essentially any depth, magma can flow for thousands of kilometers laterally, accounting for volcanism that doesn’t occur where expected. For example, it has been proposed that “the” Iceland plume has in fact been fixed relative to other Atlantic hotspots but that magma from it has persistently flowed laterally to the mid-Atlantic ridge. Plumes have been proposed to be either narrow – a useful feature if they can’t be seen in seismic experiments – or broad. Types that have no “mushroom head”, one head or multiple heads have been proposed, and pulsing in the “mushroom stem” has been proposed to account for volcanic production rates that deviate from the monotonic decrease with time predicted by the original model. The list goes on and on.

It’s reasonable to adapt an original model in the light of new data. However, in the case of the plume hypothesis many scientists feel that things have gone too far and have reached the point where the model has become unfalsifiable – it is essentially observation-independent. Many papers amount to little more than reporting new observations and selecting from the rich palette of variants available to explain how the particular plume studied differs from the others. This approach is adding little to our understanding.

As a result, plume skepticism has grown in recent years and a new generation of models has emerged that doesn’t involve exceptionally high temperatures or the tapping of material from the deep mantle. These models are based on the suggestion that anomalous volcanism is driven by plate tectonic processes at the Earth’s *top* thermal boundary layer, i.e. its surface. There are two key elements – variations in lithospheric stress, and mantle composition. Simply put, the state of stress in the plate controls the location of volcanism, and the fusibility of the source material beneath governs the volume produced.

The mantle is dehomogenised by processes at mid-ocean ridges, where basalt magma is extracted from the mantle to create new crust. This separates mantle material into fusible basalt and refractory residue. The fusible basalt crust, along with material accreted to its underside during its journey across the ocean, is recirculated back into the mantle at subduction zones. Other processes such as lithospheric delamination can also introduce fusible material back into the shallow mantle. Experiments show that recycled fusible material can produce several times as much melt at a given temperature as peridotite, the rock commonly assumed to comprise the bulk of the mantle.

The most significant processes that cause stress to vary in the lithosphere are differential cooling and variable plate boundary types. The great Pacific plate comprises about a third of our planet. Stress within it due to spatial variations in cooling rate, has been modeled using finite-element analysis. This shows that stress from this source is orientated optimally for encouraging the propagation of a crack in the line of the Hawaiian island chain. It has also been suggested that volcanism along the Cameroon volcanic line in Africa occurs because of the almost ninety-degree change in direction of the continental edge there. It would be interesting to model this using the finite-element approach as well.

In summary, the alternative proposal to plumes for the origin of anomalous volcanism is that it occurs where the stress field is extensional and where the mantle is unusually fusible. So how does this model fit the observations? "Hot spots" preferentially occur where stress in the crust is extensional. One third of all "hot spots" are at or near spreading plate boundaries. Others, are in continental extensional zones such as the East African rift and the Basin Range province in the western USA.

The plume model can only be tested if it makes predictions. Currently it does not do this because in practice all its predictions are negotiable. The "plate tectonic processes" model predicts extension and evidence for unusual fertile source composition. It does not require unusually high temperature in the mantle source.