

Mantle plumes persevere

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The ocean floor is littered with hundreds of thousands of mostly extinct volcanoes. The origin of at least some of these seamounts seems to rest with mantle plumes.

A recent census suggests that seamounts¹ — typically extinct underwater volcanoes — are numerous. It has been estimated that about 125,000 seamounts with a height of more than one kilometre exist on our ocean floors. Most of these are postulated to form at volcanic hotspots that are the surface expressions of mantle plumes — hot material upwelling from Earth's interior. Yet, many seamounts do not show the typical characteristics expected for volcanoes that have formed above a mantle plume. So, debate about the feasibility of the mantle plume hypothesis is ongoing. The most straightforward explanation is that not all hotspot volcanoes are alike, and that some groups of seamounts are better explained by mechanisms other than mantle plumes.

Morgan's mantle plumes

Some hotspots form seamount trails along the surface of tectonic plates, far away from their volcanically active plate boundaries. Forty years ago, W. Jason Morgan introduced the concept of mantle plumes to explain this kind of hotspot volcanism^{2,3}. According to his theory, plumes of hot material upwell from the deep mantle. During ascent and on impact with the overlying tectonic plates, these plumes drive melting and the production of magma, which erupts to form volcanic seamounts at the plate surface. Morgan proposed that the migration of tectonic plates over stationary and long-lived mantle plumes would generate chains of volcanoes on the ocean floor. However, because mantle plumes themselves cannot be directly sampled and the thin plume

conduits are difficult to resolve using seismic data^{4,5}, their existence has been difficult to confirm. Many question whether all hotspot volcanism is formed by mantle plumes^{6,7} and some doubt whether mantle plumes exist at all^{8,9}.

Perhaps the most captivating aspect of Morgan's plume model is that he could explain the formation of the Hawaiian–Emperor and three other seamount trails along the Pacific Ocean floor. These three trails track each other in such a way that they can be explained by the rotation of a rigid Pacific plate that is drifting over four plumes fixed in the mantle (Fig. 1a). With this observation, Morgan supplied compelling support for the existence of plumes and also provided independent proof for the motion of tectonic plates relative to the underlying mantle. The mantle plume model also opened up potential new avenues of research into the Earth's deepest regions¹⁰. Specifically, if the volcanic seamounts are the surface expression of a mantle plume, their erupted lavas could potentially preserve a record of long-lived variations in mantle composition and could provide insights into mantle convection.

Holes in the theory

The plume model calls on an extensive global network of long-lived stationary mantle plumes that are continually delivering hot material from deep in the Earth. However, such a global network never fully materialized. It now seems that there aren't many active hotspot systems around the world, maybe a few dozen — too few to have produced all of the world's seamounts.

Of those seamounts that do seem to have formed above a mantle plume, some show evidence that the underlying plume was neither long-lived nor stationary. Improved mapping of seamount trails using satellite altimetry reveals that most seamount trails have typical life spans of just 30 million years¹¹. And samples of lava collected from the Emperor seamounts during the Deep

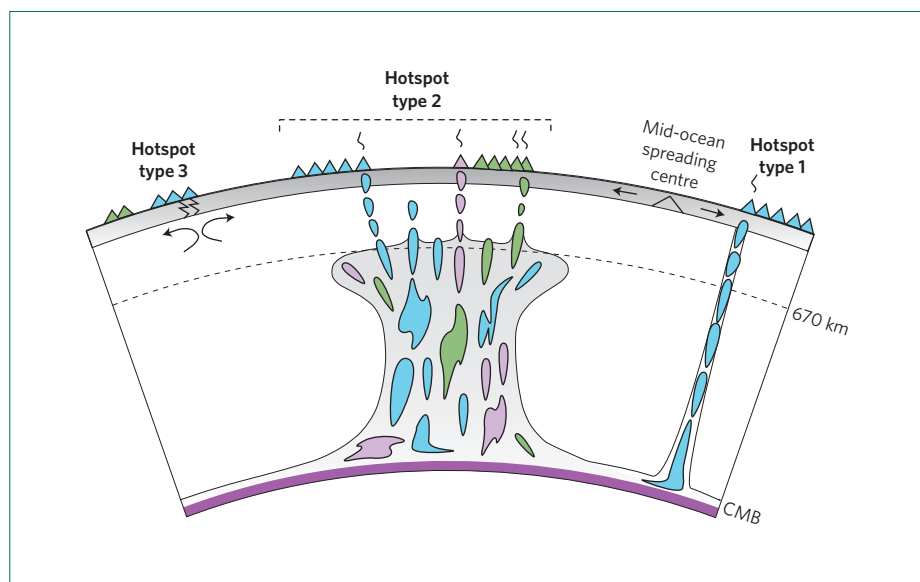


Figure 1 | Models of ocean-island and seamount-trail formation: Courtillot's framework⁶ of three hotspot types. The first, a classical Morgan-style long-lived mantle plume, originates from as deep in the mantle as the core–mantle boundary (CMB). The second hotspot type includes short-lived, smaller plumes originating from shallower parts of the mantle, probably as offshoots from large superplumes. These secondary hotspots are more common. The third type of hotspot is not related to any kind of mantle plume and may form where the oceanic lithosphere cracks or extends. This kind is the least investigated and may overlap considerably with the other hotspot types.

Sea Drilling Project and Ocean Drilling Program show that the mantle plume sourcing the Hawaiian–Emperor seamount trail has moved south. These lava samples preserve a magnetic record that can be used to reconstruct the position of the Hawaiian mantle plume through time, which now shows us that the Hawaiian plume moved almost 15° southwards between 80 and 50 million years ago^{12,13}.

Furthermore, the geochemistry of lava samples from different seamounts suggests that some indeed formed above hot mantle, but others formed above damp, cold mantle. In the latter case, the mantle seems to have been enriched in volatile components, such as H₂O and CO₂, which could have triggered melting. Thus, not all seamounts require extra heat to explain their volcanism¹⁴.

The trademark of a Morgan-style mantle plume is the systematic increase in age of the individual volcanoes along the trail, contemporaneous with plate motion. Yet, some seamount trails do not show the expected linear age progressions. Additionally, when a tectonic plate has changed direction, all seamount chains formed on that plate should exhibit a bend in their chain at a time that corresponds to the change in plate motion. However, many hotspot chains on the Pacific Ocean plate, such as the Gilbert Ridge, Tokelau and Louisville seamount trails, do not show such synchronous bends when compared with the infamous 145° bend in the Hawaiian–Emperor trail^{7,15}. The lack of age progression and the occurrence of asynchronous bends in seamount trails have been puzzling to say the least.

In short, current evidence suggests that hotspot volcanism is often short-lived, sometimes supplied by a moving source, not always hot and may lack the predicted age progression. Taken at face value, each of these observations violates one of the basic assumptions of Morgan's model.

Moving on from mantle plumes

Before we reject the mantle plume model, we should regroup our findings and centre our thinking on the possibility that different processes can form different types of hotspot. About a decade ago, Courtillot and co-workers⁶ proposed a new framework (Fig. 1) in which they distinguished three different hotspot types.

The first type is the classical Morgan-style mantle plume. Only a few such seamounts have been found, including the Hawaii, Louisville and Samoa hotspots in the Pacific Ocean, the Walvis in the Atlantic Ocean and Reunion in the Indian

Ocean. In these cases, the mantle-plume origin perseveres. These hotspots show the telltale signs of a deep mantle source, possibly near the core–mantle boundary, that has been active for a long time.

However, the southward movement of the Hawaiian plume tells us that we need to entertain more sophisticated ideas for this type of hotspot, that consider the motion of the mantle plumes themselves¹³. This in itself is exciting because seamount trails could potentially tell us about changes in mantle flow.

The second hotspot type includes those that are sourced from shallower parts of the mantle. These hotspots are far more abundant, but shorter lived. At the surface, they are often distributed in large seamount provinces, such as the volcanic islands and seamounts of French Polynesia in the Pacific, which correlate with the occurrences of so-called superplumes in the Earth's mantle. These giant superplumes extend from the core–mantle boundary up to depths of about 1,000 km, close to the base of the upper mantle. From here the superplumes generate smaller plumes. Seismic data that can image the deep Earth have identified two superplume areas in the deep mantle beneath Africa and the Pacific Ocean. These two regions might be formed of material that is chemically distinct from and warmer than the surrounding mantle¹⁶.

The third type of hotspot may form where the oceanic lithosphere cracks or extends, allowing small magma pockets to erupt at the surface. Cracking can occur as a result of plate tectonic stretching forces^{8,9} or owing to cooling and thermal contraction of the plate¹⁷. Additionally, shallow motions in the underlying mantle, such as small-scale convection¹⁸ or shear movements¹⁹, can drive melting and the generation of magma that erupts to form seamounts. The Puka Puka ridge in the equatorial Pacific and many seamount trails formed close to mid-ocean spreading centres belong to this tertiary hotspot type. And a large seamount province surrounding Christmas Island in the Indian Ocean seems to have formed in a juvenile ocean basin from the shallow recycling and melting of close-by continental lithosphere²⁰.

Interestingly, overlap between Courtillot's three hotspot types may exist. For example, the geochemistry of Hawaii has a strong geographical asymmetry and temporal variation that could be explained by chemical heterogeneity in the mantle plume^{21,22} inherited from a thermal disturbance at the core–mantle boundary, at the bottom edge of the Pacific

superplume. Another recent study shows that these geochemical variations also could have been caused by small-scale mantle convection causing a variation in plate thickness beneath this hotspot²³ and thus creating different melting regimes in the shallow upper mantle. It is entirely plausible that both processes are at play during the formation of the Hawaiian volcanoes.

A place for plumes

Clearly, not all seamounts can be attributed to the upwelling of mantle plumes from deep inside the Earth. Today, many geoscientists propose alternative explanations for the formation of seamounts and seamount trails. Thus, on its fortieth anniversary, Morgan's model may have outlived its use for some. However, for many the model still provides a useful basic framework for understanding seamount formation. Future exploration and sampling is required to bring further insight to this hotly debated topic, as we continue to search for a better understanding of the processes in the deep Earth that are responsible for the formation of thousands of seamounts. □

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