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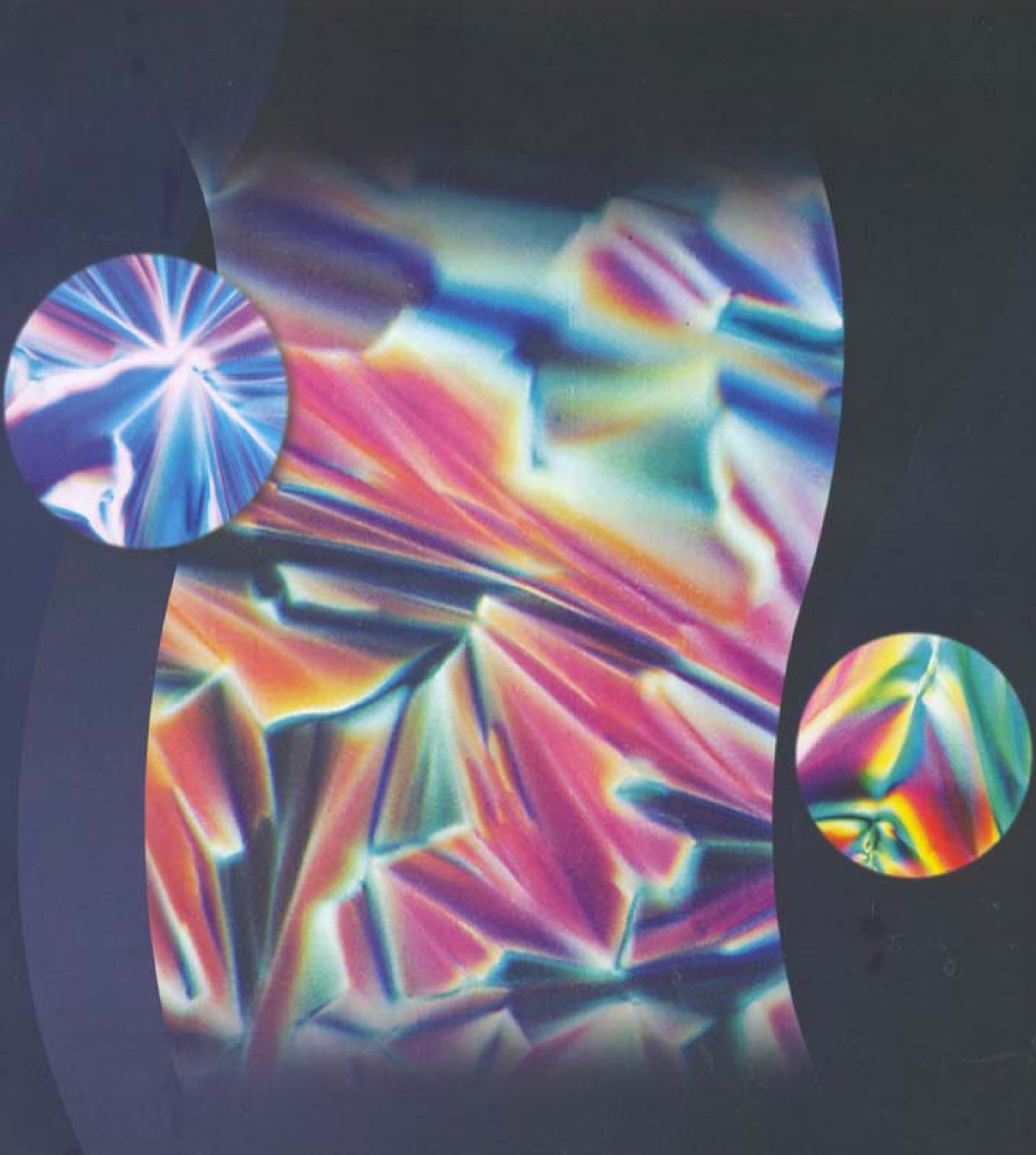

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# Mantle plumes: Why the current skepticism?

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Abstract **The present reappraisal of the mantle plume hypothesis is perhaps the most exciting current debate in Earth science. Nevertheless, the fundamental reasons for why it has arisen are often not well understood. They are that 1) many observations do not agree with the predictions of the original model, 2) it is possible that convection of the sort required to generate thermal plumes in the Earth's mantle does not occur, 3) so many variants of the original model have been invoked to accommodate conflicting data that the plume hypthesis is in practice no longer testable, and 4) alternative models are viable, though these have been largely neglected by researchers. Regardless of the final outcome, the present vigorous debate is to be welcomed since it is likely to stimulate new discoveries in a way that unquestioning acceptance of the conventional plume model will not.**

**Keywords: plume, volcanism, hotspots, convection, mantle, plate tectonics.**

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The current vigorous re-appraisal of the mantle plume hypothesis[1] has been described as potentially the most radical development in Earth Science since the advent of the plate tectonic theory in the 1960s. The foundation of mantle plume theory was laid in 1963, when Wilson[2] suggested that Hawaii and the time-progressive island/seamount trail northwest of it could be explained by passage of the Pacific ocean floor over a hot region in the mantle, which he termed a "hot spot". The mantle plume hypothesis proper was born in 1971 when W. Jason Morgan proposed that there were approximately 20 such "hot spots" and that the source material rose convectively in structures resembling "pipes to the deep mantle"[3]. He hypothesized that these "pipes" were rooted in the deep mantle, assumed to be relatively immobile, in order to explain the apparent relative fixity of surface "hot spots". Despite the lack of radiometric dates at that time, Morgan presumed many volcanic chains to be time-progressive like the Hawaiian and Emperor chains.

For the first two decades following the original hypothesis, interest in mantle plumes was slight (Fig. 1)[4]. However, their popularity exploded about 1990 following the publication of papers describing laboratory simulations of plume-mode convection in fluid-filled tanks[5], and proposing that mantle plumes deliver a high flux of $^3$He which comprises a primordial-mantle tracer[6]. The rate of publication of papers advocating mantle plumes leapt by almost an order of magnitude as a result, and subsequently remained high.

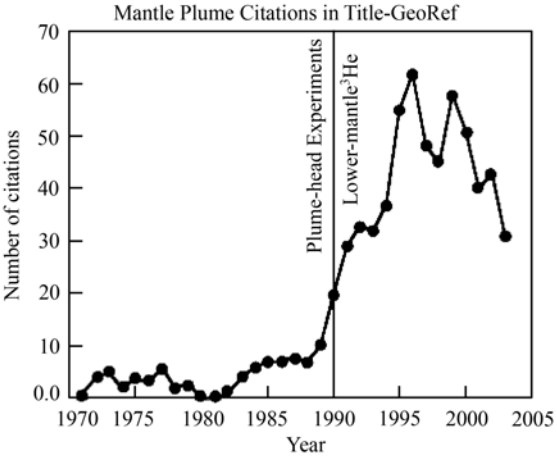

Fig. 1. Number of citations with the word "plume" in the title, in reference to mantle plumes, by year since 1971, listed in GeoRef, the online data base of the American Geological Institute. The vertical line gives the year of publication of a paper by Campbell and Griffiths[5] depicting plume heads and tails. The same year saw publication of a paper by Kellogg and Wasserburg[6] proposing a contribution from the lower mantle to $^3$He flux via mantle plumes. Following these papers, the plume hypothesis attained a great degree of acceptance (reproduced from Anderson and Natland, 2005).

Nevertheless, dissenting voices were never entirely absent, and included some who had been influential contributors to the development of plate tectonics. During the 1990s, skeptics were in the minority. Most papers published about mantle plumes assumed the hypothesis to be correct and sought to validate it rather than to test it. The task at hand was to find more plumes, not to look critically at existing ones.

The present decade has ushered in a vigorous upsurge in skepticism, however. Why did this occur, when the hypothesis had moved from embryonic status through vigorous research and on to general acceptance? There are four primary reasons for this, as detailed below.

## 1 Observations do not agree with the predictions of the classical plume model

The basic, classical mantle plume model makes a number of fundamental predictions. However, for many of the 19 plume locations originally proposed[3], and the much larger number subsequently added to that list[7], confirmation of these predictions by observation has remained elusive:

(1) Volcanic tracks are predicted to extend away from the present-day locus of active volcanism (the "hot spot") and to be time-progressive. This is not observed at many locations, e.g., Iceland and Ascension. Furthermore, the reliability of many ages used to define "hot spot tracks" has recently come under criticism[8,9].

(2) “Hot spots” are predicted to have been fixed relative to one another through time. Their degree of relative fixity is variable, however, e.g., Atlantic “hot spots” were not fixed relative to Pacific ones prior to about 50 Ma[10].

(3) Active “hot spots” should be underlain by vertical, quasi-cylindrical bodies of anomalously hot rock that extend from the core-mantle boundary to the Earth’s surface. Seismology has failed to image convincingly and consistently such structures, despite over 30 years of experiments of increasing sophistication. For example, the seismic anomalies beneath Iceland, Tristan and Afar are consistently found to be confined to the upper mantle only, and no anomalies at all are found beneath many other “hot spots”, e.g., Reunion and Hoggar.

(4) Lavas at “hot spots” should reflect sources that are hotter than those elsewhere, e.g., beneath mid-ocean ridges. Petrology provides little unambiguous evidence for this, however. Hawaii is the only currently active “hot spot” where picrite glass been found, suggesting high temperature, and the spatial extent of this is unknown. The mantle source of Icelandic basalts may be a few tens of degrees warmer than typical ridges, but such an anomaly is probably too weak for a mantle plume and may be of regional extent rather than only local[11,12]. This might also apply to Hawaii. At most other “hot spots” there is no petrological evidence at all for elevated temperature and even voluminous tholeiitic basalts, which suggest high heat flux, are absent[13,14].

(5) Some proposed plumes lack the large igneous provinces (LIPs) assumed to represent the “plume head”, e.g., Hawaii. Other LIPs lack the time-progressive volcanic track associated with the “plume tail”, e.g. the Ontong Java Plateau and the Siberian Traps.

In addition to these difficulties, many common geological associations must be attributed to coincidence in the classical plume model. For example, the Yellowstone “track” follows the northern boundary of the Basin & Range province, and the Azores “hot spot” is located on a ridge-ridge-ridge triple junction.

In some cases, the observations conflict so acutely with the plume hypothesis that they cannot be ignored or attributed to incomplete sampling. For example, there is no evidence that the Ontong Java Plateau, the largest LIP on Earth with a volume of 60 $\times 10^6$ km$^3$, was preceded by the uplift predicted by the plume hypothesis[15]. For the Siberian Traps, the continental sister of the Ontong Java Plateau, geological evidence suggests pre-emplacement subsidence[16,17]. Although these are only two of the many LIPs on Earth, if the plume hypothesis fails there, and an alternative mechanism is required for them, it naturally follows that the alternative is a candidate for other LIPs also.

It is not the case that no observations at all are consistent with the plume hypothesis-some are[18]. Nevertheless, many scientists find the predictive power of the classical plume hypothesis unsatisfactory.

## 2 Convection of the kind required to generate classical mantle plumes may be precluded by the physical properties of the mantle

All regions of the mantle probably convect in some way. However, given the physics of the interior of the Earth it is questionable whether convective upwellings from the deep mantle rise to the surface and produce the local volcanic features known as “hot spots”[19]. It is even more questionable whether deep upwellings could produce the regular behaviour of some of these volcanic features, which occurs on spatial scales of the order of kilometers and timescales of the order of millions of years. It has also been pointed out that the hypothesis requires mutually exclusive assumptions-plumes were proposed to be rooted deeper than the convecting upper mantle in order to explain the relative fixity of surface “hot spots”, but a convecting upper mantle is not consistent with relative hotspot fixity[20].

The effect of high pressure on convection in the deep mantle is important. Pressure has a strong, non-linear effect on thermal expansion, conductivity and viscosity. At high pressure, temperature has less effect on density and less buoyancy is imparted to material warmed, for example, by heat transfer from the core. Similarly, thermal conductivity increases with pressure, reducing the tendency for heat to be removed by convection. Viscosity increases by 1—2 orders of magnitude with depth in the mantle, further hindering convection. The effects of pressure on material properties further suggest that the lower mantle may be chemically stratified. Plausible temperature variations in the deep mantle may then cause density variations that are smaller than those across the chemical interfaces, hindering or precluding the rising of warmed material from the deep mantle.

These variations in physical properties within the Earth suggest that, whereas in the upper mantle convective features have characteristic dimensions of hundreds of kilometers and lifetimes of the order of hundreds of millions of years, the deep mantle, in contrast, may convect only slowly and on a vast scale, with timescales of billions of years and spatial scales of thousands of kilometers.

Whole-mantle tomography supports this picture, showing that the lower third of the mantle is characterised by global-scale sized bodies[21]. How should these bodies be interpreted, and are the “superplumes” observed by seismic tomography beneath the south Pacific and the south Atlantic thermal upwellings? Shear velocity is affected by temperature, density, and composition, but is a poor proxy any one of these alone. Temperature and chemical composition affect shear velocity only weakly, especially in the deep mantle, and correlations between velocity and density may be positive or negative[22]. The most recent seismic studies of the “superplumes” suggest that they are probably ancient, slowly-developing structures and may be dense and not buoyant[23]. Thermal plumes of the sort postulated to fuel surface "hot spots" must almost certainly rise from a thermal boundary layer clearly visible seismically, and given the physical properties of the very deep mantle it would seem that such a layer would have to lie higher up. However, the major seismic discontinuities are known to result from mineralogical phase changes, not temperature or composition changes. There is no evidence for strong thermal boundary layers anywhere in the Earth except at the surface and the core-mantle boundary.

This view is not at odds with the requirement to get heat out of the core in order to power the dynamo. The lowermost mantle heats up only slowly and this, coupled with its inferred low thermal buoyancy, results in large sluggish upwellings that carry away any heat not conducted or radiated away. It does not follow that classical mantle plumes of the sort proposed by Morgan[3] exist or that the upwellings cause the surface features popularly assigned to plumes. It has been suggested further that heat loss from the core may have been overestimated, and much of the heat lost from the surface of the Earth may be radiogenically generated in the mid- and upper mantle[24]. McKenzie & Weiss[20] have also pointed out that the plume mode of convection is inconsistent with the behaviour of an internally heated fluid, which is expected, on the contrary, to exhibit narrow downwellings and diffuse upwellings.

No laboratory, and few numerical demonstrations of plume-mode convection model the Earth realistically and many do not include all of the critical factors described above. The laboratory convection models that were influential in popularising the plume model in the early 1990s[25] involved injecting low-density fluids into tanks containing higher-density fluid. The plumes produced were not self-sustaining, and the apparatus did not simulate the effects of pressure within the Earth. The future development of numerical convection models that include the effects of temperature and pressure on all the relevant physical properties, along with the variation in thermal expansivity and increase in conductivity and viscosity with depth in the mantle, will be of great interest.

In summary, it is not disputed that some form of convection probably occurs at all levels in the mantle. What is questioned is that the mantle can produce coherent, narrow convective structures that traverse its entire thickness and deliver samples of the core-mantle boundary layer to the Earth's surface. If the thermal plumes postulated to feed "hot spots" do not rise from the only strong thermal boundary layer known to exist in the interior of the Earth, it is then not clear whence they can rise. The conclusion that such thermal plumes possibly may not occur at all in the Earth then becomes a natural corollary.

## 3 The contemporary plume hypothesis is so flexible that it cannot be disproved

I make the distinction between the original, classical plume hypothesis and its modern, contemporary form. A plume is a well-defined term in fluid dynamics, and Morgan's original meaning was clear[3]. However, subsequently the term "mantle plume" has been applied to such a diversity of phenomena that in many cases it signifies little more than whatever lies beneath a volcanic area[26]. In practice, it has become the case that no observation or absence thereof is considered sufficient to disprove the hypothesis.

Plumes have been suggested to come from almost any depth, including the core-mantle boundary, chemical discontinuities in the lower mantle, the tops of the lower-mantle "superplumes", the mineralogical phase-change boundaries at 410 and 650 km depth, the base of the lithosphere or from arbitrary levels in the mantle[20,27]. They have been suggested to be vertical or to tilt, and for some "hot spots" multiple papers suggest different tilts. For example, the postulated Iceland plume has been variously suggested to tilt to the west[28], south[29] and southeast[30]. Some melting anomalies are very localised, e.g., Hawaii. Nevertheless, scattered volcanic production has been explained by lateral flow for distances of up to thousands of kilometres, e.g., at Iceland[31] or multiple plumes in close proximity e.g., in the Azores region. Different authors have varying perceptions of the width of mantle plumes. Widths of the order of 1000 kilometres have been assigned to plumes on the basis of seismic tomography experiments[32] but single volcanoes only a few kilometres in diameter have been suggested to represent the plume centre at "hot spots" such as Iceland, Hawaii and Yellowstone. Stable or unstable flow on all timescales is considered plausible. Volcanic production at Hawaii has increased by an order of magnitude during the last 5 Ma. Cyclic pulsing behaviour in a plume beneath Iceland has been suggested to account for diachronous bathymetric ridges to the south and north of Iceland[33]. The measurement of ages of 120 Ma and 90 Ma for lavas from the Ontong Java plateau led to the suggestion that this LIP resulted from a two-headed plume[34], but the recent demonstration that the latter ages were in error[35] led to a return to a single-headed plume model.

Relative fixity was one of the original, fundamental properties attributed to mantle plumes, but the subsequent discovery that this did not occur for many pairs of "hot spots" was not considered to be an impediment, but explained by deflection by convection currents in the mantle ("mantle wind"), lateral flow, or "plume capture" by ridges. For example, the Hawaiian "hot spot" is interpreted to have migrated south by ~ 800 km with respect to the Earth's magnetic pole between emplacement of the oldest Emperor seamount (the Detroit seamount, 75.8 Ma) and the Hawaiian-Emperor bend at 47 Ma[36]. Some, but not all of this has been explained as deflection by flow in the mantle. The persistence of the Iceland melting anomaly at the mid-Atlantic ridge has been attributed to lateral flow from a plume centre further west, beneath Greenland or the Greenland-Iceland-Faeroe ridge[37].

The postulated longevity of plumes varies from about 80 Ma (e.g., Hawaii) to only a few Ma, e.g., the Caroline chain in the Pacific ocean. The plume head-tail model, which arose from laboratory convection experiments, has been applied to some melting anomalies e.g., the Deccan Traps—Laccadive-Chagos ridge-Reunion system, which appears to fit the model well. Many LIPs without chains, and chains without LIPs, have also been attributed to plumes, however. In addition, the predicted precursory kilometre-scale uplift is observed at some localities[18] but not at others[17]. Recently it has even been suggested that simple domal uplift accompanying the arrival of a plume head at the base of the lithosphere is not required[38].

The discovery in the early 1970s that geochemistry different from that of MORB characterized "hot spots" and island and seamount chains[39] was attributed to plumes tapping a chemically distinct source. Nevertheless, the discovery that many "hot spot" lavas have compositions that overlap with MORB was explained by entrainment of upper-mantle MORB source into plumes. The discovery that high maximum $^3$He/$^4$He ratios occur at Hawaii led to the suggestion that the lower mantle plume source is high in primordial $^3$He. However, the failure to find basalts with high $^3$He/$^4$He ratios at some "hot spots" e.g., Tristan da Cunha, was explained as contamination by helium high in radiogenic $^4$He of crustal origin, or incomplete sampling Petrology and other methods have also been applied to seek evidence for locally elevated temperature beneath "hot spots". Evidence has been cited from a small subset of currently proposed plume localities, but its lack at others is explained by incomplete sampling or fundamental inaccessibility of the expected rocks.

Few scientists would continue to defend the classical plume hypothesis in its pure, original form, just as few are ready to abandon the model altogether. It is reasonable that an original hypothesis evolves and is amended as new data accumulate. Nevertheless, all scientific hypotheses must remain fundamentally disprovable, or they cease to be hypotheses and become a priori assumptions. If wrong, they may then prevent further progress. Many feel that the plume hypothesis has become, in practice and in its contemporary flexible form, not disprovable[26]. A clear definition of a plume agreed upon by all is a necessary prerequisite for focused discussion of whether they exist or not and if meaningful tests are to be designed and performed.

## 4 Alternative models are viable

Much work on melting anomalies has focused on adapting the plume hypothesis to account for new observations, but relatively little has been done on developing alternative models. As a consequence, many have remained qualitative only. Quantification of alternative theories is a new and rapidly developing subject. Models include:

### 4.1 EDGE convection

When continents split, linear volcanic margins generally form, followed by anomalous magmatism in some parts of the new ocean, e.g. the north Atlantic. The theory of EDGE convection is based on the observation that where thick, cold continental lithosphere is juxtaposed against hot, oceanic asthenosphere, small-scale convection may develop at the continental edge and cause vigorous, time-dependent magmatism[40].

### 4.2 Plate-tectonic processes

Ocean-island basalt geochemistry has long been linked to subducting slabs, including the crustal and mantle lithosphere sections. Furthermore, fusible materials such as these are required to account for the relatively large volume of eruptives that is the primary feature of all melting anomalies. The deep-mantle plume hypothesis requires that this fusible material is transported to the core-mantle boundary and back again. The plate-tectonic processes model (also called "the plate model") suggests that it is instead circulated at much shallower depths. The model suggests that "anomalous" volcanism occurs where plates are in extension, either in their interiors or near their boundaries, and that the volume of magma produced is a function of the fertility and fusibility of the source material being tapped. If old subducted slab material in the shallow mantle is tapped, volcanism will have ocean-island basalt geochemistry and be more voluminous than if mantle peridotite only is available in the source region[41].

### 4.3 Melt focusing

It is relatively common for melting anomalies to lie at complicated tectonic junctions such as ridge-ridge-ridge triple junctions, ridge-transform intersections and microplates, e.g., the Azores, the Bouvet triple junction, the Easter microplate and at Iceland. Melt focusing has long been assumed to occur beneath mid-ocean ridges, within a two-dimensional region triangular in cross section perpendicular to the ridge. Quantitative modeling predicts three-dimensional focusing of melt from a cone-shaped region beneath some plate boundary junctions e.g, ridge-transform and ridge-ridge-ridge triple junctions, increasing the amount of melt expected[42, 43].

### 4.4 Large-scale melt ponding

Numerical modeling has been unable to simulate the vast melt volumes and eruption rates associated with large LIPs such as the Ontong Java Plateau, even if a fusible source is assumed[44]. It seems inevitable that if the volumes and rates have been correctly estimated, the melt must have formed over a longer period than the eruption time. This suggests that large-volume ponding might be possible, despite the usual assumption that melt is extracted from its source region as it forms, at a relatively low degree of melting[45]. In support of this, recent work has shown that non-texturally equilibrated rocks may retain melt fractions of up to 11%[46]. Melt might pond at the base of the lithosphere and be retained there if the lower lithosphere were in compression.

### 4.5 Continental lithospheric delamination and slab break-off

In addition to the large eruption rates, the lack of uplift prior to LIP emplacement reported from some localities must be explained[15,16]. Lithospheric delamination can potentially fit the observations for continental LIPs. Delamination can occur if the continental lithosphere becomes thickened, transforms to dense phases such as eclogite, and catastrophically sinks and detaches. Numerical modeling predicts that preliminary surface subsidence is followed by extensive magmatism[47]. An analogous process is slab breakoff, which may rapidly alter the pattern of flow in the mantle in collision zones and lead to bursts of magmatism[48].

### 4.6 Rifting decompression melting

Numerical modelling of the rifting that accompanies continental breakup suggests that the volume, timing and distribution of decompressional melting is related to lithosphere thickness and composition and pre-existing structures. The volumes calculated are sufficient to explain those observed at LIPs and volcanic passive margins, suggesting that plumes are not required to generate these melting anomalies[49].

### 4.7 Meteorite impacts

The possibility that impacts could generate the large volumes of magma observed in LIPs has recently been revisited, since such a mechanism could elegantly explain the very short timescales over which LIP formation is thought to occur. The potential of pressure-release (decompression) melting was overlooked in early modeling and recent work has demonstrated that it is capable of triggering the volumes and rates observed in LIPs[50].

It has been suggested that such diversification of mechanisms amounts to increased model complexity and is thus moving in the wrong direction. However, there is great diversity in the nature of melting anomalies, which vary from small-volume, short-lived, intraplate alkalic chains such as the Caroline Islands to large-volume, long-lived, ridge-centred tholeiitic features such as Iceland. It seems unlikely, given such diversity, that all are caused by the same process. For few if any melting anomalies can it be claimed that any one theory, plume or alternative, fits the observations without residual problems. For this reason it is essential to consider multiple hypotheses and not to assume one model a priori to the exclusion of all others.

## 5 Closing remarks

In this short essay I have attempted to describe why many scientists have recently begun seeking alternative explanations for the origin of “hot spot” magmatism, either for individual localities or in general. It is difficult to adequately convey the atmosphere of excitement and enthusiasm that has gripped the many practitioners who feel that their own work and the subject have been unexpectedly invigorated by the new questions being posed. The explosion of critical, innovative thinking in the field owes its thanks largely to the huge expansion of Earth Science data available, and to the advent of new internet-based data-distribution and communication tools, which have transformed the way we all work. Not least does the new subject owe its thanks to the generous and unselfish mentoring of the many newcomers to the field by the few who kept the torch burning during the long decades when interest was relatively low. The subject has now flowered to a state of enthusiastic global debate. Whatever the outcome, it is this debate that is important; only if theories are criticised and tested will new discoveries and real progress be made.

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## References

1. Foulger, G. R., Sheth, H. C., Anderson, D. L. et al., www.MantlePlumes.org., 2005.
2. Wilson, J. T., A possible origin of the Hawaiian Islands, Canadian Journal of Physics, 1963, 41: 863—870.
3. Morgan, W. J., Convection plumes in the lower mantle, Nature, 1971, 230: 42—43.
4. Anderson, D. L., Natland, J. H., A brief history of the plume hypothesis and its competitors: Concept and controversy, in Plates, Plumes & Paradigms (ed. Foulger, G. R., Natland, J. H., Presnall, D. C.), Geol. Soc. Amer., 2005, Spec. Paper 388, (in press).
5. Campbell, I. H., Griffiths, R. W., Implications of mantle plume structure for the evolution of flood basalts, Earth Planet. Sci. Lett., 1990, 99: 79—93.[DOI]
6. Kellogg, L. H., Wasserburg, G. J., The role of plumes in mantle helium fluxes, Earth Planet. Sci. Lett., 1990, 99: 276—289. [DOI]
7. Sleep, N. H., Hotspot volcanism and mantle plumes, Ann. Rev. Earth Planet. Sci., 1992, 20: 19—43. [DOI]
8. Baksi, A. K., Reevaluation of plate motion models based on hotspot tracks in the Atlantic and Indian Oceans, J Geol., 1999, 107: 13—26.
9. Baksi, A. K., 2004, http://www.mantleplumes.org/ArAr.html.
10. Raymond, C. A., Stock, J. M., Cande, S. C., Fast Paleogene motion of the Pacific hotspots from revised global plate circuit constraints, in History and Dynamics of Plate Motions (eds. Richards, M. A., Gordon, R. G., van der Hilst, R. D.), Geophys. Monogr., 2000, 121: 359—375.
11. Foulger, G. R., Vinnik, L. P., Du, Z., The mantle potential temperature anomaly beneath Iceland is insufficient for a thermal plume,

EOS Trans. AGU, 85, Fall Meet. Suppl., Abstract, 2004, 85: V51B－0569.

12. Vinnik, L. P., Du, Z., Foulger, G. R., Seismic boundaries in the mantle beneath Iceland: a new constraint on temperature, Geophy. J. Int., 2005, 160: 533－538. [DOI]
13. Herzberg, C., How many hotspots are on present-day earth, and are all plumes hot? EOS Trans. AGU, 85, Fall Meet. Suppl., Abstract, 2004, 85: V43G－04.
14. Foulger, G. R., http://www.mantleplumes.org/PlumesOrNot/PlumesOrNotOrals.html, 2004.
15. Ingle, S., Coffin, M. F., Impact origin for the greater Ontong Java Plateau? , Earth Planet. Sci. Lett., 2004, 218: 123－134.
16. Czamanske, G. K., Demise of the Siberian plume: Paleogeographic and paleotectonic reconstruction from the prevolcanic and volcanic records, north-central Siberia, Int. Geol. Rev., 1998, 40: 95－115.
17. Czamanske, G. K., Fedorenko, V. A., http://www.mantleplumes.org/Siberia.html, 2003.
18. He, B., Xu, Y. G., Ching, S. L., et al., Sedimentary evidence for rapid crustal doming prior to the eruption of the Emeishan floods basalts, Earth Planet. Sci. Lett., 2003, 213: 319－405.
19. Anderson, D. L., Simple scaling relations in geodynamics: the role of pressure in mantle convection and plume formation, Chinese Sci. Bull., 2004, 49: 2017－2021. [DOI]
20. McKenzie, D. P., Weiss, N., Speculations on the thermal and tectonic history of the Earth, Geophys. J. R. Astr. Soc., 1975, 42: 131－174.
21. Ritsema, J., van Heijst, H. J., Woodhouse, J. H., Complex shear wave velocity structure imaged beneath Africa and Iceland, Science, 1999, 286: 1925－1928. [DOI]
22. Ishii, M., Tromp, J., Constraining large-scale mantle heterogeneity using mantle and inner-core sensitive normal modes, Phys. Earth Planet. Inter., 2004, 146: 113－124.
23. Trampert, J., Deschamps, F., Resovsky, J. et al., Probabilistic tomography maps chemical heterogeneities throughout the lower mantle, Science, 2004, 306: 853－856. [DOI]
24. Hofmeister, A. M., Criss, R. E., Heat flow and mantle convection in the triaxial Earth, in Plates, Plumes & Paradigms (ed. Foulger, G. R., Natland, J. H., Presnall, D. C. et al.), Geol. Soc. Amer., Spec Paper 388, 2005, (in press).
25. Griffiths, R. W., Campbell, I. H., Stirring and structure in mantle plumes, Earth Planet. Sci. Lett., 1990, 99: 66－78. [DOI]
26. Foulger, G. R., http://www.mantleplumes.org/DefinitionOfAPlume.html, 2004.
27. Courtillot, V., Davaillie, A., Besse, J. et al., Three distinct types of hotspots in the Earth's mantle, Earth Planet Sci Lett, 2003, 205: 295－308. [DOI]
28. Bijwaard, H., Spakman, W., Tomographic evidence for a narrow whole mantle plume below Iceland, Earth Planet. Sci. Lett., 1999, 166: 121－126. [DOI]
29. Shen, Y., Solomon, S. C., Bjarnason, I. T. et al., Seismic evidence for a tilted mantle plume and north-south mantle flow beneath Iceland, Earth Planet. Sci. Lett., 2002, 197: 261－272. [DOI]
30. Helmberger, D. V., Wen, L., Ding, X., Seismic evidence that the source of the Iceland hotspot lies at the core-mantle boundary, Nature, 1998, 396: 251－255. [DOI]
31. White, R. S., Morton, A. C., The iceland plume and its influence on the evolution of the north Atlantic, J. Geol. Soc., 1995, 152: 933－933.
32. Montelli, R., Nolet, G., Dahlen, F. A. et al., Finite frequency tomography reveals a variety of plumes in the mantle, Science, 2004, 303: 338－343.[DOI]
33. White, R. S., Bown, J. W., Smallwood, J. R., The temperature of the Iceland plume and origin of outward-propagating V-shaped ridges, J. Geol. Soc., 1995, 152: 1039－1045.
34. Tejada, M. L. G., Mahoney, J. J., Castillo, P. R. et al., Pin-pricking the elephant: Evidence on the origin of the Ontong Java Plateau from Pb-Sr-Hf-Nd isotopic characteristics of ODP Leg 192 basalts, in Origin and Evolution of the Ontong Java Plateau (eds. Fitton, G., Mahoney, J., Wallace, P. et al.) , Geol. Soc. Lond, Spec. Publ., 2004, 229: 133－150
35. Fitton, J., G., Mahoney, J. J., Wallace, P. J. et al., Origin and Evolution of the Ontong Java Plateau: Introduction, in Origin and Evolution of the Ontong Java Plateau (eds. Fitton, J., G., Mahoney, J. J., Wallace, P. J. et al.), Geol. Soc. Lond. Spec. Publ., 2004, 229:1－8.
36. Tarduno, J. A., Cottrell, R. D., Paleomagnetic evidence for motion of the Hawaiian hotspot during formation of the Emperor seamounts, Earth Planet. Sci. Lett., 1997, 153: 171－180. [DOI]
37. Vink, G. E., A hotspot model for Iceland and the Voring Plateau, J. Geophys. Res., 1984, 89: 9949－9959.
38. Burov, E., Guillou-Frottier, L., Burov, E. et al., The plume head-continental lithosphere interaction using a tectonically realistic formulation for the lithosphere, Geophys. J. Int., 2005, (in press).
39. Schilling, J. G., Iceland mantle plume, Nature, 1973, 243: 141－143.
40. King, S. D., Anderson, D. L., Edge-driven convection, Earth Planet. Sci. Lett, 1998, 160: 289－296. [DOI]
41. Foulger, G. R., http://www.mantleplumes.org/PTProcesses.html, 2004.
42. Beutel, E. K., Stress induced seamount formation at ridge-transform-intersections, in Plates, Plumes & Paradigms (ed. Foulger, G. R., Natland, J. H., Presnall, D. C. et al.), Geol. Soc. Amer., Spec Paper 388, 2005, (in press).
43. Georgen, J. E., Lin, J., Three-dimensional passive flow and temperature structure beneath oceanic ridge-ridge-ridge triple junctions, Earth Planet. Sci. Lett., 2002, 204: 115－132. [DOI]
44. Cordery, M. J., Davies, G. F., Campbell, I. H., Genesis of flood basalts from eclogite-bearing mantle plumes, J. Geophys. Res., 1997, 102: 20179－20197.[DOI]
45. McKenzie, D., Some remarks on the movement of small melt fractions in the mantle, Earth. Planet. Sci. Lett., 1989, 95: 53－72. [DOI]
46. Cheadle, M. J., Elliott, M. T., McKenzie, D., Percolation threshold and permeability of crystallizing igneous rocks: The importance of textural equilibrium, Geology, 2004, 32: 757－760. [DOI]
47. Elkins-Tanton, L. T., Continental magmatism caused by lithospheric delamination, in Plates, Plumes & Paradigms (ed. Foulger, G. R., Natland, J. H., Presnall, D. C. et al.), Geol. Soc. Amer., Spec Paper, 2005, (in press).
48. Keskin, M., Magma generation by slab steepening and breakoff beneath a subduction-accretion complex: An alternative model for collision-related volcanism in Eastern Anatolia, Turkey, Geophy. Res. Lett., 2003, 30: 8046－8049. [DOI]
49. Corti, G., van Wijk, J. W., Bonini, M.et al., Transition from continental break-up to punctiform seafloor spreading: how fast, symmetric and magmatic, Geophys. Res. Lett., 2003, 30: 1604－1607.[DOI]
50. Jones, A. P., Wunemann, K., Price, D., Impact volcanism as a possible origin for the Ontong Java Plateau (OJP), in Plates, Plumes & Paradigms (ed. Foulger, G. R., Natland, J. H., Presnall, D. C. et al.) , Geol. Soc. Amer., Spec Paper, 2005, (in press).

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