

**PLATE TECTONICS: Lecture 7**

**MANTLE PLUMES: from PLATE TECTONICS to PLATEAU TECTONICS**

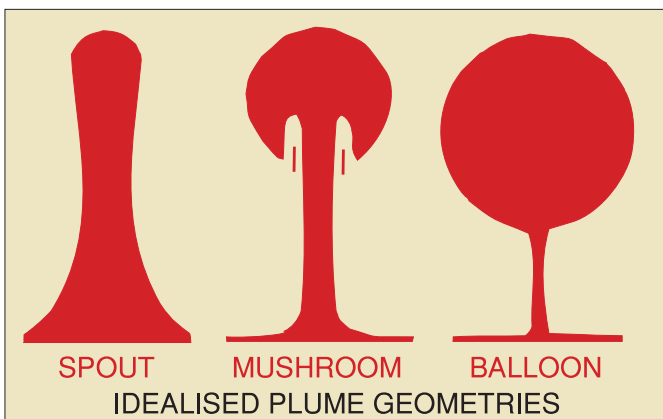
The important question arises: how far back in time did plate tectonic processes operate? Is it just a modern phenomena? Or can we interpret global geology in terms of plate tectonic concepts right back to the early Archaean?

The common markers of plate tectonics are:

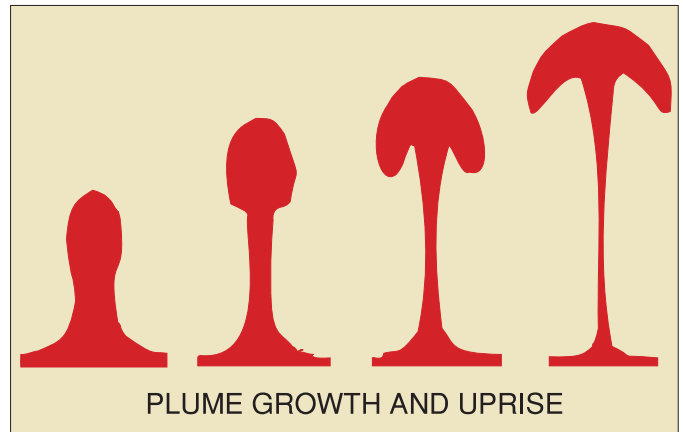
- (1) Ophiolite complexes, that textbooks usually argue represent obducted fragments of ocean floor (though most are probably back-arc basin or young forearc). But these appear to be absent before the latest Proterozoic (ca. 700 Ma)
- (2) Blueschists (with the Na-amphibole glaucophane) are indicative of a high-P, low-T hydrous environment that is only achieved in a subduction zone. Again, these appear to be absent before the latest Proterozoic (ca. 700 Ma).
- (3) Island Arcs (like the Marianas), formed where oceanic plates subduct beneath one another. They are common at the present day, but are much less easy to recognise back in time, particularly in the Precambrian.

So for a majority of geological time (4.0 b.y. to 0.6 b.y.) some of the common markers of plate tectonics are absent. Was the mantle regime too hot to allow preservation of blueschists? Because arcs and back-arcs require a subduction-flip or major change of plate direction to initiate them, perhaps these flips or plate direction changes did not occur, and there was a more regular, small scale pattern of mantle convection in the Precambrian? It has been suggested quite a long time ago (e.g. Fyfe, 1978) that "hot-spot tectonics" may have been more important in the past than "plate tectonics". However this does not mean that one excludes the other, because hotspots (e.g. Iceland, Hawaii) occur at the present day, and it may just mean that one was dominant over the other.

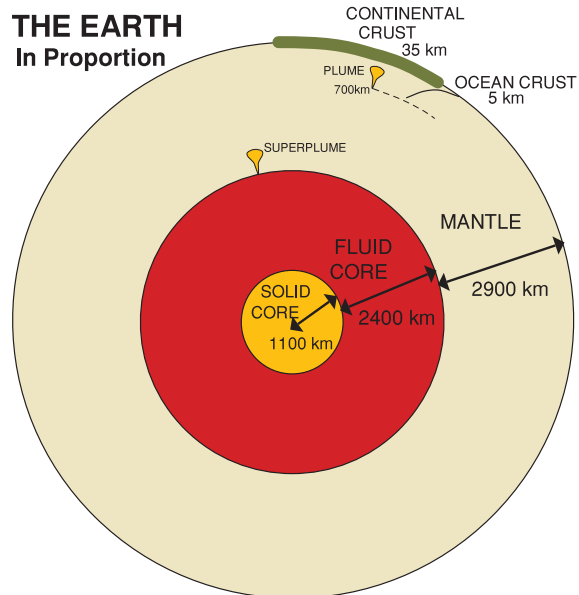
That low-density solid bodies can rise up through other solid material as large diapirs has been long known from observing salt domes. Ramberg did laboratory experiments to simulate this and showed that these would have one of the following forms (of which the mushroom shape is generally regarded as the most probable):



If the low density is due to excess heat, as in the mantle, they are usually referred to as plumes. Note that as plumes rise, a "spout" or "balloon" will eventually turn into a "mushroom" as it entrains the surrounding mantle material:

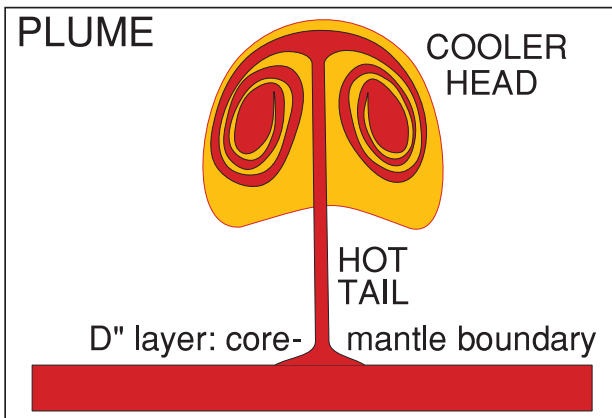


An important feature is that plumes must be initiated at some thermo-mechanical boundary layer within the Earth, for instance at the core – lower-mantle boundary [2900km depth] or at the shallower 700km discontinuity:

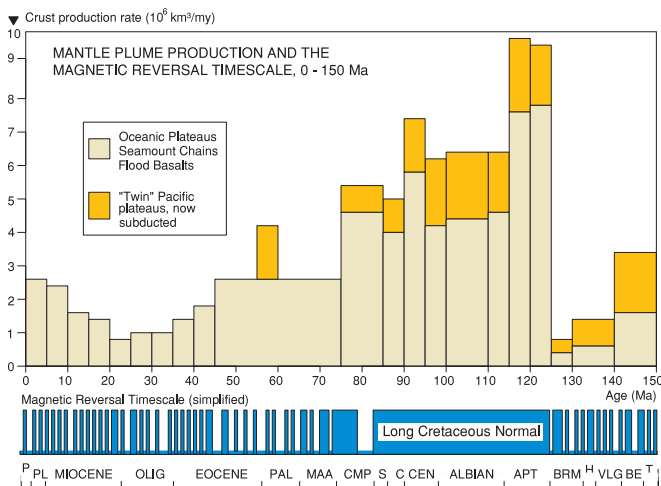


It is at these boundaries where either compositional differences (core-mantle) or phase differences (700km discontinuity) permit denser but hotter material to exist beneath lighter cooler rock, so that any instabilities in the convective patterns across the boundary layer may spawn a hot plume. At initiation, such plumes can be several hundred degrees hotter than the surrounding mantle, and will rise, the excess heat then causing a lowering of the viscosity of the surrounding mantle (or even melting it slightly) so allowing it to be entrained into the mushroom head of the plume. In this way the plume head gradually enlarges itself and becomes cooler (relatively), whereas the tail of the plume is narrower, but hotter, the hot material continually rising up into the head.

These features have been described by Campbell, Griffiths, Hill & Co., and in simplified form can be summarised as follows:



These plume heads can become quite large as they ascend to the surface, and diameters of 500 - 1000 km have been suggested. The question arises: how often are these plumes released? And which discontinuity do they come from? Larson (1991a) showed that there was correlation between the rate of ocean crust production and the magnetic reversal time scale:



This shows that the mafic crust production rate was at a maximum during the Cretaceous magnetic quiet period, between 125 – 80Ma. This leads to 2 important conclusions. First, correlation can only occur if in fact the plume originated at the core-mantle boundary (D" layer), because it is convection in the Earth's core that is responsible for the magnetic field, and hence release of a major plume may have upset core convection (see Larson & Olsen, 1991 for details). Second, this excess crust production could be accounted for almost entirely by that represented by ocean plateaus. These ocean plateaus are regions where the ocean crust is anomalously thick. This reflects the fact that if the energetic mantle plumes rise up beneath the mid-ocean ridges, then all the excess heat is converted into basic magma, and so the ocean crust may be over 15 km thick, compared with ca. 6 km of normal ocean crust. This has two further effects. One is that the plateau may become land, like Iceland, instead of being submerged 2 to 6 km beneath the oceans. A consequence is that the ocean water displaced (sea level rise) then floods the low-lying

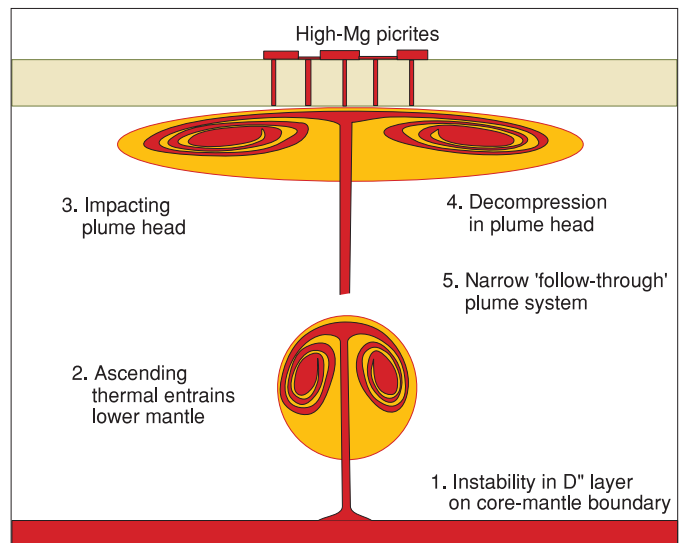
continental margins, so that chalk is deposited in abundance in the shallow warm seas (see Larson, 1991b).

The main body of ocean plateaus are in the Western Pacific (Ontong Java; Manihiki Rise; Hess Rise, etc.) are all about 120 my old, which corresponds with the start of the Cretaceous magnetic quiet period. Note that these are only one half of the plateaus – the other half (that formed over the other side of the mid-ocean ridge) may have been subducted beneath South America. A second phase of plume activity occurred at ca. 87 Ma, and corresponds with the end of the magnetic quiet period. The biggest plume here came through at the Galapagos hotspot in the eastern Pacific, and bits of it are found scattered around the Caribbean (see below). Note that the Iceland plume started at 60 Ma. Now this may indicate that large plumes are perhaps more frequent than had been thought. Could they occur far back in time? Is their release periodic or cyclic, or infrequent? Do they get more common as we go back in time? How could we recognise them? They do represent a big pulse of energy transferred from the outer core to the Earth's surface, so they should have associated features. For instance, the large phase of diamond-bearing kimberlite pipes occurs around 120Ma, and the phase of global warming occurred then (see Larson, 1991b).

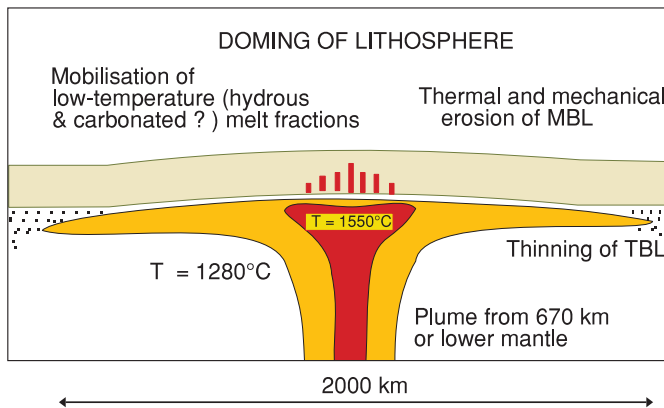
Large Igneous Provinces

What happens when plumes – after ascending almost 2900 kms vertically – approach the surface? Whether they can break through will depend on the thickness of the mechanical boundary layer (MBL), or lithosphere. The MBL is thin at ocean ridges, so plumes can easily break through, and the energy converted to extensive melting and formation of an ocean plateau. Note that the ridge and plume-hotspot cannot stay together for long because ridges are always moving and hotspots are fixed. So eventually plateaus must end up as ocean island chains (e.g. Hawaiian chain), as the hotspot keeps burning through the plate.

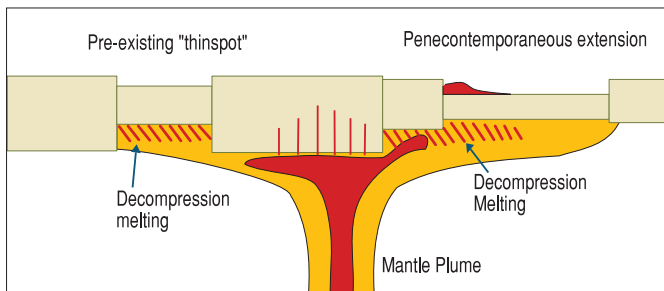
However, if the plume rises beneath thick lithosphere, then it cannot easily break through, and must spread out beneath the lithosphere in the manner shown (after ADS):



It may "incubate" here for some time, perhaps causing extensive melting of the base of the lithosphere, and interactions between plume and lithosphere. If there is enough extension during this time, then the magmas may be poured out as continental flood basalts (examples: Deccan - India, Karoo - S. Africa; Ferrar - Antarctica; and many more. Most of these large igneous provinces erupt vast amounts of basalt, apparently in quite a short time (ca. 1 or 2 m.y.), so it may only be the more vigorous plumes that get through in this way. The diagram below shows how lithosphere is domed as the plume spreads out to a diameter of over 1000 km, and then as the plume melts away at the base of the lithosphere, the magmas get through:

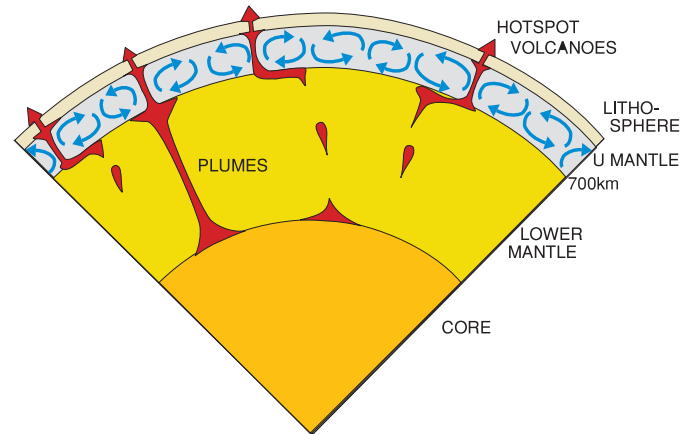


In other cases, the plume may search out weak zones or "thin spots". A good example of this may be the British Tertiary Volcanic Province, which was initiated 60Ma ago when the Iceland plume started, but was over within a few m.y. In this case the "thin spot" extended all the way from Iceland, through NW Scotland, to Lundy in the Bristol Channel. The diagram below shows how uprising plumes may be channeled along thinspots and eventually break through:



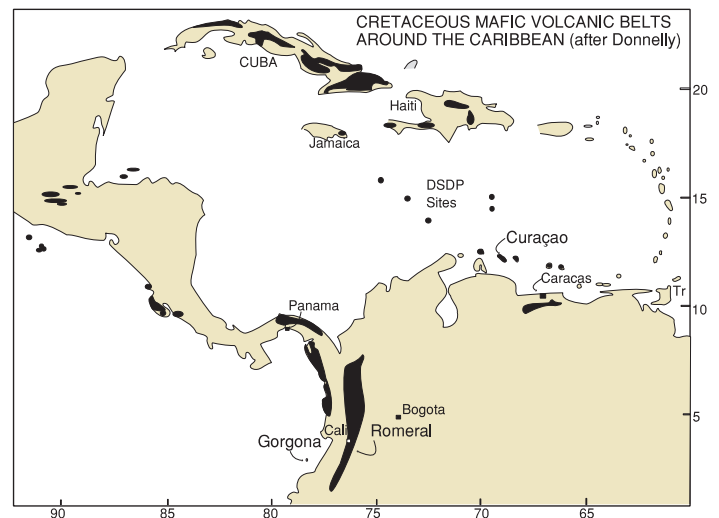
Note that the British Tertiary Province is characterised by some quite high-Mg magma compositions (perhaps as high as 22% MgO), particularly on Rhum and on Skye. Such high-Mg composition usually mean high degrees of mantle melting, which in turn requires a lot of thermal energy that can really only be attained by rapid uprise of vigorous plumes from depth. These high temperature magmas have the excess thermal energy that can initiate melting of upper crustal rocks, or lower crustal rocks, or lithosphere. So maybe that is why quite a lot of granite magma (e.g. Red Hills, Skye; Northern Granite, Arran) appears within a m.y. or two of the emplacement of the high-temperature mafic magmas.

Now not all hot-spots have high temperature Mg-rich magmas. Some have very different trace element compositions from Iceland or Hawaii lavas. One possibility for this is that deep mantle plumes don't always rise straight up to the surface at a ridge system. If instead they rise up beneath a down-going convection cell in the upper mantle, then they may be directed sideways and interact with material stored at the 700km discontinuity (the Ringwood "megalith" layer in Lecture 1), and much of their energy may be consumed in mobilising this material, which would then rise up to form a less energetic plume under an ocean island rather than a plateau:

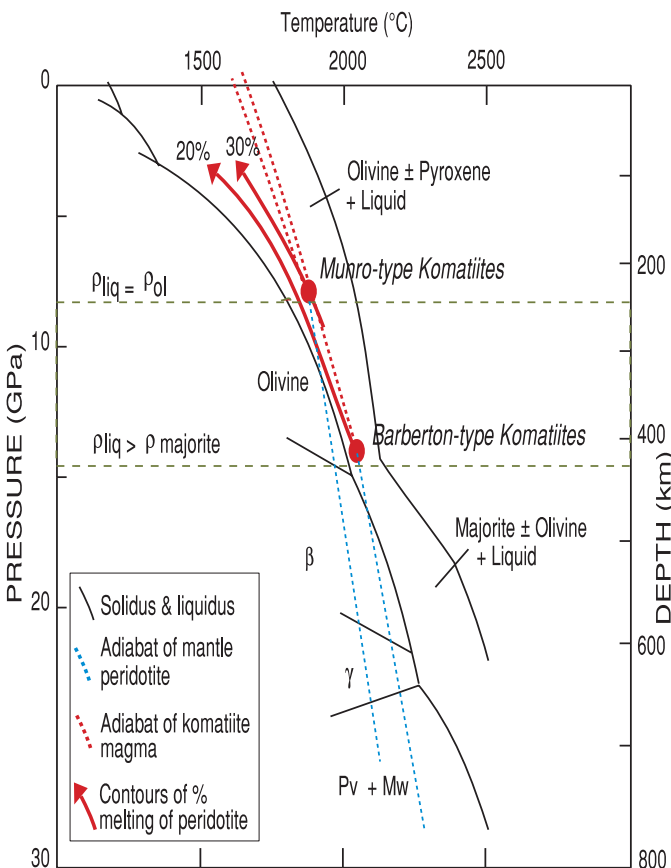


**Komatiites and Precambrian Greenstone Belts**

Komatiites are very high temperature lavas with MgO contents up to 33%. Uprise from great depths is the easiest way to achieve such high liquid temperatures. Now it used to be thought that such high temperatures (>1600°C) could only be achieved in the mantle of the early Earth (Archaean). However, the discovery of komatiitic lavas on the small island of Gorgona, off Colombia, at Romeral in the Coca belt of Colombia, and equivalent picrites on Curaçao in the Caribbean (see below), all in a Cretaceous lava pile, shows that it is not Precambrian mantle that was especially hot, but that the explanation lies in vigorous ascending deep mantle plumes. So instead it may be that Precambrian greenstone belts actually represent the uprise of Precambrian plumes.



Now the Colombian/Caribbean occurrences actually illustrate another aspect of plumes very well. First there is a lot of mafic material scattered around the Caribbean (shown in black): All of this mafic material seems to have an age of 87Ma and formed at the Galapagos hotspot at this time. Now whereas most ocean crust of this age has subducted beneath the Andes, it is clear that this plateau was too hot to subduct, and instead was obducted onto the continental margin of Colombia, etc. Could this mean that Precambrian greenstone belts are just obducted ocean plateaus? For those interested, the most recent (1992) mantle phase diagram illustrating the P-T conditions for uprising deep mantle plumes is shown below:



The blue dashed lines show the paths of uprising diapirs. Once they cross the solidus curve, melting will occur. As melting mantle minerals (with a high latent heat of fusion) absorbs energy, the melting curves for 30% and 20% melting follows the red line paths, to lower temperatures. To some extent the chemistry of the komatiitic liquids is governed by the nature of the residual mantle minerals (olivine or majorite) - hence the two paths shown. In any case it can be seen that even higher degrees of melting than 30% would generate even higher temperature liquids by the time they reached the surface.

**Precambrian Plate Tectonics?**

Because komatiites are common in Archaean (>2.5 Ga) or early Proterozoic (ca. 2.1 Ga) greenstone belts, it could be argued either that the mantle was hotter in the Precambrian (Burke & Kidd, 1978), or that deep mantle plumes (forming plateaus that are now

greenstone belts) were more important in Precambrian tectonics than was plate tectonics (Storey et al. 1991). Arndt (1983) wanted there to be a hot thin komatiitic ocean crust in the Archaean (which would not necessarily have produced much slab-pull). Hargreaves (1986) argued that more heat would mean more ridges in the Archaean, and therefore smaller plates; this also would not mean so much slab-pull. See also Nisbet & Fowler (1983) and Fyfe (1978). So there is a general consensus that without the slab-pull that is so important in modern plate tectonics, there may not have been plate tectonics as such (although there may have been subduction).

Another important argument is that if plateaus are hot and difficult to subduct to depths of 700km, they may just underplate the continents. In which case there is more opportunity for them to heat up later and melt, possibly giving rise to voluminous tonalitic granitoids that are common in the early Precambrian. It is possible that this is the explanation for the 70 km thick crustal keel under the Andes: was this just Pacific ocean plateau?

**References** (these cover many different aspects of plumes)

AITKEN, B.G. & ECHEVERRIA, L.M. 1984. Petrology and geochemistry of komatiites and tholeiites from Gorgana Island, Colombia. *Contributions to Mineralogy and Petrology* **86**, 94-105.

ANDERSON, D.L., TANIMOTO, T. & ZHANG, Y-S. 1992. Plate tectonics and hotspots: the third dimension. *Science* **256**, 1645-1651.

ARNDT, N.T. 1977. Ultrabasic magma and high-degree melting of the mantle. *Contributions to Mineralogy and Petrology* **64**, 205-221.

ARNDT, N.T. 1983. Role of a thin, komatiite-rich oceanic crust in the Archean plate-tectonic process. *Geology* **11**, 372-375.

BERCOVICI, D. & MAHONEY, J. 1994. Double flood basalts and plume head separation at the 660-kilometer discontinuity. *Science* **266**, 1367-1369.

BURKE, K. & KIDD, W.S.F. 1978. Were Archean continental geothermal gradients much steeper than those of today? *Nature* **272**, 240-241.

CAMPBELL, I.H. & GRIFFITHS, R.W. 1990. Implications of mantle plume structure for the evolution of flood basalts. *Earth and Planetary Science Letters* **99**, 79-93.

CAMPBELL, I.H., GRIFFITHS, R.W. & HILL, R.I. 1989. Melting in an Archaean mantle plume: heads it's basalts, tails it's komatiites. *Nature* **339**, 697-699.

COFFIN, M.F. & ELDHOLM, O. 1993. Scratching the surface: Estimating dimensions of large igneous provinces. *Geology* **21**, 515-518.

DAVIES, G.F. 1992. On the emergence of plate tectonics. *Geology* **20**, 963-966.

DAVIES, G.F. & RICHARDS, M.A. 1992. Mantle convection. *Journal of Geology* **100**, 151-206.

DUNCAN, R.A. & RICHARDS, M.A. 1991. Hotspots, mantle plumes, flood basalts and true polar wander. *Reviews of Geophysics* **29**, 31-50.

FYFE, W.S. 1978. Evolution of the Earth's crust: modern plate tectonics to ancient hot-spot tectonics? *Chemical Geology* **23**, 89-114.

GRIFFITHS, R.W. & CAMPBELL, I.H. 1990. Stirring and structure in mantle starting plumes. *Earth and Planetary Science Letters* **99**, 66-78.

- GRIFFITHS, R.W. & CAMPBELL, I.H. 1991. Interaction of mantle plume heads with the Earth's surface, and onset of small-scale convection. *Journal of Geophysical Research* **96**, 18295-18310.
- HARGRAVES, R.B. 1986. Faster spreading or greater ridge length in the Archean? *Geology* **14**, 750-752.
- HILL, R.I. 1991. Starting plumes and continental break-up. *Earth and Planetary Science Letters* **104**, 398-416
- HILL, R.I., CAMPBELL, I.H., DAVIES, G.F. & GRIFFITHS, R.W. 1992. Mantle plumes and continental tectonics. *Science* **256**, 186-193.
- KENT, R.W. 1991. Lithospheric uplift in eastern Gondwana: Evidence for a long-lived mantle plume system? *Geology* **19**, 19-23.
- KERR, A.C., SAUNDERS, A.D., TARNEY, J., BERRY, N.H. & HARDS, V.L. 1995. Depleted mantle-plume geochemical signatures: no paradox for plume theories. *Geology* **23**, 843-846.
- KUSKY, T.M. & KIDD, W.S.F. 1990. Remnants of an Archean oceanic plateau, Belingwe greenstone belt, Zimbabwe. *Geology* **43**, 43-46.
- LARSON, R.L. 1991. Latest pulse of Earth: Evidence for a mid-Cretaceous superplume. *Geology* **19**, 547-550.
- LARSON, R.L. 1991. Geological consequences of superplumes. *Geology* **19**, 963-966.
- LARSON, R.L. & OLSON, P. 1991. Mantle plumes control magnetic reversal frequency. *Earth and Planetary Science Letters* **107**, 437-447.
- LARSON, R.L. & KINCAID, C. 1996. Onset of mid-Cretaceous volcanism by elevation of the 670 km thermal boundary layer. *Geology* **24**, 551-554.
- NISBET, E.G. & FOWLER, C.M.R. 1983. Model for Archean plate tectonics. *Geology* **11**, 376-379.
- SAUNDERS, A.D., TARNEY, J., KERR, A.C. & KENT, R.W. 1996. The formation and fate of large oceanic igneous provinces. *Lithos* **37**, 81-95.
- STOREY, M., MAHONEY, J.J., KROENKE, L.W. & SAUNDERS, A.D. 1991. Are oceanic plateaus sites of komatiite formation? *Geology* **19**, 376-379.
- THOMPSON, R.N. & GIBSON, S.A. 1991. Sub-continental mantle plumes, hotspots, and pre-existing thinspots. *Journal of the Geological Society, London* **148**, 973-977.
- WHITE, R. & MCKENZIE, D. 1989. Magmatism at rift zones: the generation of volcanic continental margins and flood basalts. *Journal of Geophysical Research* **94**, 7685-7729.
- YAMAJI, A. 1992. Periodic hotspot distribution and small-scale convection in the upper mantle. *Earth and Planetary Science Letters* **109**, 107-116.