

Deep plumes, kimberlites and diamonds – a peep inside the earth through time

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Diamonds are formed at great depths, in excess of 150 km within the earth, and are transported to the surface by a type of potassic volcanic rock known as kimberlite. Conventionally, it is argued that the bulk of the diamonds had formed during the Archaean and Palaeoproterozoic times (~3300–2000 m.y. ago) and resided deep within the continental lithospheric roots. However, their ascent to the surface of the earth through kimberlite volcanic eruptions was a much later episode.

In the 15 July issue of *Nature*, Torsvik *et al.*¹ have attempted to understand the global distribution of most of the preserved kimberlites of the Phanerozoic (30–540 m.y. ago with a focus on eruptions during 65–200 m.y. ago) and the associated causal mechanism. Their plate reconstructions with constraints from palaeomagnetism² when integrated with seismic tomographic results of the deepest part of the lower mantle³, close to the

core–mantle boundary (CMB), reveal that at least since the past 200 m.y. or possibly even up to the earliest Phanerozoic (~540 m.y.), the diamond-bearing kimberlite rocks distributed globally can be linked to two distinct plume-generation zones (PGZs) close to CMB beneath Africa and the Pacific. Interestingly, these PGZs are also close to the edges on CMB of two hot and dense large low-shear-wave-velocity provinces (LLSVPs) as reflected from the seismic tomography³. Although the origin of LLSVPs is not yet fully understood, it has been proposed by Torsvik *et al.*¹ that they can be used as ‘fixed markers’ of absolute palaeolongitude in the mantle. The high-resolution reconstructions of palaeo locations of large igneous provinces (LIPs) and kimberlites that erupted during 70–250 m.y. clearly show their strong association with the current LLSVPs, to suggest that such stark deep mantle anomalies have remained stable since

then. Such an inference can also possibly be extended to the earliest Phanerozoic kimberlites (~540 m.y.) to envisage the control of LLSVPs in most Cambrian kimberlite eruptions. Further, these authors suggest that their results can act as a guide to strategize future diamond exploration programmes.

On the contrary, as pointed out by Evans⁴, the palaeogeographic reconstructions of large igneous provinces, kimberlites and their linkages to LLSVPs for ages greater than 200 m.y. put forth by Torsvik *et al.*¹ are not sufficiently strong (for example, Permo-Triassic Siberian traps). Therefore, yet another plausible interpretation for the origin of LLSVPs is put forth⁴. LLSVPs perhaps are associated with the recent supercontinent, Pangaea, and might have been generated about 200 m.y. ago, synchronous with the eruption of the ‘preserved kimberlites’ and large igneous provinces. Evans⁴ further proposes that ‘the global

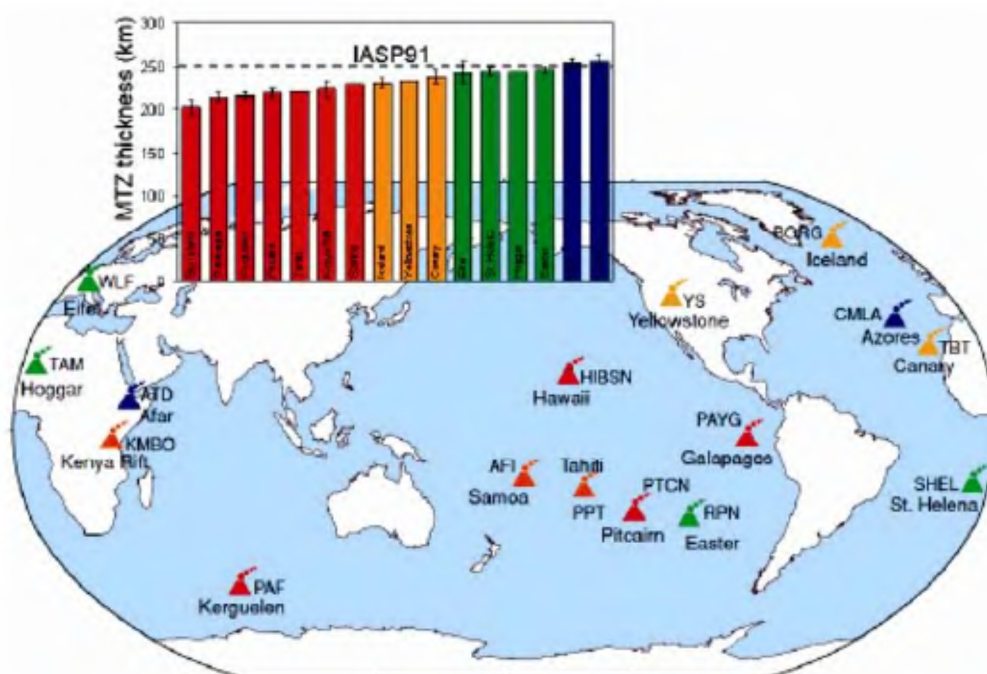


Figure 1. Seismic station and hotspot location map. Green triangles are hotspots with smaller buoyancy flux ($B \leq 1$) and associated with marginal mantle transition zone (MTZ) thickness. Progressive MTZ thinning by way of anomalous MTZ thickness is represented by various grades of hot colours (yellow through orange to red) that increase with increasing flux (see inset). Blue triangles are outliers¹⁵.

convection system breaks its engagement with the ring of plume generation zones every 500 million years or so, through each supercontinental cycle⁵.

Notwithstanding the above diverse hypotheses on the origin of LLSVPs, it is remarkable to note that they play host to at least 12 hotspots sourced by deep plumes based on the recent finite-frequency tomographic results⁵.

The above two stated hypotheses proposed on LLSVPs either as 'fixed markers' of absolute palaeolongitude in the mantle¹ or their disruption during each supercontinental cycle of about 500 m.y. (ref. 4) remain a subject of active future research. However, the ongoing debate on the depth origin of mantle plumes either as shallow upper mantle fertile blobs^{6–9} or from the deep lower mantle^{5,10–14} is getting better resolved with the present findings of Torsvik *et al.*¹.

In the above context, we wish to reiterate our recent work on global hotspots where the depth of origin of mantle plumes is addressed through integration of geophysical results¹⁵ and $^{230}\text{Th}/^{238}\text{U}$ disequilibria data¹¹ from various ocean island basalts, with the strength of the plumes measured as buoyancy flux, B . We test our results on plumes classified by us as having deep-mantle origin (i.e. those originating below the mantle transition zone (MTZ) depths) by plotting their locations on the globe to verify how many of these correlate with LLSVP margins beneath Africa and the Pacific.

For the benefit of the readers to comprehend our results better, we present an outline of our approach and results. The basic premise of our work is to register the movements of 410 and 660 km seismic discontinuities in response to excess thermal anomalies associated with mantle plumes. The transition of α to β phase of olivine with positive dP/dT (ref. 16) results in downward movement of the 410 km seismic boundary, whereas breakdown of γ -olivine to perovskite and magnesiowüstite with negative dP/dT (ref. 17) causes upward movement of the 660 km discontinuity. Thus if the plumes originate in the lower mantle, the thickness of MTZs near the hotspot locations should shrink. The extent of shrinkage of MTZ is dictated by the thermal anomaly associated with the plume under consideration.

Using P -to- S -converted seismic waves from the 410 and 660 km depth disconti-

nities (P410s and P660s), we studied disposition of these boundaries beneath prominent oceanic hotspot regions distributed on the globe (Figure 1). The thickness of MTZ, measured as P660s to P410s differential times (t_{MTZ}), is deter-

mined. We find that the strength of the plume taken on logarithmic scale ($\log B$) bears a linear correlation with MTZ thickness¹⁵. Out of 16 hotspots analysed by us, 10 exhibited moderate to extreme shrinkage of MTZ compared to the

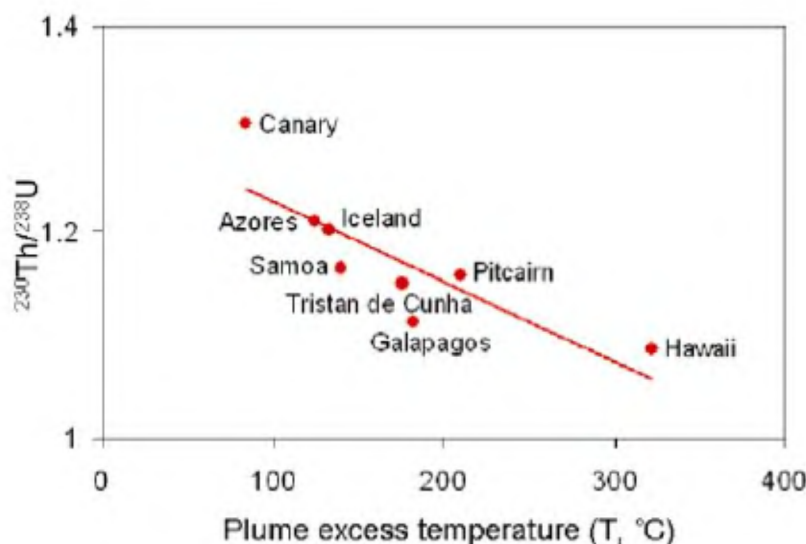


Figure 2. Plot integrating plume excess temperature obtained from geophysical parameter t_{MTZ} (ref. 15) with isotopic parameter $^{230}\text{Th}/^{238}\text{U}$ (ref. 11) showing good correlation. Plume excess temperatures for hotspots Azores and Tristan de Cunha are taken from Putirka¹⁴.

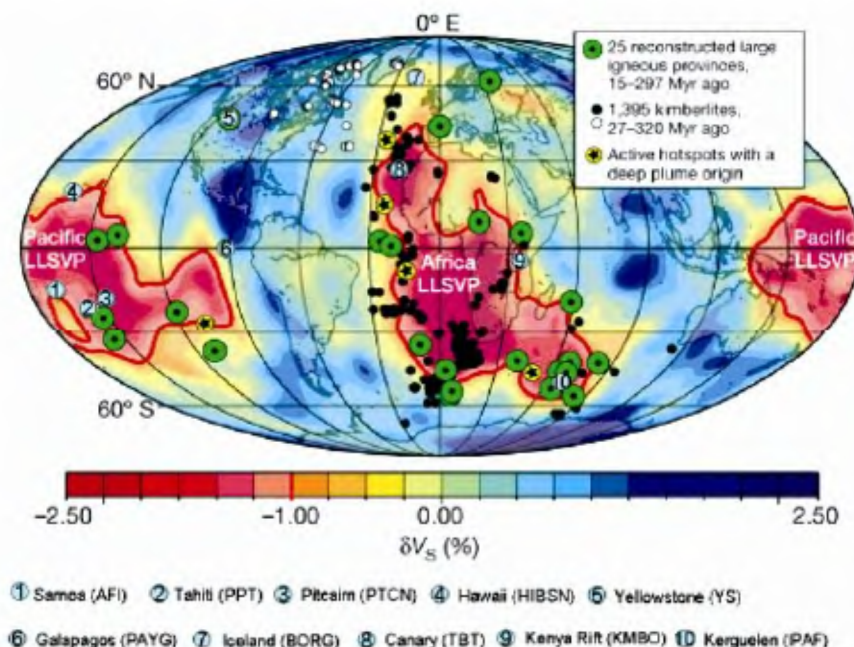


Figure 3. Map showing reconstruction of large igneous provinces and kimberlites for the past 320 m.y. with respect to two distinct hot and dense large low-shear-wave-velocity provinces (LLSVPs) beneath Africa and the Pacific. Present-day positions of continents along with 10 hotspots (numbered 1–10) that are designated as lower-mantle origin in our study are shown¹⁵ (inset, Figure 1). Five hotspots marked as yellow circles with black asterisks inside are also of deep plume origin⁵ (adapted and presented with permission from Macmillan Publishers Ltd [*Nature*]¹).

normal global average thickness of 250 km (inset, Figure 1). Excursions induced to MTZ thickness were used to estimate the excess temperatures beneath the hotspots using the concept of effective seismological Clapeyron slope. These plume excess temperatures and their relationship with the available U-series disequilibria¹¹ were correlated (Figure 2).

Ten hotspots designated as yellow through orange to red triangles in Figure 1, that signify moderate to extreme shrinkage of MTZ, which share a depth origin within the lower mantle are plotted on Figure 3 (Figure 3 has been adapted from figure 1 of Torsvik *et al.*¹). We find that remarkably 9 out of 10 hotspots fall within the two LLSVPs delineated beneath Africa and the Pacific that approximate the designated two distinct plume generation zones (PGZs). The Yellowstone hotspot, which according to our analysis is characterized as lower mantle origin, however, falls outside the contours of the designated LLSVPs. Interestingly, the Columbia River basalt LIP related to the Yellowstone hotspot is shown to be associated with the edge on CMB of a smaller LLVSP (see figure S6 of Torsvik *et al.*¹). It is pertinent to mention that some hotspots that exhibit near-normal to marginally low MTZ thickness compared to the global average of ~250 km, may possibly qualify as low heat budget hotspots or relatively small-sized hotspots, or both. It is also possible that the observed MTZ response beneath such hotspots relates to the waning stage

of hotspot activity, well past their energetic phase.

Spatial correlation of LLSVPs/PGZs and hotspots of deep mantle origin identified through receiver functions by us¹⁵ and those imaged by Montelli *et al.*⁵ is significant as it corroborates the fact that many ocean island hotspots are indeed seismologically detectable and are associated with shrinkage of MTZ related to plume excess temperatures in the range of 100–300°C (Figure 2). Hence the idea of hotter sources for hotspots as also demonstrated independently from geochemistry of the basalts of ocean plateaus¹⁸ fits well both with our study and PGZs on CMB proposed by Torsvik *et al.*¹. This therefore confirms that these hotspots do originate in the lower mantle.

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ACKNOWLEDGEMENTS. We thank Prof. Kevin Burke, University of Houston for a painstaking review of the draft version that led to significant improvements in the manuscript. We also thank Prof. C. Leelanandam for his keen interest in our research.

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