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Plume Generation Zones at the margins of Large Low Shear Velocity Provinces on the core–mantle boundary

Kevin Burke [a,b], Bernhard Steinberger [c,*], Trond H. Torsvik [c,1], Mark A. Smethurst [c]

[a] *Department of Geosciences, University of Houston, 312 S&R1 Houston Tx 77204-5007, USA*
[b] *School of Geosciences, University of Witwatersrand, WITS 2050, South Africa*
[c] *Centre for Geodynamics, Geological Survey of Norway, Leiv Eirikssons vei 39, N-7491 Trondheim, Norway*

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Abstract

Large Igneous Province (LIP) eruption sites of the past 300 My lie vertically above 1% slow shear wave velocity (V_s) contours bounding the African and Pacific Large Low Shear Velocity Provinces (LLSVPs) at the core–mantle boundary (CMB), or in the cases of the Siberian and Columbia River LIPs, bounding one or other of two smaller, Low Shear Velocity Provinces (LSVPs). Steep gradients in V_s at the CMB coincide with those 1% slow contours. The sites of 24 active hotspot volcanoes project down to the same narrowly defined borders of the LLSVPs at the CMB. Plumes that have generated LIPs and major hotspot volcanoes have risen only from the immediate neighbourhoods of the 1% slow V_s contours at the CMB which thus define Plume Generation Zones (PGZs). PGZs projected vertically upward approximately match the +10 m elevation contour of the geoid showing that the LLSVPs are a dominant control on the positively elevated geoid. Minima in the frequency distribution of shear wave velocities in the lowermost mantle near $V_s = -1\%$ indicate that regions with more negative velocities, forming ~2% of total mantle mass, are likely to be of material compositionally different from the rest of the mantle. Because all LIP eruption sites with ages younger than 300 Ma lie above the borders of LLSVPs or LSVPs at the CMB, PGZ footprints are inferred to have remained in the same places for the past 300 My. Because no plumes have risen from the interior of the LLSVPs and because no lithospheric slabs have penetrated those bodies the volumes of the LLSVPs are inferred to have also remained unchanged for the past 300 My. Because the LLSVPs are the dominant control on the positively elevated areas of the geoid those too must have remained as they now are since 300 Ma. The LLSVPs are not rising buoyant objects but stable features of the deep mantle. LIPs have been erupted throughout the past 2.5 Gy indicating that PGZs comparable to those of the past 0.3 Gy and LLSVPs (of which PGZs mark the margins at the CMB) have also existed for at least that long. LLSVPs could thus form the isolated reservoir invoked by some to explain the distinctive isotopic compositions of terrestrial rocks. PGZs lie at places where the boundaries of: (i) The outer core, (ii) one of the LLSVPs or LSVPs, and (iii) the seismically faster part of the deep mantle meet. Horizontal temperature gradients across the steeply inclined margins to the LLSVPs, the interiors of which are hotter than the surrounding mantle, at the CMB are key controls for the generation of plumes. Near the CMB the association of the high temperature of the outer core with an inclined thermal boundary layer at the margins of LLSVPs facilitates the generation of mantle plumes in the PGZs.

Keywords: Large Igneous Provinces; Plume Generation Zones; Large Low Shear Velocity Provinces; core–mantle boundary; mantle plume; hotspot

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* Corresponding author. Tel.: +47 7390 4371; fax: +47 7392 1620.
E-mail address: bernhard.steinberger@ngu.no (B. Steinberger).

[1] Also at PGP, University of Oslo, 0316 Oslo, Norway, and School of Geosciences, University of Witwatersrand, WITS 2050, South Africa.

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1. Introduction

Large Igneous Provinces (LIPs) are commonly viewed as caused by eruptions from major plumeheads risen from the core–mantle boundary (CMB) (e.g. Richards et al., 1989). Since this view is not universally accepted, it is important to look for relations between LIP sites and features near the CMB, and to devise models that provide explanations for the relations.

Burke and Torsvik (2004) and Torsvik et al. (2006, submitted for publication-a) showed that the centres of most LIPs of the past 300 My, when restored to their eruption sites, lie vertically above one or other of two narrow belts centred on the 1% slow shear wave velocity contour of the SMEAN model (Becker and Boschi, 2002) at the CMB (92 km contour, Fig. 1a). They also found that 24 active hot spot volcanoes project down to the CMB within 10° of this contour and that steep horizontal gradients in shear wave velocity are concentrated along that contour (Fig. 1).

The two narrow belts occupy the margins on the CMB of the Earth's two Large Low Shear wave Velocity Provinces (LLSVPs, Garnero et al., in 2007). The Siberian LIP eruption site is not related to either of those two narrow belts but lies vertically above the margin of a separate, much smaller, low shear wave velocity province ("LSVP"). We estimate that LLSVPs and LSVPs occupy approximately one fifth of the CMB area. The belts around the LLSVPs and LSVPs have been the Plume Generation Zones (PGZs) of the Earth's deep mantle for 300 My.

In this paper we use the frequency distribution of velocity in tomographic models as evidence that the LLSVPs are chemically distinct bodies and estimate their sizes and shapes. Using probability theory, we show that the chance coincidence of reconstructed LIPs and LLSVP boundaries is extremely unlikely. Recognition of PGZs helps to shed light on the nature and the history of the deep mantle and more generally on Earth dynamics for the past 300 My and possibly for a much longer time. As newly recognized features of the deep mantle the PGZs represent a challenge to understanding that is unlikely to be soon fully resolved. Here we describe PGZs and present some of the more obvious implications of PGZ discovery.

2. LLSVPs in the lowermost mantle as bodies of distinct material: Evidence for their existence, size and shape

The concentration of steep gradients along the −1% contour can be understood from the frequency distribution of the SMEAN tomography model shown in Fig. 1b: These graphs show, at each depth level, the area with a given shear wave velocity anomaly, in bins of 0.1% width, multiplied with a constant factor. In its lowest layer (92 km above the CMB) the model has a distinct bimodal frequency distribution with a large peak at +0.6%, a smaller peak at −1.6% and a saddle in between at −1%. The bimodal distribution may be caused by the presence of two different kinds of material: If material within the LLSVPs and LSVPs on one hand, and material elsewhere on the other, each have shear wave velocity anomalies approximately characterized by a normal (Gaussian) distribution, but with different mean values, the total distribution will be bimodal. A bimodal frequency distribution can also be discerned in the D'' tomography models of Kuo et al. (2000) and Castle et al. (2000), although less clearly.

For the SMEAN model, the area of the peak at negative velocity anomaly diminishes and the peak becomes less clear higher up in the mantle (Fig. 1b). Nevertheless, we assume that the −1% contour marks the boundary between LLSVP material and "normal" mantle (Fig. 1a). The LLSVPs so defined are bodies that gradually taper upward in the mantle; the Pacific LLSVP extends up to a height 1384 km above the CMB (1507 km below the surface) and the African LLSVP reaches a height of 1814 km (1077 km below the surface) (Fig. 2). The uppermost parts appear as narrow cones or columns, and it is difficult to say whether they are still part of the chemically distinct bodies. Those might well be restricted to the lowermost few hundred kilometres of the mantle, where the bimodal frequency distribution in the tomography models is most distinct (Fig. 1b). The relation between what appears to be thermochemical bodies and present-day mantle plume conduits in tomography models is further discussed by Boschi et al. (2007).

The LLSVP area reduces from 21% at 92 km above the CMB to 13% at 235 km and 6% at 378 km (Fig. 1c) and we estimate that the LLSVPs together contain 1.6 vol.% and 1.9 mass% of the mantle (Table 1). Volume % are converted to mass % using the PREM (Dziewonski and Anderson, 1981) mantle density structure. The African LLSVP is slightly larger with 0.9 vol.% and 1.1 mass% of the mantle. The centres of mass of the two LLSVPs are almost exactly 180° apart in longitude, but they are both located at slightly southerly latitudes (Table 1). The centre of mass (not considering curvature of the Earth) of the Africa LLSVP lies ~400 km above the CMB while the centre of mass of the Pacific LLSVP is at ~200 km (Table 1).

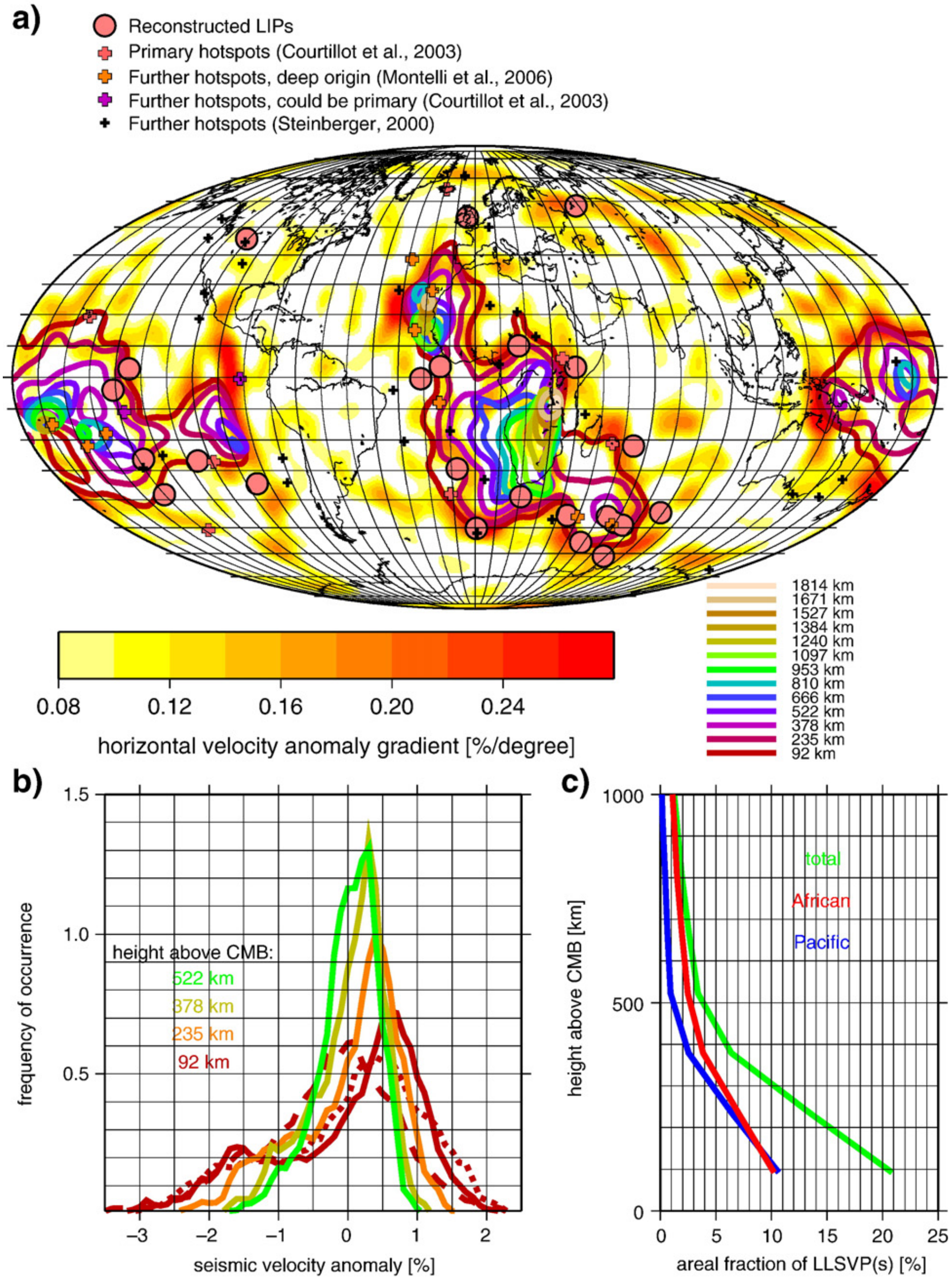

Fig. 1. (a) LIP eruption sites reconstructed in the global paleomagnetic reference frame and hotspots (Courtillot et al., 2003; Montelli et al., 2006; Steinberger, 2000; crosses) plotted with −1% contours of the SMEAN tomography model (Becker and Boschi, 2002) at different heights above the CMB. These contours approximately outline the shape of the two LLSVPs. All 23 LIPs listed by Torsvik et al. (2006) plus the Skagerrak Centred Large Igneous Province (SCLIP) proposed by Torsvik et al. (2007a) (age 297 Ma, reconstructed at 10°N 17°E) are included. Also shown are horizontal velocity anomaly gradients in the lowermost layer of SMEAN 92 km above the CMB. (b) Frequency distribution of seismic velocity anomaly in the SMEAN model at different depths (continuous lines), and the D'' models of Kuo et al. (2000) (dashed line) and Castle et al. (2000) (dotted line), showing the area in bins of width 0.1% anomaly normalized to total surface area. (c) Area fraction of SMEAN with anomaly $<-1\%$. green = total, blue = Pacific hemisphere only, red = African hemisphere only.

If both LLSVP volumes are restricted to lie within the lowermost 600 km of the mantle, both centres of mass lie ~200 km above the CMB.

Wang and Wen (2004) estimated a volume of $4.9 \cdot 10^9$ km^3 for the African LLSVP with an area of about $1.8 \cdot 10^7$ km^2 on the CMB and 300 km thickness.

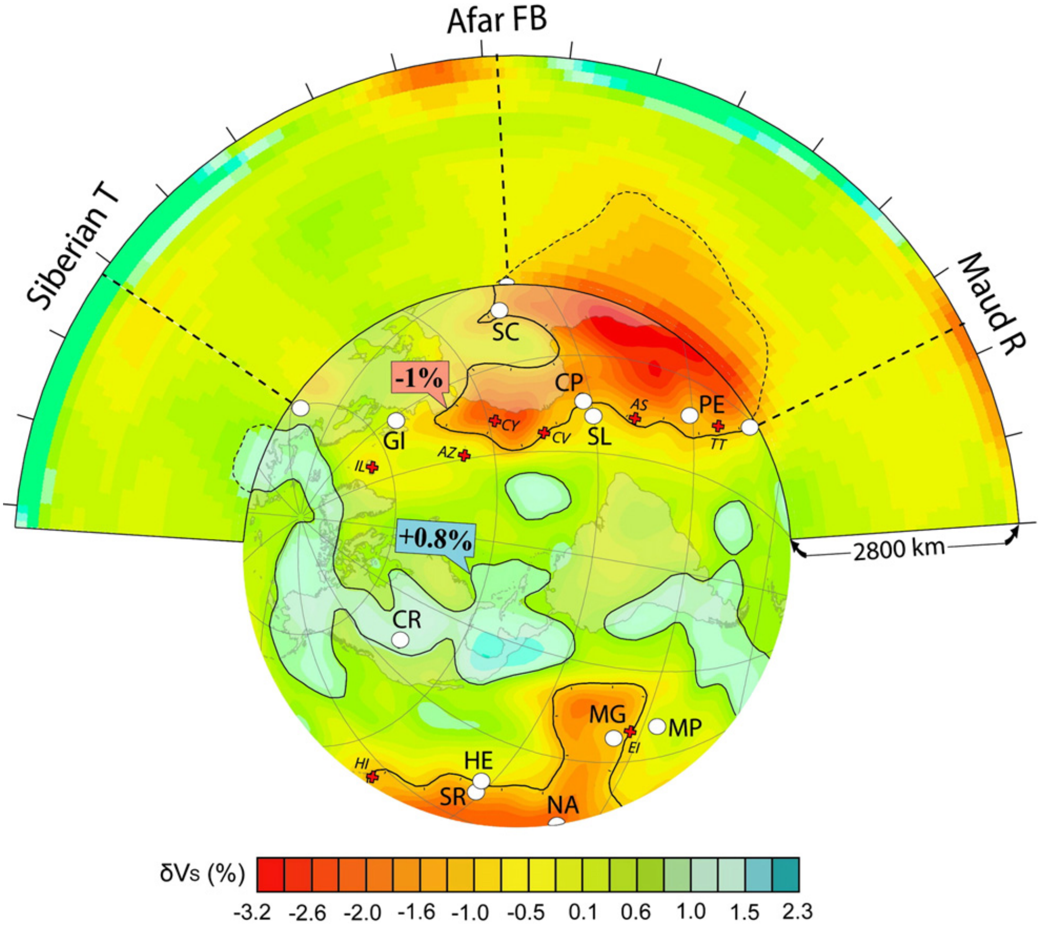

Fig. 2. Some reconstructed LIP eruption sites (open white circles: Siberian Traps; Afar Flood Basalts; Maud Rise; GI, Greenland–Iceland; SC, Skagerrak Centred; CP, CAMP; SL, Sierra Leone; Pe, Parana-Etendeka; SR, Shatsky Rise; HE, Hess Rise; NA, Nauru Basin; MG, Magellan Rise; MP, Manihiki Plateau), hotspots argued to originate from deep plumes (Red crosses: IL, Iceland; AZ, Azores; CY, Canary; CV, Cap Verde; AS, Ascension; TT, Tristan; EI, Easter Island, HI, Hawaii) and continental outlines projected onto the CMB. We show the 1% slow and the 0.8% fast contours at the CMB and a tomographic profile based on SMEAN. Diagram based on Torsvik et al. (2006, Fig. 12).

With the same assumed thickness, our volume estimate is only slightly smaller, corresponding to a somewhat smaller area estimate (Table 1). Our total mass estimate of 4.8–7.7 · 10^{22} kg can be compared with that of Tolstikhin and Hofmann (2005). They estimate the minimum mass of a “distinct dense post-giant impact” reservoir that could maintain the present-day helium flux from the Earth into the atmosphere for 4.5 Ga to be 6.2 · 10^{22} kg.

3. Location of the PGZs

Torsvik et al. (2006; submitted for publication-a) concluded that, because LIP eruption sites with ages throughout the past 300 My all project downward onto the margins of the LLSVPs and LSVPs, those PGZs have not moved for 300 My. This result is not dependent on the choice of a particular tomographic model: We show here reconstructed LIP positions in the paleomagnetic reference frame (Torsvik et al., 2006) together with the *D*″ tomographic models of Kuo et al. (2000) and Castle et al. (2000) (Figs. 3 and 4 respectively). The −0.77% contour of Kuo et al. (2000) and the −0.96% contour of Castle et al. (2000) (drawn in black in Figs. 3 and 4) approximately correspond to the −1% contour of SMEAN, because 21% of the areas of each of the three models have velocity anomalies below the respective contour values. We will refer to the contours as LLSVP and LSVP margins on the CMB. Restored LIP eruption sites lie, on average, 4.8° from the LLSVP and LSVP margins in the Kuo et al. (2000) model and 3.7° from the same margins in the Castle et al. (2000) model. LIPs restored using other reference frames in Torsvik et al. (2006) lie no more than 6°, on average, from the LLSVP and LSVP margins in the models.

Burke and Torsvik (2004) and Torsvik et al. (2006) observed that the Columbia River LIP eruption site does not lie above the margin of an LLSVP or LSVP in the

Table 1
Size and shape of LLSVPs

	African LLSVP	Pacific LLSVP	Total
Volume	8.4 (6.2; 4.4) · 10^9 km^3	5.8 (5.3; 4.4) · 10^9 km^3	14.2 · 10^9 km^3
Vol.% of mantle	0.94% (0.69%; 0.49%)	0.65% (0.59%; 0.49%)	1.59%
Mass	4.5 (3.4; 2.4) · 10^{22} kg	3.1 (2.9; 2.4) · 10^{22} kg	7.7 · 10^{22} kg
Mass% of mantle	1.13% (0.84%; 0.61%)	0.79% (0.73%; 0.60%)	1.91%
Area on CMB	1.6 · 10^7 km^2	1.6 · 10^7 km^2	3.2 · 10^7 km^2
% of CMB	10.2%	10.6%	20.9%
Max. height	1.8 (0.6; 0.3) 10^3 km	1.4 (0.6; 0.3) 10^3 km	

Mean location and depth	African LLSVP	Pacific LLSVP	Total
Total	15.6°S, 13.0°E, 409 km	11.0°S, 162.9°W, 239 km	339 km
Lowermost 4 layers	15.7°S, 12.0°E, 229 km	10.9°S, 162.4°W, 192 km	211 km
Lowermost layer	17.0°S, 13.6°E	11.4°S, 164.3°W	

They are assumed to be the regions in the SMEAN (Becker and Boschi, 2002) tomography model with more than 1% negative velocity anomaly and continuous from the lowermost layer. Numbers in brackets are restricted to lowermost 4 layers (~600 km) and lowermost two layers (~300 km).

SMEAN model. However, we now observe that the LIP eruption site overlies a small LSVP evident in the tomographic models of Kuo et al. (2000) and Castle et al. (2000). Also, in previous contributions we observed that the Greenland–Iceland LIP eruption site lies relatively far from the margin of the Africa LLSVP in the SMEAN model. Now, we note that the vertical downward projection of the LIP lies much closer to a version of the northern margin of the Africa LLSVP from Kuo and Castle led studies. Under the Pacific Ocean, Kuo et al. (2000) mapped a major re-entrant in the shape of the LLSVP margin. That indentation places the rotated and vertically downward projected Ontong Java, Nauru, Magellan and Manihiki LIPs much closer to the LLSVP margin. Integrating the results of these three tomographic studies shows that (1) 22 LIP eruption sites of the past 300 My projected downward lie within 10° of one or other LLSVP margin and (2) the restored and downward projected Siberian and Columbia River LIPs lie within 10° of the margins of two LSVPs.

How likely is it that such a LIP distribution occurs by chance? 18 out of 24 LIPs reconstructed in the global paleomagnetic frame (Torsvik et al., 2006) lie within

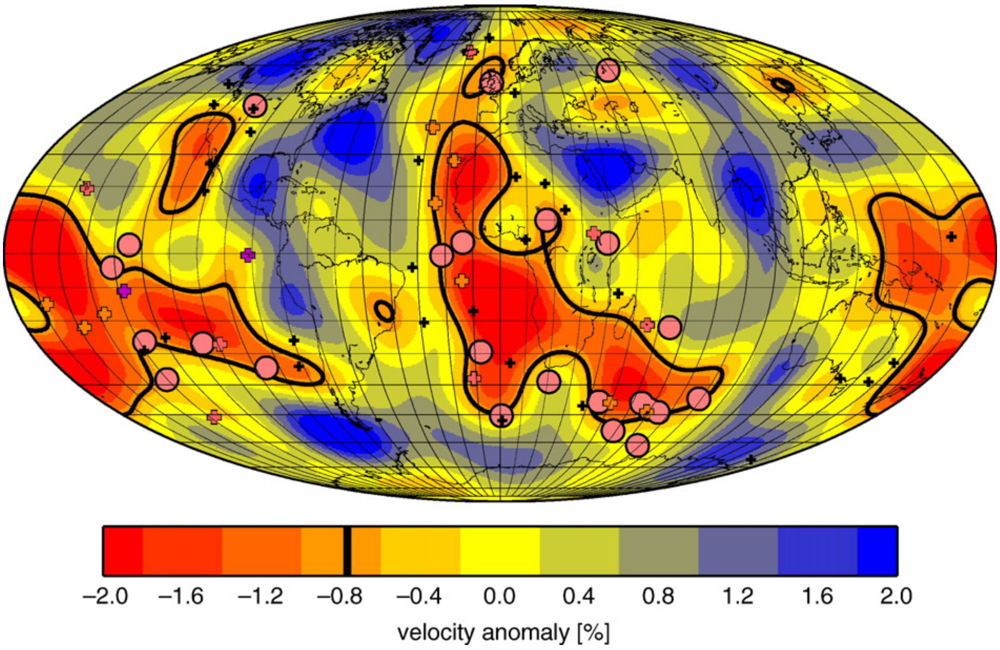

Fig. 3. LIP eruption sites reconstructed in the global paleomagnetic reference frame (pink circles) and hotspots (crosses, see Fig. 1) plotted on top of the Kuo et al. (2000) D'' tomography model. Average separation of LIPS from the −0.77% contour on this map is 4.8°. It would be less were it not for a remote location for the Afar LIP.

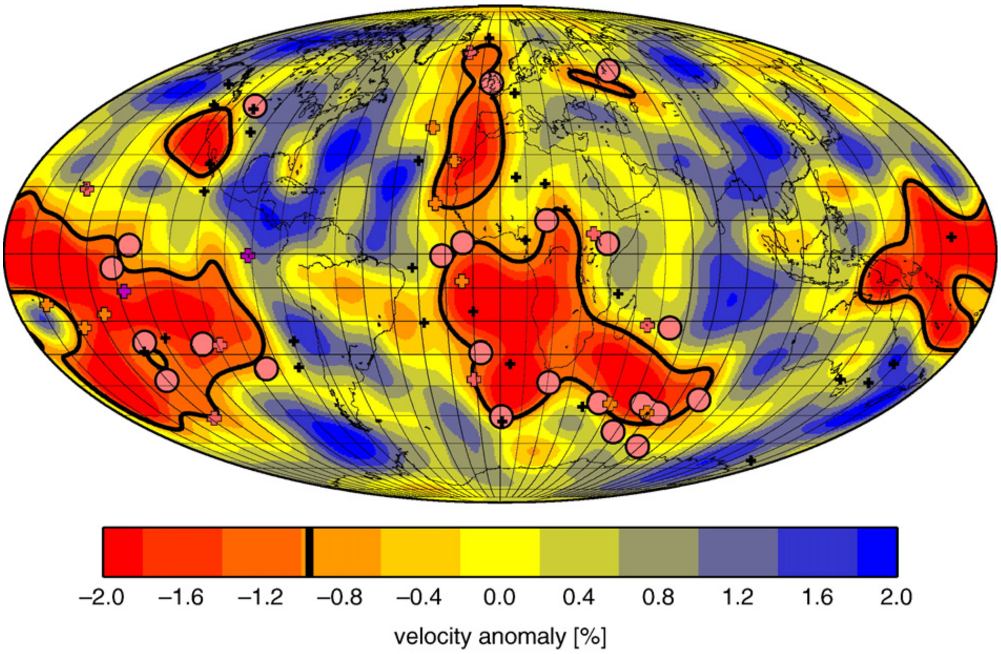

Fig. 4. LIP eruption sites reconstructed in the global paleomagnetic reference frame (pink circles) and hotspots (crosses, see Fig. 1) plotted on top of the Castle et al. (2000) D'' tomography model. Average separation of LIPs from the 0.96% contour on this map is 3.7°. Proximity to the margin is less close than that of Kuo et al. (2000) in the SE Pacific.

belts of 5° half-width centred on the −0.96% contours of the Castle et al. (2000) D'' model. The probability that 18 or more out of 24 randomly chosen points lie within the belts (23.5% of the CMB area) is about 1 in 7 million ($p = 1.47 \cdot 10^{-7}$). Fig. 5 shows similarly determined probabilities for different belt half-widths and different D'' models. Use of other reconstruction reference frames results in increased but nonetheless extremely low probabilities that the pattern developed by chance. Examining the present-day distribution of LIPs with respect to the LLSVP margins, we find that only 6 out of 24 LIPs fall in the same 23.5% of the CMB area. The probability for 6 or more LIPs to lie within these belts by chance is 51% (Fig. 5), demonstrating that the LIPs were most likely erupted above the LLSVP and LSVP margins at the CMB, the PGZs, and later widely distributed across the globe embedded within their respective tectonic plates.

The resolution of the rotations and projections that we use depends on (1) the horizontal dimensions of a plume head at the time of its impact on the base of the lithosphere, (2) the location of the eruption centre within a LIP with respect to the corresponding plume impact site on the base of the lithosphere (Sleep 1997, 2007; Torsvik et al 2006, submitted for publication-a), (3) the rotation methods by which LIPs have been restored to their eruption sites (Torsvik et al., submitted for publication-b), and (4) the tomographic mapping of deep structures, specifically the structures at the contact of LLSVPs and LSVPs with the CMB. Poor resolution in these four quantities limits the ability to determine how well a LIP maps onto a PGZ. Three of the quantities are related to near surface phenomena and one to a boundary at the CMB. Resolution of the near surface phenomena

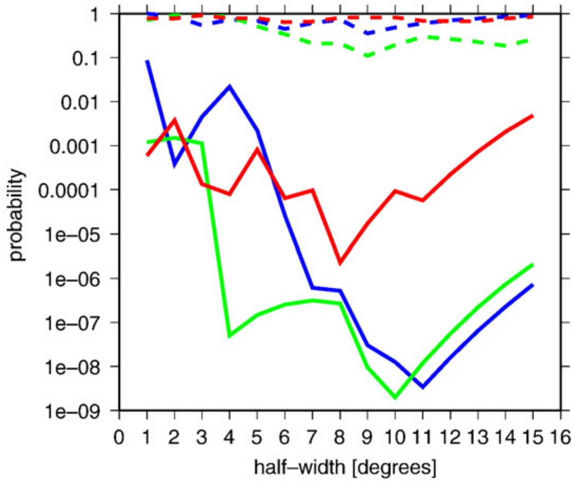

Fig. 5. Probability that the number of LIPs found within a given distance from the LLSVP and LSVP margins (horizontal axis) is as large as it is, or larger, if LIPs are placed randomly. For further explanation, an example is given in the text. Larger numbers indicate a closer approach to a random distribution. For LLSVP and LSVP margins we use the −1% contour of the SMEAN model lowermost layer (blue line), the −0.96% contour of the Castle et al. (2000) D'' model (green line) and the −0.77% contour of the Kuo et al. (2000) D'' model (red line). Solid lines are for LIPs reconstructed in global paleomagnetic reference frame, dashed lines for LIPs in situ.

varies from one LIP to another and may also vary systematically, for example between the African and the Pacific regions or between sub-continental and sub-oceanic LIPs. Resolution can also be expected to deteriorate as data sets become less complete back into the past so that the rotated locations of older LIPS are likely to be less accurate. At this time it is not possible to estimate the magnitude of the four individual sources of uncertainty.

4. Structure and history of the deep mantle Low Shear Velocity Provinces (LLSVPs and LSVPs) from LIP distribution and history — have LLSVP and LSVP volumes remained constant for 0.3 Ga?

Recognition of the existence of long-lived PGZs at the margins of LSVPs indicates that their "footprints" on the CMB have remained unchanged for a long time — ~7% of Earth's history in the case of the African LLSVP. If the volumes of the two LLSVPs have also remained unchanged for 0.3 Gy then they cannot be buoyant. If the LLSVPs are not buoyant yet slow in shear wave velocity compared with their surroundings (Figs. 1–4) they must be compositionally distinct from the faster parts of the deep mantle in which they are embedded. Kellogg et al. (1999) and Tan and Gurnis (2005) also concluded that the material in the deep mantle corresponding to that in LLSVPs is compositionally distinct. McNamara and Zhong (2004) concluded that for the compositionally distinct structures to acquire a rounded shape, which may be more compatible with observations, an intrinsic compositional viscosity increase is required for the dense material. Such a viscosity increase also helps to maintain long-term stability of these features. McNamara and Zhong (2005) showed that the Earth's subduction history can lead to thermochemical structures similar in shape to the observed LLSVPs. Anticorrelation between shear wave speed and bulk sound speed (Masters et al., 2000) provides seismological evidence for compositional variations in the lowermost mantle. Further evidence in favour of compositionally distinct LLSVPs, and implications for mantle plumes are discussed by Torsvik et al. (2006) and Garnero et al. (2007).

Another way of addressing the issue of LLSVP buoyancy is to consider whether near surface features above the higher parts of the LLSVPs might indicate an upward flux of material from within those relatively

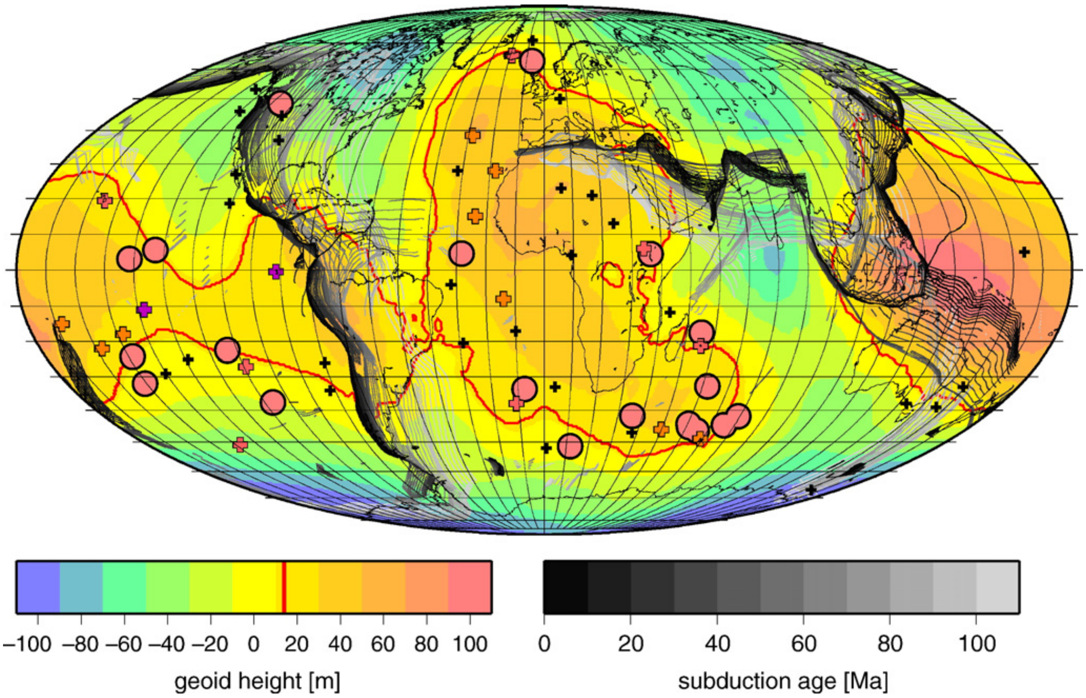

Fig. 6. Eruption sites of 20 LIPs of the past 150 Ma reconstructed in the global moving hotspot reference frame (pink circles) and hotspots (crosses, see Fig. 1) plotted on top of the geoid relative to hydrostatic equilibrium shape (Nakiboglu, 1982). The mean separation of the sites from the +14 m contour (shown in red) is 6.2°. Because subducted slabs in the mantle influence the shape of the geoid and partly obscure the dominant influence of the LLSVPs subduction locations over the past 110 Ma, computed based on the plate motion and boundary models of Gordon and Jurdy (1986) and Lithgow-Bertelloni et al. (1993) are shown. These models are outdated and subduction locations are shown for illustrative purposes only and not for quantitative analysis.

high regions or a downward flux of material from the near surface into the LLSVPs. Tomographic imaging of slabs and slab debris both at shallow depths and in the lower mantle indicates that the two LLSVP volumes have not been modified by the penetration of slab material during the past few hundred million years (e.g. Richards and Engebretson 1992, and Fig. 6). Restoring plate positions back to the time of the formation of the world's oldest ocean floor (~180 Ma) permits subduction locations and directions to be mapped back through time. From that mapping it can be seen that subducted slabs have generally penetrated the mantle outside the upward projected locations of the LLSVPs.

Similarly there is no evidence of material having left the LLSVPs. Using the tomography models of Kuo et al. (2000) and Castle et al. (2000) in addition to SMEAN we find no projected LIP and only one hotspot (Tahiti) eruption site argued to have a deep plume origin that lies more than 10° inside the LLSVP margins (Figs. 1, 3 and 4). The question of whether or not there are upwellings generated above the LLSVPs is not addressed in this paper (but see e.g. McKenzie and Weiss, 1975; England and Houseman, 1984; Burke et al., 2003; Li and Burke, 2006). The possibility of time dependent changes in the much smaller LSVP volumes cannot be addressed on presently available information but by analogy with LLSVPs they would also appear likely to have remained stable in volume. In summary, evidence of the constancy of LLSVP volume over the past 0.3 Ga is less complete than the evidence of constancy of the area of the footprints of the LLSVPs on the CMB; if there was material flux into or out of the LLSVPs, it cannot be detected from our results.

5. LLSVPs, the PGZs and the geoid

An association has long been suggested to exist between global hotspot distribution and geoid elevation (e.g. Anderson, 1982). That association appears closer for a residual geoid, from which geoid elevations associated with subduction zones are removed (see Hager, 1984). Contributions of hotspot sources to both deep and shallow mantle structure under geoid highs were both postulated and modelled (e.g. Richards et al., 1988). Those and other studies inferred hotspots to be scattered within the high areas of the residual geoid. Our observations are different in that we find the rotated LIPs and the major hotspots to be concentrated at the edges of elevated geoid regions near the +10 m contour. The smallest mean distance of 6.2° is found between the 20 reconstructed LIPs in the global moving hotspot reference frame of Torsvik et al. (submitted for publication-b) and the +14 m contour (Fig. 6). We therefore find that LIP eruption sites and major hotspots lie at the edges of elevated geoid regions just as they lie above the PGZs at the edges of the LLSVPs. This is inevitable because upward projected LLSVPs correspond well with geoid regions above 10 m — especially if we disregard geoid highs related to recent subduction (South America, Indonesia; Hager, 1984). Since we have evidence to show that the LLSVPs have been stable for the past 0.3 Gy, we infer that the corresponding features of the geoid have remained quasi-stationary over the same time period. This is the first time evidence has been presented showing this.

With geoid highs remaining along the equator, it is possible that the Earth's rotation axis moves relative to the mantle along a line of longitude 90° from the antipodal geoid highs ("true polar wander"; TPW). TPW is integral to the three hotspot reference frames considered by Torsvik et al. (2006; submitted for publication-b), and by definition absent in their global paleomagnetic reference frame. All of these reference frames were used to restore LIPs to their eruption sites and all of the resulting eruption site distributions fall close to the margins of the LLSVPs. Therefore this line of investigation cannot shed light on TPW at this stage.

6. Were there PGZs on the CMB before 0.3 Ga?

We have provided compelling evidence that the plumes which generated LIPs of the past 300 My rose vertically from PGZs on the edges of LLSVPs and LSVPs at the CMB. Ernst and Buchan (2003) showed that LIPs as old as 2.5 Gy are the same in (1) huge volume (2) rapidity of eruption and (3) association with giant dyke-swarms as those of the past 300 My so that there would appear to have been PGZs on the CMB at least as far back as 2.5 Ga. Because the PGZs of the past 300 My lie at the edges of either LLSVPs or LSVPs we consider that the PGZs of earlier times are likely also to have occupied the edges of LLSVPs or LSVPs on the CMB.

An outstanding question is: Are today's LLSVPs and LSVPs stable features whose margins have hosted PGZs since 2.5 Ga or were there ancient LLSVPs and LSVPs that differed in shape, location and number from those of today? Because it is not feasible to determine longitude for times before the assembly of Pangea at ca.0.3 Ga the LIP eruption site record cannot answer that question. However, we cannot discern a change in area of the LLSVPs over the last 300 Ma and consider that indication of long-term stability of the LLSVPs sufficient to justify some speculation on possible implications.

7. Speculations on the geochemical significance of long-term LLSVP stability

Geochemists have long considered that there might be an isolated reservoir of distinct composition within the mantle that has escaped being involved in making ocean floor and continents. Recent measurements of contrasts in ^{142}Nd/^{144}Nd between terrestrial rocks and meteorites (Boyet and Carlson, 2005; 2006) have made a new case for the existence of such a reservoir. We have shown that the LLSVPs are unlikely to have either gained or lost significant mass during the past 0.3 Gy and argue that they may have been similarly isolated since at least 2.5 Ga. If that is the case LLSVPs are candidates for the hidden reservoir. Because quantitative estimates of the composition of a hidden reservoir are model dependent we draw attention only to three basic geochemical implications of isolation: (1) If LLSVPs are parts of the mantle that have not been involved in making ocean floor, island arcs and continents, they are richer in incompatible elements than the rest of the mantle. (2) If basalt has not been melted out of them the LLSVPs are richer in iron than the rest of the mantle because basalt has a higher iron content than mantle rock (McDonough and Sun, 1995). That could help to account for slower LLSVP velocities (Forte and Mitrovica, 2001; Jackson, 1998). The resulting higher density would also help to explain why they have remained at the base of the mantle. (3) LLSVPs, if they have been isolated, contain more U, Th and K than the rest of the mantle. That would make them hotter, as they indeed appear to be, than the mantle in which they are embedded. (4) Isolation and a distinctive concentration of radioactive nuclides will make for a ^{3}He/^{4}He ratio in the LLSVPs that is different from that of the rest of the mantle. Consistent with the estimate (Tolstikhin and Hofmann, 2005) that the minimum mass of a “ distinct dense post-giant impact” reservoir which could maintain the present helium flux from the Earth into the atmosphere for 4.5 Ga is $6.2 \cdot 10^{22}$ kg, our estimate of total LLSVP mass (Table 1) is very close to that value.

8. Structure of the PGZs: How, when and where do plumes develop?

Three distinct volumes of the Earth's deep interior contribute to plume generation: (i) The outer core, (ii) one or other of the two LLSVPs and the two LSVPs (iii) the rest of the deep mantle which is dominantly, if not overwhelmingly, the slab graveyard. The core provides heat by conduction to the other two. If, as we suggest, the LLSVPs are chemically isolated, only the slab graveyard dominated deep mantle supplies material to the plumes. Where thermal instabilities that can generate plumes will develop within a spherical layer heated from below does not follow from the governing equations but the formation of plumes will be localized where there are inclined thermal boundary layers within such a spherical layer, as there are at the edges of the LLSVPs close to the CMB (see Fig. 2).

Our work implies that plume initiation is episodic and sporadic along the length of a PGZ. A dynamic PGZ replenishment process is therefore needed to provide material for new plumes. Given LLSVP isolation plume material has to be advected from the slab graveyard dominated part of the deep mantle. The ability to flow is enhanced by heat conducted across the CMB so that advection to the PGZs is expected to occur only within the basal few hundred km that are strongly heated by conduction from the core.

Material capable of generating plumes at a PGZ flowing along the base of the slab graveyard is likely to constitute the hottest part of the deep mantle, at least outside the LLSVPs. That material becomes capable of flowing by being heated internally and from the core. It is not buoyant enough to rise through the slab graveyard but from time to time and at locations sporadically distributed along the length of a PGZ a volume of the core-hugging material appears to respond to encountering the steep slope on the flank of an LLSVP by releasing a hot buoyant plume. The ascent of plumes from the PGZs at the CMB appears to have been rapid because LIP eruption site and hotspot positions on the Earth's surface project vertically down onto the PGZs. There is no indication of appreciable plume head flow along the margins of LLSVPs above the CMB or of diversion by mantle flow. Nakagawa and Tackley (2005 Fig. 2b) illustrated one possibly relevant model in which a slab, somewhat like a broom (Fig. 7), pushed hot material along the CMB. Broom-swept hot material could generate a plume in a PGZ where it encountered an LLSVP or LSVP. Eruptions along the lengths of PGZs do not appear to be uniformly distributed through time. A Kerguelen cluster of eruptions, for example, marked a corner of the African PGZ between 135 Ma and 85 Ma. Higher eruption frequency may be the cause or the consequence of higher mantle temperatures in that region (Trampert et al., 2004).

9. Conclusions and recommendations for further work

1.) Plume Generation Zones (PGZs) of the deep mantle are narrow horizontal belts at the CMB from which plumes that have generated LIPs and hotspots

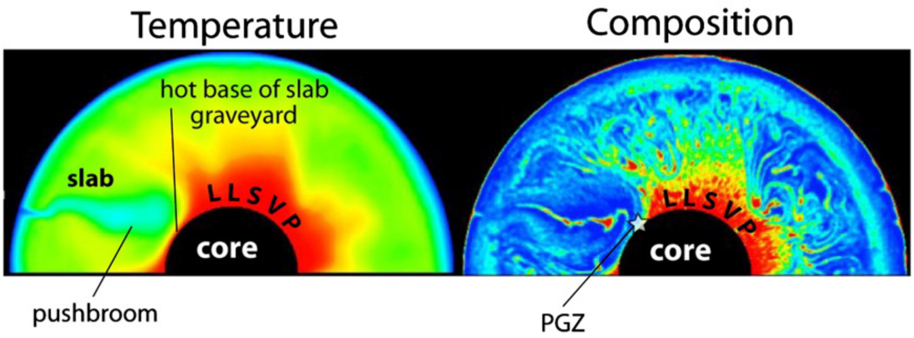

Fig. 7. Plume generation at the CMB — cross section showing mantle structure (based on Nakagawa and Tackley, 2005, Fig. 2b) used here to illustrate the idea that plumes are generated only in narrow Plume Generation Zones (PGZs) on the CMB at places where LLSVP or LSVP boundaries intersect the core. What we suggest may be a pushbroom of slab material is indicated as driving hot material along the CMB at the base of the slab graveyard. Plumes form where hot material of that kind reaches a PGZ.

have risen (Figs. 1–4, Torsvik et al., 2006). They straddle the 1% slow shear wave velocity contour in the SMEAN tomographic model of Becker and Boschi (2002) (Figs. 1 and 2). By using the Castle et al. (2000) and the Kuo et al. (2000) tomographic models of the deep mantle we find that all 24 rotatable LIP eruption sites of the past 0.3 Gy, i.e. those located on plates or terranes that are linked through plate circuits (Torsvik et al., submitted for publication-a) to the reference frames used here, lie above the PGZs at an average separation of about 5° from the 1% slow contours that mark the edges of LLSVPs and LSVPs at the CMB (Figs. 3 and 4). 24 out of 47 hotspots lie in the same zones. Statistical analyses show that the concentration of plume sources in the PGZs is very unlikely to be a coincidence. No LIPs can be linked to any source in the deep mantle remote from PGZs.

2.) We have used the frequency distribution of tomography models as additional evidence that the LLSVPs are bodies of distinct material in the lowermost mantle, and that their boundary occurs approximately at the 1% slow contour. They occupy about 20% of the CMB area, and less area higher up. We estimate that each LLSVP contains about 1% of the mass of the mantle.

3.) Within the regions where LIP eruption sites and hotspots are located, there are minor differences among the three tomographic models that we show. Differences in input and in processing are both likely causes. An opportunity for improving understanding of deep mantle structure exists in finding out how and why existing tomographic models differ slightly regionally in mapping of PGZs.

4.) Nearly all models of mantle convection embody mantle plumes but none shows plumes rising solely from PGZs. Our findings provide a stimulus for the construction of more realistic mantle convection models in which plumes are self-consistently generated only in PGZs.

5.) Because so many hotspots and LIPs with ages as old as 0.3 Ga, irrespective of individual age, rotate and project on to PGZs at the edges of LLSVPs we infer that the footprints of the LLSVPs on the CMB have been fixed in their present locations for the past 0.3 Ga.

6.) The total volumes of the LLSVPs have not changed for 0.3 Ga although evidence for that long-term persistence is less strong than the evidence of the constancy in location of the LLSVP footprints on the CMB.

7.) LIPs, comparable to those of the past 0.3 Ga have been erupted since at least 2.5 Ga. From that observation we infer that there have been PGZs on the CMB at the margins of LSVPs since that time. Whether those LSVPs have been the LLSVPs of the past 0.3 Ga is less certain but possible.

8.) Coincidence of the upward projected LLSVPs with the positively elevated parts of the geoid shows that they are the dominant contributor to that elevation. Reconstructed LIP locations plot close to the +13 m elevation of the geoid.

9.) Because the LLSVPs have been in their present location for at least 0.3 Ga we infer that the residual geoid (i.e. with the part related to subduction removed) has not changed its location and shape during the same interval.

10.) The residual geoid, like the two LLSVPs, may have been the same for at least 2.5 Ga.

11.) If the LLSVPs have persisted in size and isolation from the rest of the mantle for at least 2.5 Gy they are strong candidates to represent the chemically isolated reservoir that has been suggested by some geochemists to occur within the deep mantle.

12.) The relatively high $^{3}He/^{4}He$ ratio of hotspots and young LIPs can be attributed to diffusion into the PGZs from the hot basal parts of the LLSVPs.

13.) Plumes have formed only in PGZs because those are the places where the core, a LLSVP and the slab graveyard meet. Horizontal temperature gradients across the steeply sloping flanks of the LLSVPs just above the CMB, where the basal part of the slab graveyard is hottest, have facilitated the initiation of plumes in an environment that exists nowhere else in the mantle.

14.) Hot material that has been heated by conduction from the core in the basal part of the slab graveyard may be driven toward the PGZs by slabs or slab fragments acting like pushbrooms (Fig. 7). If slabs sink approximately vertically in the lower mantle, this mechanism may work in both the African and Pacific hemisphere.

15.) The ascent of plumes is likely to have been rapid because LIP eruption sites, and many hotspots, lie vertically above the PGZs. There is little evidence of plume heads having been diverted from the vertical by flow in the mantle.

16.) Long-lived, hot and compositionally distinct LLSVPs with footprints extending over about 25% of the CMB will have reduced heat flux from the core and in that way slowed core cooling. Such a reduction in heat flux is necessary for a successful model of thermal evolution of the core (Nakagawa and Tackley, 2004; 2005). Reduction due to the blanketing effect of the LLSVPs may, alone or with other factors, have been sufficient to account for the heat flux from the core having stayed large enough over billions of years to maintain the geodynamo without the inner core growing to a much larger size than observed.

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