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# Derivation of Large Igneous Provinces of the past 200 million years from long-term heterogeneities in the deep mantle

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## Abstract

Large Igneous Provinces (LIPs) result from local catastrophically rapid dissipation of great quantities of internal heat. LIPs are overwhelmingly of basaltic affinity representing partial melting of the mantle at shallow depths but whether any of the heat or material involved in the generation of LIP rocks comes from great depth has remained controversial. To address this fundamental issue we restored 25 LIPs of the past 200 My to their eruption sites using a new global palaeomagnetic reference model. Ninety percent of the LIPs, when erupted, lay above low-velocity seismic-shear-wave regions of the D″ zone just above the core–mantle boundary (CMB) and ~50% overlay CMB low-velocity regions with $\delta V_s \leq -1\%$. Considering the modifying effects of plume advection, palaeolongitudinal uncertainty and plate circuit errors, the majority of the restored LIPs may in fact overlie regions with $\delta V_s \leq -1\%$. Because those low velocity regions occupy only 27% of the D″ zone, the concentration of LIPs above them indicates that the low velocity (hotter?) regions are the sources of the mantle plumes that generated the LIPs. We demonstrate that most LIPs of the past 200 My owe their origin to plumes that rose from low-velocity regions of the lower mantle, and that this long-term association indicates that the low-velocity regions have been relatively stationary with respect to the Earth's spin-axis and the core since the Early Jurassic, and perhaps since the Permo-Triassic boundary.

*Keywords:* Large Igneous Provinces; plumes; palaeomagnetic reconstructions; seismic tomography; core–mantle boundary

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## 1. Introduction

Large Igneous Provinces (LIPs) have been identified mainly on compositional grounds and as dike-swarms in rocks with ages extending as far back as the

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Archean (>2.5 Ga) but it is only among those LIPs which have erupted since the Pangea Supercontinent began to break up that the definitive huge volumes of rock erupted over short intervals are well-preserved. Some association with continental break-up is clear among those LIPs but it is far from general and LIPs have also erupted, forming oceanic plateaus, within the Indian and Pacific Oceans in places remote from the continents. We looked for possible controls of LIP eruption using the reports of Coffin et al. [1,2] who catalogued, and plotted the global distribution of LIPs that have been erupted at the Earth's surface during the past 250 My (Fig. 1a). Plate motions have moved these LIPs about on the Earth's surface since they were erupted. Some, such as the Parana (South America) and Etendeka (Africa) LIPs, have broken in two and others have been caught up at convergent plate margins being preserved only in fault-bounded slices. Slices of LIPs probably exist that have not yet been recognized, and yet other LIPs may have been completely destroyed. The record of LIPs in the Pacific realm is probably incomplete because fast moving plates have carried LIPs to convergent boundaries as was the fate of the Hess Rise Twin [3]. The LIP record in the Indian Ocean region is more likely to be complete because plate motions in this region have been generally slow, except during consumption of eastern Neotethys, so that few if any LIPs have been carried to convergent boundaries or destroyed.

Volcanism unrelated to plate boundaries or rifts has been widely attributed to mantle plumes from the deep mantle and hotspots (Fig. 1a) have been correlated with low-shear wave velocity structures ($\delta V_s<0$) in the mantle [4]. However, such plumes have not been indisputably detected seismically [5] and lower mantle anomalies could prove of chemical, rather than thermal origin [6,7]. The majority of hotspots are probably caused by shallow processes [8,9]. Ritsema and Allan [5] concluded that only eight hotspots (including Afar, Easter, Hawaii, Iceland and Louisville) could have a deep plume origin based on underlying low-shear-wave-velocities in both the upper and lower mantle (Fig. 1a). Using additional criteria Courtillot et al. [10] considered that seven hotspots had a deep origin, five of which corresponded to those of Ritsema and Allan [5]. The deep plume model is thus controversial and alternative models associate some or all [11–13] hotspot volcanism with superficial processes especially within-plate extensional stresses.

## 2. Analytical strategy

In order to explore the spatial relation between LIPs, which may be products of deep-seated plumes, and the deep mantle we restored LIPs of the past 200 Ma comparing their locations at the time of their eruption with shear-wave anomalies in the lower mantle using several available global mantle models. LIPs can be reconstructed using hotspot models [14,15] that provide both latitudinal and longitudinal information ('absolute') but that approach could be considered to involve circular reasoning because hotspot models are based on assumed plume–hotspot associations (no need to reconstruct—just compare hotspot location with tomographic model). Furthermore, hotspot models are arguably not very reliable prior to 84 Ma and some authors reject hotspot models altogether. We therefore used a novel and independent approach to exploring spatial relations between LIPs and the deep mantle. In our analysis we used a global apparent polar wander path (APW) detailed in Torsvik and Van der Voo [16] and in Torsvik et al. [17]. We used their global geocentric axial dipole (GAD) models since the incorporation of non-dipole field contributions is controversial. Their GAD model used here shows gross similarities with that of Besse and Courtillot [18].

Palaeomagnetic data yield palaeolatitude and rotation but palaeolongitude is not determined. In order to minimize longitudinal uncertainty, the choice of initial plate reference matters. As an example, rotating all LIPs to a North America frame (relative fits) and then applying a global APW path in North American co-ordinates produces reconstructions of Africa that differ in apparent longitude from those produced by using Africa as a reference frame (Fig. 2a,b). We also show the position of Africa in a fixed hotspot frame [14]. Notice the improved fit in fixed hotspot and apparent palaeomagnetic longitude when using an African initial plate reference. The relatively large latitudinal difference between hotspot

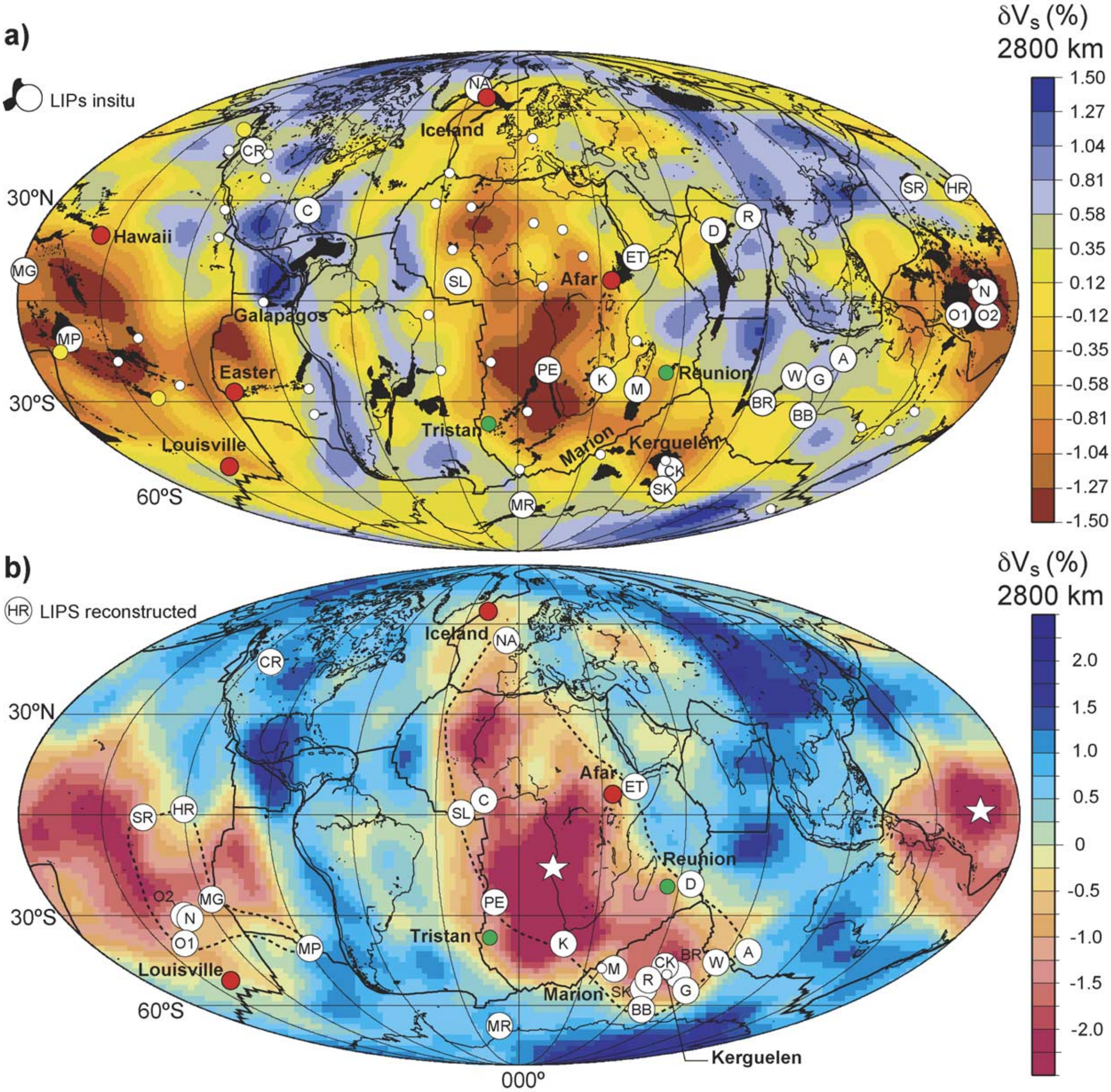

Fig. 1. (a) Distribution of LIPs, current plate boundaries and the location of 44 hotspots [15] shown as open white circles. Hotspots argued to have a deep origin are shown as red [5,10], green (exclusively picked by Courtillot et al. [10]) and yellow dots (exclusively picked by Ritsema and Allan [5]). Hotspots discussed in the text are named. Present LIP locations (Table 1), which are probably correct within a radius of ~500 km, are shown as annotated white circles. Some LIPs, for example the Parana (South America) and Etendeka (Africa) LIPs, have been broken in two and only shown as one symbol (e.g. PE), and linked to their appropriate plate (Table 1). The background map [22] is a tomographic model (S20RTS) of shear wave velocity anomalies ($\delta V_s$) near the CMB (2800 km depth). Blue is fast shear wave speed and red is slow. (b) LIPs reconstructed back through time (201–15 Ma) from their present locations to those in which they were erupted (Table 1). The background map shows the SMEAN shear-wave tomography model [21], which is based on an average of three global intermediate wavelength shear-wave tomography models. Note that $\delta V_s$ color contours differ from those in (a), highlighting the red (slower speed) and blue (higher speed) regions. Our reconstructed LIPs plots within or overlay the edges of low-velocity regions of the D″ zone in the Sub-African and Sub-Pacific regions when erupted (stippled lines). The Columbia River and Maud Ridge LIPs are the only exceptions. The maximum negative shear velocity anomalies for the Sub-African ($\delta V_s$=−3.2%) and Sub-Pacific ($\delta V_s$=−2.5%) regions are indicated as white stars. Mollweide projections.

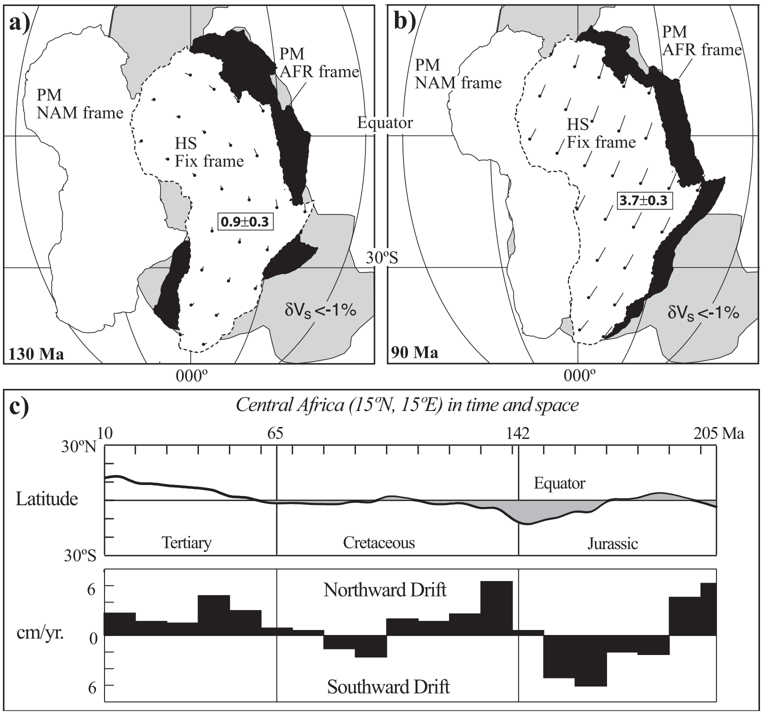

Fig. 2. (a,b) Examples of reconstructing Africa using a North American (NAM) and African (AFR) palaeomagnetic (PM) reference frames [16] that produce apparent differences in longitude. We also show Africa reconstructed in a fix hotspot (HS) frame [14]. The latter reconstructions show the 130→120 and 90→80 Ma velocity fields. Mean plate velocities (cm/year±1$\sigma$) are calculated for a 10×10° grid. Grey-shaded background show the Sub-African low-velocity shear-wave region ($\delta V_s \leq -1\%$ in Fig. 1b) (c) Latitudinal movement of a Central African location since the Early Jurassic based on palaeomagnetic data [16]. Lower diagram shows mean latitudinal velocities calculated from palaeomagnetic data. Note that the HS frame suggests NNE movement between 90 and 80 Ma (a), whereas the PM frame indicates southward drift (2 cm/year) over the same interval.

and palaeomagnetic frames at 130 Ma (Fig. 2a) has been attributed to true polar wander or to hotspot drift [17].

Our analytical trick has been to choose a plate as an initial reference that has undergone the smallest amount of longitudinal movement. Africa is the ideal candidate because it has remained extremely stable for the past 200 My having been surrounded by spreading centers since the Jurassic except in the Neotethys. Central Africa straddled the equator from Late Triassic to Early Tertiary times (Fig. 2c) except for a southward departure at the end of the Jurassic. Latitudinal velocities were low except for more rapid motion: (1) in the Late Jurassic at the time of opening of the central Atlantic and Mozambique Oceans, (2) in the Early Cretaceous at the time of opening of the southernmost South Atlantic (6 cm/year) and (3) in Mid Eocene time. Africa has remained very stable for the last 20 My [8,19], angular rotation [16] has always been low (<1°/My), and hotspot reconstructions indicate only minor longitudinal changes (<10°) during the past 130 My (Fig. 3b). LIP locations (Fig. 1a) were first rotated to African co-ordinates and then palaeomagnetically reconstructed. Relative fits and palaeomagnetic reconstruction parameters [16] were interpolated to fit the ages of the individual LIPs. The largest uncertainty in this procedure arose in fitting the Pacific LIPs to Africa for which we used Pacific to East Antarctic rotations summarized in Norton [20]. Unrecognized plate boundaries between West and East Antarctica could have introduced large errors into the analysis. Using our paleomagnetic approach we were not able to restore the Caribbean oceanic plateau to its eruption site because adequate data are unavailable. On the fixed hotspot and plume track model correlation between the Caribbean plateau

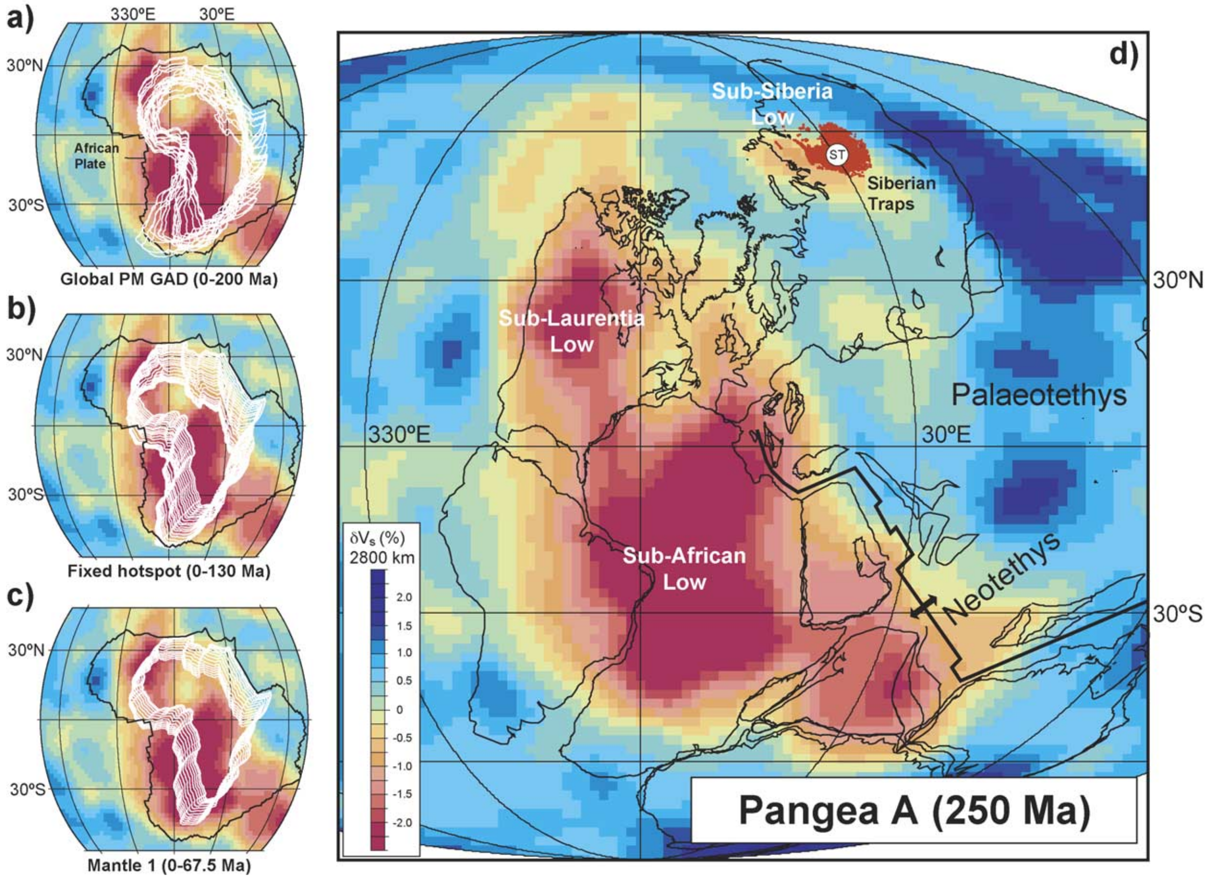

Fig. 3. (a–c) Reconstructing Africa with palaeomagnetic, fixed hotspot [14] and mantle frames [15]. (d) Palaeomagnetic Pangea A GAD-based reconstruction (after [27] but using the apparent palaeolongitude strategy outlined in the text). The present ‘sub-African’ low of Fig. 1 now covers parts of Laurentia and is centered below the supercontinent whilst the Siberian Traps (251 Ma) overlie hotter (?) deep mantle. This was the climax of Pangea but North and South China were not part of Pangea, and new oceanic crust was formed along its eastern margin (Neothethys). Continents are draped on shear wave velocity anomalies near the CMB [21]. The distribution of the Siberian Traps is outlined in red shading and the estimated location of the LIP center (65°N, 097°E) would plot at 54.5°N and 60.6°E when reconstructed to 251 Ma (annotated white circle denoted ST).

with the Galapagos is good but we deliberately avoid that approach in this paper.

## 3. Reconstructed LIPs

LIP distribution after reconstruction (Fig. 1b) clearly becomes more concentrated than the present LIP distribution with most of the LIPs falling into one or other of two groups. One group, spanning Africa and extending into the Atlantic and Indian Oceans, includes a cluster of 11 LIPs in the SW Indian Ocean. The other group also includes a cluster, the Pacific Ocean cluster. Seismic tomography has shown that low-velocity seismic-shear-wave D″ zone regions also fall into Sub-African and Sub-Pacific areas. We examined three global mantle models in detail, all of which provide broadly similar results. Fig. 1b and our quantitative analysis (Table 1) is based on the SMEAN shear wave velocity model [21] for the lower mantle (2800 km), but for comparison we also show the S20RTS [22] model (Fig. 1a). Our analysis demonstrates that 23 out of 25 reconstructed LIPs fall within the area of slow shear-wave velocity (mean $\delta V_s = -1.0 \pm 0.7\%$) regions of the D″ zone (Fig. 1b) and ~50% of the LIPs overlie regions with $\delta V_s \leq -1\%$

Table 1
Locations of Large Igneous Provinces (LIPS) of the past 200 My

| LIP[a] | | Age | Today | | | At eruption PM frame | | | OBS PM | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | (Ma) | Lat. | Long. | LINK | Lat. | Long. | $\delta V_s$ | Lat. | (δLat) |
| C | CAMP | 201 | 27 | 279 | NAM | 4 | 347 | −1.0 | 2 | (2)[b] |
| K | Karroo | 183 | −23 | 32 | AFR | −39 | 19 | −2.5 | −43 | (4)[b] |
| A | Argo margin | 155 | −17 | 120 | AUS | −42 | 99 | −0.4 | | |
| SR | Shatsky Rise | 147 | 34 | 160 | PAC | −1 | 225 | −1.0 | | |
| MG | Magellan Rise | 145 | 9 | 181 | PAC | −25 | 243 | −1.2 | | |
| G | Gascoyne | 136 | −23 | 114 | AUS | −55 | 84 | −1.1 | | |
| PE | Parana–Etendeka | 132 | −20 | 11 | AFR | −26 | 350 | −1.8 | −24 | (2)[b] |
| BB | Banbury Basalts | 132 | −34 | 115 | AUS | −62 | 70 | −0.1 | −53 | (9)[b] |
| MP | Manihiki Plateau | 123 | −11 | 197 | PAC | −40 | 271 | +0.4 | | |
| O1 | Ontong Java 1 | 121 | −4 | 158 | PAC | −39 | 220 | −0.9 | −24 | (15) |
| R | Rajmahal Traps | 118 | 25 | 88 | IND | −51 | 62 | −1.7 | −46 | (5)[b] |
| SK | Southern Kerguelen (110–119 Ma) | 114 | −59 | 79 | EANT | −54 | 62 | −1.3 | −44 | (10) |
| N | Nauru | 111 | 3 | 168 | PAC | −31 | 230 | −0.9 | | |
| CK | Central Kerguelen | 100 | −52 | 74 | EANT | −46 | 66 | −2.0 | −44 | (2) |
| HR | Hess Rise | 99 | 34 | 177 | PAC | 2 | 239 | 0.0 | | |
| W | Wallaby Plateau | 96 | −22 | 104 | AUS | −45 | 88 | −0.4 | | |
| BR | Broken Ridge | 95 | −30 | 96 | AUS | −49 | 74 | −1.8 | | |
| O2 | Ontong Java 2 | 90 | −4 | 169 | PAC | −30 | 228 | −1.0 | | |
| M | Madagascar | 84 | −26 | 46 | AFR | −47 | 43 | −1.0 | −45 | (2)[b] |
| SL | S. Leone Rise | 73 | 6 | 338 | AFR | 0 | 339 | −0.7 | | |
| MR | Maud Rise | 73? | −65 | 3 | EANT | −68 | 347 | +1.0 | | |
| D | Deccan Traps | 65 | 21 | 73 | IND | −20 | 64 | +0.1 | −26 | (6)[b] |
| NA | North Atlantic | 54 | 69 | 333 | GRE | 54 | 354 | −0.4 | 53 | (1)[b] |
| ET | Ethiopia | 31 | 13 | 43 | AFR | 8 | 41 | +0.2 | 7 | (1) |
| CR | Columbia River | 15 | 46 | 241 | NAM | 47 | 248 | +1.0 | | |

Plate LINK: NAM=North America, AFR=Africa; AUS=Australia; IND=India; GRE=Greenland; PAC=Pacific; EANT=East Antarctica; $\delta V_s$=shear wave anomaly at 2800 km [21] beneath estimated LIP location at eruption time; δLat=difference between latitude predicted from the global palaeomagnetic (PM) model [16] and observed (OBS) measurements from a specific LIP (when available).

[a] Mostly compiled from Eldholm and Coffin [1] and Coffin et al. [2].

[b] Recalculated latitude from original sampling point to 'initial' eruption point (TODAY column).

(Table 1). Only two LIPs, the Columbia River (North America) and Maud Rise (East Antarctica) overlay significantly faster regions. Because the slow regions ($\delta V_s \leq -1\%$) of the D″ zone extend over ~27% of the core–mantle boundary (CMB) (calculated from Fig. 1b) we have demonstrated a clear association between the eruption locations of LIPs and the lower velocity regions of the D″ zone. It is noteworthy that the reconstructed LIPs form a ring at the edge of the low velocity regions rather than clustering in the regions of peak negative velocity (Fig. 1b). This pattern has also been recognized for the location of hotspots [23, 10], notably those argued to have a deep plume origin (Fig. 1a).

Fig. 1b shows a few discrepancies between our palaeomagnetically reconstructed LIPs and the locations expected from hotspot models although LIPs may not have erupted exactly above a plume. Noteworthy deviations are shown for Tristan (linked to Parana–Entendeka volcanism) and Louisville (Ontong Java) which are located at considerably lower latitudes than Parana–Entendeka and Ontong Java (O1/O2), perhaps as a result of southerly hotspot drift [17,24]. A large mismatch is also noted for the postulated Iceland plume that appears to have drifted northward (if responsible for the Early Tertiary North Atlantic LIP). In contrast, Afar, Marion, Kerguelen and Reunion match better with suggested LIP links (0–9°). LIP latitudes predicted from the global palaeomagnetic model and direct palaeomagnetic measurements from some individual LIPs are similar lying within 1–10° of each other (Table 1) but Ontong Java

[24] shows a substantial offset of 15°. Ontong Java (O1) should therefore plot more northerly than indicated in Fig. 1b but still within the low shear-wave velocity region. That mismatch indicates that problems may exist with the Pacific–Africa plate circuit. A comparison of the global palaeomagnetic frame and hotspot frames where Pacific plate motions are determined independently [25] also underscores this problem and yields latitudinal differences of 8 to 18°. However, as noted above, large Cretaceous palaeomagnetic-hotspot misfits are also recognized within the Indo-Atlantic domain pointing to additional problems such as hotspot drift.

## 4. Conclusion and speculations

Regardless of *caveats* such as palaeolongitudinal uncertainty, problems with the Pacific–Africa plate circuit and the advection of plumes in a convecting mantle we argue: (1) that most LIPs of the past 200 My owe their origin to plumes that rose from low-velocity regions of the D″ zone and (2) that the long-term association of LIPs with low-velocity regions indicates that the low-velocity CMB regions have been where they are now with respect to the spin-axis of the Earth and the core for the past 200 My. This is consistent with the observation that the parts of the deepest mantle into which refrigerant slabs of lithosphere have descended over the past ~200 My are those of the high-velocity D″ regions [26]. The low-velocity regions have been heated by conduction from the core and internally by the decay of radioactive nuclides and have not mixed with the descending subducted cold slabs of lithosphere that appear to constitute the mantle's dominant refrigerant. Parts of the D″ zones that escaped cooling became hotter than the neighboring mantle. We attribute the generation of LIPs to some of that hotter material having left the D″ zone episodically and sporadically in thermally buoyant mantle plumes that have risen to the base of the lithosphere.

If CMB heterogeneities have remained fairly stationary relative to the spin-axis (i.e. 'insignificant' true polar wander) then we can reconstruct the continents while keeping the present-day tomography of the deep mantle fixed. This approach is exemplified in Fig. 3a to c where palaeomagnetic (≤200 Ma; this paper), fixed hotspot (≤130 Ma; [14]) and mantle models (≤67.5 Ma; Mantle 1 of [15]) are compared. In all cases, and for all times, Africa remains located above the CMB low velocity zone. If the inference that Africa has moved relatively little in palaeolongitude over the last 200 My can be extended further back in time, the possibility is open for speculating on links between the Pangea Supercontinent and mantle heterogeneities (Fig. 3d). It is perhaps no coincidence that Pangea is centered above the hotter(?) deep mantle and that the Siberian Traps were underlain by a low shear wave velocity anomaly ($\delta V_s = -0.5\%$) when erupted at ~251 Ma. The heterogeneities near the CMB observed today under parts of Africa are probably the residual effect of supercontinent insulation (Fig. 3d), protecting the Pangea mantle from subduction and cooling. Pangea break-up drove most continents toward cold and down-welling mantle [28], whilst Africa (Fig. 3) remained extremely stationary above the Sub-African low shear-wave velocity region at the CMB.

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