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A compositional anomaly at the Earth's core–mantle boundary as an anchor to the relatively slowly moving surface hotspots and as source to the DUPAL anomaly

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Abstract

Analyses of the relative motion using hotspot tracks, age progressions and plate circuits, and of the absolute motion using paleolatitude data indicate that three major long-lived surface hotspots geographically within a very low velocity province (VLVP) at the base of the Earth's mantle, Tristan, Marion and Kerguelen, exhibit small relative motions (<9 mm/yr) in the past 80 Ma. The geochemical DUPAL anomaly maximum in the South Atlantic and Indian Oceans is also shown to geographically coincide with the VLVP boundary when the past plate motions are taken into account. These observations can be explained and related by invoking a mechanism that the VLVP, a compositional anomaly at the core–mantle boundary, serves as an anchor to thermochemical mantle plumes that give rise to these three long-lived and relatively-slowly moving surface hotspots with the DUPAL signature, and as source to the DUPAL anomaly in the South Atlantic and Indian Oceans.

Keywords: VLVP; thermochemical plume; hotspot; compositional anomaly; DUPAL anomaly

1. Introduction

Thermochemical plumes are known to exist in fluid experiments containing compositional anomalies [1–3]. In those experiments, thermochemical plumes are long-lived and exhibit small relative motion to one another [1–3]. If these thermochemical plumes exist and are manifested as hotspots at the surface of the Earth, the anchoring of a basal compositional anomaly offers a physical mechanism for explaining relative fixity of hotspots. The entrainment of the compositionally distinct material by thermochemical plumes may also give rise to distinct geochemistry in the lavas of those hotspots at the Earth's surface.

Recent extensive seismic waveform modeling and travel time analyses revealed a rapidly structurally-varying very-low velocity province (VLVP) at the base of the mantle extending from the South Atlantic Ocean to the Indian Ocean [4–7]. The VLVP has steeply dipping edges, rapidly varying thicknesses (0–300 km) and geometries, and anomalously low shear wave velocities decreasing from −2% at 300 km above the core–mantle boundary to −9% to −12% at the core–mantle boundary [4,5,7]. The maximum P velocity decrease associated with the seismic anomaly is −3% [4,5]. The VLVP regionally extends about 1300 km into the lower mantle beneath southern Africa with both sides of the anomaly

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dipping toward its center [8]. The seismic velocity and structural features unambiguously suggest the VLVP is a compositional anomaly [4–7]. The magnitude of shear-velocity perturbations of the VLVP would also require unreasonable temperature elevations, if the VLVP is purely a thermal anomaly [4]. For a compositional anomaly, an anomaly produced by the core–mantle reaction or segregation of subducted oceanic crust would not likely explain the unique presence and the steeply dipping edges of the VLVP [4]. Thus, it was suggested that the seismic characteristics associated with the VLVP can best be explained by partial melt driven by a compositional change produced early in the Earth's history [4]. Recent geodynamic modeling further indicated that the Earth's subduction history can lead to thermochemical structures similar in shape to the VLVP [9] and a distinct composition could explain the shape of the anomaly in the lower mantle [10].

To understand whether thermochemical plumes are actually at work in the Earth and to explore the relationship between the geochemical anomaly at the Earth's surface and the VLVP at the core–mantle boundary, I study the motions of the hotspots and geochemistry on the ocean floor in the South Atlantic and Indian Oceans.

2. Motions of the hotspots in the South Atlantic and Indian Oceans

Hotspot motions can be studied in two ways. The relative motions between hotspots can be studied using hotspot track orientations, age progressions along the tracks and plate circuits. The absolute motion of the hotspots can also be studied using paleolatitude data along the tracks. The South Atlantic and Indian Oceans have a large number of hotspots and many impressive island chains and aseismic ridges (Fig. 1, Table 1), that are thought to be the tracks left by the passage of surface plates over major hotspots [11–16]. The Tristan hotspot is thought to have created the Walvis Ridge on the African plate and the Rio Grande Rise on the South American plate [11–14]. The Kerguelen hotspot is proposed to have created the Ninetyeast Ridge on rapidly northward-moving Indian plate until at about 45 Ma when the Southeast Indian Ridge migrated over the hotspot, and then left trace entirely on the Antarctic plate [12–14]. The Marion hotspot is suggested to have generated the widespread Cretaceous flood basalts on the Madagascar Island and subsequently created the submarine Madagascar Plateau [13–16]. The Réunion hotspot is thought to have progressed along the Laccadives, Maldives, and Chagos Islands, and then after the Carlsberg Rise migrated over the hotspot, made the southern part of the Mascarene Plateau, the individual islands of Mauritius and the Réunion Island [12–14]. Among these hotspots, Tristan, Marion and Kerguelen are the three longest-lived hotspots. There are now many radiometrically determined ages available along these tracks [16–24].

2.1. Relative hotspot motions based on track, age progression and plate circuits

The relative motion between the hotspots can be studied using orientations and age progressions of these hotspot tracks. If a group of hotspots are stationary with respect to each other, plate motions relative to this group of hotspots could be found so that the predicted past locations of this group of hotspots based on these inferred plate motions would follow their tracks and age progressions observed on the ocean floor. These inferred plate motions would, of course, also need to satisfy the constraints of relative motions in the plate circuits. This can usually be done by deriving a set of finite rotation poles and angles describing the plate motion of a reference plate with respect to the hotspots. The hotspot tracks on the reference plate can be calculated on the basis of the finite rotations and those on the neighboring plates can be predicted on the basis of the hotspot motion relative to the reference plate and relative motions in the plate circuits.

For convenience, the African plate is chosen as the reference plate, and the Tristan and Kerguelen hotspots and their track observations are chosen to test their relative motion first and to derive the motion of the African plate with respect to the two hotspots. Motions of other hotspots are then tested by comparing the observed tracks and age progressions to the predictions, based on the inferred African plate motion with respect to the hotspots and the relative plate motions in the plate circuits.

The finite rotation poles and angles of the African plate motion over hotspots are derived on the basis of the age progressions observed on the Walvis Ridge and the tracks observed on both the Walvis and the Ninetyeast Ridges. The age progression data on the Ninetyeast Ridge are not used in deriving the African motion, as the constraints of one track and age progression and one track are sufficient to derive a unique solution. They are used as an independent check for the fixity of the Kerguelen hotspot with respect to the Tristan hotspot. The position of finite rotation poles is searched globally with an interval of 0.5° in longitude and 0.5° in latitude. The finite rotation angle is searched by every 0.1°. At a given age, the total misfit is defined as the summation of the distance between the predicted location of the Tristan hotspot and the observed location on the Walvis Ridge at

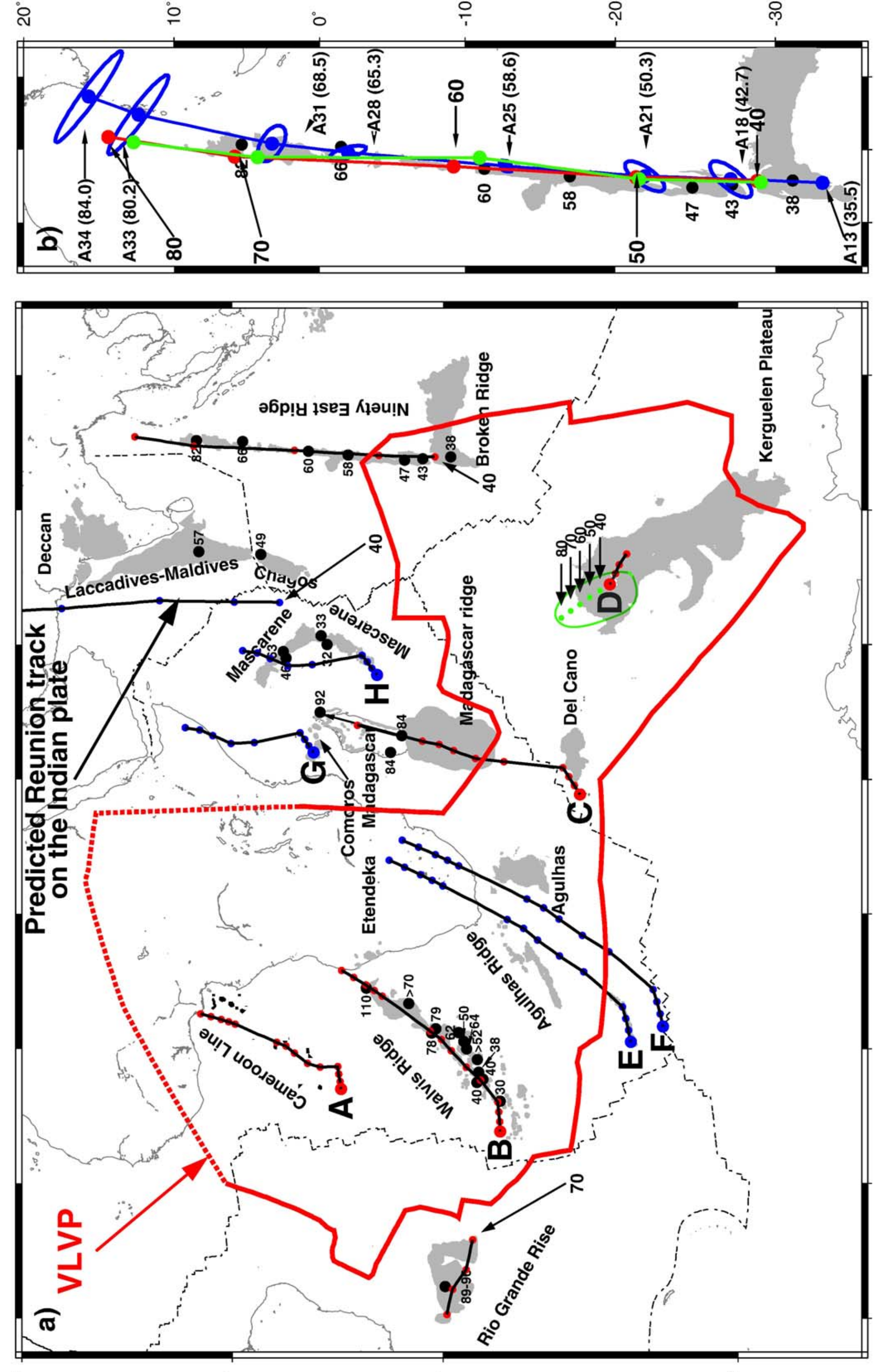
a)
VLVP
Predicted Reunion track on the Indian plate
Rio Grande Rise
89-90
70
Cameroon Line
A
Walvis Ridge
B
110
>70
79
78
62
50
>52
64
40
38
30
Agulhas Ridge
Etendeka
Agulhas
E
F
Comoros
Madagascar
G
92
84
Madagascar ridge
Del Cano
C
Mascarene
H
63
48
33
32
Laccadives-Maldives
Deccan
57
49
Chagos
40
D
80
70
60
50
40
Ninety East Ridge
82
66
60
58
47
43
38
Broken Ridge
40
Kerguelen Plateau
320°
340°
0°
20°
40°
60°
80°
100°
30°
0°
-30°
-60°
b)
A34 (84.0)
A33 (80.2)
80
70
A31 (68.5)
A28 (65.3)
60
A25 (58.6)
A21 (50.3)
50
A18 (42.7)
40
A13 (35.5)
82
66
60
58
47
43
38
85°
90°
95°
20°
10°
0°
-10°
-20°
-30°

Table 1
Hotspot locations

Hotspot	Latitude (N)	Longitude (E)	Track
St Helena (A)	−16.0	−6.0	Unknown track
Tristan (B)	−37.1	−12.3	Walvis Ridge, Rio Grande Rise
Marion (C)	−46.0	37.8	Madagascar Ridge, Madagascar Plateau
Kerguelen (D)	−49.0	69.0	Kerguelen Plateau, Ninetyeast Ridge
Shona (E)	−51.0	1.0	Unknown
Bouvet (F)	−53.9	3.4	Unknown
Comoros (G)	−12.0	44.0	Comoros Islands
Réunion (H)	−21.1	55.5	Mascarene Ridge, Laccadives–Maldives–Chagos Ridge

Table 2
Finite rotations for the African plate relative to the Tristan–Marion–Kerguelen hotspot group

Age (Ma)	Latitude (N)	Longitude (E)	Angle[a] (deg.)
10	51.5	−17.3	1.2
20	51.5	−17.3	2.3
30	51.5	−17.3	3.5
40	6.0 (13.0)	−23.0 (−25.0)	9.5 (8.5)
50	4.0 (19.0)	−26.0 (−35.0)	13.0 (11.7)
60	8.0 (30.0)	−29.0 (−44.0)	15.7 (13.1)
70	10.0 (30.0)	−30.0 (−43.0)	17.7 (14.5)
80	10.0 (30.0)	−31.0 (−44.0)	19.9 (15.9)
90	12.0	−34.0	29.0
100	12.0	−34.0	32.5
110	12.0	−34.0	36.0
120	12.0	−34.0	38.4
130	12.0	−34.0	40.0

Numbers in parentheses are for the example of moving Kerguelen hotspot models.

[a] Counter-clockwise.

that age and the distance between the predicted location of the Kerguelen hotspot and its closest point on the Ninetyeast Ridge (regardless of its age). The inferred set of finite rotation poles and angles is the one that generates the smallest total misfit. The obtained model of the African plate motion with respect to the Tristan and Kerguelen hotspots is presented in Table 2.

The hotspot locations on the South American plate are predicted by combining the derived African motion over the hotspots and reconstruction of relative motions between the South American and African plates [26,27] (rotation parameters for postchron 34 relative motions are from Ref. [26] and those for pre-chron 34 relative motions are from Ref. [27]). The hotspot tracks on the Indian plate are predicted on the basis of the African plate motion and plate reconstruction models by Royer and Sandwell [28] and Molnar et al. [29]. The hotspot tracks on the Antarctic plate are predicted on the basis of the African motion and the plate reconstruction model by Royer and Chang [31].

The predicted hotspot tracks and age progressions for the three longest-lived hotspots, Tristan, Marion and Kerguelen, fit the observations well, except for a slight mismatch of age progressions along the Ninetyeast Ridge for the Kerguelen hotspot. The predicted Tristan tracks match well the geometry and age distribution of volcanism along the Walvis Ridge on the African plate (Fig. 1a). The predictions of the Tristan hotspot also fit the geographic location and the age of the Rio Grande Rise on the South American plate (Fig. 1a), confirming the validity of our inference of the African motion over the Tristan hotspot. The predicted Marion hotspot tracks match the Madagascar Ridge and the Madagascar Plateau well, and the predicted timing when the Marion hotspot was beneath the Madagascar Plateau matches well the ages of the floor basalts there (84–92 Ma) (Fig. 1a). The predicted Kerguelen hotspot track on the Indian plate matches well the orientation along the Ninetyeast Ridge, except that the predicted age progressions are slightly younger than the observations

Fig. 1. (a) Geographic boundary of the VLVP at the core–mantle boundary (red contour, dashed portion being less certain because of the nature of the seismic data) [7], sample locations along with their radiometrically determined ages in Ma (black dots and their associated numbers), and observed (shaded regions, the track data are from Coffin and Eldholm [25]) and predicted hotspot tracks (in 10 Ma intervals, black traces) based on the African plate motion in Table 2 and plate circuits. Model paths of plate relative to hotspots are computed for the following hotspots, hotspot tracks, plates and times: St Helena (A), unknown track, African plate, 0–130 Ma; Tristan (B), Walvis Ridge, African plate, 0–130 Ma; Tristan (B), Rio Grande Rise, South American plate, 70–100 Ma; Marion (C), Madagascar Ridge and Madagascar Plateau, African plate, 0–90 Ma; Kerguelen (D), Kerguelen Plateau, Antarctic plate, 0–30 Ma; Kerguelen (D), Ninetyeast Ridge, Indian plate, 40–80 Ma; Shona (E), unknown track, African plate, 0–130 Ma; Bouvet (F), unknown track, African plate, 0–130 Ma; Comoros (G), Comoros Islands, African plate, 0–80 Ma; and Reunion (H), Mascarene Ridge, African plate, 0–80 Ma; Réunion (H), Laccadives–Maldives–Chagos Ridge, 40–80 Ma. Green ellipse is the permissible locations for the Kerguelen hotspot in the last 80 Ma. Large colored circles are present-day locations of the hotspots (Table 1). (b) The Ninetyeast Ridge (shaded region) and predicted hotspot tracks based on plate motion models by Royer and Sandwell [28] for a fixed Kerguelen hotspot (red track from 40 Ma to 80 Ma with 10 Ma intervals) and an example of a southeasterly drifted Kerguelen hotspot (green track from 40 Ma to 80 Ma with 10 Ma intervals, also see green dots in (a) for the assumed past locations of the Kerguelen hotspot in the example and rotation parameters in parentheses in Table 2; the past locations in (a) are intentionally designed to be more separated in the example to illustrate the effect of a moving hotspot) by Molnar et al. [29] (blue tracks from Chrons A13 to A34 with their associated ages in Ma) with error ellipses with 95% confidence level, calculated based on the uncertainties presented in [29] and the method in [30].

in the older part of the track. Using different plate reconstruction models yields similar results (Fig. 1b). The slight mismatch between the predicted and observed age progressions along the Ninetyeast Ridge indicates that the Kerguelen hotspot moved with respect to the Tristan hotspot in the last 80 Ma. To search for permissible Kerguelen locations in the past, the Kerguelen hotspot is assumed at various positions at different times. The African plate motion with respect to the Tristan and Kerguelen hotspots are re-determined on the basis of the new assumed Kerguelen past locations following the same procedures described above. Permissible locations are determined by searching the possible locations of the hotspot so that rotation poles can be found and the predicted tracks based on the those rotation poles would fall on the Ninetyeast Ridge, regardless of the predicted age progressions (see green ellipse for the permissible locations in the last 80 Ma in Fig. 1). The maximum distance of all the permissible locations in the last 80 Ma is about 700 km, corresponding to a maximum draft rate of about 9 mm/yr. The observed age progression can better be explained if the Kerguelen hotspot has moved in a direction between southeastwardly and eastwardly (see green dots in Fig. 1a for an example of the past hotspot locations and green track and dots in Fig. 1b for the predicted track and age predictions).

The predicted tracks for other hotspots, such as Réunion, Comoros, Bouvet and Shona, however, do not match their observed tracks and age progressions (Fig. 1), indicating these hotspots significantly drift away from the Tristan–Marion–Kerguelen group. Note that the predicted Réunion tracks mismatch the age progression along the Mascarene Ridge on the African plate and are west to the Laccadives Ridge on the Indian plate (Fig. 1a). The predicted Comoros hotspot tracks are about 30° away from the Comoros Islands. There are little coherent hotspot tracks on the ocean floor for the Bouvet and Shona hotspots, but both their predicted tracks are off from either the Agulhas Ridge or the Agulhas Plateau. The St Helena hotspot does not appear to have a clear track.

The above analyses indicate that the Tristan, Kergeulen, and Marion hotspots form a group that exhibit small relative motion (<9 mm/yr) among each other; other hotspots drift away from the Tristan–Marion–Kerguelen group. The relative motion (<9 mm/yr) among the Tristan–Marion–Kerguelen hotspot group is much smaller than the relative motion observed between the Pacific hotspots and the Indo-Atlantic hotspots (about 30 mm/yr) [32] and the drift rate of the Hawaii hotspot (about 43 to 58 mm/yr) [33].

2.2. Hotspot motions based on paleolatitude data

The motion of individual hotspots can also be studied using paleolatitude data along its track. Paleolatitude of a hotspot in the past can be determined using the characteristic remanent magnetization of basalts produced along its track by the hotspot. If secular variation is properly averaged out and the geocentric axial dipole hypothesis of the Earth's geomagnetic field holds, the inclination of the characteristic remanent magnetization should correspond to the latitude of the hotspot at the time of the eruption.

The paleolatitude data support the inference of the relatively small motion among the Tristan–Marion–Kerguelen hotspot group. Torsvik et al. [34] showed that the paleolatitude observed in the southeast Madagascar during the Late Cretaceous is 45.3°S in agreement with the present-day latitude of the Marion hotspot (46°S). They suggested that the Marion hotspot is stationary with respect to the mantle. Van Fossen and Kent [35] reported an agreement of paleolatitudes and the present-day location for the Tristan hotspot in the last 90 Ma. The new paleolatitudes data observed for the Kerguelen hotspot track place the Kerguelen hotspot 5° north of its present latitude of 49°S in the last 80 Ma [36]. Such a paleolatitude shift is within the permissible region based on the plate reconstruction (i.e., green ellipse in Fig. 1), but it would also favor a slowly southward drifted, rather than a fixed, Kerguelen hotspot in the last 80 Ma.

3. Geographical correlation with the "DUPAL anomaly"

Basalts from the ocean floor in the South Atlantic Ocean and the Indian Ocean have been noted to have high $^{87}Sr/^{86}Sr$ ratios and anomalously high $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios for a given $^{206}Pb/^{204}Pb$ ratio [37–40]. Hart termed this unique isotope signature and its geographical distribution the "DUPAL anomaly" [38]. He also suggested that the mantle entity for the DUPAL signature has probably existed for billions of years, as the positive values of isotope anomaly require high time-integrated values for the parent–daughter ratios in the source, and some isotopic ratios such as $^{207}Pb/^{204}Pb$ must date back to the early Earth's history [38].

Since early studies of the DUPAL anomaly [37–40], there have been many more measurements of those isotope ratios. I compile measurements of $^{87}Sr/^{86}Sr$, $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ ratios from the PETDB website (http://www.earthchem.org),

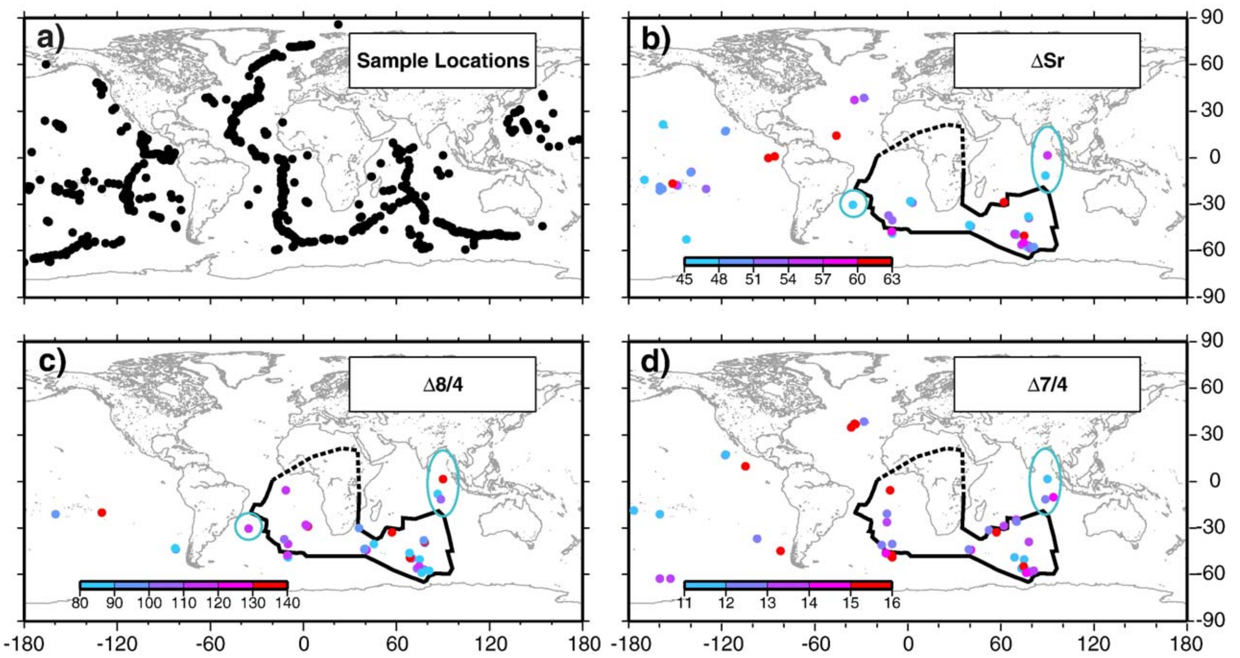

Fig. 2. (a) Sample locations, (b) ΔSr for those with values greater than 45, (c) Δ8/4 for those with values greater than 80, and (d) Δ7/4 for those with values greater than 11. The VLVP boundary at the core–mantle boundary is also plotted (black contour) as reference. Two light blue areas indicate locations of the Ninetyeast Ridge and the Rio Grande Rise.

the collection of Dr. S. Hart (personal communication) and Ref. [37]. There are now a total of 2312 measurements. I have excluded the measurements that were made from the oceanic basalts in the DSDP and ODP drillholes that are away from the hotspot tracks and with ages older than 80 Ma (e.g., 41,42]). The selected measurements provide good coverage of the ocean floor (Fig. 2a).

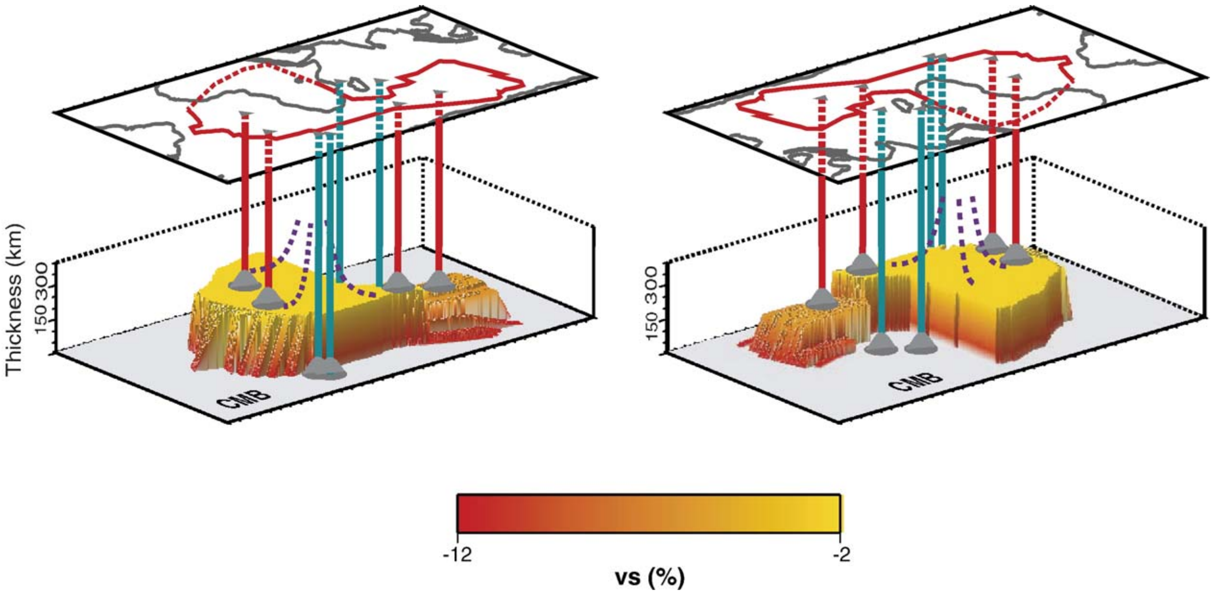

Fig. 3. Three dimensional views of a very-low velocity province (VLVP) at the core–mantle boundary with left panel viewed from 220°N and right panel viewed from 20°N [7], along with relative positions of major hotspots at the Earth's surface color-coded as those in Fig. 1. The VLVP is 300 km thick and has a linear gradient of shear wave velocity reduction from −2% (top) to −9% to −12% (bottom). The blue dashed traces indicate the approximate location of the extension of the VLVP in the mid-lower mantle.

I follow the definitions of the isotopic anomalies outlined by Hart [38]. The magnitude of the Sr anomaly is defined as:

$$\Delta\mathrm{Sr} = [(^{87}\mathrm{Sr}/^{86}\mathrm{Sr}) - 0.7]10,000$$

The magnitude of the isotopic Pb anomaly is defined as the vertical deviation in either ^{207}Pb/^{204}Pb or ^{208}Pb/^{204}Pb from the Northern Hemisphere reference line (NHRL):

$$\Delta 7/4 = [(^{207}\mathrm{Pb}/^{204}\mathrm{Pb}) - (^{207}\mathrm{Pb}/^{204}\mathrm{Pb})_{\mathrm{NHRL}}]100$$

$$\Delta 8/4 = [(^{208}\mathrm{Pb}/^{204}\mathrm{Pb}) - (^{208}\mathrm{Pb}/^{204}\mathrm{Pb})_{\mathrm{NHRL}}]100$$

The Northern Hemisphere reference line, (^{207}Pb/^{204}Pb)$_{\mathrm{NHRL}}$ and (^{208}Pb/^{204}Pb)$_{\mathrm{NHRL}}$, is defined as:

$$(^{207}\mathrm{Pb}/^{204}\mathrm{Pb})_{\mathrm{NHRL}} = 0.1084(^{206}\mathrm{Pb}/^{204}\mathrm{Pb}) + 13.491$$

$$(^{208}\mathrm{Pb}/^{204}\mathrm{Pb})_{\mathrm{NHRL}} = 1.2090(^{206}\mathrm{Pb}/^{204}\mathrm{Pb}) + 15.627$$

The updated isotope data confirm the inferences of the early studies on the DUPAL anomaly [37–40]. All three isotopic criteria, ΔSr, Δ8/4 and Δ7/4, exhibit a strikingly coherent geographic pattern (Fig. 2b–d). The maximum in the anomaly stretches from the South mid-Atlantic Ocean to the central Indian Ocean, the Rio Grande Rise, and the Ninetyeast Ridge (Fig. 2b–d).

The DUPAL maxima are geographically confined within the boundary of the VLVP at the base of the mantle, when the past plate motion is taken into account (Fig. 2). The VLVP exhibits an L-shaped form changing from a north–south orientation in the South Atlantic Ocean to an east–west direction in the Indian Ocean, occupying an area of 1.8×10^7 km^2 (Fig. 3). The VLVP boundary has an uncertainty of about 200 km in lateral location for the area represented by the heavy black contour in Fig. 2 and is less certain in the region represented by the dashed lines in Fig. 2 [7]. Note that the DUPAL maxima observed on the Ninetyeast Ridge and the Rio Grande Rise (light blue contours, Fig. 2b–d) were generated by the Kerguelen and Tristan plumes, respectively. Their locations were geographically within the VLVP at the core–mantle boundary, when the relative plate motions are taken into account (Fig. 1a).

4. Thermochemical Tristan–Marion–Kerguelen plumes as an explanation for the slowly moving hotspots and the VLVP for the "DUPAL" anomaly

The relative small motion and the unique DUPAL signature within the Tristan–Marion–Kerguelen hotspot group can be explained by a mechanism that they manifest long-lived thermochemical plumes anchored by the VLVP at the core–mantle boundary, whose structural features and velocity characteristics unambiguously suggest that it is a compositional anomaly [4,5]. This proposed mechanism is motivated and supported by the results obtained in recent fluid experiments containing compositional anomalies [1–3]. In those experiments, thermochemical mantle plumes first develop as classical thermal boundary layer instabilities from the interface of the compositional anomaly, then as they rise, they locally deform the denser compositionally distinct layer, and entrain by viscous coupling a thin film of the compositionally distinct materials. The presence of the compositional anomalies, their interfacial topography and the entrainment act to anchor the thermochemical mantle plumes [1–3]. As a result, these thermochemical plumes are long-lived and exhibit small relative motion to one another [1–3]. The fact that the Tristan–Marion–Kerguelen hotspot group is geographically within the VLVP makes this thermochemical plume proposal attractive.

The entrainment of the compositional distinct materials from the VLVP at the base of the mantle would further explain the unique isotope signature observed in the DUPAL anomaly. The observed steeply dipping edges, rapidly varying thicknesses and geometries, and anomalously low shear wave velocities associated with the VLVP (Fig. 3) can best be explained by partial melt driven by a compositional change produced early in the Earth's history [4]. In this case, the VLVP likely represents dense chemical bodies from the segregation of dense melts during the early Earth's differentiations, just as the Earth's continent crust represents light chemical bodies which were preferentially accumulated from buoyant melts. Early Earth's chemical differentiation processes likely involved melting and gravitational separation [43]. Dense melts could exist because some melts may be more iron-enriched and/or melts at depth may become intrinsically denser at high pressures [44]. Dense melts could reach the core–mantle boundary by direct sinking, percolation through perovskite solid matrix, or an avalanche of a dense layer at the top of the lower mantle [4,45,46]. The exact nature of the early Earth differentiation processes is unknown, but for a compositional anomaly segregated from such dense melts in the early Earth's history, we may expect its isotopic signature to be in equilibrium with and therefore similar to that of continent crust, which was in fact proposed as a possible source for the DUPAL anomaly [38,39,47]. Thus, the VLVP may explain the enrichments and early developments of these enrichments of the DUPAL signature.

The thermochemical plume hypothesis would explain the DUPAL signature observed in the ocean island basalts (OIBs) associated with these three hotspots. Under this hypothesis, the OIBs are generated by the tails of the thermochemical plumes and the DUPAL signature observed in those OIBs manifests the isotopic characteristics (or their mixtures with other depleted components) of the VLVP materials. The Marion hotspot, however, is worthwhile to mention. Strong DUPAL signature is observed on the ridge axis to the northeast of the hotspot and in the alkalic basalts in the older track of the hotspot in the Madagascan Ridge, but the lavas from near the current position of the hotspot (Funk Seamount, Prince Edward Island, and Marion Island) lack the DUPAL signature [39,48]. One explanation may be that the entrainment of compositionally distinct materials of the thermochemical plume is temporally and spatially heterogeneous. Funk Seamount, Marion Island and Edward Island represent only the most recent activities of the hotspot and their isotopic signature may not be representative to the history of this long-lived hotspot [48].

The DUPAL signature is also observed in the mid-ocean ridge basalts (MORB) of the Indian Ridge (Fig. 2). Although the ridges with the DUPAL signature geographically coincide with the VLVP at the core–mantle boundary, a mechanism is still required to relate the DUPAL signature observed in the Indian MORBs to the VLVP at the core–mantle boundary. The activities of the hypothesized thermochemical plumes of the Tristan–Marion–Kerguelen may explain the DUPAL signature observed in some sections of the ridge system. For example, the Marion thermochemical plume may be responsible for the enriched DUPAL signature observed in some sections of the Southwest Indian Ridge (e.g., 39°–41°E) [48]. However, the activities of the Marion–Kerguelen–Tristan hotspots in the past 80 Ma cannot account for the DUPAL signature observed widespread in the Indian Ridges, as much of the present ridges with the DUPAL signature are far away from the hotspot tracks. The upper mantle beneath those ridges, which are presumed to be the source of the enriched MORBs, would have at least one component with enriched isotope signals to account for the DUPAL signature observed in the MORBs in these ridge systems. The observed widespread DUPAL signature in the Indian MORBs suggests that the upper mantle beneath the Indian Ocean is isotopically different and is contaminated by at least an ancient enriched geochemical reservoir.

There are at least two dynamic mechanisms that could relate the DUPAL signature observed in the Indian MORBs to the VLVP in the lower mantle and explain the geographic pattern of the DUPAL anomaly: (1) a broad upwelling in response to the large-scale mantle circulation may develop surrounding the compositional anomaly in the lower mantle with entrainment of some portion of the VLVP materials. In this case, the returned flow material in the upper mantle beneath the South Atlantic and Indian Oceans, with additional input of isotopically enriched components from the VLVP, is genetically and isotopically different from other regions; and (2) the upper mantle beneath the South Atlantic and Indian Oceans may be contaminated by the initiation of those three hypothesized thermochemical plumes, similar to the proposal discussed in the context of thermal mantle plume [48,49]. In the standard models of thermal plume, a plume is initiated with a large head followed by a small tail [50,51]. A thermochemical plume exhibits same characteristics with a large head entraining a large volume of the compositionally distinct materials followed by a tail containing a small volume of the compositionally distinct materials in the center of the tail [2,3]. In the context of the thermochemical plume hypothesis, the birth of the Tristan, Marion and Kerguelen thermochemical plumes started with large plume heads entraining a large volume of compositionally distinct materials from the VLVP. Some of the entrained VLVP materials may have erupted with the flood basalts and have been carried away by plate motion, and some of them may have been dispersed and stored in the upper mantle that is currently being tapped by the Indian MORBs.

5. Discussions

Many other chemical reservoirs have also been proposed as possible sources of the upper mantle contamination beneath the Indian Ocean, including: (1) recycled ancient subcontinental lithospheric mantle, (2) subducted ancient sediments with oceanic crust and (3) delaminated ancient lower continental crust [47,52–59]. A recent study [47] suggested that the Osmium isotopic measurements would reject both subcontinental lithospheric mantle and recycled sediments with oceanic crust as the cause, and argued that delaminated lower continental crust may explain the DUPAL isotopic signature of the Indian MORBs. Such detachment and dispersal of lower continental crust are speculated to may have occurred during the rifting and breakup of Gondwana [e.g., 47].

The proposals that appeal to delaminated ancient continental lower crust dispersed in the upper mantle or an ancient compositional anomaly near the core–mantle boundary as the DUPAL source for the Indian MORBs have their own strength and weakness. The continental lower crust is known to be an end-member that is able to explain the DUPAL signature. But, it is unclear how the delamination process may have occurred, where the delaminated continental lower crust is being stored in the upper mantle, and why the DUPAL anomaly exhibits such a geographical pattern. The advantages for appealing to an ancient reservoir near the core–mantle boundary are: the existence of the VLVP is clearly recognized in seismology, its distinct composition is indicated by the inferred structural and velocity features of the anomaly, and it would explain the geographic distribution of the DUPAL anomaly. That is, a candidate for an ancient and enriched reservoir is known to exist and is recognized to geographically coincide with the DUPAL anomaly. But, the presumed isotopic signature of such an ancient, enriched, dense melt remains to be confirmed.

The VLVP beneath the South Atlantic and Indian Oceans is one of the two prominent low velocity anomalies in the lower mantle, with the other one located beneath the Pacific Ocean (the Pacific anomaly). The seismic characteristics and geographic boundary of the Pacific anomaly is less well defined. Recent seismic studies indicated that the base of the Pacific anomaly exhibits similar structural features and velocity structures as the VLVP in the South Atlantic and Indian Oceans, suggesting that the base of the Pacific anomaly is also likely compositionally distinct [60–62]. However, unlike the VLVP in the South Atlantic and Indian Oceans, the Pacific anomaly exhibits internal small-scale seismic heterogeneities [60,63]. A distinct isotopic anomaly is also noted on the ocean floor in the western Pacific, but there are no long-lived surface hotspots in the region [64–66]. Furthermore, the effect of mantle flow on the hotspot drifting rate is probably different between the Pacific Ocean and the South Atlantic and Indian Oceans [67,68]. To compare the relationships of the hotspot motion, geochemistry and seismic anomaly in the lowermost mantle in these two regions is, at present, difficult.

It is interesting to note that most of the other hotspots, such as Réunion, Comoros, Bouvet and Shona, are geographically adjacent to the VLVP near the core–mantle boundary (Fig. 3). Similar observations are also reported for other hotspots [69]. One possible explanation is that they manifest thermal plumes generated in the adjacent areas of the VLVP. The adjacent areas of the VLVP may experience a large horizontal stress, because of the VLVP interaction with the surrounding mantle. A large horizontal stress may produce local thickening of the basal thermal boundary layer, and thus create a favorable condition for the development of thermal plumes. Indeed, seismic data revealed the presence of strong small-scale heterogeneities near the core–mantle boundary beneath the Comoros hotspot [70].

The St Helena hotspot is geographically within the VLVP, but lacks the DUPAL signature. It also appears to be a short-lived hotspot. One possibility is that, unlike the Tristan–Marion–Kerguelen group, the St Helena hotspot has a shallower depth origin.

6. Concluding remarks

Three major long-lived surface hotspots geographically within a VLVP at the base of the Earth's mantle, Tristan, Marion and Kerguelen, form a group of hotspots that exhibit small relative motions (<9 mm/yr) in the past 80 Ma. Analyses of the relative motion using hotspot tracks, age progressions and plate circuits, and studies of the hotspot motion using paleolatitude data yield the same results. The geochemical DUPAL anomaly maximum in the South Atlantic and Indian Oceans is also shown to geographically coincide with the VLVP when the past plate motions are taken into account.

The relative small motion and the unique DUPAL signature within the Tristan–Marion–Kerguelen hotspot group can be explained by a mechanism that they manifest long-lived thermochemical plumes anchored by the VLVP at the core–mantle boundary. The presence of the VLVP, its interfacial topography and entrainment act to anchor the thermochemical Tristan–Marion–Kerguelen plumes. The anchoring of the VLVP thus provides a physical mechanism for explaining relative fixity of those hotspots and their longevity. The entrainment of the compositional distinct materials from the VLVP at the base of the mantle by the thermochemical plumes and broad upwelling would further explain the geographical distribution, uniqueness, enrichments and early developments of these enrichments of the DUPAL anomaly.

That the Tristan, Kerguelen, and Marion hotspots are manifestations of the relatively slowly moving long-lived thermochemical mantle plumes tapping an ancient chemical reservoir in the lowermost mantle provides a mechanism for explaining the relative small motions of the Tristan–Kerguelen–Marion hotspot group and the DUPAL anomaly. It would also have significant implications to many aspects of geophysics and geochemistry. For example, the Tristan–Kerguelen–Marion group may be used as a reference frame for studying the absolute surface plate motion and inter-hotspot motion with respect to the deep mantle. The isotopic behaviors of the DUPAL anomaly may be used to place constraints on the thermochemical convection in the mantle, the nature of the distinct materials in the VLVP, and eventually the differentiation processes in the early Earth's history.

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