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Three distinct types of hotspots in the Earth's mantle

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Abstract

The origin of mantle hotspots is a controversial topic. Only seven ('primary') out of 49 hotspots meet criteria aimed at detecting a very deep origin (three in the Pacific, four in the Indo-Atlantic hemisphere). In each hemisphere these move slowly, whereas there has been up to 50 mm/a motion between the two hemispheres prior to 50 Ma ago. This correlates with latitudinal shifts in the Hawaiian and Reunion hotspots, and with a change in true polar wander. We propose that hotspots may come from distinct mantle boundary layers, and that the primary ones trace shifts in quadrupolar convection in the lower mantle.

Keywords: hotspots; mantle plumes; convection; true polar wander

1. Introduction

As plate tectonic theory successfully accounted for much of global volcanism and seismicity, it was noted [1] that a number of volcanoes, often remote from plate boundaries, had not formed by the same processes. Morgan [2,3] proposed that deep mantle plumes created in the lowermost mantle are the source of such hotspots: these are most notable for the linear chain of extinct volcanoes they are thought to have formed on lithospheric plates, as the plates drifted over them. Hawaii and the connected Hawaiian–Emperor seamount chain are the most conspicuous example. It was soon pointed out that hotspot volcanoes could alternately have formed by tensional cracking of the lithosphere [4], whereas Morgan [5] introduced the idea of a second type of hotspot island. Other authors as well [6–8] have elaborated on aspects of primary versus secondary hotspots. Most recently, Anderson [9,10] concluded that Morgan's original deep plume model could be disproved. In his view, all non-plate boundary volcanism can be explained by shallow, plate-related stresses that fracture the lithosphere and cause volcanism along these cracks, promoted for instance by secondary, edge-driven convection in the upper mantle. That such diverse views are still concurrently held could result from hotspots having different sources in the mantle. In this paper, we outline five signatures which may be characteristic of hotspot volcanism produced by a plume originating from deep in the mantle. Then we use those five criteria to sort the hotspot

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catalogues. These criteria are: (1) the presence of a linear chain of volcanoes with monotonous age progression, (2) that of a flood basalt at the origin of this track, (3) a large buoyancy flux, (4) consistently high ratios of the three to four isotopes of helium, and (5) a significant low shear wave velocity (V_S) in the underlying mantle. These criteria are described below, and applied to a selection of 49 hotspots (Table 1) which have been active in the last Myr, based on the most cited catalogues [6,11,12].

2. Five possible characteristics of a deep plume

In a temperature-dependent viscosity fluid such as the mantle, a plume is characterized by a mushroom-shaped head and a thin, long stem. Upon impinging under a moving lithosphere, such a mantle upwelling should therefore produce a massive 'head' event, followed by smaller but long-lived 'tail' events. In this framework, hotspot tracks are produced by impinging of the plume stem, while traps correspond to the plume head [2,13]. Therefore, following previous studies, our first two criteria are (1) long-lived tracks and (2) traps at their initiation. Tracks and flood basalts have been taken from a number of papers [8,13–17].

The buoyancy flux quantifies the flow of material from the mantle which may cause the topographic swell associated with some hotspots [6]. Detailed numerical studies [18] have shown that plumes coming from the bottom of the mantle with a buoyancy flux of less than 10^3 kg s^{-1} should have cooled so much that they would not melt beneath old lithosphere. Moreover, such weak plumes would probably also be sheared by mantle flow before reaching the lithosphere (e.g. [19]). Our third criterion is therefore a flux value in excess of 10^3 kg s^{-1} as a minimum for a 'prominent' hotspot. Note that the calculation of buoyancy flux requires the presence of a topographic anomaly [6], which was one of the original criteria from Wilson [1].

The distribution of rare gas isotopic ratios in volcanic rocks has been shown to discriminate well mid-ocean ridge basalt (MORB) from ocean island basalt (OIB) sources [20]. Farley and Neroda [21] show that most OIB have ranges of ^{4}He/^{3}He ratios either higher or lower than the range of values which characterizes MORB volcanism (7 to 10 times the atmospheric ratio R_A). The distribution of ^{21}Ne/^{22}Ne also strongly supports the existence of two reservoirs [22]. High ^{4}He/^{3}He or ^{21}Ne/^{22}Ne ratios of hotspot lavas have often been attributed to upwellings from a long-isolated and more primitive reservoir [21]. The geometry, volume and location of this reservoir remain strongly debated. Since a shallow reservoir would be likely to be sampled by mid-ocean ridges, it is often considered that the primitive reservoir lies deep in the mantle, confined to the transition zone at the bottom of the upper mantle, or even deeper in the lower mantle (but see [23]). For example, Allègre [24] recently estimated that the depleted mantle reservoir corresponds to 40% of the total mantle, implying the existence of an exchange between the upper and lower mantle through the 670 km discontinuity, and a possible discontinuity

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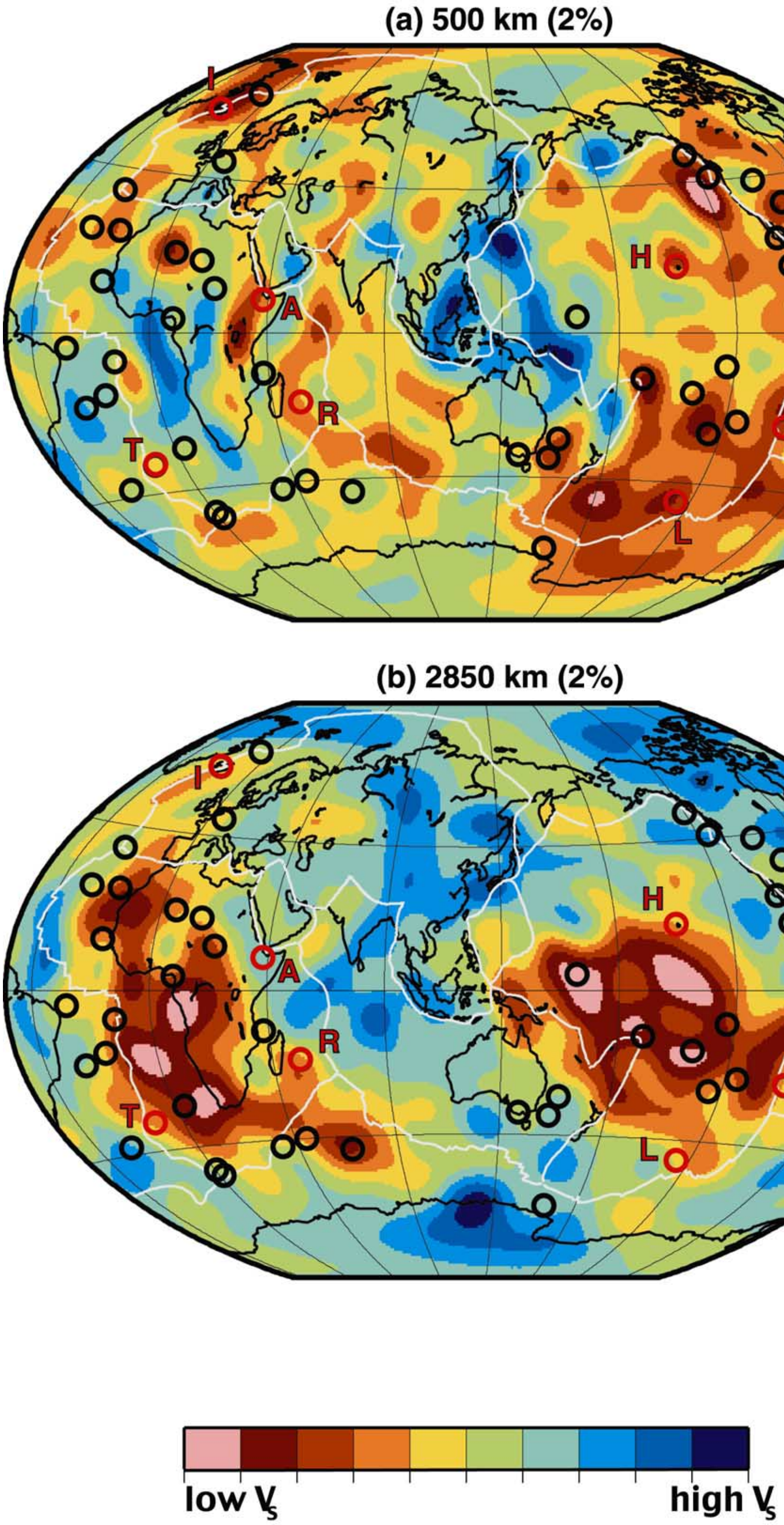
Legend of Table 1.

The hotspots listed here are those found in the most cited catalogues [6,11,12]. Columns are: (1) hotspot name; (2, 3) hotspot latitude and longitude; (4) existence of a linear track or chain of dated seamounts extending from the presently active hotspot site; (5, 6) existence and age of a trap (or flood basalt) or oceanic plateau at the onset of the seamount hotspot track [65]; (7, 8) buoyancy flux (in 10^3 kg s^{-1}) and its reliability [6]; (9) existence of consistently high ^{3}He/^{4}He ratios for the hotspot, following the review of Farley and Neroda [21] with some updates; (10) existence of a slow shear velocity (V_S) anomaly at 500 km depth below the hotspot surface trace (Fig. 1a), based on the tomographic model of Ritsema et al. [25]; (11) count of positive responses to the five characteristics listed previously (columns 4, 5, 7, 9 and 10). A count of one in each column is given if (1) buoyancy flux is larger than 10^3 kg s^{-1}; (2) He ratio is consistently above 10 times the atmospheric ratio R_A; (3) V_S in the lower quarter of the total range, which is from −2% to +2% of the reference velocity at that depth (Fig. 1a and [25]); (4) there is a track; (5) there is a flood basalt or oceanic plateau (LIP or large igneous province). When an answer to one criterion is not available and could be positive, a? is added after the total count to indicate that it could be higher. Hotspots with a total count of at least two (out of five) are shown in bold type, those with a count of at least three are in bold italics.

Table 1
Scores for 49 hotspots with respect to five criteria used to diagnose a potentially deep origin (see text)

Hotspot	Lat	Lon (°E)	Track	Flood/plateau	Age (Ma)	Buoy.	Reliab.	$^{3}He/^{4}He$	Tomo (500)	Count
Afar	***10N***	***43***	***no***	***Ethiopia***	***30***	***1***	***good***	***high***	***slow***	***4***
Ascension	8S	346	no	no	/	na	na	na	0	0+?
Australia E	38S	143	yes	no	/	0.9	fair	na	0	1+?
Azores	39N	332	no?	no	/	1.1	fair	high?	0	1+?
Baja/Guadalupe	27N	247	yes?	no	/	0.3	poor	low	0	0+?
Balleny	67S	163	no	no	/	na	na	na	0	0+?
Bermuda	33N	293	no	no?	/	1.1	good	na	0	0+?
Bouvet	54S	2	no	no	/	0.4	fair	high	0	1+?
Bowie	**53N**	**225**	**yes**	**no**	**/**	**0.3**	**poor**	**na**	**slow**	**2+**?
Cameroon	4N	9	yes?	no	/	na	na	na	0	0+?
Canary	**28N**	**340**	**no**	**no**	**/**	**1**	**fair**	**low**	**slow**	**2**
Cape Verde	**14N**	**340**	**no**	**no**	**/**	**1.6**	**poor**	**high**	**0**	**2**
Caroline	***5N***	***164***	***yes***	***no***	***/***	***2***	***poor***	***high***	***0***	***3***
Comores	12S	43	no	no	/	na	na	na	0	0+?
Crozet/Pr. Edward	45S	50	yes?	Karoo?	183	0.5	good	na	0	0+?
Darfur	13N	24	yes?	no	/	na	poor	na	0	0+?
Discovery	42S	0	no?	no	/	0.5	poor	high	0	1+?
Easter	***27S***	***250***	***yes***	***mid-Pac mnt***?	***100***?	***3***	***fair***	***high***	***slow***	***4+***?
Eifel	50N	7	yes?	no	/	na	na	na	0	0+?
Fernando	4S	328	yes?	CAMP?	201?	0.5	poor	na	0	0+?
Galapagos	**0**	**268**	**yes**?	**Carribean**?	**90**	**1**	**fair**	**high**	**0**	**2+**?
Great Meteor/New England	28N	328	yes?	no?	/	0.5	poor	na	0	0+?
Hawaii	***20N***	***204***	***yes***	***subducted***?	***> 80***?	***8.7***	***good***	***high***	***slow***	***4+***?
Hoggar	23N	6	no	No	/	0.9	poor	na	slow	1
Iceland	***65N***	***340***	***yes***?	***Greenland***	***61***	***1.4***	***good***	***high***	***slow***	***4+***?
Jan Mayen	71N	352	no?	yes?	/	na	poor	na	slow	1+?
Juan de Fuca/Cobb	**46N**	**230**	**yes**	**no**	**/**	**0.3**	**fair**	**na**	**slow**	**2+**?
Juan Fernandez	**34S**	**277**	**yes**?	**no**	**/**	**1.6**	**poor**	**high**	**0**	**2+**?
Kerguelen(Heard)	**49S**	**69**	**yes**	**Rajmahal**?	**118**	**0.5**	**poor**	**high**	**0**	**2+**?
Louisville	***51S***	***219***	***yes***	***Ontong-Java***	***122***	***0.9***	***poor***	***na***	***slow***	***3+***?
Lord Howe (Tasman East)	33S	159	yes?	no	/	0.9	poor	na	slow	1+?
Macdonald (Cook-Austral)	**30S**	**220**	**yes**?	**yes**?	**/**	**3.3**	**fair**	**high**?	**slow**	**2+**?
Marion	47S	38	yes	Madagascar?	88	na	na	na	0	1+?
Marqueses	**10S**	**222**	**yes**	**Shatski**?	**???**	**3.3**	**na**	**low**	**0**	**2+**?
Martin/Trindade	20S	331	yes?	no	/	0.5	poor	na	fast	0+?
Meteor	52S	1	yes?	no	/	0.5	poor	na	0	0+?
Pitcairn	**26S**	**230**	**yes**	**no**	**/**	**3.3**	**fair**	**high**?	**0**	**2+**?
Raton	37N	256	yes?	no	/	na	na	na	slow	1+?
Reunion	***21S***	***56***	***yes***	***Deccan***	***65***	***1.9***	***poor***	***high***	***0***	***4***
St Helena	17S	340	yes	no	/	0.5	poor	low	0	1
Samoa	***14S***	***190***	***yes***	***no***?	***14***?	***1.6***	***poor***	***high***	***slow***	***4***
San Felix	26S	280	yes?	no	/	1.6	poor	na	0	1+?
Socorro	19N	249	no	no	/	na	poor	na	slow	1+?
Tahiti/Society	**18S**	**210**	**yes**	**no**	**/**	**3.3**	**fair**	**high**?	**0**	**2+**?
Tasmanid (Tasman central)	**39S**	**156**	**yes**	**no**	**/**	**0.9**	**poor**	**na**	**slow**	**2**
Tibesti	21N	17	yes?	no	/	na	poor	na	0	0+?
Tristan	***37S***	***348***	***yes***	***Parana***	***133***	***1.7***	***poor***	***low***	***0***	***3***
Vema	33S	4	yes?	yes? (Orange R.)	/	na	poor	na	0	0+?
Yellowstone	**44N**	**249**	**yes**?	**Columbia**?	**16**	**1.5**	**fair**	**high**	**0**	**2+**?


(a) 500 km (2%)
I
H
A
R
T
E
L
(b) 2850 km (2%)
I
H
A
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E
L
low V_s
high V_s

at 820 km depth. Hence, we take a high He or Ne ratio as a fourth indicator of a deep origin for a hotspot.

Hotspots are, by definition, hot. So we have last investigated whether anomalously low shear velocities (V_S) are present in the mantle below hotspots. Such low velocities at depth would point to the presence of less dense, presumably hotter material from the plume. We have compared tomographic models S2ORTS [25] and S39 [26] at depths of 200, 500 and 2850 km. Fig. 1 shows a superposition of the 49 hotspots from our catalogue on V_S tomographic maps at 500 and 2850 km depths from S2ORTS [25]. Plume conduits (or stems) cannot yet be resolved in the lower mantle and we restrict our criterion to identification of a significantly low velocity (lower quarter of the distribution) at the level of the transition zone (Fig. 1a) below the surface trace of the hotspot. Steinberger and O'Connell [12,19,27] have shown that mantle flow may deflect originally vertical plume conduits by up to hundreds of kilometers; we are therefore likely to obtain a number of negative responses to our tomographic criterion in cases when the surface traces of hotspots are significantly displaced with respect to their deeper sources in the transition zone or D″. However, we find that taking into account possible deformation of plume conduits does not significantly alter the results from applying this fifth criterion (slow V_S at 500 km depth).

3. Different types of hotspots on Earth

3.1. Selection of the 'primary' plumes

We applied the five criteria to a list of recent hotspots. Table 1 presents the names (and some aliases) of 49 hotspots [6,11,12], hotspot coordinates (which may vary by more than 500 km in certain publications), hotspot tracks and flood basalts or oceanic plateaus (when they exist) [8,14–17], Sleep's estimate [6] of buoyancy flux and its reliability, and shear wave velocity anomalies at 500 km depth for the tomographic model of Ritsema et al. ([25], see also [26]). We propose that only the nine hotspots which meet at least three out of the five possible criteria are potentially due to deep, or 'primary' plumes. Note that some scores could become higher as more data become available, i.e. if a positive answer was obtained for a criterion for which we do not have a certain answer as yet. For example, Marquesas, Galapagos and Kerguelen may join our list of primary plumes in the future. But, despite a large buoyancy flux, the Marquesas hotspot has a low He ratio and no tomographic expression, and the Shatsky rise may not qualify as the oceanic plateau which would have marked the birth of the Marquesas hotspot. For the sake of rigor and homogeneity, we provisionally exclude Marquesas, which is retained in other analyses (see below and [8]). As far as Macdonald is concerned, it was not included in the short list because of a count of only two. Should an associated track and oceanic plateau be recognized, as suggested by some authors, it would join the group of potential primary hotspots.

One of the nine hotspots with a count of at least three, Samoa, displays a clear, short track without a flood basalt or oceanic plateau at the onset. Whereas absence of evidence (such as is the case for Hawaii, where an original flood basalt may have been subducted) does not allow us to eliminate a potential candidate for primary hotspot, evidence of absence of a starting plume head [13,28] is taken as evidence that the corresponding hotspot is not of the same type. Caroline seems to have no tomographic anomaly nor an associated flood basalt. We therefore retain only seven hotspots as qualifying candidates for deepest, primary plumes: they are Hawaii, Easter and Louisville in the Pacific hemisphere and Iceland, Afar,

←
Fig. 1. Distribution of the 49 hotspots (black circles) from the catalogue used in this paper [6,11,12] superimposed on a section at (a) 500 km and (b) 2850 km depths through Ritsema et al.'s tomographic model for shear wave velocity (V_S) [25]. Color code from −2% (red hues) to +2% (blue hues) velocity variation. The seven 'primary' hotspots outlined in this paper are shown as red circles with the first letter of their name indicated for quick reference.

Reunion and Tristan in the Indo-Atlantic hemisphere.

There are on the order of 40 remaining, non-primary hotspots. These do not have enough indications of a deep, lower mantle origin in our view. We will see below that they can themselves be subdivided into two groups, one of which may have a transition zone origin whereas the other would be much more superficial.

3.2. A fixed hotspot reference frame?

We next test whether this reduced set of seven hotspots possesses the key feature originally proposed by Morgan [2], i.e. whether they represent a fixed reference frame. There have been numerous papers on inter-hotspot motions. Molnar and Stock [14,29] show that average velocities for the last 65 Ma between the Hawaiian hotspot and those in the Indo-Atlantic hemisphere have been 10–20 mm/a. A recent paper [30] argues that motions between certain Pacific hotspots must have reached at least 60 mm/a. This is readily understood if hotspots with different origins have been (erroneously) combined. But when one restricts the analysis to the three primary hotspot candidates, there is no evidence for inter-hotspot motion significantly larger than 5 mm/a [31]. We consider that such rms velocities of 5 mm/a or less, i.e. an order of magnitude less than rms plate velocities, are to first order 'small'. Our conclusion is unchanged if Marquesas is retained in the analysis, as done by Clouard and Bonneville [8]. Clearly, the analysis of the large kinked seamount tracks left by Hawaii, Easter and Louisville, originally made by Morgan, remains valid to first order. The kinematic analysis of Müller et al. [15] shows that inter-hotspot motions between the four Indo-Atlantic hotspots are also less than about 5 mm/a. So hotspots indeed provide a quasi-fixed frame in each hemisphere over the last 80–100 Ma (the age of onset of any hotspot of course gives the maximum time for which data from that hotspot can be tested: these ages are 30 Ma for Afar, 60 Ma for Iceland, 65 Ma for Reunion, 80 Ma for Hawaii (subduction), 100 Ma for Easter, 115 Ma for Louisville, and 130 Ma for Tristan – see Table 1).

We next wish to determine if there was any motion between the two hotspot ensembles. This raises the well-known difficulty of establishing a reliable kinematic connection between the two hemispheres through Antarctica. This has most recently been addressed by Raymond et al. [17], who discuss the importance of an extinct plate boundary within the Adare trough in Antarctica. Based on updated kinematics, these authors predict the location of the Hawaiian hotspot back in time, under the hypothesis that Reunion and Hawaii have remained fixed with respect to each other; for this, they use the dated tracks left on the African and Indian plates by the Reunion hotspot since it started as the Deccan traps 65 Ma ago. The plot of distance (misfit) between the predicted and observed positions for Hawaii as a function of time (Fig. 2a) indicates that the two hotspots have actually drifted slowly, at ~10 mm/a, for the last 45 Ma, but at a much faster rate (~50 mm/a) prior to that (assuming that there is no missing plate boundary or unaccounted for motion between E and W Antarctica). This vindicates earlier conclusions reached by Norton [32] and Tarduno and Cottrell [33]. We conclude that the primary hotspots form two distinct subsets in each one of the two geodynamically distinct hemispheres. Each subset deforms an order of magnitude slower than typical plate velocities. The two subsets have been in slow motion for the last 45 Ma, but in much faster motion in the previous (at least 35 Ma long) period.

3.3. Hotspot paleolatitudes and true polar wander

Fig. 2b and c displays paleomagnetically derived paleolatitudes for the Hawaii [34,35] and Reunion [36–38] hotspots, which can be taken as the best documented representatives from each hemisphere. However sparse, the data are compatible with the same simple two-phase history, in which there was little latitudinal motion in the last 45 Ma, but significant equatorward motion prior to this, at about 60 mm/a for Hawaii and 30 mm/a for Reunion. There is an uncertainty of a few Ma (up to 5) on the timing of the change from one phase to the next at 40–50 Ma. The ~45 Ma date is most accurately fixed by the

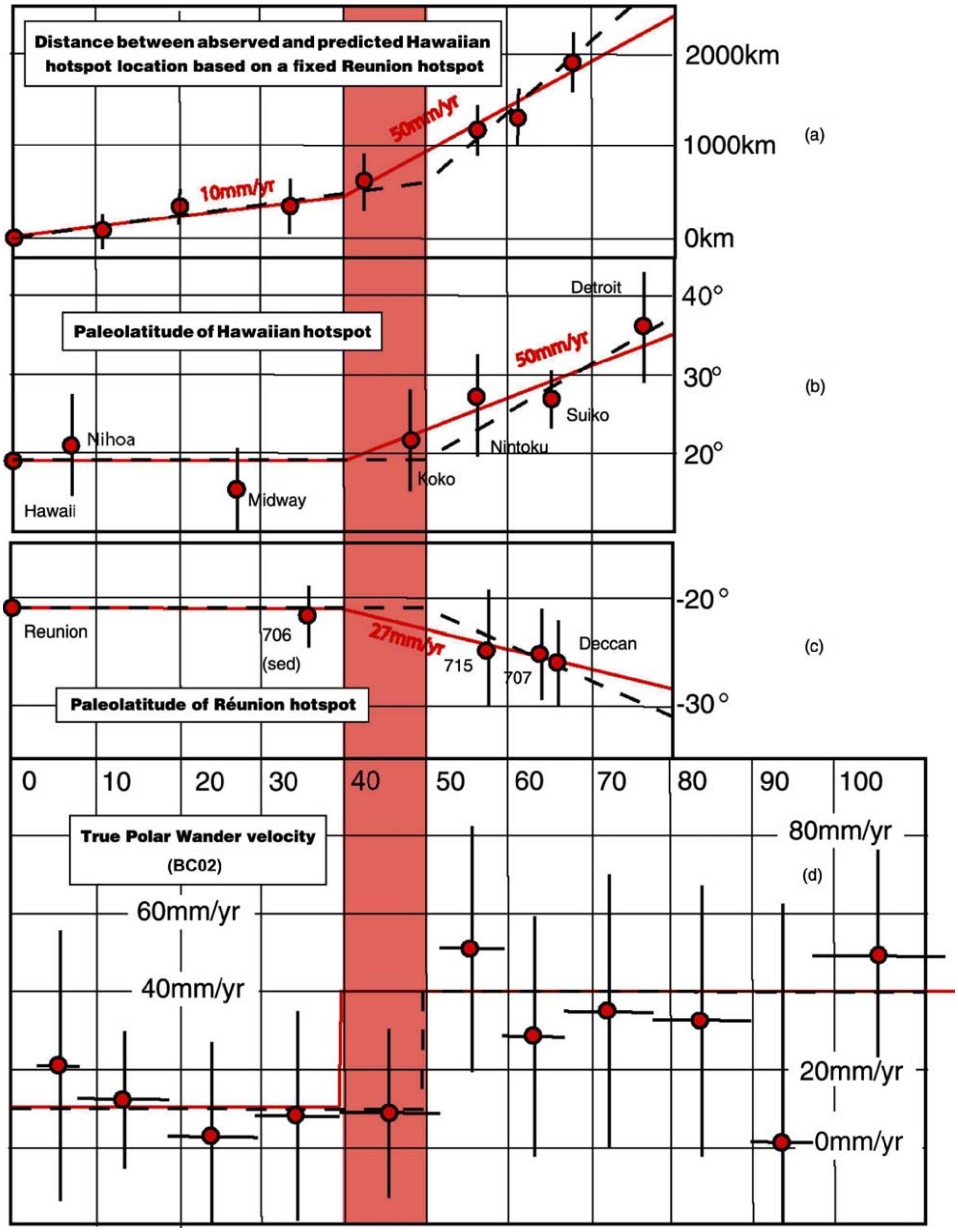

Fig. 2. Time variations of four significant kinematic, geographic or dynamic indicators of hotspot motion (all on the same time scale in million years BP). All display a step-like (Heavyside) change in velocity at ∼40–50 Ma. Velocity patterns are shown as full red or black dashed lines, depending on whether the change happened at 40 or 50 Ma. (a) Distance between observed and predicted positions for the Hawaiian hotspot [17]. Predicted positions are based on the hypothesis that the Reunion and Hawaiian hotspots have remained fixed with respect to each other; the dated track of the Reunion hotspot is transferred to the Pacific plate following kinematic parameters discussed by [17], notably those in the Adare trough between E and W Antarctica. (b) and (c) Latitudinal evolution of the Hawaiian and Reunion hotspots based on data from [34–38]. (d) Along track true polar wander velocity at 10 Ma intervals [39].

age of the bend of the Hawaiian–Emperor chain, if this is indeed the common time of change of all processes described in Fig. 2, which we assume to be the case to a first approximation.

Besse and Courtillot [39] have recently re-evaluated estimates of true polar wander (TPW) over the last 200 Ma. This is based on the paleomagnetically constrained motion of a reference frame linked to hotspots with respect to the Earth's rotation axis. There was little TPW over the last ∼50 Ma, preceded by constant, significant TPW, at ∼30 mm/a, back to about 130 Ma (Fig. 2d). As emphasized by Besse and Courtillot, this estimate of TPW is uncertain, being based only on hotspots from the Indo-Atlantic hemisphere; it fails to include Pacific data, partly because these data do not meet the selection (reliability) criteria imposed on the study, partly because transfer of these data through Antarctica was deemed too uncertain. Another TPW curve can be estimated using Pacific-only data [39,40]; it is similar to the Indo-Atlantic TPW, seemingly validating to first order the concept that TPW is a global phenomenon [39]. But, on closer inspection, it is found that TPW pole positions for the two hemispheres are significantly displaced (by ∼12 ± 5°) between ∼50 and ∼90 Ma.

4. 'Primary' plumes and convection in the lower mantle

The similarity between the four curves shown in Fig. 2, each displaying a step-like change in velocity at ∼40–50 Ma, is striking. These common features may be used in an attempt to constrain the depth from which the primary plumes originate, the origin of the motion they trace, and perhaps the origin of episodic true polar wander.

4.1. Plumes and superplumes

We have seen that the kinematics of primary hotspots outline their distribution as part of two separate hemispheres. These two hemispheres have been found to extend from the transition zone to the core–mantle boundary in seismic images of the lower mantle, whose resolution has steadily increased over the last 20 years [25,26, 41–45] (Fig. 1b). The two hemispheres also correspond to the dominant degree 2 observed in the geoid [41–47]. Present-day convection in the lower mantle appears to be dominated by a quadrupolar mode [48], in which cold, denser material subducts and sinks in the mantle, circumventing two large areas centered on roughly antipodal equatorial regions situated under Africa and the central Pacific where hot, less dense, and seismically slower material (the two superplumes) rises. Many hotspots are located above these 'hot' regions [49] (Fig. 1b). On closer inspection, the pattern in the hot hemispheres may be more complex. The two massive upwellings responsible for the superswells beneath western Africa and French Polynesia [25,26,50] are not only hotter but likely chemically heterogeneous (e.g. [51]). Since the superplumes are situated at more or less central locations in the hot areas, six out of seven of our primary hotspots are found at their margins. Only the Icelandic plume is rather remote from them. However, it is worth noting that the dynamic swells associated with the superplumes and at least five of our primary plumes (Louisville, Hawaii, Tristan, Réunion and Iceland) do not overlap (Fig. 3). So, although primary hotspots seem to be closely associated with convection in the lower mantle, they may not originate from the superplumes.

4.2. Origin of primary plumes

Primary hotspots can be traced in the upper mantle down to the transition zone; they can only be produced by plumes which originate from instabilities out of a thermal boundary layer. The most likely locations of such boundary layers are in the transition zone and at the core–mantle boundary. Seismology is as yet unable to resolve the stems of individual plumes in the lower mantle and therefore cannot tell if the primary plumes come from deeper than the transition zone. A recent geochemical analysis advocates such a transition zone origin [24]. Another [52] invokes a lower mantle enriched in Fe and Si and depleted in Mg; the fact that lavas from flood basalts may be significantly enriched in Fe with respect to

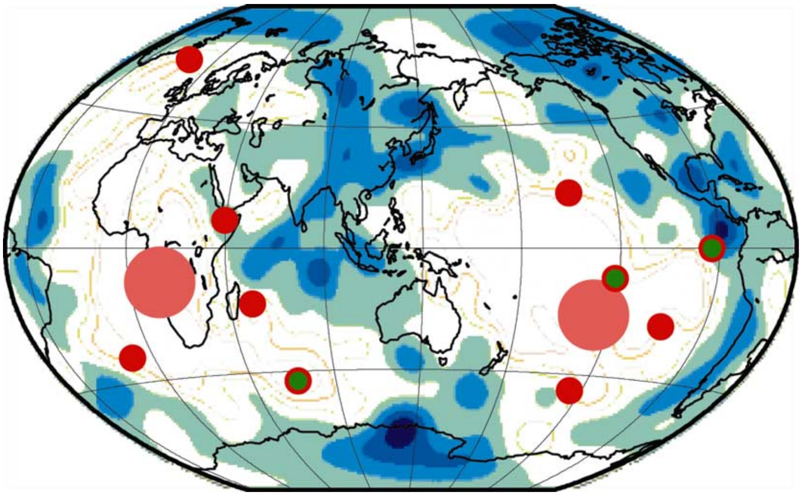

Fig. 3. Primary plumes and superswells shown on a tomographic map of shear wave velocity at 2850 km depth [25]. Only the positive (fast, cold) anomalies are shown in blue shades. The negative (slow, hot) anomalies are in white (the complete tomographic picture is seen in Fig. 1b). The locations of the Pacific and African superswells are indicated as large pink dots. The seven primary hotspots identified in the paper are shown as smaller red dots. Three hotspots that could be part of the primary group (see text) are shown as green dots with red edges. The primary hotspots tend to form above hot regions but away from both superswells and the cold (subduction-related?) belts.

OIB (E. Humler, personal communication, 2002) would then favor a lower mantle origin for primary plumes. As advocated for instance by Richards et al. [13] and Campbell and Griffiths [28], producing traps at the onset of a hotspot as melt related to the impingement of a cavity plume head requires melting of more than 10^8 km^3 of mantle material, potentially filling the upper mantle. It is not easy to see how such a large instability could form in the transition zone. Idealized laboratory and numerical fluid mechanics experiments show that it is easier to produce such an instability in the thermal boundary layer at the core–mantle boundary [53–56]. The tails (stems) of primary plumes tend to last on the order of 130 Ma. Indeed, all plumes born as traps in the last 100 Ma (Ethiopia-Yemen/Afar, Greenland/Iceland, Deccan/Reunion) are still quite active, whereas those born between 100 and 140 Ma may be failing (Ontong-Java/Louisville, Parana-Etendeka/Tristan) and those older than 150 Ma do not in general have an active trace (Karoo, CAMP, Siberia, Emeishan) [16]. Fluid mechanics arguments show that the joint presence of a very large head and a small but long enduring tail can only be produced at depths much in excess of the transition zone [53–56]. In conclusion, though seismology and geochemistry have yet to demonstrate a CMB origin for primary plumes, such an origin seems likely to us, based on (1) fluid mechanics arguments, (2) the observations of the huge volumes that must be melted to produce flood basalts and (3) the long durations of their conduits which must produce island chains.

4.3. *Two types of upwelling in the lower mantle and two types of hotspots*

The question now is whether two scales of upwelling, 'superplumes' and 'primary' plumes, can both originate from the bottom of the lower mantle. Recent experiments by Davaille et al. [57,58] show that simultaneous generation of superplumes and hotspot plumes indeed arises naturally from thermochemical convection in a heterogeneous mantle. Its style depends on a local buoyancy ratio (ratio of the chemical density anomaly to the thermal density anomaly): for low buoyancy ratio (i.e. weak density anomaly of chemical origin), large domes or 'superplumes' are generated, whereas for higher buoyancy ratio

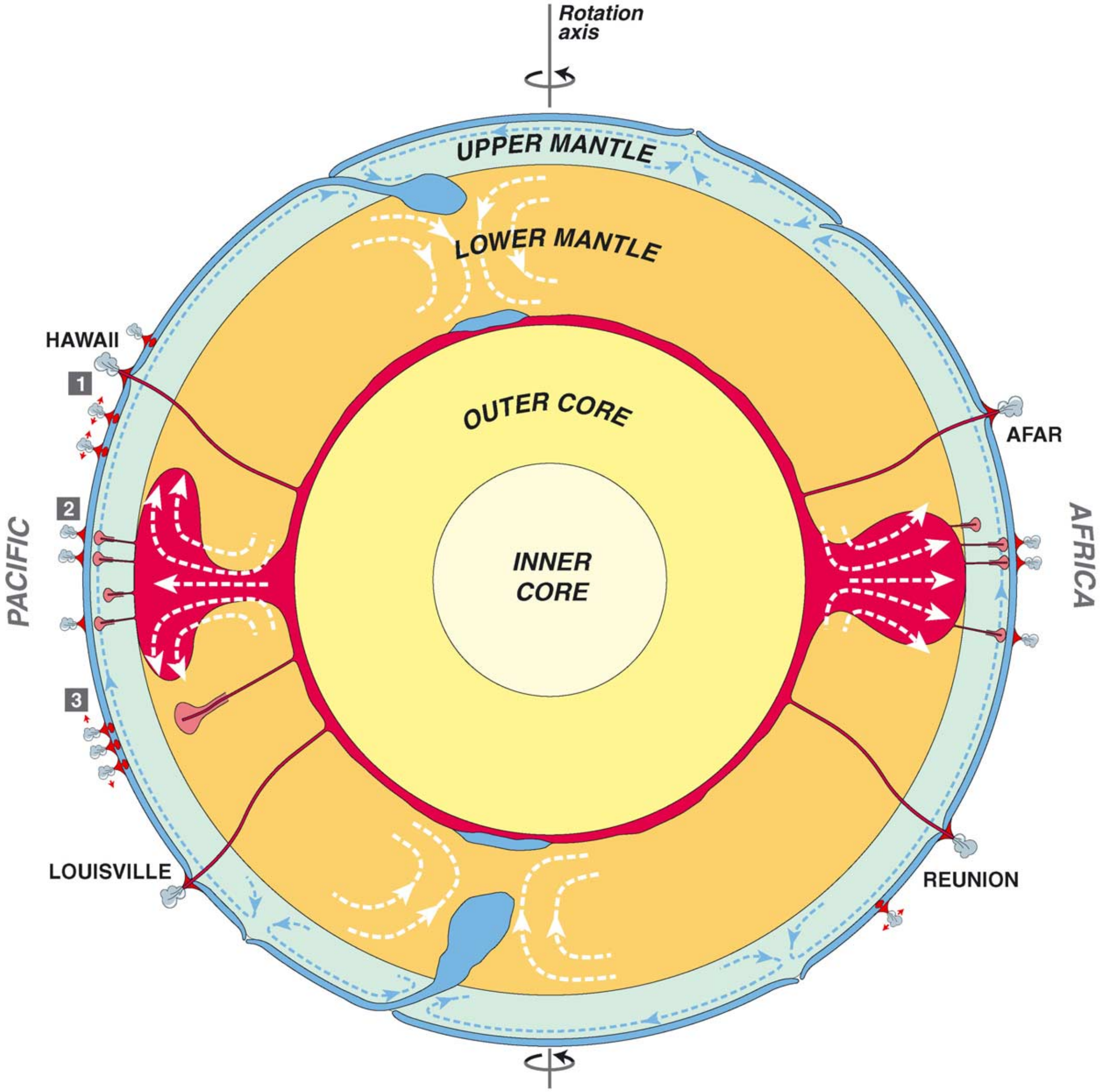

Fig. 4. A schematic cross-section of the dynamic Earth going through its rotation axis, outlining the sources of the three types of plumes/hotspots identified in this paper: the 'primary' or main, deeper plumes possibly coming from the lowermost mantle boundary layer (D″ in the broad sense) are the main topic of the paper; the 'secondary' plumes possibly coming from the top of domes near the depth of the transition zone at the locations of the superswells are indicated [46,47]; the 'tertiary' hotspots may have a superficial origin, linked to tensile stresses in the lithosphere and decompression melting [9,10]. There are on the order of 10 primary (deeper) plumes forming a girdle around the two antipodal domes upwelling below the central Pacific and Africa. At present only plume tails and no plume heads are active and close to the surface, and the number of plumes in a single cross-section is less. The fluid mechanics aspects are based on the experimental study of thermochemical plumes by Davaille et al. [57,58], and the lower mantle domes are based on seismic tomography [25,26]. The location of possible avalanches [63] at the downwellings of the lower mantle quadrupolar convection cells are indicated by sagging in the transition zone, though no such event is thought to be presently active.

long-lived thermochemical plumes are produced [57,58]. Density anomalies of chemical origin in the Earth's mantle inferred from seismic data and mineral physics studies (probably less than 2% [59]) would be sufficient to produce both modes. In this framework, a primary plume could be a thermochemical plume issuing from an instability involving higher chemical density anomalies. Moreover, since a thermal boundary layer would exist at the interface between a superplume and the rest of the mantle, it could generate secondary thermal plumes, all the more if the dome is stuck at the transition zone, as seems to be the case presently under Polynesia: many of the hotspots which did produce short linear tracks without flood basalts (e.g. Tahiti, Cook-Australs and Pitcairn) could correspond to this secondary type of plumes. Note that surface motions of these secondary plumes could also reflect lower mantle convection, hence be consistent with those derived for primary plumes. However, the associated tracks are in most cases too short for a significant test of this (but see [8,12,15,19]). In any case, the short length and duration of these tracks and the lack of a flood basalt at the onset seem to distinguish these secondary hotspots from the primary ones.

4.4. Tracing convection in the lower mantle

Due to the high viscosity of the bulk of the lower mantle [12,27], the primary (and probably also the secondary) plumes behave as quasi-passive tracers of the large-scale motion imposed on the lower mantle by quadrupolar convection. The two subsets of primary hotspots indicate that the two separate reservoirs of quadrupolar convection, centered on the Pacific and African super-upwellings, have moved little ($\sim$10 mm/a) in the last $\sim$40–50 Ma with respect to each other, but underwent significant ($\sim$50 mm/a) rather uniform relative motion in the previous tens of millions of years. This motion was already going on prior to the oldest preserved trace of the Hawaiian hotspot (e.g. prior to 80 Ma). We turn to TPW curves to estimate when this motion may have started. Hotspot tracks become fewer and more uncertain as one goes back in the past and pre-100 Ma TPW estimates should be regarded with caution. However, there are indications [39] that a major phase of true polar wander may have started $\sim$130 Ma ago. What could have triggered it? The geometry of density anomalies associated with upwellings (notably with the two superswells) does not have a large effect on the principal axes of inertia of the Earth and hence on TPW [60]. On the other hand, cold subducted material, accumulated at the base of subduction zones, in the transition zone, along the great circle of quadrupolar convection in the lower mantle, may trigger a major avalanche in the lower mantle [61–63]. Such an avalanche could have started at the transition zone some 130 Ma ago, and could well have set Earth on the episode of TPW which lasted until $\sim$40–50 Ma ago. An alternate interpretation would be the disappearance of a major subduction zone system, after which both heat flow and mean temperature would have been rapidly and significantly altered (S. Labrosse and L.-E. Ricou, personal communication, 2002). The more recent event at 40–50 Ma could then be related to the closure of the huge Tethys subduction zone, following the generalization of Indian collision, as has been suggested for a long time in order to interpret the Hawaii–Emperor bend [64]. Episodes of TPW could be the result of such (rare) events, with alternate episodes of quiescence lasting tens of millions of years. And primary hotspots would be our main source of information on their time history, being the passive markers of readjustments in the two-cell geometry of the lower mantle reservoirs.

5. Conclusions

We suggest that surface hotspots on Earth may have three distinct origins (Fig. 4): (a) At least seven would originate from the deepest part of the lower mantle (we might call them 'Morganian'), probably anchored on chemical heterogeneities deposited in the D″ layer [55,56]. Because we made a conservative count, the actual number of primary hotspots could be higher, maybe on the order of 10. (b) Some ($\sim$20) may originate from the bottom of the transition zone at the top of the large transient domes that correspond to the superswells: Caroline, Mc Donald, Pitcairn, Samoa and Tahiti are good candidates for these secondary hotspots. (c) The remainder ($\sim$20) could be upper mantle features, and in that sense 'Andersonian'. These hotspots may be linked to the asthenosphere and be a passive response to forms of lithospheric breakup. They are the subject of extensive work [7,10].

Mixing the three distinct types of hotspots, with the hope of establishing a single origin, could be the reason for most of the debates that have opposed apparently conflicting, endmember models for the last decades. The three types of hotspots may simply correspond to the three boundary layers between the core–mantle boundary and the surface of the Earth. Hence, that there may not be more than these three hotspot types could have been anticipated.

6. Note added in proof

The authors would like to also refer the reader to the paper by G.F. Davies (Cooling the core and mantle by plume and plate flows, Geophys. J. Int. 115 (1993) 132–146), in which Davies summarizes Earth cooling in a nutshell, the function of plate tectonics being to cool the mantle, and that of plumes to cool the core.

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