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Relative hotspot motions versus True Polar Wander

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Abstract

The fixity of hotspots and mantle plume locations has long been axiomatic. If the assumption of fixed hotspots is granted, 'absolute' plate motions and movements of the spin axis with respect to the hotspot framework, defined by some as True Polar Wander (TPW), can be determined. However, this assumption can be tested by paleomagnetic data, and such tests are gradually raising some doubts about the fixity of hotspots. The result is that discrepancies between Cretaceous and Tertiary hotspot and paleomagnetic reference frames are now beginning to be interpreted as the result of plume drift within a convective mantle. In the Indo–Atlantic, hotspots have remained relatively stationary with respect to the spin axis for the last 95 million yr. However, the Pacific hotspots, notably Hawaii, appear to have undergone large-scale southward drift with respect to the spin axis during the Early Tertiary. Global paleomagnetic data do not indicate that any TPW occurred during the Late Cretaceous or Tertiary. Although the Early Cretaceous paleomagnetic and hotspot frames for the Indo–Atlantic realm can be interpreted as slow TPW, direct estimates of paleolatitude and hotspot motion, in particular the Kerguelen hotspot, challenge TPW as a global phenomenon. At present, we consider that the large Early Cretaceous discrepancy between hotspot and paleomagnetic data is best explained by southward drift of the Atlantic hotspots prior to ~95 Ma.

Keywords: hot spots; paleomagnetism; reconstruction; true polar wander; apparent polar wandering

1. Introduction

In this review we address the issue of the fixity of hotspots and the mantle plumes that feed them. If hotspots are fixed, then the framework they provide is suitable for determining 'absolute' plate movements, and any discrepancies with movements determined from paleomagnetic data can then be ascribed either to imperfections in the latter technique, or to True Polar Wander (TPW). Moreover, fixed hotspots can present a unique contribution to reconstructions because they would provide paleolongitudinal control, in contrast to reconstructions based on paleomagnetic data alone. The underlying assumption that hotspots are stationary, or move at insignificant speeds relative to plate-tectonic velocities [1–3], has long been taken for granted. However,

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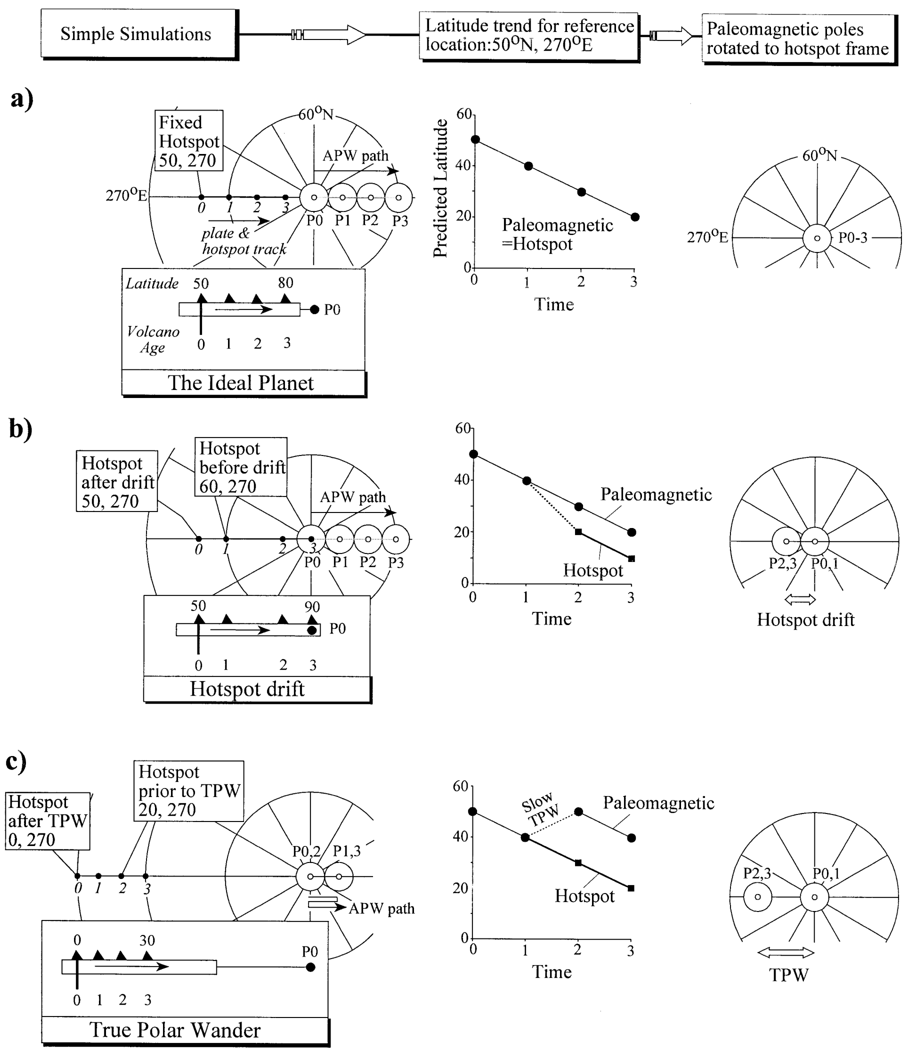
if hotspots are not stationary (e.g. [4–6]), then TPW does not necessarily need to be invoked. Moreover, assessing whether and how hotspots and mantle plumes move, is of primary importance for our understanding of mantle dynamics. Fortunately, there are tests available to discriminate between TPW and hotspots moving with respect to each other, and these tests will be described in the main sections of this review.

TPW is here defined as the rotation of the entire earth with respect to the spin axis [7]. Because the most robust plate kinematic and paleomagnetic data are from the Late Mesozoic and Cenozoic, TPW can be best evaluated during these times; thus we restrict our review to the last 130 Ma. Recent claims for either TPW or moving hotspots during Early [6,8–11] as well as Late Cretaceous times [12,13] have generated heated discussions in the literature. Thus, we focus here on the enigmatic difference between the two relevant reference frameworks during the Cretaceous. We blend observational data with simple simulations to clarify the principles behind the data sets and the resulting plate reconstruction scenarios in which TPW and hotspot drift may be responsible for discrepancies between data sets.



2. Simulation 1: the ideal planet

Consider a plate moving north across a stationary hotspot at constant speed (Fig. 1a). Its hotspot track is defined by a volcanic chain and because all the volcanoes acquired their magnetic vectors at the same latitude (50°N), identical paleomagnetic inclinations (67.2°) and declinations (0°) would be measured at each volcano. However, because the volcanoes now span a wide latitude (50–80°N), the resulting paleomagnetic poles must span the same latitudinal range as the chain of volcanoes, from the current north pole, in our example, to 60°N, 90°E. On this ideal planet the hotspot is stationary, no TPW occurred, and the paleomagnetic data represent a perfect time average of a geocentric axial dipole field.

Apparent Polar Wander (APW) is defined as the motion of the Earth's rotation (≈dipole) axis relative to a fixed plate. An APW path is a sequence of paleomagnetic poles in time and space, and can easily be inverted to represent plate motion relative to a fixed rotation axis (e.g. 'continental drift'). By definition, APW = continental drift+TPW. In our simulation, our equation reduces to APW = continental drift, and the stationary hotspot produces a volcanic track that perfectly matches the APW path. If we select an arbitrary reference location (50°N, 270°E), plots showing latitude vs. time for the paleomagnetic and hotspot data will be identical. As an additional test, we can use the hotspot reconstruction parameters to rotate the paleomagnetic poles back in time. In our ideal world, all paleomagnetic poles will plot at 90°N in the hotspot frame (Fig. 1a, right-hand diagram).

3. Simulation 2: hotspot drift

Departures from the idealized case above produce misfits between reference frames. In the next simulation we introduce a change in the location of the hotspot between t = 2 and t = 1 (Fig. 1b). The resultant APW path is the same as before, but the hotspot track is different: there will be a greater spacing between the ancient volcanoes with ages t = 1 and t = 2. Whereas the plate only

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Fig. 1. Simple simulations (left hand diagrams), latitudinal trend for an arbitrary location (in our case we used present-day 50°N) based on the hotspot and paleomagnetic frameworks (center diagrams), and stereographic projection (right-hand diagrams) showing paleomagnetic poles (P0–P3) in left-hand diagrams rotated into the hotspot frame using Euler poles calculated from the hotspot tracks. (a) Pure continental drift on the ideal planet. A plate moves north across a stationary hotspot (50°N, 270°E). Plate movement is described by Euler latitude = 0°N, longitude = 0°E and angles incremented in 10° steps. The hotspot track (black dots) defines a chain of volcanoes spanning latitudes 50–80°N. The position of the paleomagnetic pole calculated with the geocentric axial dipole model is independent of the observation point on a given plate and paleomagnetic poles are expected to represent the past geographic north and south pole when the rocks were magnetized. Paleomagnetic poles are fixed relative to a plate, so as the plate moves northward the paleomagnetic poles (P1–P3) move with it. In this simulation, all volcanoes locked their magnetic vectors at the same latitude (50°N) and should yield inclinations of 67.2°. The hotspot and paleomagnetic frames produce identical latitudinal trends vs. time (0–3), and when paleomagnetic poles (P0–P3) are rotated into the hotspot frame, all paleomagnetic poles plot at 90°N because the hotspot and paleomagnetic frameworks coincide. Pure continental drift should produce similar hotspot and APW tracks, and continental drift involving a significant change in plate direction produces a bend in both the hotspot track and the APW path. (b) Continental drift plus hotspot migration. We simulate drift as in (a) but between t = 2 and t = 1 we impose a change in the hotspot location. Current hotspot location is 50°N–270°E (t = 0 and t = 1) but at t = 2 and t = 3 it was located at 60°N–270°E. The resultant APW path will be identical to that of (a), but hotspot drift in this example will cause a wider volcano spacing. The hotspot latitude trend for a point on the plate, which today is at 50°N, predicts a lower latitude at t = 2 and t = 3 than the paleomagnetic framework. Paleomagnetic poles rotated to the hotspot frame will be as in Simulation 1 for t = 0,1 but produces a 10° misfit for t = 2,3. (c) Continental drift plus slow TPW. Between t = 2 and t = 1 we introduce 20° of TPW (Euler pole of latitude = 0, longitude = 0). The plate and its existing volcanoes, the older paleomagnetic poles and the hotspot source will be displaced by 20° relative to the spin axis during the TPW event. However, we maintain northward continental drift before, during, and after the TPW event. The hotspot track will be as in Simulation 1, but the APW path moves back-and-forth. Paleomagnetic frame now shows higher latitudes for t = 2 and t = 3 (before TPW) compared with the hotspot frame, and paleomagnetic poles rotated into the hotspot frame will show the spin axis orientation before (t = 2,3) and after 20° TPW (t = 0,1).

moved 30° from t = 3 to t = 0, the hotspot track is now 40° long. The latitude trend for a present-day location on the plate shows that the hotspot frame predicts a lower latitude at t = 2 and t = 3 than does the paleomagnetic frame. Rotating the paleomagnetic poles to the hotspot frame produces a misfit for t = 2 and t = 3, whilst the poles for t = 0 and t = 1 coincide with the spin axis. Clearly, hotspot drift will produce a gap (Fig. 1b) or a bend in the hotspot track, whilst the APW path will be unaffected and remain similar to Simulation 1. However, the effects will be seen only in plates located above the particular hotspot that moved, and will not have a global coherence.

4. Simulation 3: slow TPW

Given that TPW occurs today, it is easily observable that all continents, past locations of the rotation axis, hotspot tracks and the mantle plume sources themselves are rotating around the same Euler pole, which by definition is always located at the equator. In order to detect this phenomenon for geological times, we need to know several things, foremost among these being the past location of the rotation axis. Thus, we must assume that the geocentric axial dipole remains locked to the spin axis so that we can utilize paleomagnetic observations for this purpose. It also follows that paleomagnetic poles calculated for times immediately prior to, or after a rapid and large TPW event, (TPW ≫ continental drift) should be different for any site. In other words, the 'signature' APW for a significant TPW episode is recognizable for all locations on Earth, should have everywhere the same magnitude, and be attributable to a rotation about the same Euler pole for all plates when restored to their ancient paleogeography.

In Simulation 3 we introduce 20° of slow TPW between t = 2 and t = 1 (Fig. 1c). This results in slow southward movement of both the hotspot and the plate with respect to the rotation axis held fixed. Because relative motion between the plate and the hotspot was the same as in Simulation 1, a chain of southward younging volcanoes will be produced. On this (and any other) plate, TPW will cause the older paleomagnetic poles to be displaced northward by 20°. However, if the hotspot remained fixed in the mantle, the reconstruction parameters derived from its track would be identical to Simulation 1. The APW path appears to move back-and-forth, which with some noise in the data could manifest itself as an APW standstill. The hotspot track predicts a smooth latitudinal change from 20° (t = 3) to 50° (t = 0).

Clearly the hotspot prediction takes no account of paleomagnetic pole shifts caused by TPW. In contrast, the paleomagnetic latitudes are based on the complement of the distance between the reference site (50°N, 270°E) and the paleopoles (at 90°N, and 80°N, 90°E alternatingly). This results in paleomagnetic-predicted paleolatitude values that oscillate between 50 and 40°, and sub-parallel hotspot and paleomagnetic curves for t = 3 and t = 2 indicate that TPW occurred after t = 2 (Fig. 1c, center diagram).

5. Real data and models

The above simulations give us the insight to analyze real data. We use Early Cretaceous to Recent paleomagnetic data from Laurussia (North America, Europe) and Gondwana (Africa, South America, Madagascar, India) [14–16]. Relative fits [14,17] were interpolated to 1 Ma to allow a direct age comparison with paleomagnetic poles. Paleomagnetic data are compared to a fixed hotspot model [3] and three different mantle models (Mantle-1–3) that incorporate some hotspot motion [5].

6. Laurussia and lead-in to the Early Cretaceous enigma

When the APW path for Laurussia (Fig. 2a) is rotated into a North American hotspot frame (Fig. 2b) we notice (1) the near-sided Early Cretaceous offset (dark dots), which reaches ∼20° for 125 Ma, and (2) the far-sided, more minor, offset of the 95–0-Ma poles from 90°N (open circles). The hotspot frame predicts a systematic increase in the latitudinal trend for a location central in

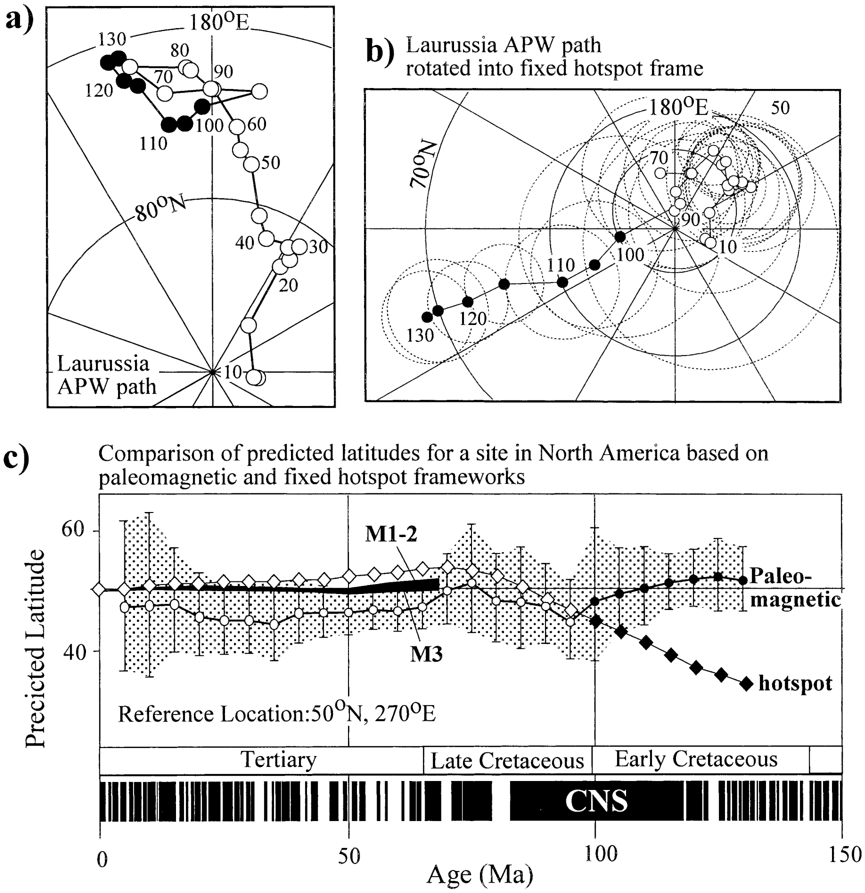

Fig. 2. (a) APW path based only on North American–European (Laurussia) poles (shown without A_{95} for diagram clarity). APW paths are running mean paths (20-Myr window) and shown in 5-Myr intervals. (b) APW path (as in (a)) with A_{95} confidence circles rotated into a fixed hotspot frame. Note the systematic offset from the spin axis of open-circle poles. (c) Latitude for a North American location (50°N, 270°E) based on the paleomagnetic (as in (a)) and hotspot frame. Notice the large deviation during the Early Cretaceous, whilst the two frames overlap within error from 100 Ma onwards. Predicted paleomagnetic latitudes shown with 95% error bars as gray shading. Magnetic polarity time-scale after Cande and Kent [26]. Abbreviations: CNS, Cretaceous Normal Superchron; M1–2 and M3 denote Mantle models 1–3 [5]. The broad black latitude band is the envelope of latitudes predicted from these models.

North America during the Early Cretaceous, whilst the paleomagnetic latitudes show an almost stationary North America (Fig. 2c). As in our simulations, pole movement was dominantly north along a meridian. After 95–100 Ma the two frames are similar, although predicted paleomagnetic latitudes are systematically lower than those predicted from the hotspot frame. Mantle models 1–3 [5] improve the Tertiary misfit, but the small systematic offset between hotspot and paleomagnetic data remains (Fig. 2c).

The large Early Cretaceous discordance has been recognized in several studies [8,9,18,19], and has been explained either by TPW or by southward drift of the Atlantic (Great Meteor and Tristan da Cunha) hotspots relative to the rotation axis. In the most recent debate about how to distinguish hotspot mobility from TPW, Tarduno and Smirnov [6,11] and Camps et al. [10] employed the same North American paleomagnetic poles, yet drew opposite conclusions. Our own data selection, adding <98-Ma European

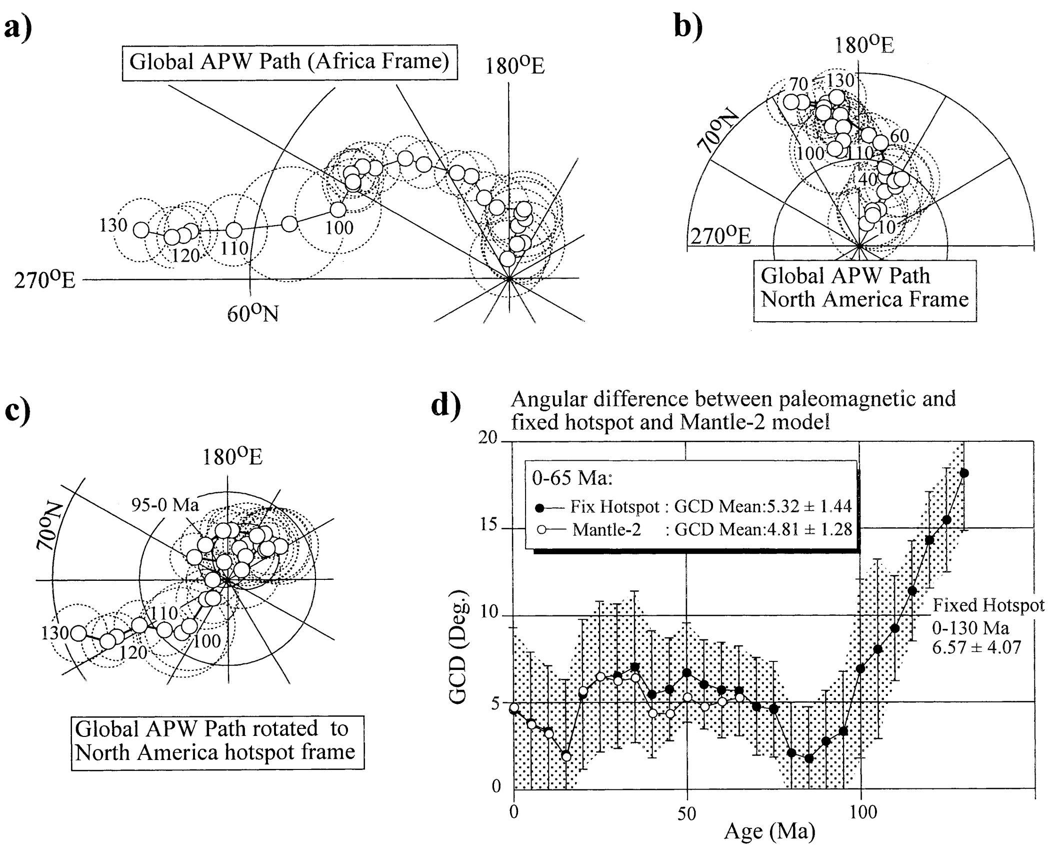

Fig. 3. Global APW path shown in (a) African and (b) North American (Table 1) co-ordinates. (c) APW path rotated into a hotspot frame fixed to North America. (d) GCD between mean poles in (c) and 90°N (the fixed hotspot frame reference). Mantle models 1–3 invoking hotspot motion (Tristan de Cunha 1–4 mm/yr, and the Great Meteor 0–4 mm/yr; average drift rates depending on Mantle models 1–3; [5]) produce similar results and we only show the one with the best fit (Mantle-2; Table 1). GCD for fixed hotspot shown with 95 error bars and gray shading.

poles adjusted for Labrador Sea and North Atlantic sea-floor spreading [14], shows a similar discordance between the hotspot and paleomagnetic frameworks.

7. A global perspective

We now combine Laurussia with the most reliable paleomagnetic poles from Gondwana. The composite APW path is first shown in African coordinates (Fig. 3a). Between 130 Ma and the present, the path tracks north from 47°N–262°E to a location close to the North Pole. If plate velocities calculated for a stationary hotspot model are accurate to the first approximation, Africa has remained four times more stable than North America during the Early Cretaceous (e.g. less continental drift) in the hotspot frame. Plotting paleomagnetic data in a North American frame should therefore reveal a much greater component of continental drift (e.g. APW). However, the APW path in North American co-ordinates (Fig. 3b; Table 1) appears shorter! Either the stationary hotspot hypothesis is invalid, or counter-balancing interaction of slow TPW and continental drift might cause apparent shortening of the total APW length.

8. Is Early Cretaceous TPW probable?

A plot of the great circle distance (GCD) difference between the two frames vs. time (Fig. 3d) highlights their discrepancy. GCD is at its maximum of ~18° at 130 Ma and declines to a low of ~2° by 85 Ma. It then climbs slightly and remains stable throughout the Tertiary (mean of 5.32 ± 1.44). Invoking some hotspot drift [5] shows an improved fit, but is applicable only after 65 Ma (Fig. 3d; Table 1). Early Cretaceous mantle models are not available and we are therefore limited to a fixed hotspot model that shows a difference of approximately 18° at 130 Ma. Can this discrepancy be attributed to TPW?

Simulation 3 (Fig. 1c) provides some clues how Cretaceous poles older and younger than a TPW event should appear relative to one another. For a more 'earth-like' example we assume that the stationary hotspot frame is valid, which predicts North America to have moved north during the Early Cretaceous. We can then synthesize an APW path for North America. If we further hypothesize that the difference between the hotspot and paleomagnetic frames (Fig. 3c) is entirely caused by TPW, we can add the hypothesized TPW to the synthetic APW path for North America. This produces an APW path (Fig. 4a) that at first glance resembles the observed North American path (Fig. 3b). However, from 130 to 70 Ma, the synthetic path proceeds southward before heading north again, whereas the observed APW path does not. Given some noise in the data, the loop in the synthetic path might appear as a polar

Table 1
Global APW path (North American co-ordinates; Fig. 3b), fixed hotspot [3], and Mantle-2 [5] frame Euler poles (interpolated)

APW Path					Fixed Hotspot			Mantle-2		
Age	N	A95	Plat	Plon	Elat	Elon	EAng	Elat	Elon	EAng
0	11	4.7	85.2	151.4	0	0	0	0	0	0
5	13	4.1	85.6	159.8	46.7	73.6	0.7	39.6	76.7	0.8
10	15	3.8	86.1	156.0	43.6	120.7	1.4	36.8	118.3	1.6
15	13	4.4	87.3	162.3	39.3	116.1	2.4	39.7	115.9	2.3
20	18	4.3	83.1	154.8	35.0	112.2	3.4	42.5	113.2	3.1
25	20	4.3	81.9	148.6	37.4	111.4	4.2	38.3	108.8	4.1
30	20	4.2	81.4	151.2	41.0	110.2	5.4	33.9	104.9	5.0
35	18	4.4	80.9	147.6	44.0	109.1	6.5	30.4	102.1	5.8
40	18	3.7	81.4	159.2	46.2	109.7	7.6	29.4	100.2	7.1
45	20	3.0	80.4	161.7	47.4	111.1	9.4	32.1	99.9	8.6
50	28	2.9	77.8	168.2	46.8	112.7	11.3	37.4	101.4	10.3
55	33	2.6	77.1	174.9	46.5	114.3	12.9	38.6	104.7	11.8
60	37	2.8	74.7	187.9	46.2	116.1	14.9	40.1	108.9	14.0
65	34	2.6	73.0	192.6	46.1	118.0	17.0	41.0	111.3	15.9
70	31	2.8	72.1	201.4	46.7	119.5	19.2	–	–	–
75	30	2.8	71.6	205.0	50.3	119.0	22.0	–	–	–
80	33	2.9	73.5	194.0	53.4	117.0	24.6	–	–	–
85	33	3.0	74.1	194.8	55.0	110.1	26.2	–	–	–
90	31	2.9	75.8	192.6	57.4	104.4	28.2	–	–	–
95	25	3.4	76.2	187.5	60.4	97.5	30.0	–	–	–
100	11	5.2	78.4	193.9	62.9	89.4	31.7	–	–	–
105	9	5.1	78.7	191.3	64.6	83.6	34.5	–	–	–
110	16	3.0	77.7	188.5	66.1	77.0	37.3	–	–	–
115	22	2.9	75.9	187.1	66.5	70.0	39.6	–	–	–
120	24	2.8	75.7	189.2	66.4	63.1	42.0	–	–	–
125	22	3.0	75.5	187.9	66.2	60.0	43.7	–	–	–
130	16	3.3	72.6	188.3	65.9	56.9	45.4	–	–	–

Age in million yr (± 10 Ma). The APW path is a running mean path (20-Myr window length). Abbreviations: N, number of poles; A95, 95% confidence circle around the mean pole; Plat/Plon, pole latitude/longitude; Elat/Elon, Euler pole latitude/longitude for fixed hotspot and Mantle-2 frames; EAng, Euler rotation angle.

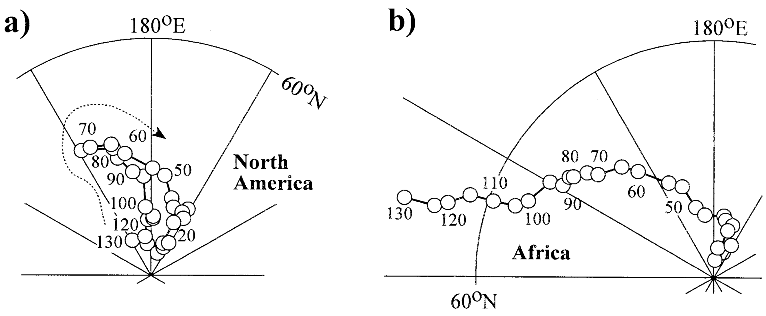

Fig. 4. From a fixed hotspot model we can calculate a synthetic APW path. If we further assume that the difference between an observed APW path when rotated into the hotspot frame is caused by TPW (Fig. 3c), we can add this TPW component to the synthetic APW path. The resultant APW path is shown in (a) North American and (b) African co-ordinates. Notice that in the 130–70-Ma range, the synthetic APW path in (a) proceeds southward before heading north again, whereas the observed APW path (Fig. 3b) does not.

standstill. Repeating this exercise in African co-ordinates reveals a much better fit (Figs. 3a and 4b), and TPW is therefore difficult to exclude completely unless precluded by other global data. Any analysis technique of any TPW event must use APW paths the poles of which are smoothed over time. This means any identifiable TPW must have been slow. For the Early Cretaceous, permissible TPW could not have exceeded normal continental drift rates. This is also made clear in Fig. 3d in which GCD shows a smooth decline during the Early Cretaceous.

9. Non-dipole fields – a joker in the pack?

Van der Voo and Torsvik [20] have revived earlier concerns about the validity of the geocentric axial dipole hypothesis, and estimated an octupole contribution of ∼10% between Late Carbonifer-

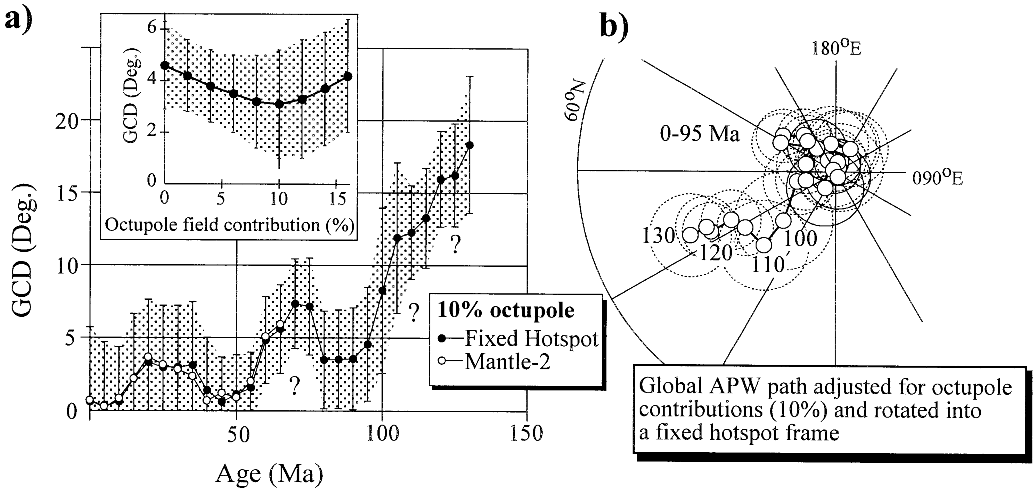

Fig. 5. (a) Comparison of GCD differences between the fixed hotspot (solid circles, 95% error bars in gray shading) and Mantle-2 (open circles) vs. paleomagnetic frame when poles are re-calculated with octupole field contributions of 10%. Inset: Mean GCD (0–95 Ma) with varying octupole field contributions; 10% yields the best fit. (b) Paleomagnetic poles with 10% octupole field contributions rotated into the fixed hotspot frame. Note the improved centering of 0–95-Ma poles as compared with the geocentric axial dipole model (Fig. 3c).

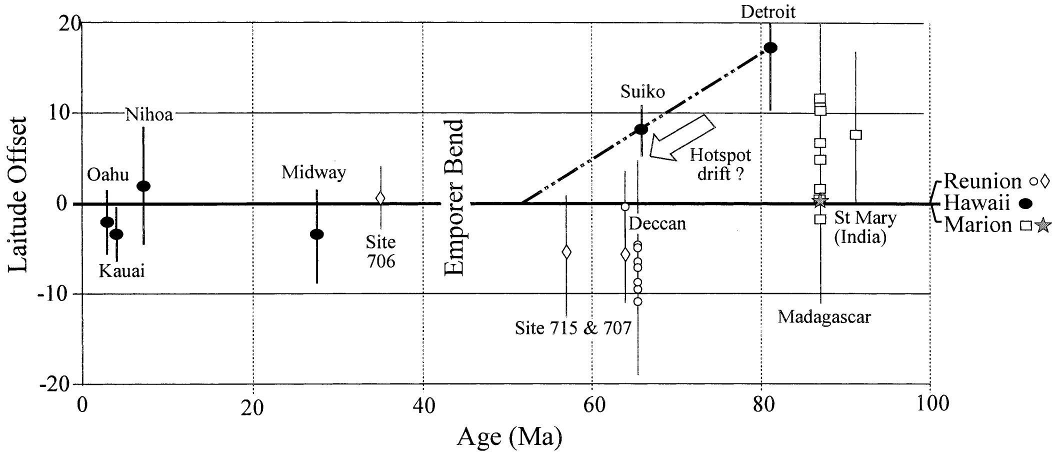

Fig. 6. Latitude offset ('drift') of the Hawaii, Reunion and Marion hotspots based on paleomagnetic-inclination data from the Hawaii–Emperor chain [27,21], Indian Ocean ODP Leg 115, Sites 706–707, 715 [28], Deccan Traps (compiled in [16]) and Madagascar–Southeast India [29,30]. Volcanic chains produced over a stationary plume should acquire their magnetic vectors at the same latitude (as in Fig. 1a). For example, paleolatitude along the Hawaii–Emperor chain should be identical to the current latitude of the Hawaii plume. In this diagram, we plot the latitude offset (observed minus predicted); positive (negative) offsets indicate southerly (northerly movement) of selected plumes. The large offset spread ($>10°$) for Deccan (Reunion hotspot) and Madagascar–India (Marion hotspot) relate to the large size of these volcanic provinces, and hence many sampling regions would be at a considerable distance from an assumed plume center. For example, paleomagnetic data from Madagascar recalculated to the proposed focal point of the Marion plume in Southeast Madagascar, yield a mean offset of less than one degree (star symbol in diagram).

ous and Early Tertiary times. Following the procedure in Torsvik et al. [9] we recalculated all paleomagnetic poles with different octupole field contributions (2–16%), calculated new APW paths, rotated the new mean poles into the fixed hotspot frame, and calculated the average GCD. An octupole contribution of 10% yields the lowest GCD value ($3.1 \pm 2.1°$) for the last 95 million yr (Fig. 5a, inset). We also tested the GCD against mantle models for the last 65 Ma [5], and once again, Mantle-2 produced the best fit ($2.6 \pm 1.8°$). Comparing the paleomagnetic and fixed hotspot frame over the entire 130-Ma range shows that a mean octupole field contribution of 10% uniformly improves the Tertiary record whilst the Cretaceous section shows a worse fit (compare Figs. 3d and 5a). The latter may imply that octupole field contributions vary with time [16].

10. Hotspot drift vs. TPW – the 'direct' approach

That the bulk of Late Cretaceous–Tertiary hotspot and paleomagnetic discrepancies in the Indo–Atlantic domain can potentially be rectified with non-dipole field contributions suggests that Indo–Atlantic plumes during this time period remained relatively stationary with respect to each other. However, when individual Indian Ocean hotspots are studied in detail, we do find minor misfits. As an example, the Reunion hotspot (Indian Ocean) may have migrated 400–500 km northward since the Early Tertiary (Fig. 6; sites 707, 715, and Deccan). However, the Indo–Atlantic plumes do not generally show systematic northward motion (e.g. Marion in Fig. 6 (= Madagascar and St. Mary Islands) and Kerguelen in Fig. 7b).

The best example of hotspot drift comes from the Hawaii–Emperor chain. Latitude estimates for seamounts younger than the Emperor Bend (∼43 Ma) overlap with the current location of the Hawaii plume, but the Suiko and Detroit Seamounts differ markedly (filled ovals, Fig. 6). Suiko and Detroit yield too high northerly latitudes, and because the postulated Early Tertiary octupole fields cause an underestimate in latitude, the

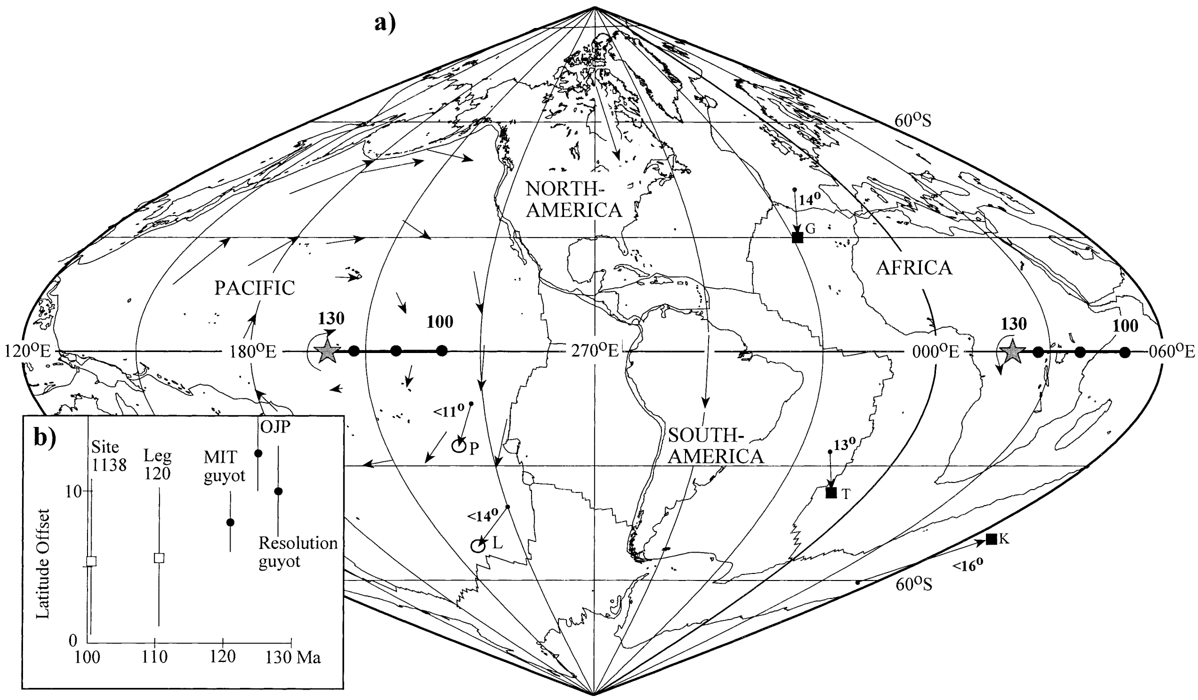

Fig. 7. (a) At 130 Ma the difference between the paleomagnetic and hotspot reconstructions (Figs. 3c and 9a,b) is fully rectified with an Euler pole at 0°, 200°E and a rotation of 18°. The Great Meteor (G) and the Tristan da Cunha (T) hotspots move 14.3° and 12.9° south with respect to the spin axis (Euler rotation poles calculated for 130–100-Ma paleomagnetic-hotspot misfits vary somewhat; compare solid circles with 130-Ma star symbol). TPW must involve the entire mantle, so that we can predict corresponding hotspot displacements for the Pacific. Note that Pitcairn (P, 11°) and the Louisville (L, 14.2°) hotspots are predicted to show a southerly drift; this sense of drift is indeed compatible with observational data (b). However, the TPW model also predicts that the Kerguelen hotspot should drift northeastward which is incompatible with the observed data (Leg 120 and Site 1138 in (b)). Our analyzing technique is similar to [4], testing a different TPW model [18], but in our study we calculate a different Euler pole which results in different predictions of hotspot motions. (b) Relative drift of Louisville (linked to OJP, i.e. Ontong Java Plateau), Pitcairn (linked to Resolution guyot), Mehitia (linked to MIT guyot)[4,23] and Kerguelen (Leg 120 and Site 1138 [31,32]) hotspots, based exclusively on inclination data. The Mehitia hotspot is not shown in (a). Note that the Pacific offsets cannot be rectified with positive octupole field contributions. Conversely, Leg 120 and Site 1138 results from Kerguelen show lower inclinations than expected and this can be rectified with octupole field contributions of about 5% (they can even become overcorrected to show northerly movements in accordance with a TPW model).

Hawaii misfit cannot be rectified by positive octupole fields (i.e. of same sign as the dipole field). The Hawaii hotspot migrated southward during the Late Cretaceous–Early Tertiary, while the Indo–Atlantic hotspots were nearly stationary. It appears that the Hawaii hotspot became 'fixed' in the mantle after 43 Ma [21]. Whether the Hawaii hotspot moved southward as part of a Pacific hotspot group [21], or alone [22], is critical to the Early Cretaceous analysis below.

TPW requires that the entire mantle (and the lithosphere) must rotate, and the sense of rotation of any hotspot drift in the Pacific Ocean is critical to the advancement of TPW as the cause of observed misfits between the hotspot and paleomagnetic frameworks discussed earlier for the Early Cretaceous. An Euler pole at 0°N, 200°E (angle = 18°) rectifies the contrasting paleomagnetic and hotspot reconstructions in the Early Cretaceous. (We obtained this Euler pole by returning the 130-Ma pole to the hotspot framework in Fig. 3c.) The longitudinal location of the Euler pole determines whether Pacific hotspots far away from the Atlantic hotspots should show northerly or southerly migration relative to the spin axis. Tarduno et al. [23] inferred that the Louisville hotspot was the source for the Ontong Java Plateau and argued that the Louisville hotspot has moved 10–15° southward since 125 Ma (Fig. 7b). Southerly drift of Louisville, Pitcairn (source for the 128-Ma Resolution guyot), and the Mehitia (source for the 121-Ma MIT guyot [30]) hotspots, may therefore be used to support a TPW model (Fig. 7b).

However, two lines of evidence argue against TPW. Southward drift of the Early Cretaceous Pacific hotspots (Fig. 7b) is comparable to Late Cretaceous–Early Tertiary Hawaii hotspot offsets (Fig. 6), suggesting that all Pacific hotspots drifted with respect to the rotation axis as well as the Indo–Atlantic hotspots during the Early Tertiary [4]. This assumes that the Pacific hotspots drifted as a Group. Also, northeasterly movement of the Kerguelen hotspot is predicted from our TPW model, but a small southerly component (Leg 120 and Site 1138 in Fig. 7b) is actually observed. Early Cretaceous volcanism linked to the Kerguelen hotspot is somewhat younger than the Pacific examples, but using younger Euler rotation poles based on 100–110 Ma paleomagnetic-hotspot misfits would all predict north–east drift.

11. Pacific APW - Late Cretaceous TPW?

Estimates of Pacific APW are not very robust and paleopoles are mostly based on seamount magnetizations and drilling sites where only colatitude information is retrieved. The resulting APW path in Fig. 8a (Pacific 1) has been used extensively (e.g. [24]). The best Tertiary fit with the hotspot frame is achieved with the Mantle-2 model (Fig. 8b), but it is only marginally better than a fixed hotspot model (Fig. 8c). When viewed in a fixed hotspot frame, the Pacific and Global APW paths differ substantially but both paths show pronounced Early Cretaceous offsets. Moreover, a different APW path [12], exclusively based on seamount poles (Fig. 8d), differs substantially from the Pacific 1 APW path (Fig. 8a). Some poles better fit the Global path when viewed in hotspot frames (Fig. 8e), but the 117-Ma and 104-Ma poles remain highly discordant. Sager and Koppers [12] argued for an instantaneous (jerky) TPW at 84 Ma due to the large differences of two poles with almost the same age (shown with filled A_{95} confidence circles in Fig. 8d,e). We find such claims premature, as they are based on only two mean seamount poles, and little support for such an event has been found in the continental record [13].

12. The state of the Earth and future research

In this overview we have attempted to clarify current debates on hotspot motion versus TPW, and have examined how different research groups can arrive at opposite conclusions. The choice of data (continental paleomagnetic and APW paths, 'direct' inclination data, choice of plate/hotspot model, etc.) can fundamentally influence the conclusions. However, in the debate about Early Cretaceous Atlantic hotspot mobility vs. TPW [10,11] data selection has not played a major role. In the Indo–Atlantic realm, we find that Late Cretaceous and Tertiary continental paleomagnetic data adjusted for sea-floor spreading provide a good fit with a fixed hotspot model [3]. Some of the minor discrepancies between paleomagnetic and fixed hotspot frames can be attributed to plumes advecting in a convective mantle and non-dipole fields, making it unnecessary to invoke TPW for any time after 95 Ma and before the Quaternary TPW due to deglaciation. The Indo–Atlantic hotspots appear stable relative to plate tectonic speeds during this time period. The only good example of hotspot drift comes from the Pacific Ocean [21], where the Hawaii–Emperor chain suggests southward motion during the Early Tertiary before becoming 'fixed' in the mantle after 43 Ma.

Very fast, and large-scale, TPW and some dramatic consequences for the evolution of life on planet Earth have been invoked for earlier geological time periods (e.g. [25]). Examples of Cretaceous–Tertiary TPW have been cited as evidence that this phenomenon could actually have occurred – but how much, if any, TPW can conclu-

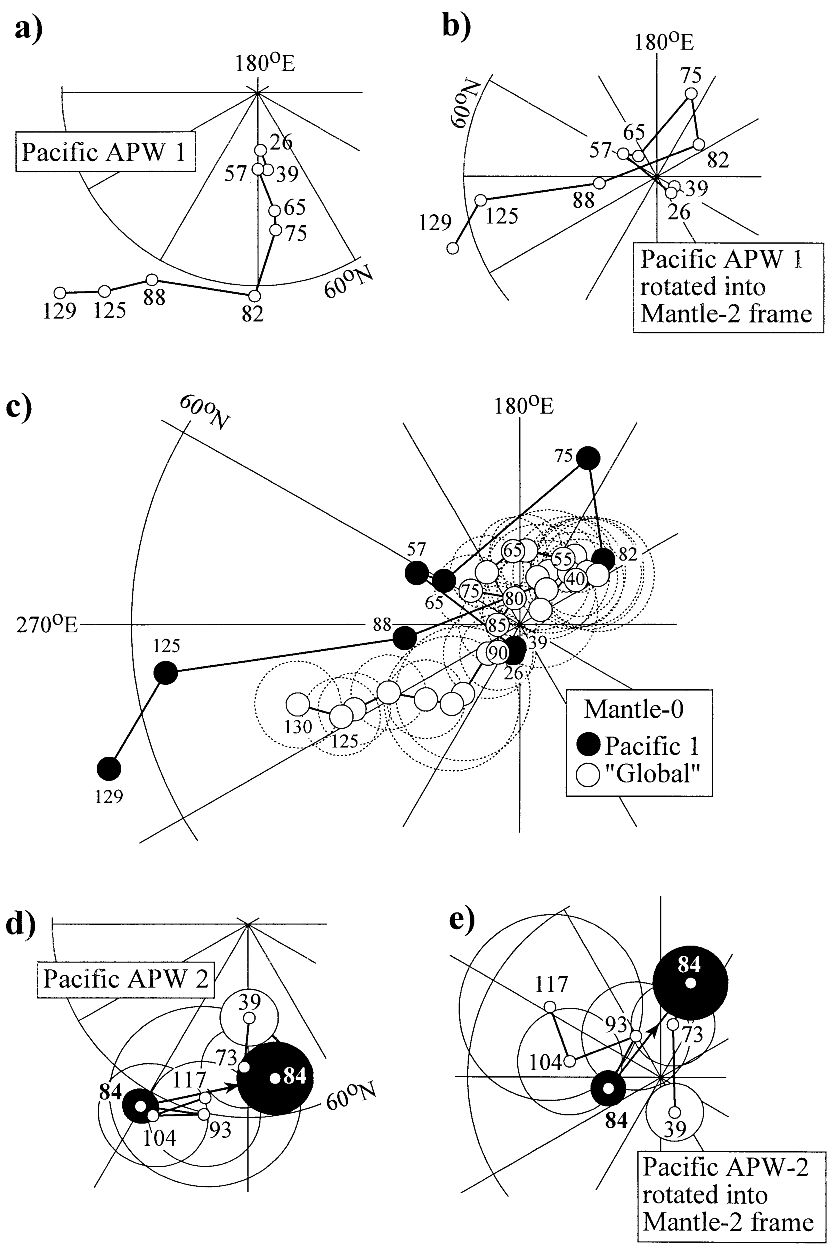

Fig. 8. (a) Pacific APW path [24]. (b) Pacific APW path (as in (a)) rotated into the Mantle-2 frame [5]. (c) Comparison of Pacific APW path 1 (solid circles) and the global path (open circles) rotated into a fixed hotspot frame (Mantle-0 [5]). (d) Alternative Pacific path (APW 2), exclusively based on seamount poles [12]. Sager and Koppers [12] have argued that the difference between the two 84-Ma poles (with filled cones of 95% confidence) reflects instantaneous TPW. (e) Alternative Pacific path (APW 2) rotated into the Mantle-2 frame. Note that Mantle-2 = Mantle-0 for the Cretaceous [33].

sively be found in the Cretaceous–Tertiary record? And was this TPW fast (TPW 'jerks', i.e. >30 cm/yr) or slow, on the order of TPW rates this past century (~ 11 cm/yr or less)?

The Early Cretaceous is perhaps one of the few geological periods for which the paleomagnetic-hotspot data might hint that TPW has occurred, but it probably was not very fast, nor extremely

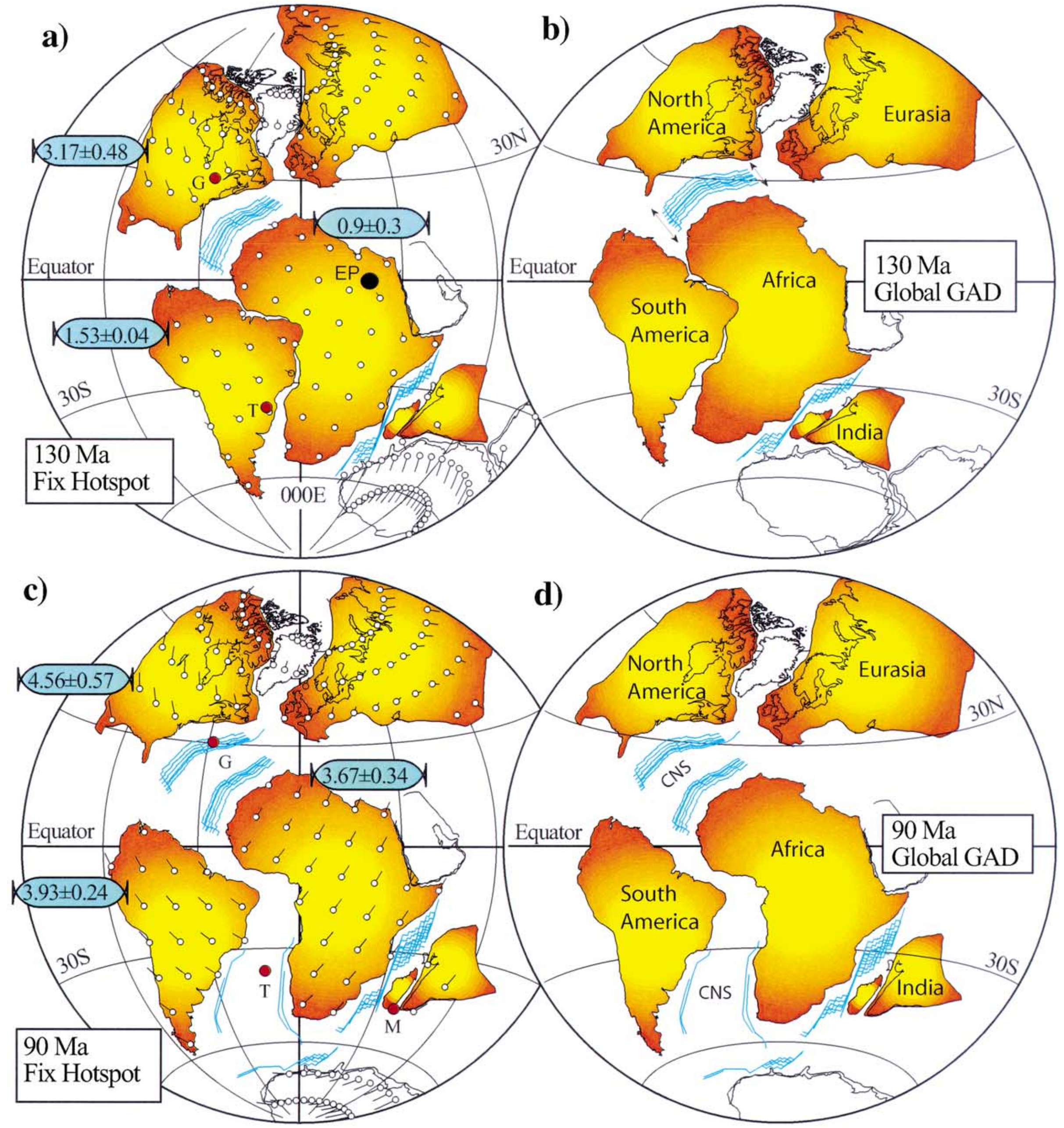

Fig. 9. Paleoreconstructions based on a fixed hotspot frame (a,c) and the global paleomagnetic frame (b,d). Hotspot reconstructions show the velocity field projected 10 Ma into the 'future' (i.e. the 130–120-Ma and 90–80-Ma velocity fields). Mean continent velocities $\pm 1\sigma$ for North America, Africa and South America are calculated for a 10×10° grid (radius of open circles approximately 1 cm/yr). Continents with paleomagnetic data used in this study (0–130 Ma) are colored. Blue lines are magnetic anomalies of crust formed at the actual reconstruction times [20]. The large gap in the anomaly record in (c,d) represents the Cretaceous Normal Superchron (118–84 Ma). Note that the 90-Ma paleomagnetic and hotspot reconstruction in (c) and (d) are almost identical whilst (a) and (b) are perfectly matched by a rotation about an Euler pole of 0°, 200° (angle = 18°).

large. In our final illustration (Fig. 9), we highlight the Cretaceous differences in hotspot and paleomagnetic reconstructions. At 130 Ma, fixed hotspot-based reconstructions place North and South America in much lower latitudes than their positions would be in the paleomagnetic-based reconstruction (compare Fig. 9a,b), yet the 130-Ma and 90-Ma paleomagnetic reconstructions (Fig. 9b,d) are almost identical for North America–Europe. If the paleomagnetic frame is correct, North America–Europe remained stationary in latitude for 40 million yr. During the same period, sea-floor spreading documents slow southward movement of Africa. Conversely, hotspot reconstructions show North and South America moving northward (Fig. 9a,c) compared to an almost stationary Africa. The 130-Ma discrepancy can be resolved by invoking TPW, and our proposed Euler pole would produce the needed clockwise rotation of the Americas, as well as the rest of the Atlantic hemisphere. However, we re-emphasize that the possibility exists that all the Pacific hotspots underwent a later southward drift, during the Early Tertiary (and not during the Early Cretaceous, as expected from our TPW model). Moreover, the Kerguelen hotspot shows southward instead of northward TPW-induced drift. Thus, we are hesitant to invoke TPW as a causal mechanism, until better global data coverage for the Early Cretaceous provides more compelling evidence. Consequently, we favor that the 130-Ma discrepancy is best explained by southward drift of the Great Meteor and the Tristan de Cunha hotspots prior to 95–100 Ma [4].

We conclude that we cannot find solid evidence that any TPW occurred during Late Cretaceous and Tertiary times. Seen in isolation, the Early Cretaceous paleomagnetic and hotspot frames for the Indo–Atlantic realm can be interpreted as very slow TPW, while counter-active continental drift in parts of the world can account for the Cretaceous polar standstill observed in for example North and South America. However, at present TPW is most seriously at odds with 'direct' estimates of paleolatitude and hotspot motion from the Kerguelen hotspot [32]. Clearly much more direct data are needed to finalize the issue of hotspot drift vs. TPW. Realistic mantle models back to the Early Cretaceous would be extremely useful for future hypothesis testing, while the paleomagnetic database for the Cretaceous in the Indo–Atlantic realm has room for some improvements. However, a reliable APW path for the Pacific plate is critical. A better understanding of non-dipole field contributions in the ancient geomagnetic record is also of importance. For example, an octupole field contribution of 10% will not only rectify the minor latitude offset of the Kerguelen hotspot (Fig. 7b), but the drift can then be re-interpreted as northward drift which would then corroborate a TPW model. Clearly, the last word has not been spoken on this matter.

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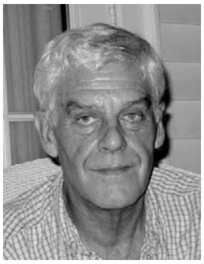

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