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Longitude: Linking Earth's ancient surface to its deep interior

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ABSTRACT

Earth scientists have had no direct way of calculating longitudes for times before those of the oldest hotspot track eruption sites in the Cretaceous (~130 Myr ago). For earlier times palaeomagnetic data constrain only ancient latitudes and continental rotations. We have recently devised a hybrid plate motion reference frame that permits the calculation of longitude back to Pangean assembly at ~320 Ma. This reference frame, here corrected for True Polar Wander (TPW), places most reconstructed Large Igneous Provinces (LIPs) of the past 300 Myr radially above the edges of the Large Low Shear wave Velocity Provinces (LLSVPs) in Earth's lowermost mantle. This remarkable correlation between surface and deep mantle features, which is also discernible for all hotspots with a deep-plume origin, provides a new way of reconstructing the original positions of LIP sites, and therefore the position of continents whose longitudes have hitherto been unknown. We place the 258 Ma Emeishan LIP eruption of South China at 4°N and 140°E, in that way constraining the width and the geometry of the Palaeotethys Ocean during the Late Permian. If LLSVPs have remained stable for even longer and TPW has been small, we can, under these assumptions, also restore Siberia and Gondwana longitudinally for Late Devonian (~360 Ma) and Late Cambrian (~510 Ma) times.

1. Introduction

Navigation was transformed in the mid-eighteenth century by the invention of a robust and accurate sea-going chronometer (Sobel, 1995). The calibration of longitude against the prime meridian at Greenwich gave mariners confidence for the first time that they could, in combination with latitude derived from the positions of the sun or stars, reliably calculate their position on the Earth's surface. Until now, Earth scientists have been in the comparable position of having no way of calculating the longitudes of geological entities during the long eons before the Cretaceous eruptions of the world's oldest hotspot tracks. In contrast, past latitudes have been quantitatively determinable using palaeomagnetism for more than 50 years. Here we describe novel ways of quantitatively establishing ancient longitudes, and demonstrate how the Earth's deep interior can be linked to its surface. The first part of our method makes use of the fact that longitudinal uncertainty of continents that were assembled in Pangea can, for subsequent times, be eliminated, if longitude motion is known for only one of these continents (Burke and Torsvik, 2004; Torsvik et al., 2006). We will argue here that the best possible assumption is zero longitude motion for Africa (Section 2). We will then show that this assumption yields reconstructed eruption locations of Large Igneous Provinces (LIPs) since 300 Ma almost exclusively above the margins of the Large Low Shear wave Velocity Provinces (LLSVPs) of the lowermost mantle (Sections 3 and 4). This finding, here also considering the effect of True Polar Wander (TPW), then leads to the second and novel part of our method — that the relation of LIP eruptions to LLSVP margins also allows continents that were not part of Pangea during a LIP eruption to be repositioned (Section 5). On the assumption that LLSVPs were stable in their present positions for even longer than 300 Myr, we venture, somewhat speculatively, to locate the eruption sites of two LIPs older than 300 Ma (Sections 5.2 and 5.3).

2. The hybrid reference frame

The position of ancient continents can be reconstructed by using palaeomagnetic data or by using hotspot trails, assuming that the hotspot-generating plumes are either fixed with respect to the mantle (e.g. Wilson, 1963; Morgan, 1971; Müller et al., 1993), or advected in mantle flow — the moving hotspot reference frame of Steinberger et al. (2004). Hotspot-based reference frames become less reliable before 83 Ma because there are only two confirmed older tracks (New England Seamounts, Central Atlantic and the Rio Grande Rise/Walvis

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Ridge, South Atlantic) and they cannot be used at all before ~130 Ma, the age at the end of the oldest track. That leaves palaeomagnetism, which cannot determine longitude, as the only current quantitative way of positioning objects on the globe before the Cretaceous.

Uncertainty can be minimized by selecting a reference continent that has moved least longitudinally (Burke and Torsvik, 2004). We have analyzed all the major continents to establish which has been most stable longitudinally since the Cretaceous, using both fixed and moving hotspot reference frames (Torsvik et al., 2008b). In a moving hotspot reference frame, we find that Africa has moved less than 500 km in the past 100 Myr, whilst a fixed (but not recommended) hotspot frame predicts a displacement of ~900 km (Fig. 1). The cumulative longitudinal motions of Eurasia and Africa have been comparable since ~100 Ma, but we use Africa and not Eurasia as a reference continent because of (1) the relatively recent assembly and substantial intra-plate deformations within Eurasia, (2) the dominance of spreading centers around Africa for more than 170 Myr (which indicates that the opposing ridge-push forces on the continent have roughly cancelled), and (3) using a continent that was in the center of Pangea, and earlier in the center of Gondwana, minimizes uncertainties due to errors in relative motions of blocks for all of the Phanerozoic.

Mantle flow models are not very robust before 100 Ma, and so we have developed a hybrid reference frame consisting of an African moving hotspot frame (O'Neill et al., 2005) for the past 100 Myr and before that time a global palaeomagnetic frame back to the initial assembly of Pangea at 320 Ma (Torsvik et al., 2008b). That palaeomagnetic frame has been adjusted 5° in longitude so as to correct for the longitudinal motion of Africa during the past 100 Myr (Fig. 1). In the absence of any other reference frame, zero longitudinal average motion for Pangea (Africa) is the null assumption back to the time when South Africa was close to the South Pole at 330–320 Ma.

3. The hybrid reference frame at work

Two antipodal Large Low Shear wave Velocity Provinces on the equator (LLSVPs, Garnero et al., 2007), isolated within the faster "subduction graveyard" (Richards and Engebretsen, 1992) parts of the deep mantle (Figs. 2 and 3a), dominate all global shear-wave

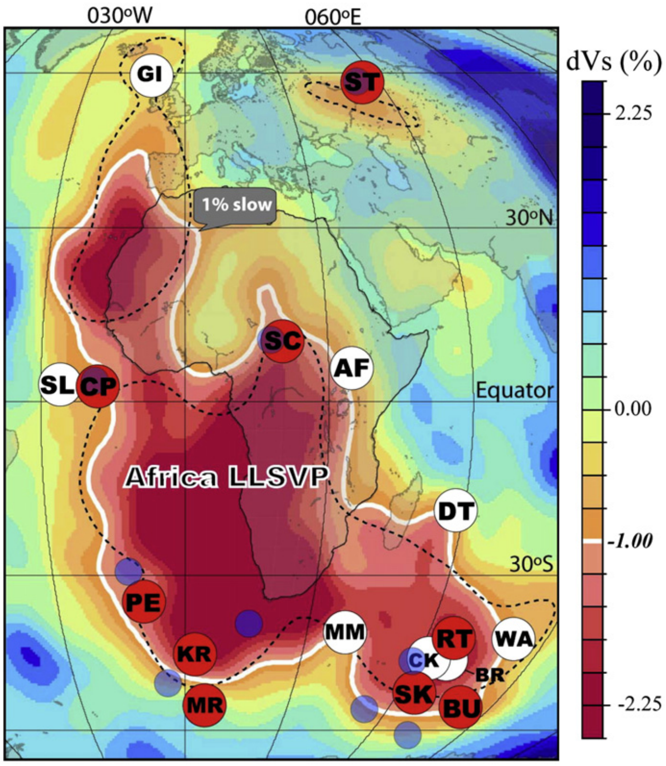

Fig. 2. Reconstructed LIP eruption sites of the Plume Generation Zone (PGZ) surrounding the African LLSVP plotted above seismic velocity anomalies (δVs) of the lowermost mantle (SMEAN model of Becker and Boschi, 2002). We combine relative plate rotations (Torsvik et al., 2008b) with two 'absolute' reference frames: the 'hybrid' frame described in the text (blue transparent smaller dots; white for LIPs ≤ 100 Ma), and another 'hybrid' frame (red annotated dots), additionally corrected for true polar wander (only for times > 100 Ma; Steinberger and Torsvik, 2008). Note that the blue transparent dots for CP, SC and ST are partly hidden behind the true polar wander corrected red dots. The white thick line is the 1% slow contour in the SMEAN model and the thin stippled black line is the ~0.8% slow contour in a *D″* tomography model (Castle et al., 2000). See Table 1 for LIP abbreviations and ages.

tomography models. To our surprise, when LIPs were reconstructed to their eruption sites over the past 300 Myr, they were seen to be concentrated radially above the edges of the two LLSVPs (Burke and Torsvik, 2004; Davaille et al., 2005; Torsvik et al., 2006, 2008c; Burke et al., 2008), near the 1% slow contour in the *SMEAN* tomography model of Becker and Boschi (2002), at a depth just above the core–mantle boundary (CMB). This is a robust result because that concentration is seen in all tested reference frames, i.e. fixed/moving hotspot and palaeomagnetic frames, and in the latter case whether the effect of TPW is considered or not. In Fig. 2, LIPs, shown as red circles are corrected for TPW, but the smaller blue circles represent LIPs reconstructed palaeomagnetically without considering TPW. Four phases of significant TPW have been postulated for the past 320 Myr but cumulative TPW over this interval sums to close to zero because clockwise and counter-clockwise phases of TPW (10°–18°) approximately cancel each other during that time (Steinberger and Torsvik, 2008). In summary, the reconstructed positions of LIPs are mostly very close to the 1% slow contour on the CMB whether TPW is considered or not. We emphasize that pure east–west motion of all continents potentially disturbs the approach that assumes zero-longitudinal motion of first Pangea and later Africa, but does not correspond to any TPW, so the inferred amount of TPW is independent on any assumption of east–west motion.

The correlation of the positions of reconstructed LIPs with the 1% slow contour is striking; but a second remarkable observation is that every one of the nineteen LIPs with ages between 200 and 65 Ma (i.e. associated with the major phases of Pangea break-up) erupted at

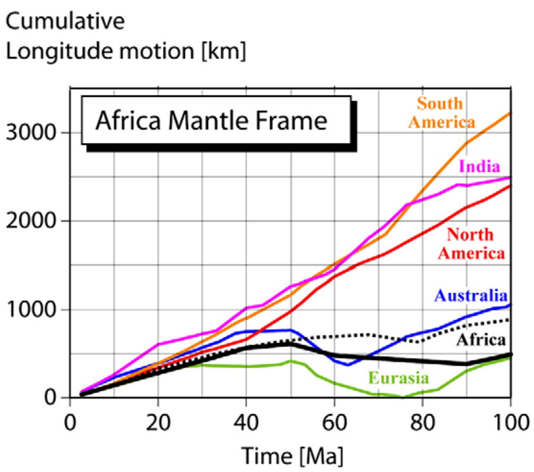

Fig. 1. Cumulative continent longitude motions during the past 100 million years in an Africa mantle (moving hotspot) reference frame (calculated from O'Neill et al., 2005; Torsvik et al., 2008b). They were calculated for all the major continents, but are only shown here for selected continents. To minimize longitude uncertainties in palaeomagnetic reconstructions, so-called global apparent polar wander paths should be constructed with reference to the continent that shows the smallest longitudinal motion, for example Eurasia or Africa and *not* continents such as South America, India or North America. For comparison we also show the cumulative longitudinal motion for Africa in the fixed hotspot frame of Torsvik et al. (2008b) as a black stippled line.

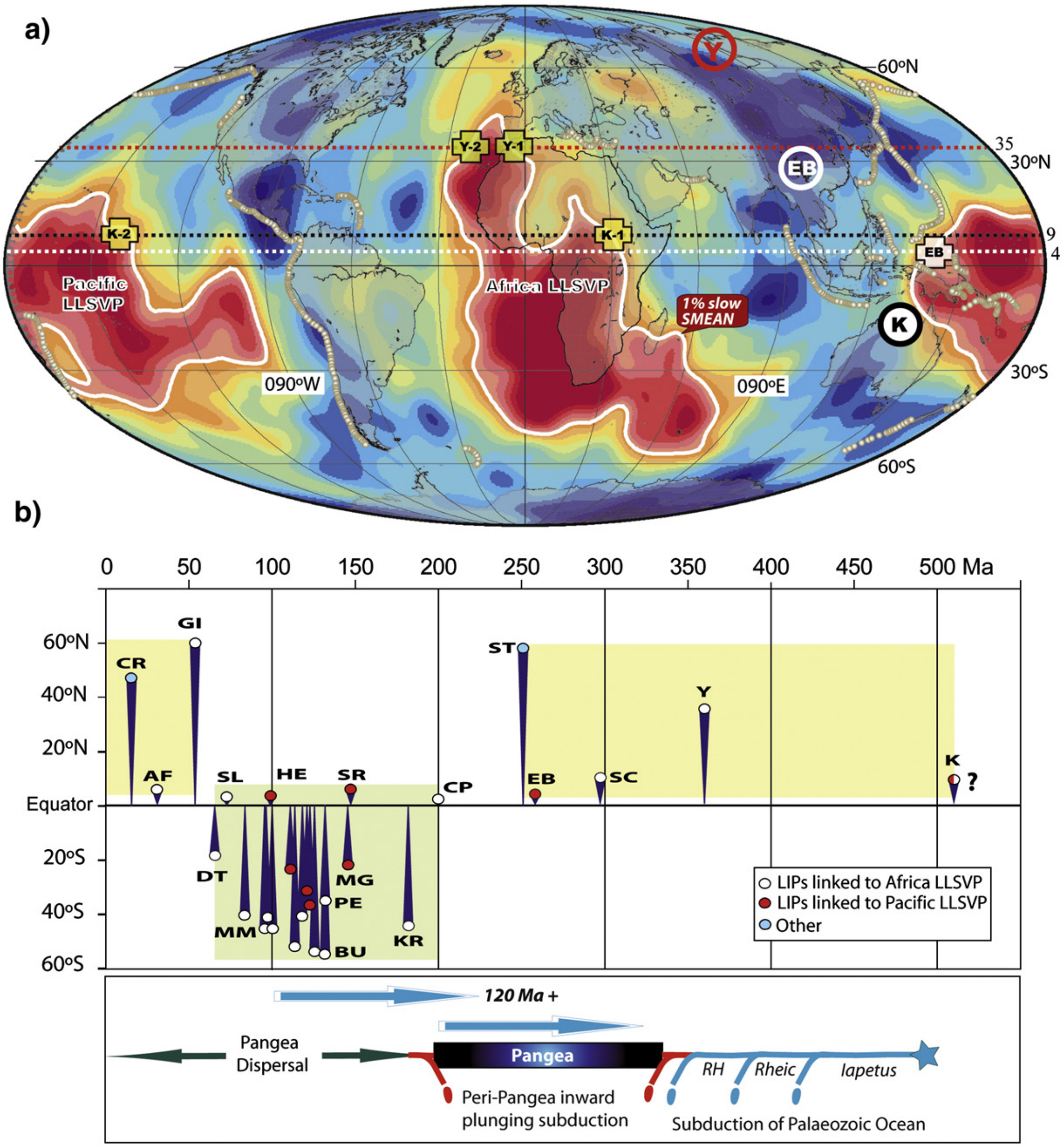

Fig. 3. (a) Palaeomagnetically determined latitudes of the ~258 Ma Emeishan (EB) LIP of China (white stippled line), the 360 Ma Yakutsk (Y) LIP of Siberia (red stippled), and the ~510 Ma old Kalkarindji (K) LIP of Australia (black stippled line), and their most likely eruption sites (thick annotated crosses) near the edge of the LLSVPs. K1 is our preferred location of the Kalkarindji LIP at ~510 Ma. They are superimposed on shear wave speed anomalies in the lowermost mantle (as in Fig. 2, with the same color scale). We have also included subduction zones as dashed gray circles; today they overly the high-velocity zones near the CMB (83% and 40.000 km in total subduction length) except for a small region in the southwestern Pacific. Present positions of EB, Y and K shown as large circles in white, red and black. (b) LIP eruption latitudes (including Pacific LIPs) for the last 510 million years. Except for three high northerly LIP eruption sites (CR, GI and ST), all erupted near the 1% slow SMEAN contour. The palaeomagnetically-derived latitudes for EB, Y and K (based directly on palaeomagnetics or on apparent polar wander paths) are also included. EB and Y are argued to belong to the Pacific and African LLSVP, respectively, whilst K is somewhat more uncertain (see text). The bottom cartoon illustrates bulk Pangea assembly at around 320–330 Ma and the first major break-up of Pangea at around 190–195 Ma (opening of the Central Atlantic), shortly after the eruption of the CAMP LIP. The right-hand blue star at around 490–500 Ma marks the maximum continental dispersal of the earlier Rodinia supercontinent (Torsvik, 2003) with vast oceanic areas between for example Gondwana, Baltica and Laurentia (Iapetus Ocean). After that time subduction of Palaeozoic Oceans (RH, Rheno-Hercynian Ocean) led to the formation of Pangea. If deep plumes generated at the CMB are triggered by mantle avalanches that have sunken into the deep mantle we expect at least 120 Myr time difference between subduction and LIP eruption. As an example, Cretaceous LIPs can be considered linked to Peri-Pangean subduction zones (in red) in Late Palaeozoic and Mesozoic times (see text). Some annotated Pacific LIPs and other (not listed in Table 1) are: CR, Columbia River; HE, Hess Rise; MG, Magellan Rise; SR, Shatsky Rise (see Torsvik et al., 2006).

equatorial or intermediate southerly latitudes (Fig. 3b). That asymmetry could be partly a preservation artefact (for example, of subducted LIPs), but it is much more likely to confirm that the surface LIP distribution is directly controlled by deep mantle structure. Before 200 Ma and after 65 Ma, all LIPs were erupted in the northern hemisphere at low or intermediate to high latitudes. Two out of three of those high-latitude LIPs, the Siberian Traps of Russia (ST in Fig. 2) and Columbia River of North America, are not associated with the margins of either LLSVP, but with two smaller low shear wave velocity anomalies at the CMB (Burke et al., 2008). The third high-latitude LIP, the North Atlantic Igneous Province (GI in Fig. 2), falls not very far (~15°) from the 1% slow contour (Table 1). Its distance to the 0.8% slow contour of the Castle et al. (2000) model, which globally approximately corresponds to the 1% slow SMEAN contour, is even much less. We conclude that all the LIPs that have erupted at low or southerly latitudes over the past 300 Myr have been directly related to the LLSVP

Table 1
Large Igneous Provinces in the Indo-Atlantic domain and the Siberian Traps (sorted by age; based on Torsvik et al., 2006, 2008c)

Name	Age	Symbol	PLat	Plong	RLat	RLong	−1%	RF	Linked hotspot	Deep	HLat	HLong	−1%	GCD
Afar Flood Basalts	31	AF	10.0	39.5	5.6	35.0	3	M	East Africa (Afar)	YES	7	39.0	7	4
Greenland/Iceland	54	GI	69.0	−27.0	59.2	349.6	15	M	Iceland	YES	64	343.0	20	6
Deccan Traps	65	DT	21.0	73.0	−18.7	58.4	2	M	Reunion	YES	−21.2	55.7	−1	3
Sierra Leone Rise	73	SL	6.0	−22.0	2.7	334.2	7	M	*Unknown*					
Madagascar/Marion	87	MM	−26.0	46.0	−40.5	39.5	0	M	Marion		−46.9	37.8	5	6
Broken Ridge	95	BR	−30.0	96.0	−45.7	68.0	−10	M	Kerguelen	YES	−49	69.0	−8	3
Wallaby Plateau	96	WA	−22.0	104.0	−41.8	82.0	2	M	Kerguelen	YES	−49	69.0	−8	11
Central Kerguelen	100	CK	−52.0	74.0	−45.4	63.3	−13	M	Kerguelen	YES	−49	69.0	−8	5
South Kerguelen	114	SK	−59.0	79.0	−52.3	64.9	−7	PT	Kerguelen	YES	−49	69.0	−8	4
Rajhmahal Traps	118	RT	25.0	88.0	−41.6	67.0	−13	PT	Kerguelen	YES	−49	69.0	−8	7
Maud Rise	125	MR	−65.0	3.0	−54.7	5.9	4	PT	Meteor (Bouvet)		−52	1.0	3	4
Parana-Etendeka	132	PE	−20.0	11.0	−34.9	350.6	−9	PT	Tristan	YES	−38	349.0	−2	3
Bunbury Basalts	132	BU	−34.0	115.0	−55.3	81.6	−3	PT	*Unknown*					
Karroo Basalts	182	KR	−23.0	32.0	−44.6	2.8	−5	PT						
CAMP	200	CP	27.0	−81.0	2.5	341.9	−7	PT						
Siberian Traps	251	ST	65.0	97.0	57.7	54.7	–	PT						
Skagerrak LIP	297	SC	57.5	9.0	10.2	20.6	−6	PT						

LIPs are restored to their emplacement positions according to the hybrid reference frames described in the text. PLat/PLong is the estimated latitude/longitude center for where the plume impinged the lithosphere in present day co-ordinates. RLat/RLong is latitude/longitude for the reconstructed LIP eruption center. HLat/HLon is location of some present day hotspots that have been linked to the listed LIPs. Names and locations of these hotspots are from Steinberger (2000), except for Afar and Iceland where we use locations from Montelli et al. (2006) who identify plumes through tomography; alternative names are in brackets. "−1%" is distance in degrees from the 1% slow SMEAN contour (negative if inside). Distance is calculated by *downward* projection of plumes or reconstructed LIPs to the CMB. RF = reference frame [M = Mantle, Indo-Atlantic moving hotspot frame; PT = Palaeomagnetic, with zero longitudinal motion of Africa before 100 Ma, but corrected for TPW and with 5° change in longitude since 100 Ma as inferred from the Mantle frame]. LIP Symbols are as used in Figs. 2 and 4. Deep: YES indicates that the hotpot is considered to have a deep origin from the CMB based on seismic tomography and other criteria. GCD = great-circle distance (shortest distance on a sphere) between reconstructed LIP location and the location of linked hotspot.

margins in the deep mantle. It is still unclear how deep plumes have been sourced in the Plume Generating Zones (PGZ) at the LLSVP edges. Temporal variations in the passage of subducted slabs into the lower mantle and, in the extreme case, mantle avalanches, may explain the episodicity and sporadicity in plume generation (Burke et al., 2008). The time lag between subduction and LIP eruption would depend on slab sinking speed and later plume ascent speed from the CMB. Based on usual assumptions of speeds in the mantle, one can estimate ≥120 Myr time difference. The Central Atlantic Magmatic Province (CP in Figs. 2 and 3b) and older LIPs may thus be related to the subduction of Palaeozoic (e.g. Iapetus) and older ocean floors, whilst the large concentration of Cretaceous LIPs can be linked to Peri-Pangean, mostly inward plunging, subduction zones (incl. Palaeo-and Neotethys), during Permian to Early Jurassic times.

4. Comparison of tomographic models

Details of our finding of the concentration of LIP sourcing plumes in the PGZs surrounding the LLSVPs depend on many factors (reviewed in Torsvik et al., 2008c), including the choice of tomographic model. There is no universally agreed model because different groups have used slightly different datasets and computational methods. We have therefore examined and tested eight global shear wave velocity models. Burke and Torsvik (2004) originally used the *S20RTS* model of Ritsema et al. (1999) and the *SMEAN* model of Becker and Boschi (2002) for the lower mantle (~2800 km). Those models provide broadly similar results, which is not surprising, because our favoured *SMEAN* model is based on the *S20RTS*, *NGRAND* (Grand, 2002) and *SB4L18* (Masters et al., 2000) models (Fig. 4a–c). We here show for comparison four additional S-wave models (Fig. 4e–h), *SAW24b16* (Megnin and Romanowicz, 2000), *S362d1* (Gu et al., 2001), *TX2007* (Simmons et al., 2007) and *PRI-S05* (Montelli et al., 2006), and we further compare *SMEAN* with the ~0.8% slow contour in the Castle et al. (2000) *D″* model (Fig. 2). Globally, that contour at the CMB corresponds approximately to the 1% slow contour of SMEAN (Burke et al., 2008).

All the models (perhaps *S362d1* the least) show broadly similar characteristics near the CMB (see also Romanowicz, 2008, with reference to tomography models *SAW24b16*, *S362d1* and *S20RTS*). They all demonstrate that reconstructed LIPs (except the 251 Ma Siberian Traps; ST in Figs. 2 and 4), and deep-plume sourced hotspots in the Indo-Atlantic realm (Steinberger, 2000; Courtillot et al., 2003; Montelli et al., 2004, 2006), project radially downwards to the CMB close to the 1% slow shear wave velocity contour in the *SMEAN* model. Steep shear wave velocity gradients have been mapped near the PGZ along much of the lengths of the LLSVP margins (Torsvik et al., 2006, Fig. 10). We conclude, from the similarity of all the models, that the choice of any specific tomographic model is not critical to our conclusions when linking LIPs to these well-defined long-term heterogeneities in the deep mantle. Thorne et al. (2004) have also demonstrated that the majority of hotspots overly shear-wave velocity gradients near the edges of the LLSVPs. These observations concern the locations where plumes originally form, and their present-day surface locations, but not the present-day plume source locations: Boschi et al. (2007) found that models where plume sources have moved with large-scale flow towards the centers of LLSVPs fit better with seismic tomography models than the assumption of vertical plume conduits.

17 LIPs in the circum African LLSVP plot at an average distance of −2.5±7.7° from the 1% slow *SMEAN* contour. Seven hotspots linked in earlier studies to eleven of these LIPs (Table 1) plot within a mean distance of +3° from the 1% slow contour. The angular distance between reconstructed LIP eruption sites and the corresponding hotspot locations today is on average only 5°. Obviously, a perfect agreement cannot be expected, because plumes may have moved somewhat since LIP eruption. Also, for some hotspots present locations are uncertain. Note, for example, that the actual location of Bouvet Island (54.4°S, 3.4°E) agrees much better with the reconstructed Maud Rise location than the hotspot location assumed in Table 1 (52.0°S, 1.0°E) does. Furthermore, plume eruption sites at the Earth's surface may not be the places where the plume heads impinged on the base of the lithosphere (e.g. Sleep, 1997; Courtillot et al., 1999; Sleep, 2006; Burke et al., 2008; Torsvik et al., 2008c), so that locating plume eruption sites with higher resolution than ~5° is probably unrealistic.

5. A new reconstruction method: the plume Generation Zone frame

The concentration of LIPs in the PGZs on the CMB for the past 300 million years indicates that the LLSVP margins must have remained essentially stable in their present positions for at least as long as that. We use here this remarkable long-term relation to calculate the positions of LIPs whose longitudes have hitherto been unknown either because the LIPs erupted on plates that were not part of Pangea (Case 1 below: South China), or the LIPs are older (>320 Ma) than Pangea assembly (Cases 2 and 3: Siberia and the

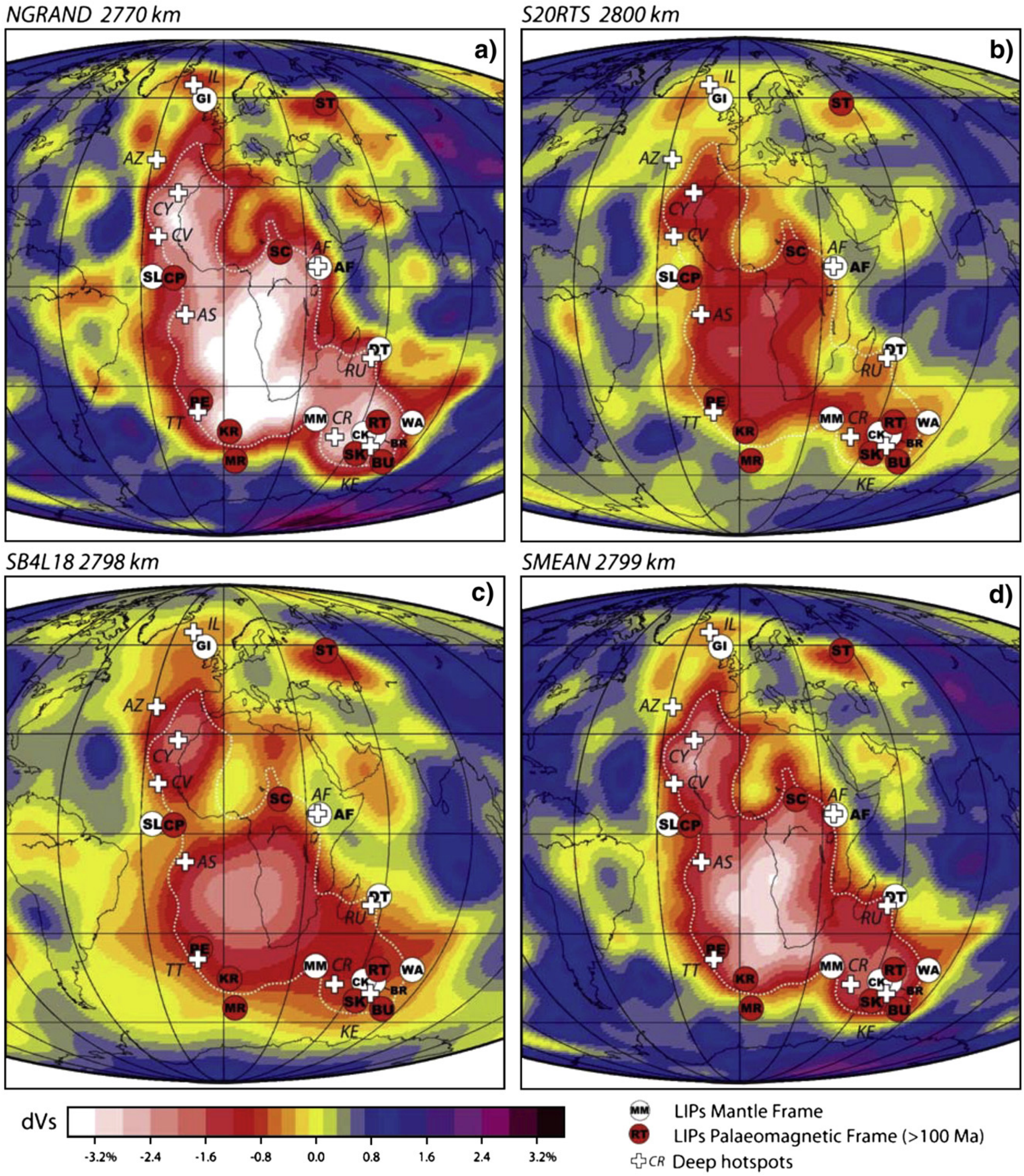

Fig. 4. Reconstructed LIP eruption sites for the last 300 million years using the TPW-corrected hybrid plate motion frame described in the text and Fig. 2, i.e. white circles (≤100 Ma) are based on a moving-hotspot (mantle) frame and red circles on a palaeomagnetic frame corrected for TPW (Table 1). Hotspots argued to have originated from deep plumes (Steinberger, 2000; Courtillot et al., 2003; Montelli et al., 2004, 2006) are shown as white crosses (IL, Iceland; AZ, Azores; CY, Canary; TT, Tristan; RU, Reunion; AF, Afar (East Africa); AS, Ascension; CR, Crozet; CV, Cap Verde; KE, Kerguelen). The data are draped on three different shear wave velocity anomaly (δVs) models (Ritsema et al., 1999; Masters et al., 2000; Grand, 2002) at ca. 2800 km (a–c) that form the basis for the SMEAN model of Becker and Boschi (2002) (d). Four other and grossly similar shear wave velocity anomaly models (Mégnin and Romanowicz, 2000; Gu et al., 2001; Montelli et al., 2006; Simmons et al., 2007) are shown in panels (e–h). The −1% SMEAN contour is shown as a white stippled line in all panels. Active deep-plume sourced hotspots are commonly linked to LIPs; for example Tristan (TT, white cross) is linked to the ~132 Ma Parana-Etendeka LIP (PE, red circle) whereas Afar (AF), Iceland (IL), Reunion (RU) and Kerguelen (KE) are linked to the ~31 Ma Afar (AF), the ~54 Ma Greenland-Iceland (GI), the ~65 Ma Deccan Traps (DT) and the 95–118 Ma southwest cluster of LIPs (BR, WA, CK, SK, RT), respectively (Table 1).

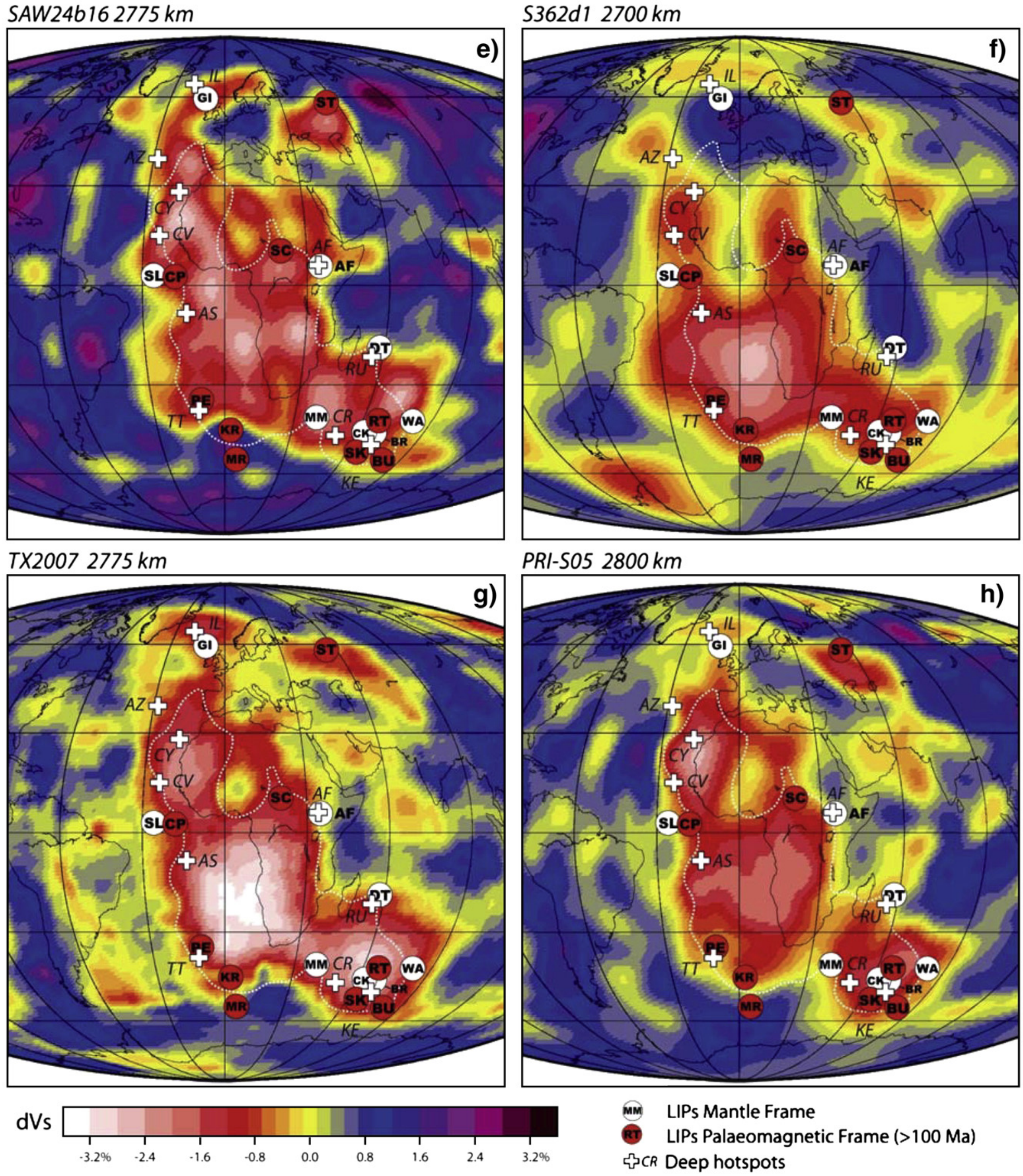

Fig. 4 (*continued*).

Australian part of Gondwana). All three palaeolatitudes are known from palaeomagnetism.

5.1. Pangea and the deep mantle

Pangea had been amalgamated by Permian times, but the supercontinent did not include the two substantial North and South China blocks (Torsvik 2003; Torsvik and Cocks, 2004), which are thus without longitudinal constraints. In the Late Permian, our hybrid plate motion frame places the bulk of Pangea centered above the African LLSVP with North and South China, based on palaeomagnetic data, in tropical to subtropical latitudes somewhere within the Palaeotethys Ocean (Fig. 5). Permian Cathaysian brachiopod faunas of the Chinese blocks are different from those of the rest of the world (Shi and Archbold, 1998), indicating their isolation from Pangea. The 258 Ma Emeishan LIP is on the South China block (Zhou et al., 2002), and excellent palaeomagnetic latitude results (Huang and Opdyke, 1998; Torsvik and Cocks, 2004) position it at 4°N (white stippled line in Fig. 3a) at a time little affected by TPW (Steinberger and Torsvik, 2008). If this LIP erupted from a PGZ (as did all observed low-latitude

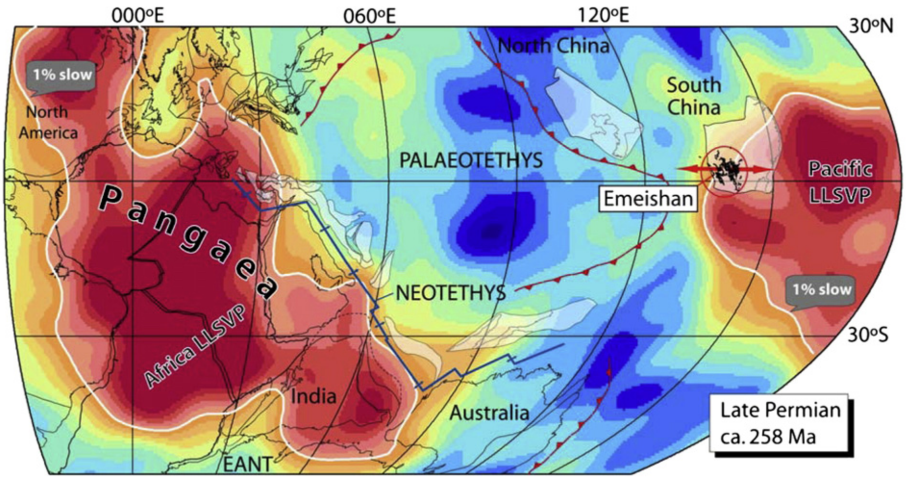

Fig. 5. Map of part of the Pangea supercontinent (from India through Central Africa to Greenland) in Late Permian times, when Pangea was centered above the African LLSVP. Shear wave speed anomalies of the lowermost mantle are shown from the SMEAN model (colour scale as in Fig. 2). New oceanic crust was forming along Pangea's eastern margin in the initial opening of the Neotethys. Pangea did not include North and South China, which were then located within the Palaeotethys, Pacific or the Panthalassan Ocean. Because South China was not part of Pangea, its longitudinal relation to South Africa is unknown and, on palaeomagnetic evidence, it can be placed anywhere in palaeolongitude but not adjacent to Pangea and the African LLSVP. However, if the 258 Ma Emeishan LIP was erupted from a plume derived from the 1% slow shear wave velocity contour in the lowermost mantle of one of the Earth's two major LLSVP's, the only likely position would be along the western edge of the Pacific LLSVP (see also Fig. 3a). Subduction zones are shown as red-tagged lines and spreading centers in blue. The diagram demonstrates both our new reconstruction methods: Pangea is reconstructed with the hybrid reference frame method, whilst the important outcome of this reference frame that LIPs erupted above the edges of the LLSVPs is then used to reconstruct South China in longitude (PGZ frame).

LIPs), there are five possible longitudinal locations on the 4°N line of latitude. Pangea covered the three African LLSVP options, leaving only the two options related to the Pacific LLSVP. The reconstruction in Fig. 5, with Emeishan erupted above the western margin of the Pacific LLSVP at 140°E, is the more realistic alternative. To have concluded (in contrast) that Emeishan erupted above the eastern margin of the Pacific LLSVP would imply unrealistically high convergence rates between Eurasia and South China (250–300 mm/yr) for the ~50 Myr interval between the Late Permian and the Jurassic. We have thus established both the latitude and longitude of South China in the Late Permian (4°N, 140°E). That positioning also determines the previously unknown width of the Palaeotethys Ocean between South China and Pangea at that time, which was as much as 7000 km.

The stability of LLSVPs in their present locations on the CMB can only be demonstrated for the past 300 Myr (Torsvik et al., 2008c), but we have shown that there are good reasons for assuming that the shapes and the antipodal locations of the LLSVPs on the equator have been time-invariant for a much longer period (Burke et al., 2008). We also consider that there was no cumulative TPW, as has been the case since 300 Ma. Using these assumptions, we can reposition continents older than Pangea for times before the zero-longitude motion of Africa approach is viable. We illustrate that procedure in the following two examples.

5.2. Siberia

Very few LIPs have been described from the Palaeozoic and we are only aware of two LIPs (Fig. 3b) that pre-date the 297 Ma Skagerrak-Centered LIP (Torsvik et al., 2008c; SC in Figs. 2 and 4). One of these, the Devonian Yakutsk LIP, intruded the then passive margin of the Siberian Craton (Fig. 6), and nearly broke the continent into two along the substantial Vilyuy Rift System (Cocks and Torsvik, 2007). From radiating dyke swarms, the LIP center is estimated to be at 63°N, 130°E today (Ernst and Buchan, 1997). The eruption time is not precisely dated but estimated at 360 Ma (Kravchinsky et al., 2002). Palaeomagnetic data are directly available from the Yakutsk LIP. We have used the 360 Ma mean pole listed in Cocks and Torsvik (2007) and calculated the eruption latitude to have been at 35°N. That latitude indicates that the Yakutsk LIP can only be related to the northern margin of the African LLSVP. There are two intersections with that LLSVP on its 1% slow contour (Y1 and Y2 on Fig. 3a), but those sites are only separated by 14° of longitude (~1300 km). The Yakutsk LIP might have been at either site, but for the purpose of this paper and discussion below we consider a position at the northeast tip of the Africa LLSVP slightly more probable.

A Late Devonian 360 Ma reconstruction (modified from Torsvik and Cocks, 2004; Cocks and Torsvik, 2007) is shown in Fig. 6, at a time after Laurentia, Baltica and Avalonia had merged to form Laurussia, and most of the Rheic Ocean that once separated Gondwana from Laurussia had disappeared. Initial Pangean assembly occurred some 30 million years later, but Gondwana and Laurussia, which eventually formed the bulk of Pangea creating the Variscan mountain belt in the process, were close to their final relative positions with respect to each other by 360 Ma, at more southerly latitudes. Siberia was an independent continent for almost the entire Palaeozoic (Cocks and Torsvik, 2007) and in Late Devonian times, it was located some distance from the Baltica sector of the eastern margin of Laurussia. At that time its present Arctic margin (Taimyr), which eventually collided with NW Baltica in Permian–Early Mesozoic times, faced southward.

The precise distance between Siberia and Laurussia in the Late Devonian is not known but the relatively short distance indicated in Fig. 6 is here considered realistic for two reasons. First, the future location of the Skagerrak Centered LIP that erupted at 297 Ma was located at around 5°S and 38°E in our Late Devonian reconstruction. That was 6600 km away from its 297 Ma destination, and calls for a mean plate speed of Laurussia of ~100 mm/yr for 63 million years. That is somewhat high for a large continental plate (see below) but moving Laurussia much further westward would increase the Late Palaeozoic velocities beyond reasonable plate speeds. Secondly, in our reconstruction the majority of Devonian subduction zones were located above the high seismic shear-wave velocity regions at the CMB. Today, only 17% of all subduction zones overlie the LLSVPs, and all those are in the SW Pacific (Fig. 3a). Even lower percentages for the last 320 million years of subduction history have been found by using our hybrid TPW corrected reference frame (Stegman and Torsvik, in preparation).

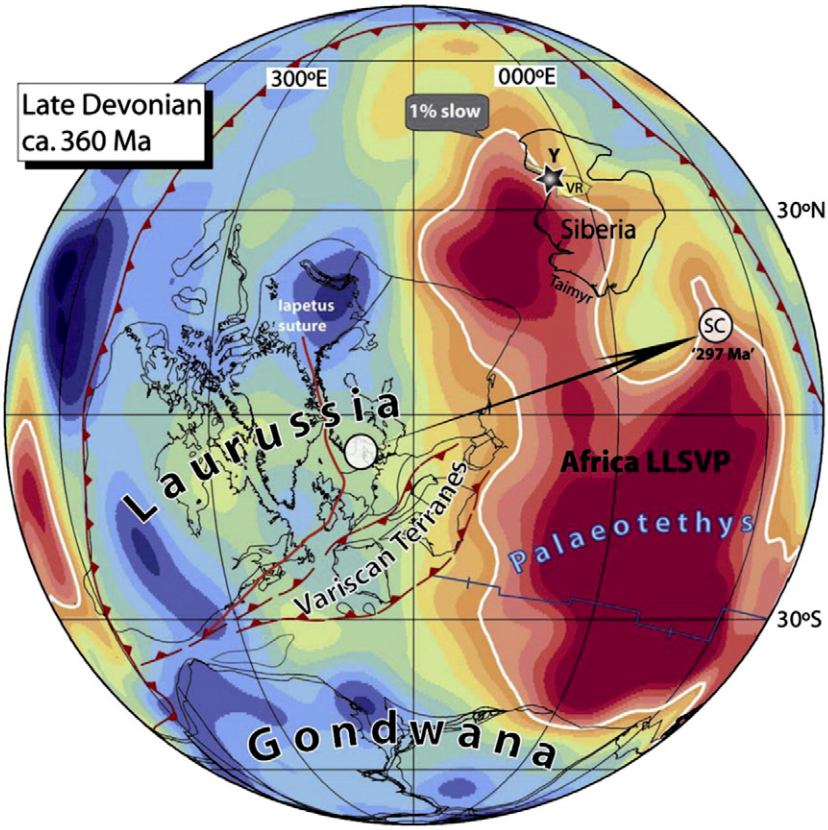

Fig. 6. Late Devonian reconstruction of Siberia, Laurussia, Gondwana and Variscan terranes draped on the SMEAN model (colour scale as in Fig. 2). We also show general subduction zones. The older Late Silurian Iapetus Suture (extinct by the Devonian), resulting in the Caledonian Orogeny, is shown as thick red line. A possible location of the Yakutsk LIP (Y) is shown as a star symbol overlying the NE tip of the African LLSVP edge. We also show the 360 Ma location of the Skagerrak region, south of Norway (white circle), and the future erupting location at 297 Ma (white annotated circle, SC) as in Figs. 2 and 4 and Table 1. VR = Vilyuy Rift.

Our 360 Ma reconstruction is a consequence of the fixed LLSVPs assumption that requires LIPs (in this case Yakutsk) to originate off their edges, defining our PGZ frame, but it is also reliant on palaeomagnetically-derived latitudes from both Laurussia and Gondwana (Torsvik and Cocks, 2004). Unfortunately the Late Devonian palaeomagnetic record is rather poor for both these large terranes. For example, there are no reliable palaeomagnetic data from Laurussia between 396 and 337 Ma. Our 360 Ma reconstruction of Laurussia is thus based on profound interpolation and we have placed Laurussia west of Siberia, and far away from the African LLSVP (compare location of North America in Figs. 5 and 6), in order to avoid continental overlap. During Devonian times, Laurussia is moving northward and by placing Laurussia at more southerly latitudes at 360 Ma (combined with moving Gondwana eastward to avoid overlap with SW Laurussia) we could place Laurussia more to the south of Siberia, and hence much closer to the African LLSVP — that would dramatically reduce the distance to the future location of the Skagerrak Centered LIP and thereby the plate speed of Laurussia between 360 and 297 Ma to perhaps more realistic values.

5.3. Gondwana (Australia)

Gondwana was by far the largest continent during the Early Palaeozoic, for long intervals covering more than 20% of the whole planet and making up 50% of total continental area in those times. It stretched from the South Pole in NW Africa to north of the equator in Australia (Fig. 7). The Gondwana margin from NE Africa to NW Australia was passive during the Lower Palaeozoic (Torsvik and Cocks, in press), and the Kalkarindji Continental Flood Basalt Province (CFBP) of central Australia, a LIP extending over more than 1,000,000 km^2, erupted near that margin at ~510 Ma during the Middle Cambrian (Glass and Phillips, 2006). It includes the Antrim Plateau Volcanics extending over 400,000 km^2 (Veevers, 2004), but we here use the new name suggested by Glass and Phillips (2006) in order to avoid confusion with the Early Tertiary Antrim Basalts of Northern Ireland. There are seven sites on the LLSVP margins at the palaeolatitude of the Kalkarindji CFBP (in Fig. 3a at the intersections of the stippled black line at 9°N with the 1% slow contour), but when we drape a new complete 510 Ma Gondwana reconstruction onto the *SMEAN* map, the choice of the position shown in Fig. 7a (9°N, 28°E) becomes by far the most probable, with the Kalkarindji LIP erupted at the present location of Central Africa (near the present day Afar hotspot) above the margin of the African LLSVP. All other alternatives (except Fig. 7b) can be eliminated because they do not position the majority of long-lived subduction margins of Gondwana (Veevers, 2004; Torsvik et al., 2008a) at the edges of South America, East Antarctica and East Australia above the regions of high seismic velocity in the mantle that mark the subduction graveyards.

6. Discussion: time-scales for LLSVPs

The observation that LLSVPs are time-invariant for 300 Myr and perhaps much longer (Sections 5.2 and 5.3), and thus insensitive to surface plate motions (including the formation of Pangea), may appear problematic (e.g. McNamara and Zhong, 2005) and provides a challenge to be explained in mantle dynamic models. Zhong et al. (2007), in a numerical model, argued that Pangea actually assembled above a major down-welling, and calculated that, following the assembly, a sub-Pangea upwelling developed relatively fast as mantle return flow in response to circum-Pangea subduction. In such a model,

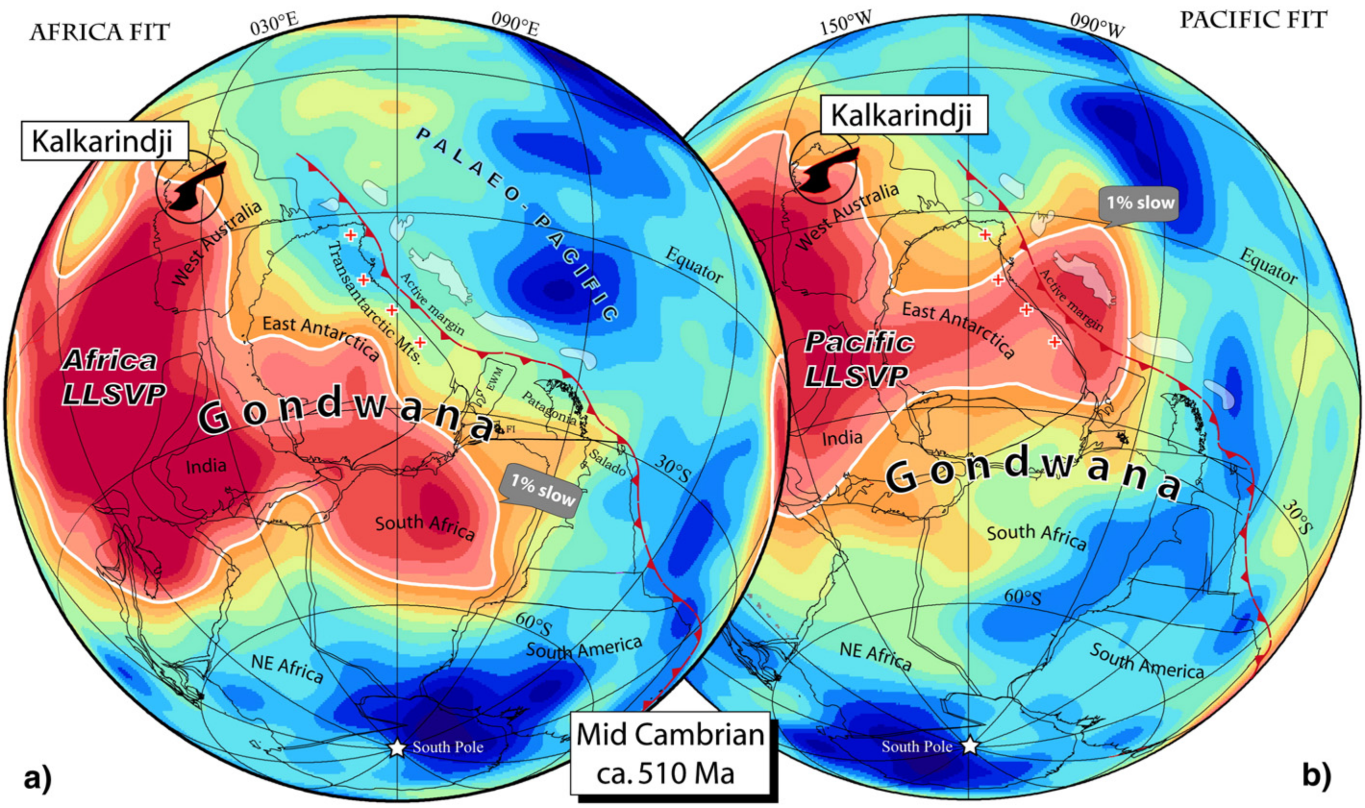

Fig. 7. (a). Middle Cambrian (510 Ma) reconstruction of the Gondwana continent (Torsvik and Cocks, in press; Torsvik et al., 2008a) superimposed on a map of shear wave speed anomalies (colour scale as in Fig. 2) in the lowermost mantle (SMEAN) so that the Kalkarindji LIP in Australia is on the eastern edge of the African LLSVP. This preferred reconstruction places the then active subduction margins of Gondwana above regions of high seismic velocity (subduction graveyards). (b). Alternative reconstruction positioning the Kalkarindji LIP on the eastern edge of the Pacific LLSVP. In that case ongoing Peri-Gondwana subduction along East Antarctica would party cut through the Pacific LLSVP (as seen in the SW Pacific today). The 1% slow contour (SMEAN) is shown as a white thick line.

(1) the African LLSVP should not have existed before Pangea, because convection would have been dominated by a degree-1 mode with only one upwelling, presumably above the Pacific LLSVP, and (2) TPW before Pangea may have been larger, thus complicating the interpretation of ancient palaeomagnetically derived latitudes in relation to deep mantle heterogeneities. Supercontinent formation was mostly complete by 360 Ma (see Fig. 6), thus with the model of Zhong et al. (2007) upwelling plumes could have formed beneath Pangea as early as 330–320 Ma, and, given reasonable estimates for plume rise time, erupted as early as 300 Ma. Hence our findings for the past 300 Myr are not necessarily inconsistent with the Zhong et al. (2007) model.

At face value, mantle flow models used to compute advection of plumes (e.g. Steinberger, 2000) would also predict changes of LLSVPs with time. The fixity of LLSVPs and formation of plumes at their edges for the past 300 Myr is based on observations. After their formation, plume conduits may get distorted and their sources may move off the edges of LLSVPs, and hotspot surface locations may move if there is large-scale flow in the mantle above the LLSVPs. This does not necessarily contradict that the LLSVPs themselves do not move, or much more slowly.

7. Conclusions

We have presented examples of the application of two new reference frames (hybrid and PGZ frames) in determining longitude through time. The hybrid reference frame is the most viable method for constraining continental palaeolongitudes with reasonable confidence before ~130 Ma. We here confirm that Pangea was centered above the African LLSVP in Late Permian times and that reconstructed LIPs erupted radially above the edges of the LLSVPs at the CMB for at least the last 300 million years. The zero longitudinal Pangea (Africa) motion assumption must therefore provide a reasonable proxy for longitude motion before 100 Ma, because large longitudinal changes would not have produced the remarkable LIP concentrations in the PGZs of Figs. 2 and 4.

The relation between reconstructed LIP eruption sites and PGZs at the LLSVP edges, extended back to ~300 Ma with our hybrid plate motion frame, is discernible from both fixed and moving hotspot reconstructions, as well as for most hotspots advocated to have had a deep-plume origin (Figs. 2 and 4). With this derived pattern we have developed a second new reference frame (PGZ frame). Using this frame we can, for the first time, speculate about the sizes and locations of both vanished oceans and old continents such as Gondwana. Knowing ancient longitudes is important and in many cases critical for improving understanding in fields as diverse as palaeogeography, palaeobiology, long-term environmental evolution ("global change"), tectonics, mantle dynamics and Earth history on the grandest scale. Fundamental questions that we have addressed (Burke et al., 2008) that now need further analysis include: (1) are all LIPs derived from deep sources? (2) why do reconstructed LIPs form a ring on the LLSVP edges? (3) how do plumes develop?, and (4) were deep mantle heterogeneities initiated as a result of Pangea assembly (e.g. Zhong et al., 2007) or are they older? High-resolution ages and high-resolution palaeolatitude determination in combination with improved global tomography, incorporated into new mantle dynamic models are essential starting materials for the critical tests that we anticipate.

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References

Becker, T.W., Boschi, L., 2002. A comparison of tomographic and geodynamic mantle models. Geochem. Geophys. Geosyst. 3, 1003. doi:10.1029/2001GC000168.

Boschi, L., Becker, T.W., Steinberger, B., 2007. Mantle plumes: dynamic models and seismic images. Geochem. Geophys. Geosyst. 8, Q10006. doi:10.1029/2007GC001733.

Burke, K., Torsvik, T.H., 2004. Derivation of Large Igneous Provinces of the past 200 million years from long-term heterogeneities in the deep mantle. Earth Planet. Sci. Lett. 227, 531–538.

Burke, K., Steinberger, B., Torsvik, T.H., Smethurst, M.A., 2008. Plume Generation Zones at the margins of large low shear velocity provinces on the core-mantle boundary. Earth Planet. Sci. Lett. 265, 49–60.

Castle, J.C., Creager, K.C., Winchester, J.P., van der Hilst, R.D., 2000. Shear wave speeds at the base of the mantle. J. Geophys. Res. 105, 21543–21558.

Cocks, L.R.M., Torsvik, T.H., 2007. Siberia, the wandering northern terrane and its changing geography through the Palaeozoic. Earth Sci. Rev. 82, 29–74.

Courtillot, V., Jaupart, C., Manighetti, I., Taponier, P., Besse, J., 1999. On causal links between flood basalts and continental breakup. Earth Planet. Sci. Lett. 166, 177–195.

Courtillot, V., Davaille, A., Besse, J., Stock, J., 2003. Three distinct types of hotspots in the Earth's mantle. Earth Planet. Sci. Lett. 205, 295–308.

Davaille, A., Stutzmann, E., Silveira, G., Besse, J., Courtillot, V., 2005. Convective patterns under the Indo-Atlantic. Earth Planet. Sci. Lett. 239, 233–252.

Ernst, R.E., Buchan, K.L., 1997. Giant radiating dyke swarms: their use in identifying pre-Mesozoic Large Igneous Provinces and mantle plumes. AGU Geophys. Monogr. Ser. 100, 297–333.

Garnero, E.J., Lay, T., McNamara, A., 2007. Implications of lower mantle structural heterogeneity for existence and nature of whole mantle plumes. In: Foulger, G.R., Jurdy, D.M. (Eds.), Plates, Plumes, and Planetary Processes. GSA Special Paper, vol. 430, pp. 79–102.

Glass, L.M., Phillips, D., 2006. The Kalkarindji continental flood basalt province: a new Cambrian Large Igneous Province in Australia with possible links to faunal extinctions. Geology 34, 461–464.

Grand, S.P., 2002. Mantel shear-wave tomography and the fate of subducted slabs. Phil. Trans. R. Soc. Lond., Ser. A 360, 2475–2491.

Gu, Y.J.A., Dziewonski, M., Su, W.J., Ekstrom, G., 2001. Models of the mantle shear velocity and discontinuities in the pattern of lateral heterogeneities. J. Geophys. Res. 106, 11169–11199.

Huang, K., Opdyke, N.D., 1998. Magnetostratigraphic investigations on an Emeishan basalt section in western Guizhou province, China. Earth Planet. Sci. Lett. 163, 1–14.

Kravchinsky, V.A., Konstantinov, K.M., Courtillot, V., Savrasov, J.I., Valet, J.P., Cherniy, S.D., Mishenin, S.G., Parasotka, B.S., 2002. Palaeomagnetism of East Siberian traps and kimberlites: two new poles and palaeogeographic reconstructions at about 360 and 250 Ma. Geophys. J. Int. 148, 1–33.

Masters, G., Laske, G., Bolton, H., Dziewonski, A., 2000. The relative behavior of shear velocity, bulk sound speed, and compressional velocity in the mantle: implications for chemical and thermal structure. In: Karato, A. (Ed.), Seismology and Mineral Physics. AGU Geophys. Monogr. Ser., vol. 117, pp. 63–87.

McNamara, A.K., Zhong, S., 2005. Thermochemical structures beneath Africa and the Pacific Ocean. Nature 437, 1136–1139.

Mégnin, C., Romanowicz, B., 2000. The 3D shear velocity structure of the mantle from the inversion of body surface and higher mode waveforms. Geophys. J. Int. 143, 709–729.

Montelli, R., Nolet, G., Dahlen, F., Masters, G., Engdahl, E., Hung, S., 2004. Finite-frequency tomography reveals a variety of mantle plumes. Science 303, 338–343.

Montelli, R., Nolet, G., Dahlen, F., Masters, G., 2006. A catalogue of deep mantle plumes: new results from finite-frequency tomography. Geochem. Geophys. Geosyst. 7, Q11007. doi:10.1029/2006GC001248.

Morgan, W.J., 1971. Convection plumes in the lower mantle. Nature 230, 42–43.

Müller, R.D., Royer, J.-Y., Lawver, L.A., 1993. Revised plate motions relative to the hotspots from combined Atlantic and Indian Ocean hotspot tracks. Geology 16, 275–278.

O'Neill, C., Müller, R.D., Steinberger, B., 2005. On the uncertainties in hot spot reconstructions and the significance of moving hotspot reference frames. Geochem. Geophys. Geosyst. 6, Q04003. doi:10.1029/2004GC000784.

Richards, M.A., Engebretson, D.C., 1992. Large scale mantle convection and the history of subduction. Nature 355, 437–440.

Ritsema, H.J., van Heijst, J.H., Woodhouse, J.H., 1999. Complex shear velocity structure beneath Africa and Iceland. Science 286, 1925–1928.

Romanowicz, B., 2008. Using seismic waves to image Earth's internal structure. Nature 451, 266–268.

Shi, G.G., Archbold, N.W., 1998. Evolution of western Pacific Permian marine provincialism. J. China Univ. Geosci. 23, 1–8.

Simmons, N.A., Forte, A.M., Grand, S.P., 2007. Thermochemical structure and dynamics of the African superplume. Gephys. Res. Lett. 34. doi:10.1029/2006GL028009.

Sleep, N.H., 1997. Lateral flow and ponding of starting plume material. J. Geophys. Res. 102, 10001–10012.

Sleep, N.H., 2006. Mantle plumes from top to bottom. Earth Sci. Rev. 77, 231–271.

Sobel, D., 1995. Longitude: the True Story of a Lone Genius Who Solved the Greatest Scientific Problem of His Time. Walker, Washington DC.

Steinberger, B., 2000. Plumes in a convecting mantle: models and observations for individual hotspots. J. Geophys. Res. 105, 11127–11152.

Steinberger, B., Torsvik, T.H., 2008. Absolute plate motions and true polar wander in the absence of hotspot tracks. Nature 452, 620–623.

Steinberger, B., Sutherland, R., O'Connell, R.J., 2004. Prediction of Emperor-Hawaii seamount locations from a revised model of plate motion and mantle flow. Nature 430, 167–173.

Thorne, M.S., Garnero, E.J., Grand, S.P., 2004. Geographic correlation between hot spots and deep mantle lateral shear-wave velocity gradients. Phys. Earth. Planet. Int. 146, 47–63.

Torsvik, T.H., 2003. The Rodinia Jigsaw Puzzle. Science 300, 1379–1381.

Torsvik, T.H., Cocks, L.R.M., 2004. Earth geography from 400 to 250 Ma: a palaeomagnetic, faunal and facies review. J. Geol. Soc. Lond. 161, 555–572.

Torsvik, T.H., Cocks, L.R.M., in press. The Lower Palaeozoic Palaeogeographical Evolution of the Northeastern and Eastern Peri-Gondwanan Margin from Turkey to New Zealand. Geol. Soc. Lond. Spec. Pub.

Torsvik, T.H., Smethurst, M.A., 1999. Plate tectonic modeling: virtual reality with GMAP. Comp. Geosci. 25, 395–402.

Torsvik, T.H., Smethurst, M.A., Burke, K., Steinberger, B., 2006. Large Igneous Provinces generated from the margins of the large low-velocity provinces in the deep mantle. Geophys. J. Int. 167, 1447–1460.

Torsvik, T.H., Gaina, C., Redfield, T.F., 2008a. Antarctica and Global Paleogeography: from Rodinia, through Gondwanaland and Pangea, to the Birth of the Southern Ocean and the Opening of Gateways. In: Cooper, A.K., Barrett, P.J., Stagg, H., Storey, B., Stump, E., Wise, W. (Eds.), Antarctica: A Keystone in a Changing World. Proc. 10th Int. Symp. on Antarctic Earth Sci. The National Academies Press, Washington, DC, pp. 125–140. doi:10.3133/of2007-1047.kp11.

Torsvik, T.H., Müller, R.D., Van der Voo, R., Steinberger, B., Gaina, C., 2008b. Global plate motion frames: towards a unified model. Rev. Geophys. 46. doi:10.1029/2007RG000227.

Torsvik, T.H., Smethurst, M.A., Burke, K., Steinberger, B., 2008c. Long term stability in deep mantle structure: evidence from the ca. 300 Ma Skagerrak-Centered Large Igneous Province (the SCLIP). Earth Planet. Sci. Lett. 267, 444–452.

Veevers, J.J., 2004. Gondwanaland from 650–500 Ma assembly through 320 Ma merger in Pangea to 185–100 Ma breakup: supercontinental tectonics via stratigraphy and radiometric dating. Earth-Sci. Rev. 68, 1–132.

Wessel, P., Smith, W.H.F., 1991. Free software helps map and display data. Eos 72, 441.

Wilson, J.T., 1963. Evidence from islands on the spreading of ocean floors. Nature 197, 536–538.

Zhong, S., Zhang, N., Li, Z.-X., Roberts, J.H., 2007. Supercontinent cycles, true polar wander, and very long-wavelength mantle convection. Earth Planet. Sci. Lett. 261, 551–564.

Zhou, M.-F., Malpas, J., Song, X.-Y., Robinson, P.T., Sun, M., Kennedy, A.K., Lesher, C.M., Keays, R.R., 2002. A temporal link between the Emeishan Large Igneous Province (SW China) and the end-Guadalupian mass extinction. Earth Planet. Sci. Lett. 196, 113–122.