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Research Paper

Trial by fire: Testing the paleolongitude of Pangea of competing reference frames with the African LLSVP

Ross N. Mitchell [a,b,*], Lei Wu [b], J. Brendan Murphy [b,c], Zheng-Xiang Li [b]

[a] State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China
[b] Earth Dynamics Research Group, The Institute for Geoscience Research (TIGeR), School of Earth and Planetary Sciences, Curtin University, GPO Box U1987, Perth, WA, Australia
[c] Department of Earth Sciences, St. Francis Xavier University, Antigonish, Nova Scotia, Canada

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ABSTRACT

Paleogeography can be reconstructed using various crust- or mantle-based reference frames that make fundamentally different assumptions. The various reconstruction models differ significantly in continental paleolongitude, but it has been difficult to assess which models are more valid. We suggest here a "LLSVP test", where an assumed correlation between present-day large low velocity shear-wave provinces and the paleogeography of supercontinent Pangea at breakup ca. 200 million years ago can be used to assess the relative accuracy of published reconstructions. Closest correlations between continental paleolongitude and the African LLSVP are achieved with mantle-based reference frames (moving hotspots and true polar wander), whereas shallower crust-based reference frames are shown to be invalid. The relative success of mantle-based frames, and thus the importance of the depth of reference frame, supports the notion that mantle convection is largely vertical compared to the horizontal plate motion of tectonics.

1. Introduction

Multiple paleogeographic methods have been used to reconstruct ancient plate tectonics. Ocean floor isochrons (i.e., spreading ridges of equivalent age) unequivocally reconstruct the relative configurations of continents (Muller et al., 2008). Paleomagnetism uses the time-averaged geocentric axial dipole as a reference frame (Torsvik et al., 2008, 2012; Meert, 2009), whereas the "moving hotspot" reference frame uses the slowly moving, highly viscous mantle—both approaches yield paleogeography consistent with ocean isochron-based reconstructions (Raub et al., 2007; Muller et al., 2008; Torsvik et al., 2008). Such available independent constraints on continental drift can be combined into hybrid paleogeographic models, which has become praxis in the field of paleogeography (van der Meer et al., 2010; Mitchell et al., 2012; Torsvik et al., 2012; Matthews et al., 2016). Despite such advances, determining continental paleolongitude, which is critical for testing various models of the supercontinent cycle available (Mitchell et al., 2012), remains elusive in deep time.

Various solutions to the paleolongitude problem have nonetheless been proposed. Both rising plumes (Torsvik et al., 2010) and sinking slabs (van der Meer et al., 2010) have been suggested as potential ways to anchor plate motion in mantle-based reference frames. Such constraints on paleolongitude are typically coupled with the paleomagnetic reference frame to make "hybrid" paleogeographic models (Torsvik et al., 2008, 2012; van der Meer et al., 2010; Matthews et al., 2016). Paleolongitude has long been considered impossible to detect paleomagnetically due to the axial symmetry of magnetic field. Nonetheless, as well as tracking the latitudinal component of continental drift, paleomagnetism also detects true polar wander (TPW), the wholesale motion of the solid Earth (mantle and crust) about the liquid outer core (Gold, 1955; Goldreich and Toomre, 1969; Tsai and Stevenson, 2007). The apparent polar wander (APW) path for a given continent is thus the sum of the weighted contributions from TPW and continental drift (Raub et al., 2007). APW therefore establishes paleolongitude relative to the equatorial TPW axis, which is controlled by long wavelength whole mantle convection controlling Earth's geoid (and therefore rotation axis of TPW), thus breaking the axial symmetry of Earth's magnetic field. TPW events are used as paleolongitude "check points" and added to the paleomagnetic frame to yield another type of hybrid paleogeographic model (Mitchell et al.,

* Corresponding author. State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China.
E-mail address: ross.mitchell@mail.iggcas.ac.cn (R.N. Mitchell).
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2012).

Thermochemical structures in the deep mantle characterized by large low shear-wave velocity provinces (LLSVPs) (Garnero et al., 2016) offer an additional approach to test the determination of continental paleolongitude. There is consensus that the two antipodal and equatorial African and Pacific LLSVPs are likely a reflection of degree-2 mantle convection (Zhong et al., 2007), however debate remains over whether LLSVPs are either static or dynamic in deep time (i.e., beyond 300 Ma) (Evans, 2010; Torsvik et al., 2010). Since LLSVPs appear to have been stable since at least the breakup of Pangea ca. 200 Ma (Conrad et al., 2013), comparison of competing approaches to continental paleolongitude using the African LLSVP may offer an opportunity to assess the relative accuracy of the reconstruction models. Early assessments of lower mantle tomography revealing the dominance of the degree-2 structure noted the conspicuous correlation with the position of vanished supercontinent Pangea, implying a lag between deep mantle processes and surface tectonics (Chase, 1979; Anderson, 1982; Chase and Sprowl, 1983). Decades later, seismic characterization of the LLSVPs and paleogeographic reconstructions have been independently refined and the correlation between present-day lower mantle structure and ancient paleogeography still holds (Torsvik et al., 2012). Here, for the first time, we explicitly use LLSVPs to assess competing solutions to the paleolongitude problem.

2. Methods

We compile Euler rotations in South African coordinates from five absolute plate motion models. The "Wu" model (Wu et al., 2017) uses paleomagnetic Euler pole (PEP) analysis calculated from the stable European APW path of Torsvik et al. (2012) (which is the basis for the post-180 Ma absolute plate motion of stable Europe), and hence it constrains paleolongitude using a tectonic reference frame. The "van der Meer" model (van der Meer et al., 2010) is built on the paleomagnetic frame of Torsvik et al. (2008) and then constrains paleolongitude based on tomographic images of subducting slabs distributed in the mantle, and hence is a subduction reference frame. The "Matthews" model (Matthews et al., 2016) combines the hotspot frame (0–140 Ma) and the most recent paleomagnetic frame of Torsvik et al. (2012) for earlier times, and hence

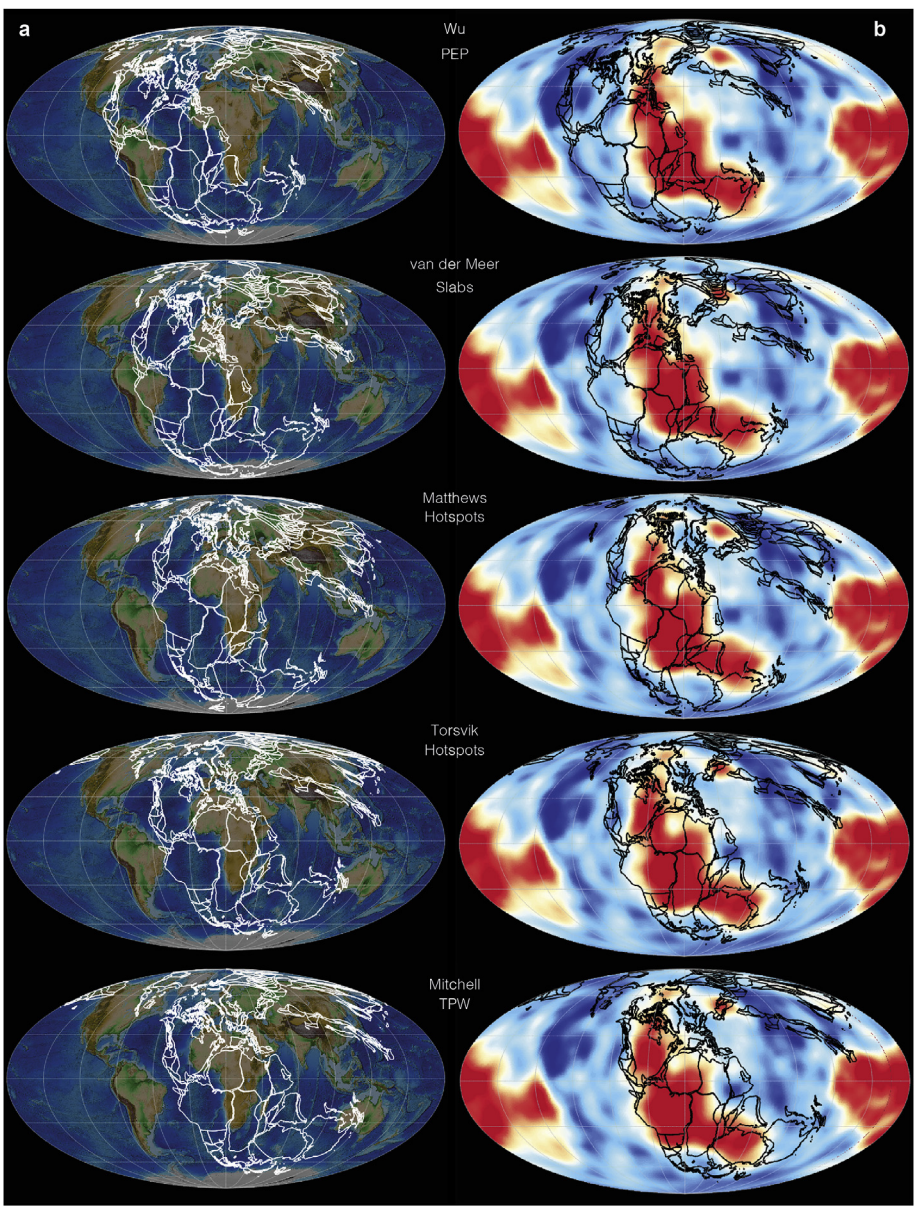

Fig. 1. Paleolongitude of Pangea and the African LLSVP. (a) Comparison between continental paleolongitude according to different reference frames at 200 Ma. Background image is present-day arrangement of continents and oceans for reference. Reconstructions used, from top to bottom: Wu et al. (2017), van der Meer et al. (2010), Matthews et al. (2016), Torsvik et al. (2012), and Mitchell et al. (2012). (b) Comparison between continental paleolongitude at 200 Ma and present-day lower mantle superplumes. Different paleogeographic reference frames are from Fig. 1a. Seismic shearwave velocity is SMEAN5 from Doubrovine et al. (2016), where red = slow velocities and blue = fast velocities. African superplume in center and Pacific superplume at edges. Note increasing correspondence between the competing solutions for the paleolongitude of Pangea and the African LLSVP towards the bottom of the figure.

is a hotspot reference frame. The "Torsvik" model (Torsvik et al., 2012) is comprised of the global moving hotspot frame of Doubrovine et al. (2012) for the last 130 Ma and the paleomagnetic frame for earlier times, and hence is also a hotspot reference frame. The "Mitchell" model (Mitchell et al., 2012) starts with the paleomagnetic frame of Torsvik et al. (2008) and then constrains paleolongitude from TPW estimates, aligning paleomagnetically-determined great circles with Earth's minimum moment of inertia (I_{min}), and hence is a TPW reference frame. These five absolute plate motion models are rotated into the South African coordinates using the post-180 Ma plate circuits from Matthews et al. (2016). Various authors provide "TPW-corrected" reconstructions (Torsvik et al., 2012; Wu et al., 2017), but this would require also rotating the LLSVPs accordingly (i.e., TPW is wholesale rotation of crust and mantle) and therefore would have no affect on the relative correlations of continental paleolongitude with the African LLSVP.

For the lower mantle thermochemical structures imaged seismically, we adopt here the s5mean model of Doubrovine et al. (2016) that is stacked from five high-quality shear-wave models: GyPSuM (Simmons et al., 2010), HMSL-S (Houser et al., 2008), S40RTS (Ritsema et al., 2011), S362ANI (Kustowski et al., 2008), and SAW642AN (Megnin and Romanowicz, 2000). Velocity perturbations at 2800 km depth represent averages of those from each of the input models after the removal of layer mean velocities (Doubrovine et al., 2016).

3. Results

Five different paleogeographic models available are compared herein (Fig. 1a): a paleomagnetic Euler pole (PEP) model by Wu et al. (2017); a subducting slabs model by van der Meer et al. (2010); moving-hotspot models by Matthews et al. (2016) and Torsvik et al. (2012); and, finally, a true polar wander (TPW) model by Mitchell et al. (2012). All of the models except PEP (Wu et al., 2017) are hybrid models incorporating paleomagnetism as well as some additional constraint (slabs, hotpots, or TPW). In this sense, PEP analysis is a strictly lithospheric (i.e., crust-based) reference frame whereas the hybrid models additionally incorporate paleolongitude information from the mantle that can be considered geodynamic (i.e., mantle-based) reference frames. Furthermore, slabs may be more influenced by the lithosphere than the other more purely geodynamic reference frames (hotspots and TPW) since subduction zones migrate at the surface due to plate tectonics (Spencer et al., 2019).

Inspection of Fig. 1a shows that the different paleogeographic models largely differ in paleolongitude, reflecting a lack of consensus on paleolongitudinal constraints. This uncertainty, combined with the different reference frames employed, explains the different solutions. Fig. 1b presents the comparison of competing reconstructions ca. 200 Ma with the present-day lower mantle, i.e., the African LLSVP. For the lithospheric reference frames (PEP and slabs), poor agreement with the African LLSVP is achieved. For the mantle reference frames (moving-hotspot and TPW), excellent agreement with the African LLSVP is achieved. If the Pangea-LLVSP correlation is indeed valid, then mantle-based reference frames appear to more reliably track paleolongitude.

4. Discussion

Although interrelated, to first order, all geodynamic references frames (slabs, hotspots, and TPW) record distinct tectonic phenomena. We note that the depth and direction of reference frames are distinct from each other, in some cases slightly, but still significantly (Fig. 2). Mantle hotspots and subducting slabs both attempt to anchor lithospheric continental drift in a mantle-based reference frame, but from opposite directions: bottom-up and top-down anchoring, respectively. TPW and moving-hotspots may offer the most accurate reference frames for tracking paleolongitude because they are both derived from LLSVPs. Due to their collectively notable (i) depth, (ii) size, and (iii) duration, the LLSVPs that control the TPW axis and generate most mantle plumes

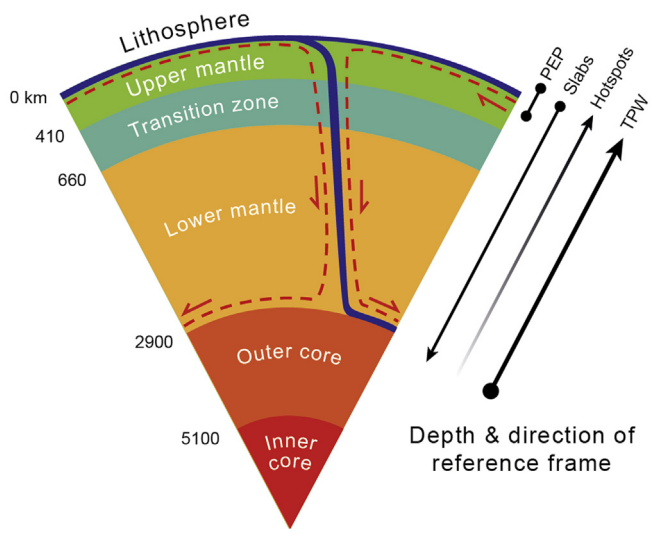

Fig. 2. Comparison of depths and directions of various reference frames. Circles denote anchor points (e.g., trench of slab). Arrows denote vertical motions (up or down). Hotspots derive from various heights within mantle. True polar wander (TPW) yields best solution for paleolongitude (Fig. 1) because TPW axis is controlled by only the deepest, largest, and longest-lived features in the mantle (i.e., the LLSVPs).

apparently provide the most accurate measure of paleolongitude. But there may also be reasons why the TPW solution yields a slightly better fit than that of the hotspots solutions: (i) most hotspots may be anchored in the mantle, but not all, or even a majority, and possibly only a few (<20%), are rooted very deep in the lower mantle (Courtillot et al., 2003; Zhao, 2007), whereas (ii) the TPW axis is defined by the minimum moment of inertia of the planet that is largely controlled by excess mantle ellipticity due to mantle convection with contributions as deep as long-wavelength dynamic topography created by such flow on the core-mantle boundary (Evans, 2003; Creveling et al., 2012; Mitchell, 2014). Although slabs may be related to the origin of LLSVPs (i.e., slab graveyards (Sleep, 2003; Niu, 2018)), the mobility of arcs due to plate tectonics (Spencer et al., 2019) argues against their utility as a stable reference frame.

Our conclusions can be tested by utilizing the well-established link between the emplacement of large igneous provinces (LIPs) at the edges of LLSVPs for the past 300 Myr (Torsvik et al., 2010). For the past 300 Myr, there is a well-established link between the emplacement of large igneous provinces (LIPs) at the edges of LLSVPs (Torsvik et al., 2010). The convention of using the −1% velocity contour in order to test the LLSVP-LIP correlation has been widely adopted (Torsvik et al., 2008; Doubrovine et al., 2016). Cluster analysis recently has updated the LLSVP-LIP correlation test (Doubrovine et al., 2012). Presumably, slab graveyards piled up beneath newly-assembled supercontinents (Maruyama et al., 2007) are prime thermochemical targets for advecting deep plumes emanating from the core-mantle boundary and emplacing LIPs (Burke et al., 2008; Tronnes, 2010). Our correlations between continental paleolongitude and the African LLSVP would predict that the mantle-based (moving-hotspot- and TPW-based) reference frames (Matthews (Matthews et al., 2016), Torsvik (Torsvik et al., 2012), and Mitchell (Mitchell et al., 2012) models) will yield better LLSVP-LIP correlations than those of the lithospheric (PEP- and slab-based) reference frames (Wu (Wu et al., 2017) and van der Meer (van der Meer et al., 2010) models).

While this analysis thus provides clarity for Mesozoic and Cenozoic reconstructions of the past 200 Myr, it also highlights the importance of testing LLSVP stability or mobility in deep time. Valiant efforts have been made to resolve the *relative* motions of continents in Paleozoic time, including full-plate topologies (Domeier and Torsvik, 2014) and

associated evolving mantle flow patterns (Young et al., 2019). Nonetheless, establishing the absolute paleolongitude of the continents (i.e., the relative paleolongitude of the continents with respect to the modern latitude/longitude grid) requires establishing whether LLSVPs are stable through time (Torsvik et al., 2010, 2014) or whether they are mobile (Zhong and Liu, 2016), e.g., shifting ~90° according to the orthoversion model of the supercontinent cycle (Mitchell et al., 2012). Tight coupling between the supercontinent cycle and LIPs, which emanate from LLSVPs, provides preliminary support for dynamic coupling between LLSVPs and the supercontinent cycle (Doucet et al., 2020). Only when a LLSVP reference frame can be established before 200 Ma, whether stationary or shifted, can the LLSVP-based parameterization of continental paleolongitude proposed here be used in Paleozoic time. In the meantime, the correlation of continents with respect to a LLSVP beneath a supercontinent at breakup may also be used to refine the relative paleolongitude of continents in the much debated Rodinia supercontinent in Neoproterozoic time.

5. Conclusion

This study shows that lower mantle structures as exemplified by LLSVPs can be used to assess the relative success of different paleogeographic reference frames. In particular, the African LLSVP can be used to assess the competing solutions for the paleolongitude of supercontinent Pangea, the formation of which is thought to have created the slab graveyard whose geochemical evolution led to the origin of the LLSVP. We categorize competing reference frames as either crust-based (paleomagnetic Euler pole (PEP) and slab tomography methods) or mantle-based (moving hotspots and true polar wander (TPW)). We find that the mantle-based reference frames yield much stronger correlations between the paleolongitude of Pangea and the African LLSVP, implying that reference frames based on the largely vertical motions of the mantle are comparatively more stable than those based on the largely horizontal motions of lithospheric plate tectonics. Furthermore, TPW, which is rooted in the lower mantle unlike a majority of hotspots, provides the best estimate of paleolongitude among the mantle-based reference frames.

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