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Anomalous Late Jurassic motion of the Pacific Plate with implications for true polar wander

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ABSTRACT

True polar wander, or TPW, is the rotation of the entire mantle–crust system about an equatorial axis that results in a coherent velocity contribution for all lithospheric plates. One of the most recent candidate TPW events consists of a ∼30° rotation during Late Jurassic time (160–145 Ma). However, existing paleomagnetic documentation of this event derives exclusively from continents, which compose less than 50% of the Earth's surface area and may not reflect motion of the entire mantle–crust system. Additional paleopositional information from the Pacific Basin would significantly enhance coverage of the Earth's surface and allow more rigorous testing for the occurrence of TPW. We perform paleomagnetic analyses on core samples from Ocean Drilling Program (ODP) Site 801B, which were taken from the oldest available Pacific crust, to determine its paleolatitude during the Late Jurassic and Early Cretaceous (167–133 Ma). We find that the Pacific Plate underwent a steady southward drift of 0.49°–0.74° My^{-1} except for an interval between Kimmeridgian and Tithonian time (157–147 Ma), during which it underwent northward motion at $1.45^\circ \pm 0.76^\circ\ \text{My}^{-1}$ (1σ). This trajectory indicates that the plates of the Pacific Basin participated in the same large-amplitude (∼30°) rotation as continental lithosphere in the 160–145 Ma interval. Such coherent motion of a large majority of the Earth's surface strongly supports the occurrence of TPW, suggesting that a combination of subducting slabs and rising mantle plumes was sufficient to significantly perturb the Earth's inertia tensor in the Late Jurassic.

1. Introduction

Paleomagnetic experiments can quantify the progressive change in the latitude of lithospheric blocks through time. Such latitudinal drift can result from the motion of lithospheric plates over the mantle (hereafter referred to as "tectonic motion") or true polar wander. The latter mechanism, abbreviated TPW, is defined as the rotation of the entire mantle–crust system around the outer core due to changes in the Earth's inertia tensor, which may arise from the redistribution of mass anomalies within the mantle or on the surface (Creveling et al., 2012; Gold, 1955). TPW is an ongoing process on the modern Earth, where an $\sim 1^\circ\ \text{My}^{-1}$ rotation of the geographic north pole towards the Hudson Bay is primarily driven by Pleistocene deglaciation with a significant component likely due to mantle flow (Wu and Peltier, 1984; Gordon, 1995; Steinberger and O'Connell, 2002). Due to the relationship between TPW and motions in the Earth's deep interior, characterization of TPW in the geological past may offer unique insights into ancient mantle dynamics (Greff-Lefftz and Besse, 2014).

The differential motion of lithospheric plates over the deep mantle complicates the characterization of TPW in the geological past. Because TPW is defined as coherent rotation of the entire mantle–crust system, the motion of the deep mantle should also be known to demonstrate conclusively the occurrence of TPW. Since ∼130 Ma, the Indo-Atlantic hotspot reference frame has been used to infer the orientation of the deep mantle (Müller et al., 1993), potentially permitting a quantitative description of TPW during this time (e.g., Gordon and Jurdy, 1986; Torsvik et al., 2008). Some investigations into the post-130 Ma past have interpreted motion of Pacific hotspots with respect to the rotation axis as TPW at 84–85 Ma (Gordon, 1983; Sager and Koppers, 2000). However, the occurrence of anomalous motion at the same time in the continental domain remains unclear (Cottrell and Tarduno, 2000).

The oldest hotspot track likely to have a deep mantle origin is Tristan da Cunha, which is traceable to 130 Ma (Courtillot et al., 2003). Therefore, studies of global lithospheric motion before that time have relied on indirect arguments to establish the occurrence of TPW. Most commonly, coherent motion of multiple

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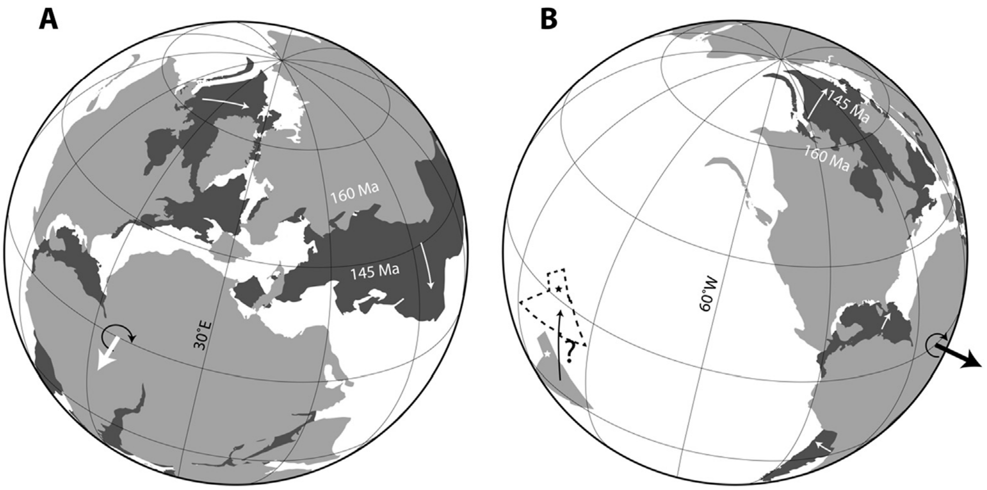

Fig. 1. Visualization of the Late Jurassic TPW hypothesis. (A) A compilation of igneous paleomagnetic poles suggests a rotation of ∼28.6° amplitude around an equatorial Euler pole between 160 and 145 Ma (Kent et al., 2015). (B) View of the same proposed 160–145 Ma rotation showing the position of the Pacific Plate at 160 Ma based on our paleomagnetic data and the estimated longitude of Seton et al. (2012). Dashed outline shows the projected position of the Pacific Plate at 145 Ma assuming the Pacific Plate participated in the candidate TPW rotation in the 160–145 Ma interval. Relative positions of continents plotted based on the paleomagnetic reconstruction of Seton et al. (2012).

lithospheric plates (i.e., the combined Euler rotation vector for a set of area-weighted plates) has been interpreted to provide evidence for TPW (McKenzie, 1972; McElhinny, 1973; Jurdy and Van der Voo, 1974). Such a global compilation of plate velocities permits the quantification of net lithosphere rotation, which, in the strict sense, describes only the motion of the crust and lithospheric mantle.

Geodynamical arguments can relate the net rotation of the lithosphere to that of the deep mantle, thereby permitting inferences of TPW. In an idealized crust–mantle system, the condition that net torque on all lithospheric plates sums to zero implies that no net rotation of the lithosphere can occur with respect to the deep mantle (Solomon and Sleep, 1974). In such a scenario, a net rotation of the lithosphere would correspond directly to rotation of the entire crust–mantle system and thereby fully quantify TPW. However, due to laterally heterogeneous rheologies and unbalanced forces at plate margins, the zero net torque condition is not equivalent to zero net lithospheric rotation, implying that knowledge of lithospheric motion, even of the entire globe, does not precisely constrain the motion of the deep mantle frame (Solomon and Sleep, 1974).

Even so, coherent lithospheric motion may constitute an imperfect but acceptable proxy for motion of the deep mantle frame because net rotation of the lithosphere is empirically small, estimated to be between 0.1° and $0.2°\,\mathrm{My}^{-1}$ over the last 60 My (Jurdy and Van der Voo, 1974; Gordon and Jurdy, 1986). Furthermore, this rate of net rotation agrees with expectations from the power of toroidal motion at higher spherical harmonic degrees, supporting the idea that the low observed rate is a natural consequence of mantle dynamics (O'Connell and Hager, 1990). Finally, numerical simulations of mantle convection show that net rotations faster than $\sim 0.2°\,\mathrm{My}^{-1}$ are difficult to produce without extremely deep continental keels (Zhong, 2001). In summary, if the net motion of the entire lithosphere or a large majority thereof is known, the motion of the entire crust–mantle frame, and hence the occurrence of TPW, can be quantified with uncertainty of order $0.2°\,\mathrm{My}^{-1}$.

Based on these arguments, most paleomagnetic studies of the >130 Ma past use observations of coherent plate motion to infer TPW. For example, Torsvik et al. (2012) proposed four episodes of possible TPW between 250 and 100 Ma by identifying apparently coherent rotations of continents around a specific equatorial axis through the large low shear velocity provinces (LLSVPs) of the lower mantle. Among these, two episodes can be combined into a single clockwise rotation of 30.5° around an equatorial Euler pole at 11°E longitude (South African coordinates) between 200 and 140 Ma. An alternative compilation by Kent and Irving (2010) using a much more stringent quality filter for individual poles shows a rotation with similar amplitude (28.6°) and similar equatorial Euler pole (∼10°W in NW African coordinates), but with much higher rate of $\sim 2°\,\mathrm{My}^{-1}$ focused between 160 and 145 Ma. Subsequent studies have shown that this 160–145 Ma rotation is consistent with stringently selected igneous paleomagnetic poles from North America, South America, Adria, South Africa, and Australia (Muttoni et al., 2013), leading Kent et al. (2015) to hypothesize that the 28.6° motion between approximately 160 and 145 Ma constitutes an episode of TPW (Fig. 1). If confirmed as such, this event would represent the most recent TPW of large (≥25°) amplitude in Earth history.

However, as with all other periods of possible TPW before 130 Ma, the motion of large fractions of the Earth's lithosphere remains poorly constrained in the Late Jurassic. The positions and velocities of all continental plates (except the United China Block; Van der Voo et al., 2015) and the nascent Atlantic Basin during the Late Jurassic may be quantified using a combination of paleomagnetic poles and seafloor magnetic lineations. However, the motion of the Pacific Basin, comprising the Pacific, Farallon, Izanagi, Phoenix, and possibly additional plates, remains poorly known in the same time interval (Larson et al., 1992). Because the lithosphere outside the Pacific Basin composed only approximately 50% of the Earth's surface area, coherent motion of the continental plates may not constitute a net rotation of the lithosphere, thereby weakening the relationship between their motion and that of the deep mantle. As such, paleomagnetic data from the continents alone cannot rigorously test the occurrence of TPW.

The recovery of paleoposition information for plates in the Pacific Basin during the Late Jurassic would provide key additional information regarding the occurrence of TPW. Because the relative motions of the Pacific, Farallon, Izanagi, and Phoenix plates are known from seafloor magnetic lineations, paleomagnetic determination of Pacific Plate motion would constrain the position of a significant additional fraction of the lithosphere. As such, if paleomagnetic data from the Pacific Plate suggest that the Pacific Basin plates participated in the same rotation as the continental plates during the 160–145 Ma interval, the combined motion would involve a large majority of the lithosphere and is therefore