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True polar wander in the Earth system

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Abstract True polar wander (TPW), or planetary reorientation, is the rotation of solid Earth (crust and mantle) about the liquid outer core in order to stabilize Earth's rotation due to mass redistribution. Although TPW is well-documented on Earth presently with satellites and for multiple planets and moons in the Solar System, the prevalence of TPW in Earth history remains contentious. Despite a history of controversy, both the physical plausibility of TPW on Earth and an empirical basis for it are now undisputed. Lingering resistance to the old idea likely stems from the fact that, like plate tectonics, TPW may influence much of the Earth system, thus acknowledging its existence requires rethinking how many different datasets are interpreted. This review summarizes the development of TPW as a concept and provides a framework for future research that no longer regards TPW like a ghost process that may or may not exist, but as an integral part of the Earth system that can relate shallow and deep processes that are otherwise only mysteriously linked. Specifically, we focus on the temporal regularity of large TPW, and discuss its relationship with the supercontinent–megacontinent cycle based on previous studies. We suggest the assembly of megacontinents has a close linkage to large TPW. Meanwhile, supercontinent tenure and breakup have a close linkage to fast TPW. The effects of TPW on sea level changes, paleoclimate, biological diversity, and other facets of the Earth system are presented and require interdisciplinary tests in the future.

Keywords True polar wander (TPW), Planetary reorientation, Apparent polar wander (APW), Mantle convection, Supercontinent cycle, Megacontinent

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1. Introduction

The rotation of a self-gravitating planet or moon can become unstable due to mass redistribution. Earth's spin axis intersects the surface at the geographic north and south poles. Usually, the geographic poles are not stable and they are moving relative to the surface, i.e., the geographic location of the spin axis changes. This phenomenon is called polar motion, a different concept from the external torques associated with the precession of the equinoxes and nutation in a celestial reference frame. In geological time, polar motion is also known as true polar wander (TPW) (Figure 1). Any quasi-rigid dynamic planet or moon must undergo TPW to stabilize its rotation vector. Strictly speaking, TPW is defined as the alignment of a celestial body's spin axis with its maximum moment of inertia (I_{max}) (Gold, 1955; Goldreich and Toomre, 1969). Any celestial body must spin about I_{max}; thus, if the body's mass is redistributed such that I_{max} changes location, then the spin axis must follow and this is achieved by TPW. By definition then, the rotation axis of a TPW event is an equatorial axis.

A perfect sphere would experience TPW in random directions, but Earth is not a sphere. Earth's equilibrium figure, the ~21-km-amplitude hydrostatic bulge due to the latitudinal dependence of gravity on a rotating body (Figure 2a), is able to adjust to TPW on 1–100 kyr time scales, but not on

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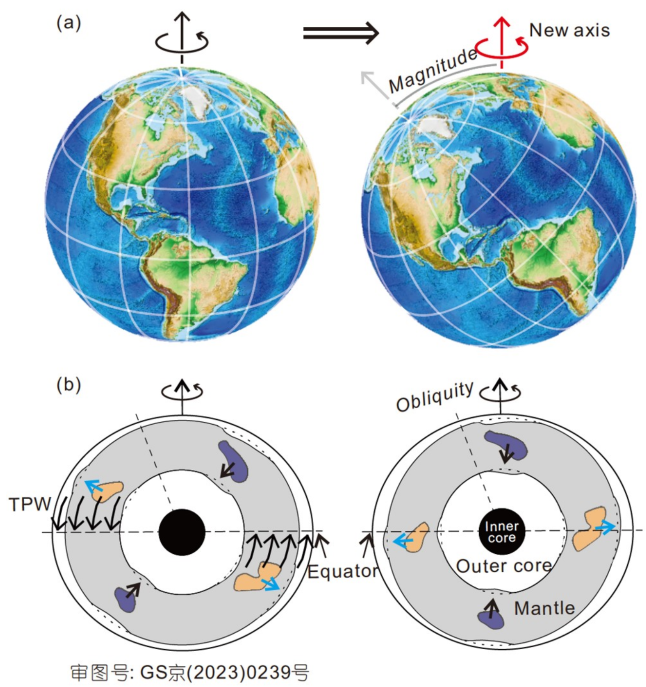

Figure 1 (a) Sketch of a ~45° TPW event if it were to occur today. (b) Cross section profiles showing forcings from sinking slabs and rising plumes during TPW (simplified after Evans (2003)). Note that Earth's obliquity is ignored in these illustrations, so that Earth's spin axis plots upright.

longer (>1 Myr) ones (Richards et al., 1997; Steinberger and O'Connell, 1997). In general, the short time scales of polar motion include (i) hours to weeks generally excited by tides, winds, atmospheric/oceanic, and earthquake forcings; (ii and iii) annual and 433-day Chandler periods excited by global solar-related forcing and a free wobble, respectively; and (iv) interannual, interdecadal and 30-yr Markowitz periods excited by global hydrological and cryospheric forcings, possibly modified by a subtle core–mantle coupling. Evans (1998) emphasized that the time scales of TPW are longer than 1 Myr. The shape of the nonhydrostatic figure of Earth (i.e., with the hydrostatic rotational bulge removed) is what dominantly controls TPW and the stability of the spin axis. Earth's nonhydrostatic moment of inertia can be described as a tensor with three principal axes (maximum, intermediate, and minimum; I_{max}, I_{int}, and I_{min}, respectively) (Figure 2b). Earth's nonhydrostatic figure is presently triaxial (i.e., three distinct axes), which renders the rotation axis relatively stable in recent times. In more ancient times, however, if Earth in the past was ever biaxial in shape, i.e., where I_{max} and I_{int} are nearly subequal and liable to interchange their relative identities, then large-amplitude, fast TPW would have been more likely to have occurred (Evans, 1998; Goldreich and Toomre, 1969; Mitchell, 2014; Steinberger et al., 2017). It is important to point out that I_{min} is not necessarily the TPW rotation axis. By definition, I_{min} and I_{int} always lie in the plane perpendicular to I_{max}. Therefore, if the new I_{max} relocates from its original orientation (Earth's spin axis) due to mass redistribution, accordingly, I_{min} could move out of the equatorial plane where it was originally located. But there can be such exceptions. For a prolate Earth's nonhydrostatic figure, which may be prevalent throughout Earth history given the dominance of degree-2 mantle convection (Mitchell et al., 2021b; Zhong et al., 2007), I_{min} may serve as the TPW rotation axis in most cases. For example, the TPW axis for the last ~300 Myr has been I_{min}, which is controlled by the largest masses in the mantle, the large low shearwave velocity provinces (LLSVPs) in the lower mantle (Mitchell et al., 2021a; Steinberger and Torsvik, 2008). Lastly, planets such as Earth with elastic lithospheres may retain a "memory" for the remanent rotational bulge (prior to TPW) and thus limit the amplitude of TPW (Creveling et al., 2012), but the importance of such a mechanism remains unclear since changes in Earth's nonhydrostatic figure can also achieve this.

The reason the planet or moon must be quasi-rigid is because the body must be able to redistribute its mass in order for TPW to be excited. Both Lord Kelvin and George Darwin considered TPW to be impossible on Earth, not because they doubted the mechanism itself, but rather because they doubted its applicability to Earth which they believed (at the time) to be rigid (Darwin, 1877). The later realization that Earth's rocky mantle is actually capable of slowly deforming subsequently removed this theoretical impedance to TPW on Earth. In fact, Earth, which not only has surface processes and internal convection, but also the potentially unique phenomenon of plate tectonics, is the most dynamic celestial body known and therefore the most likely candidate for the prevalence of TPW from an excitation point of view.

TPW has also been attributed on other planets and moons throughout the Solar System. The fact that the largest positive gravity anomaly in the Solar System, the Tharsis magmatic province of Mars, sits squarely on the Martian equator is interpreted not as a coincidence, but as TPW having brought it there (Bouley et al., 2016). Similarly but conversely, the shallow geyser squarely at the South Pole of Saturn's moon, Enceladus, is also interpreted not as coincidental, but as a result of TPW (Nimmo and Pappalardo, 2006). Because a body must deform to a new hydrostatic bulge during TPW, regions moving toward the equator undergo extension (increasing radius) and those moving poleward experience compression (decreasing radius). This so-called "membrane stress" may account for deformed shorelines on Mars (Perron et al., 2007), small-circle depressions on Jupiter's Moon Europa (Schenk et al., 2008), and possibly even some non-tectonic structural features on Earth (Liu, 1974). The presence of tectonic stresses on Earth has heretofore precluded identifying evidence for TPW from membrane stress; nonetheless, if TPW has occurred as much as this review may suggest it has on the basis of paleomagnetic

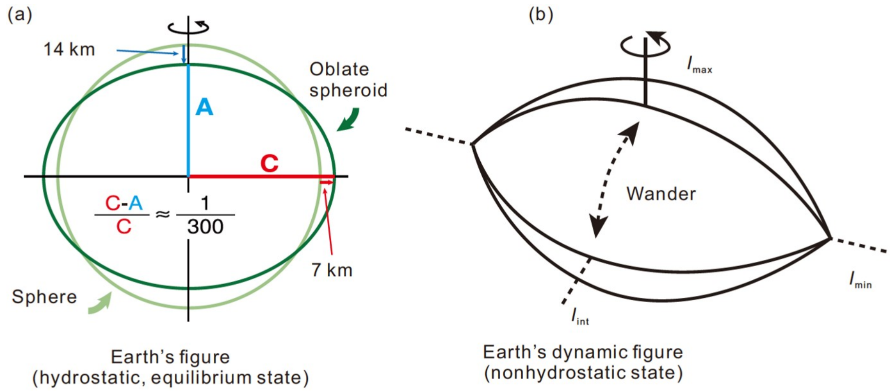

Figure 2 (a) Earth's equilibrium hydrostatic figure. (b) Earth's nonhydrostatic figure stylized as an American football; modified after Hoffman (1999). In (a), A and C are the polar and equatorial radii, respectively. The equatorial radius is ~21 km larger than the polar radius, showing an equatorial bulge and polar flattening. In (b), Earth's moment of inertia can be described as a tensor with three principal axes (I_{max}, I_{int}, and I_{min}).

data, then Earth should have a rich history of membrane stress in the form of structural features that cannot be reconciled with plate tectonic origins.

Mass redistributions trigger TPW, and the behaviors of Earth's deep interior thus constrain its properties. Conversely, revealing the principles and rules of TPW can not only provide unique insights into mantle dynamics (Greff-Lefftz and Besse, 2014), but also help us understand the causes of some heretofore enigmatic surface environmental changes (Raub et al., 2007). Traditionally, large TPW is believed to be related to the supercontinent cycle. Previous studies assert TPW was a supercontinental legacy, and paleogeographic tectonic evolution has been linked to TPW events from 1200–200 Ma (Evans, 1998, 2003). With the accrual of more paleomagnetic data, however, more TPW events have been identified or discussed since then, and it has even been argued that supercontinents may actually act to stabilize Earth's spin axis, and therefore limit TPW (Mitchell, 2014). Also, new realizations about Earth's mantle convective and tectonic evolution have since explored the relationship between the supercontinent–megacontinent phases of the supercontinent cycle (Mitchell et al., 2021b; Wang et al., 2021) and TPW events. In this paper, we introduce the concept of TPW, its physical geodynamic mechanism, and its effects on the Earth system, and review the proposed historical TPW events. We explore potential connections between the deep mantle, lithospheric tectonics, and TPW events throughout Earth history.

2. Geodynamics of TPW

The physical geodynamics of TPW are relatively straightforward compared to those of plate tectonics. Many technical reviews of TPW are already available and such details will not be repeated herein, but adequately cited. The most basic explanation for why TPW occurs come from the equation:

$$L=I\omega, \tag{1}$$

where L is angular momentum, I is the planet's moment of inertia, and ω is the spin vector (direction and magnitude). In order for L to be conserved (i.e., stay constant), if there is a change in I (due to mass redistribution), then there must be a compensatory change in ω.

Earth has many ways of redistributing mass, including: atmospheric and oceanic circulation, cryosphere/hydrosphere ice/water storage, earthquakes, and plate tectonics and mantle convection (Raub et al., 2007) (Figure 3). Glacial isostatic adjustment (GIA) and mantle convection are thought to have caused a long-term mass movement that is suggested to account for the secular spin axis wandering toward a longitude of ~74°W (approximately toward Greenland) at a speed of 10.5 ± 0.9 cm yr^{-1} since the 20th century (Adhikari et al., 2018; Seo et al., 2021). A sudden shift to eastward drifting since 2000–2005 could be driven by climate change and induced by the changes in terrestrial water storage and/or cryospheric melting (Adhikari and Ivins, 2016; Chen et al., 2013; Deng et al., 2021).

The larger the masses involved, the larger the potential amplitude of TPW. This review will therefore focus on geological time scales that witness large amplitude TPW excited by the largest redistributions of mass on Earth associated with plate tectonics and mantle convection. The main ways in which mass is redistributed in the solid Earth are sinking slabs and rising plumes. Due to the viscosity structure of Earth's mantle, these dynamic masses having different effects on TPW if they are in the upper or lower mantle. This is illustrated by the concept of Earth's geoid kernel (Steinberger and O'Connell, 1997), where a slab initially sinking through the upper mantle drives TPW equatorward, but as the slab enters the highly viscous lower mantle, it then drives TPW poleward (Figure 4a). A rising plume would have the opposite history of TPW excitation, with the plume in the lower mantle driving TPW initially equatorward, but then poleward as the plume rises into the

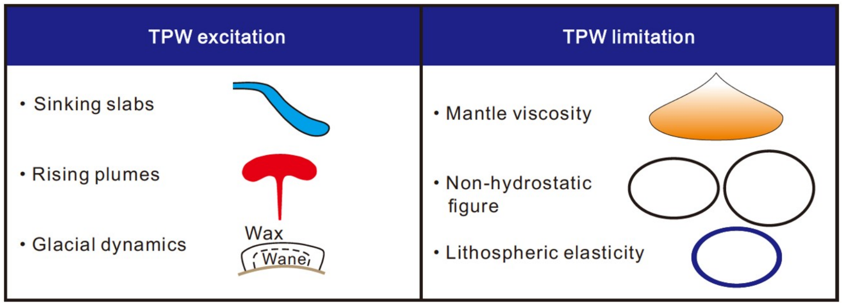

Figure 3 Geological phenomena and features that cause TPW excitation and limitation.

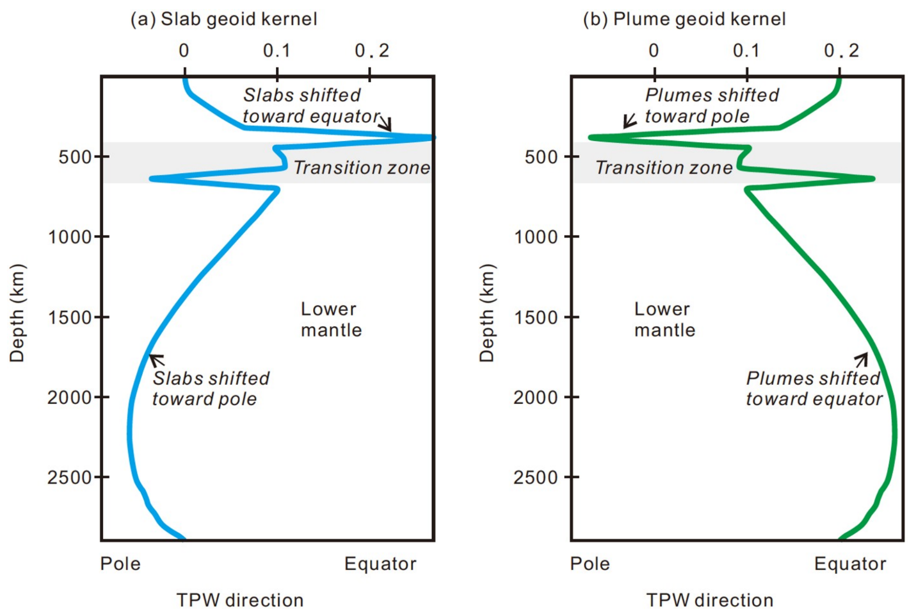

Figure 4 Degree-2 slab geoid kernel (a) (Steinberger and Calderwood, 2006; Steinberger et al., 2017) and plume geoid kernel (b) as weighting factor of how much slab and plume at given depth contribute to the total I_{min} tensor. The plume-related geoid kernel has not been computed and is shown here only schematically as an approximate inverse of the calculated slab-related geoid kernel.

upper mantle (Figure 4b). The effect of subduction on TPW is relatively well understood (Sabadini and Yuen, 1989; Steinberger and O'Connell, 1997), while the effect of plumes requires more investigation (Eyster and O'Connell, 2013). The competing effects of slabs and plumes has been used as a potential explanation to reconcile the discrepancy between a slab-only excitation of TPW modeled at ca. 90–80 Ma (Steinberger et al., 2017) and paleomagnetic data confirming a TPW oscillation at that time (Mitchell et al., 2021a).

3. Observations and measurement of TPW

The first measurement of TPW on Earth came from astronomical observations. Founded in 1895, the International Latitude Service set up 6 astronomical observatories at different longitudes along the same mid-latitude line in the north hemisphere (39°8′N) and observed common star pairs year after year. Over time, some observatories shifted south and others north relative to the same stars, with a range also in the magnitudes of the latitudinal offsets. A sinusoidal line could be drawn that systematically related the directions and magnitudes of the latitudinal offsets of the observatories at different longitudes. The senses and magnitudes of motion therefore exhibited a wholesale motion of the entire Earth with a pole of rotation that was close to the equator (Yumi and Yokoyama, 1980). Following the launch of Sputnik, TPW has since been measured instead and more precisely by satellites. The same consistent direction of long-term TPW toward the longitude of Greenland (75°–80°E) was detected in the first few decades of satellite measurements (Gross and Vondrák, 1999; Schuh et al., 2001).

TPW in geologic time can be detected with paleomagnetism, but the results have not been without controversy. Similar to its utility detecting plate tectonics, paleomagnetism is well-suited for measuring TPW, if it were to have occurred. In both cases, lithospheric motions associated with plate tectonics and the wholesale motion of the solid Earth due to TPW occur above the geodynamo generated in Earth's core, rendering Earth's geocentric axial dipole (GAD) a reliable reference frame in which to measure both processes. While this paleomagnetic reference frame is ideal, the potential simultaneous operation of both plate tectonics and TPW renders deconvolving the two signals from each other difficult. A measured paleomagnetic vector of motion (a.k.a., apparent polar wander [APW], Figure 5) represents some combination of plate tectonic and TPW vectors:

$$\text{APW} = \text{plate motion} + \text{TPW}, \qquad (2)$$

where the TPW component should be identical for all continents and each continent should have its own unique plate motion component. Various scenarios are illustrated by Evans (2003), such as a continent that is stable tectonically should have a relatively pure TPW signal (i.e., APW = TPW), and a continent with an apparent APW "standstill" may be do due the tectonic and TPW vectors essentially offsetting each other. A major focus of this review will be how this most basic problem of deconvolving paleomagnetic APW into its two major components remains a major challenge to be overcome.

Paleomagnetism remains the most quantitative method for detecting TPW. But paleomagnetic detection of TPW is not without complications and paleomagnetism is not the only means of testing TPW in Earth history. Because TPW reorients Earth, the surface environment of a continent is expected to undergo changes in both relative sea level and climatic belts. Thus, there is the possibility that changes in sea level, seawater chemistry, and climate that have proven heretofore enigmatic may be attributable to TPW. As more instances of TPW in Earth history develop paleomagnetic support, such non-paleomagnetic evidence for TPW can begin to be explored with more confidence in the future.

As alluded to earlier, the difficulty in detecting TPW with paleomagnetism is distinguishing continental motion due to TPW or plate tectonics. Despite this fundamental challenge, there are both spatial and temporal clues that can be used to distinguish the two styles of motion due to the two fundamentally different processes. Spatially, as TPW occurs about an equatorial Euler pole of rotation, TPW should appear in a paleomagnetically determined APW path as a great circle segment. This is in stark contrast to most cases of plate tectonics. Only in one case of an Euler pole being located 90° away from a continent would plate tectonics lead to a great circle APW segment (e.g., the Cenozoic motion of India during its Himalayan convergence); in all other instances, plate motion should yield an APW path that follows a small circle segment. Temporally, due to different physical limitations of the two processes, the rate of TPW can exceed that of plate tectonics. The speed limit of plate tectonics (~20 cm yr^{-1}) is set by how quickly bending stresses can be imposed on a downgoing slab (Meert et al., 1993; Conrad and Hager, 2001), although this can potentially be increased by the rheology of the slab (e.g., due to changes in grain-size reduction) (Rose and Korenaga, 2011; Gerya et al., 2021). The speed limit of TPW (~27 cm yr^{-1}) is set by mantle viscosity as the stiff mantle (particularly the high-viscosity lower mantle) must be deformed into the reoriented hydrostatic bulge (Tsai and Stevenson, 2007). Thus, even under present-day conditions, TPW may be expected to be faster than plate motion. Furthermore, as Earth's mantle is thought to have been hotter in the past (Korenaga, 2008; Davies, 2009; Herzberg et al., 2010; Ganne and Feng, 2017; Mitchell and Ganne, 2022), the accordingly reduced mantle viscosity in the past (due to temperature-dependent viscosity) should have allowed for even faster TPW in Precambrian time.

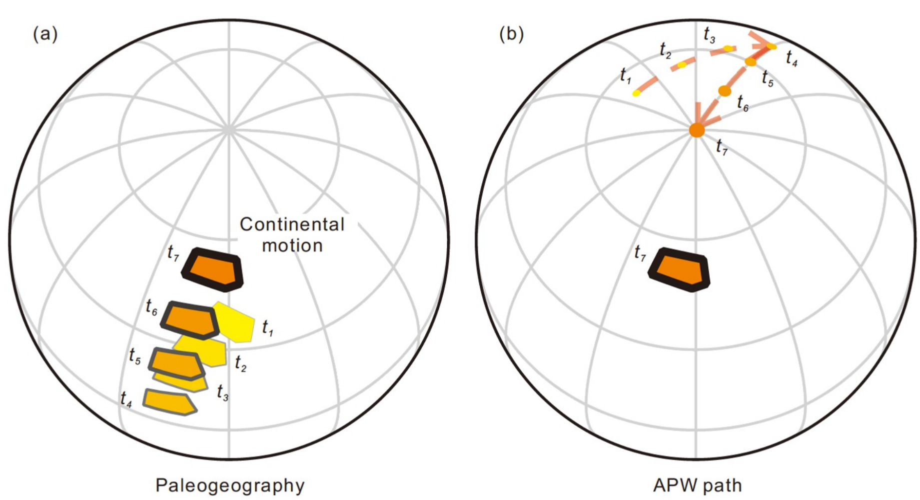

Figure 5 Illustration of paleogeography and APW. Paleomagnetism is based on the GAD assumption that Earth's magnetic field can be approximated by a single magnetic dipole at the center of the Earth that is aligned with the rotation axis if averaged sufficiently over time. Under GAD, a drifting continent (a) can record paleomagnetic poles from t_1 to t_7. Alternatively plotted, the continent is fixed at the position of t_7, and the paleomagnetic poles seem to move from t_1 to t_7 (b), i.e., forming APW path. The term "polar wander" is usually used in paleomagnetic studies, like "apparent polar wander (APW)" to refer to the shift of the "paleomagnetic" pole rather than the "geographic" pole.

In summary, if the rate of an APW path exceeds 20 cm yr^{-1}, indicating APW speeds beyond the plate tectonic speed limit, TPW may have occurred at that time. If so, this fast motion should be identified in other continents at the same time. The signature of TPW in the geological past requires at least two reliable paleomagnetic poles. Considering that the prevalent method of U-Pb geochronology usually presents ~1% age uncertainty for the dating of magmatic rocks as well as complications such as differential remagnetization and tectonic structure, one ideal target for testing the TPW hypothesis is obtaining paleomagnetic data from continuously-deposited sedimentary or volcanic successions with detailed magnetostratigraphy (Maloof et al., 2006; Mitchell et al., 2010a, 2021a; Robert et al., 2017; Park et al., 2021). Note that polar motion with small amplitude and/or happening in a short time scales (<1 Myr), e.g., due to glacial-interglacial cycles (Bills et al., 1999), is hard to recognize in deep time due to the limitations of the precision of geochronology and paleomagnetism.

Steinberger and Torsvik (2008) proposed a modified paleomagnetic reference frame to detect TPW. They separated motions of continents into collective motion ("mean motion" of all continents) and independent motion (continental motion relative to the mean). Abundant paleomagnetic poles of all continents are the prerequisite of this approach. By this method, four TPW events have been identified during the past 320 Myr (Steinberger and Torsvik, 2008; Torsvik et al., 2014). Besides the paleomagnetic-based reference frame, hotspots provide another frame in which to detect TPW. Hotspots were originally thought to be triggered by upwellings from deep mantle that were fixed (Wilson, 1963; Morgan, 1971), but a global "moving hotspot" reference frame has since been suggested for the past 130 Myr (Torsvik et al., 2008). Although hotspots may not always fixed in the convecting mantle (Tarduno et al., 2003), arguments for a reliable fixed hotspot reference frame persist (Wang et al., 2019). Steinberger and Torsvik (2008) compared the paleomagnetic and hotspot reference frames, where the former shows a shift (relative to the magnetic pole) but the latter does not, because TPW moves the mantle containing hotspots so the motion is undetected by the reference frame as the reference frame itself moves.

4. TPW in Earth history

4.1 Phanerozoic TPW

Late Cretaceous TPW (ca. 84 Ma) was originally hypothesized by Gordon (1983) on the basis of paleomagnetic data from seamounts on the Pacific plate. This dataset was subsequently updated both in terms of paleomagnetism and geochronology, refining the hypothesis to be one TPW rotation proposed to occur between the emplacement of two seamounts with Ar-Ar ages overlapping at ca. 84 Ma and paleomagnetic poles discordant by 16° ± 3° (Sager and Koppers, 2000). It was then asserted that classic paleomagnetic data from the Scaglia Rossa Limestone of Italy did not show evidence for such a shift at that age (Cottrell and Tarduno, 2000). As influential as the original Scaglia Rossa magnetostratigraphic data were in establishing the global polarity time scale (Lowrie and Alvarez, 1977), the data predated both least-squares analysis and modern cryogenic magnetometers and arguably do not provide an ideal test of TPW (Cottrell and Tarduno, 2000). To resolve this potential discrepancy, the Scaglia Rossa Limestone was resampled at much higher sampling resolution adequate to test the TPW hypothesis and modern laboratory and analytical methods were used (Mitchell et al., 2021a). With high paleomagnetic stability of >1,000 samples—about an order of magnitude more samples than in standard paleomagnetic studies—the new Italy data suggest coherent motions in both inclination and declination at ca. 84 Ma that support the TPW hypothesis (Figure 6a). In fact, the stratigraphic sampling depicts a "round trip" TPW oscillation, which is theoretically expected as the pole excurses and returns to its original pole position (Creveling et al., 2012). The ~12° TPW oscillation documented in the Scaglia Rossa Limestone of Italy represents the youngest evidence of large-amplitude (>10°) TPW (Mitchell et al., 2021a) and overturns the prior notion of limited TPW in the past 100 Myr (Tarduno and Smirnov, 2001).

Jurassic APW paths and the Jurassic "monster shift" TPW hypothesis have been hotly debated (Muttoni and Kent, 2019 and references therein). Firstly, the North America APW path had been updated by several studies and exhibits a ~30° rapid polar shift during ca. 160–140 Ma (Kent and Irving, 2010; Kent et al., 2015; Fu et al., 2020). New paleomagnetic data and a revised APW path supported a ~40° polar shift of Adria–Africa during ca. 180–150 Ma, also indicating a TPW event in the Jurassic (Muttoni et al., 2013; Muttoni and Kent, 2019). Paleomagnetic poles from Iran–Eurasia have also been revised and exhibit a paleolatitude drop before ca. 150 Ma (Mattei et al., 2014). Besides these studies, paleomagnetic analyses of the Pacific plate support a ~30° rotation of the whole lithosphere (not just the continental lithosphere) in the 160–145 Ma interval (Fu and Kent, 2018). In the North China craton, new paleomagnetic constraints of Jurassic rock units support ~25° TPW from ca. 174–157 Ma (Yi et al., 2019). However, other analyses doubt the reliability of the ca. 174 Ma paleomagnetic pole and refute the large paleographic shift of the North China craton during the Jurassic (Gao et al., 2021). A temporary low-latitude position of the Yangtze craton in the late Jurassic was once ascribed to TPW (Bai et al., 1998). Paleomagnetism of the Lhasa terrane depicts a stillstand during Jurassic TPW, which has been suggested to result from the destructive interference of

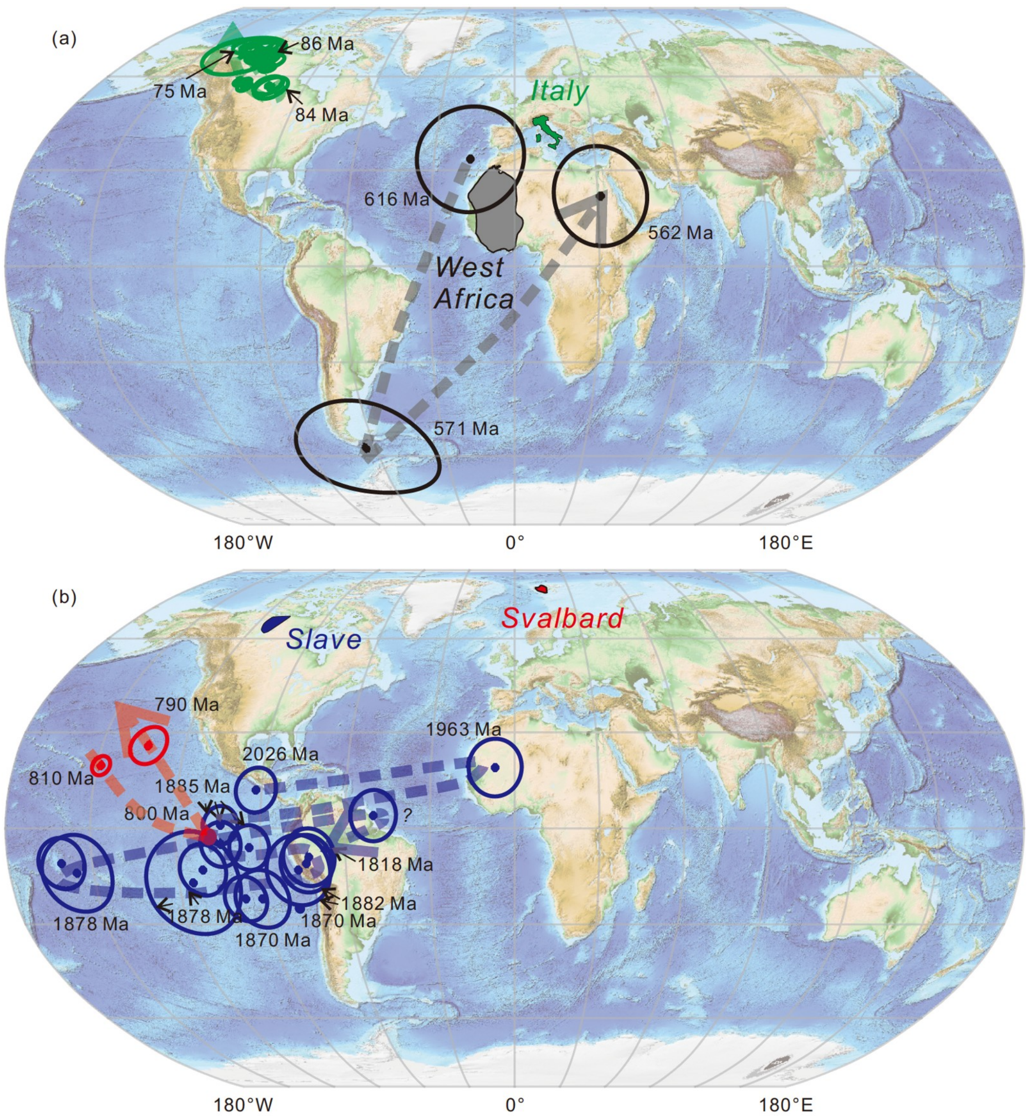

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Figure 6 Representative paleomagnetic poles and APW paths indicating TPW events. (a) Poles from Italy (green) and West African craton (black) for the Late Cretaceous TPW oscillation (86–78 Ma) (Mitchell et al., 2021a) and Ediacaran IITPW oscillation (615–565 Ma) (Robert et al., 2017); (b) Poles from Svalbard (red) and Slave craton (blue) for the Bitter Springs TPW oscillation (810–790 Ma) (Maloof et al., 2006) and the Coronation loop with multiple TPW oscillations (2050–1800 Ma) (Mitchell et al., 2010b).

southward TPW for the region and northward plate tectonic motion (Li et al., 2022). Such an APW summation phenomenon observed for the Lhasa terrane may be somewhat comparable with that observed for the North China craton (Gao et al., 2021). Data from Greenland have also been argued to challenge the Jurassic "monster shift" TPW hypothesis in favor of slower TPW (Kulakov et al., 2021). By identifying coherent continental rotations, Torsvik et al. (2012) considered that TPW events during ca. 200–140 Ma can be divided into two stages, 200–150 Ma and 150–140 Ma, with a steady rotation rate and total rotation of 30.5°.

During the Pangea period, the APW path of North America is about 35° in arc distance from 295–205 Ma, exhibiting a rotation of Pangea with respect to the paleomagnetic axis about an equatorial Euler pole, thus indicating a possible TPW event during the Permo-Triassic (Marcano et al., 1999). Using a new paleomagnetic reference frame, Steinberger and Torsvik (2008) argue for a ~18° anticlockwise rotation from 250–220 Ma, a ~18° clockwise rotation from 195–145 Ma, a ~10° clockwise rotation from 145–135 Ma, and a ~10° anticlockwise rotation from 110–100 Ma. After updating the African absolute plate motion in the paleomagnetic reference frame, relative plate motions, and plate geometry, these four episodes of TPW were revised to a ~22.5° anticlockwise rotation from 250–200 Ma around an equatorial axis at 32.3° W, a ~22.5° clockwise rotation from 200–150 Ma around an equatorial axis at 5.1°E, a ~8° clockwise rotation from 150–140 Ma around an equatorial axis at 11.3°E, and a ~8° anticlockwise rotation from 110–100 Ma around an equatorial axis at 17.1°E (Torsvik et al., 2012). Going back further still, a TPW oscillation may have occurred during the late Ordovician to late Devonian (ca. 450–370 Ma) since Laurentia, Baltica, and Gondwana seem to have similar looping APW path shapes, with a suggested cumulative ~75° of TPW during the 75 Myr interval (Van der Voo, 1994). Torsvik et al. (2012) argued that the amplitude of TPW at ca. 450–370 Ma, if TPW indeed occurred, may have been overestimated due to simultaneous convergence between Laurussia and Gondwana. However, regenerated paleomagnetic poles from South China support ~50° TPW at ca. 450–440 Ma, being consistent with the new evaluation of Tarim, Siberia, Baltica, and Gondwana (Jing et al., 2022). In addition, after reorganizing the paleogeographic models, Le Pichon et al. (2021) proposed that Pangea's 400–250 Ma northward migration, moving from polar to equatorial latitudes, likely reflects a long-term and large (50°–60°) TPW rotation.

In the early Cambrian, a ~90° TPW event was proposed (Kirschvink et al., 1997). Preliminary analyses implied that paleomagnetic poles from the basal Ediacaran Elatina Formation of southern Australia (ca. 600 Ma), to younger Tommotian (560–534 Ma), and the youngest Black Mountain pole of western Queensland (ca. 505 Ma) had shifted about 90° after considering the error limits (Kirschvink et al., 1997). This large-amplitude swing from Ediacaran–earliest Cambrian to Middle–Late Cambrian was also recorded in Laurentia and other blocks. In summary, paleomagnetic data of Australia and Laurentia in Ediacaran to Cambrian display large-scale motion, and Kirschvink et al. (1997) ascribed these rapid continental motions to an interchange event in Earth's moment of inertia tensor, namely inertial interchange true polar wander (IITPW). Evans (1998) expanded this period of TPW to early Carboniferous in terms of long-lived oscillatory TPW. However, the early Cambrian TPW hypothesis had been challenged on the grounds of the quality of the paleomagnetic poles used, and the variable APW rates among Laurentia, Baltica, Siberia, and Gondwana from Ediacaran to Ordovician (Torsvik et al., 1998). Evans et al. (1998) defended that (i) the angular distance can be up to ~70° even if excluding the disputed Sept-Îles paleopole, and (ii) the global APW paths are far from comprehensive. Later, a review of paleomagnetic data for Laurentia, Baltica, Siberia, and Gondwana implied that all the APW paths failed to reach the required length of ~90° for IITPW in the early Cambrian, and each path is of a different length and the apparent motions are non-synchronous (Meert, 1999). It was also argued that renewed paleomagnetic poles for Baltica negated large-scale polar wander from ca. 580–500 Ma (Torsvik and Rehnström, 2001).

Subsequently, a continuous paleomagnetic sampling of Lower to Middle Cambrian strata from the Amadeus Basin, central Australia, showed an ~60° declination shift, demonstrating the rapid Early Cambrian rotation of Gondwana (8–28 cm yr^{-1}) caused by plate tectonics or rapid TPW (Mitchell et al., 2010a). Another ~57° paleomagnetic directional shift was discovered from a Cambrian marine succession from ca. 500.5–494 Ma (Jiao et al., 2018). Thus, although the amplitude of the original early Cambrian TPW hypothesis has been slightly reduced, early Cambrian TPW event remains strongly viable.

4.2 Neoproterozoic TPW

Earlier in the Ediacaran, paleomagnetic poles obtained from Sutton plume magmatism of eastern Laurentia yield a wide range of paleomagnetic inclination (Hodych and Cox, 2007; McCausland et al., 2011 and references therein; Puffer, 2002), indicating large changes in paleolatitude. From the paleomagnetic data, Mitchell et al. (2011) isolated a TPW component that is nearly orthogonal to another component of plate rotation relative to the Sutton plume, and proposed a more refined plume-TPW hypothesis. Thus, two TPW events may have occurred from ca. 615–530 Ma with rates of ~35–140 cm yr^{-1} (Mitchell et al., 2011). Furthermore, subsequently obtained paleomagnetic poles from West African craton support a ~90° oscillation of poles during ca. 615–571 Ma and ca. 571–565 Ma (Robert et al., 2017) (Figure 6b), similar to what had been proposed using Laurentia poles as well as a hotspot reference frame (Mitchell et al., 2011). Robert et al. (2017) also saw a similar pattern in reappraised APW paths of Laurentia and Baltica, so interpreted this large global motion in terms of a large IITPW episode. New paleomagnetic results from Avalonia also support the Ediacaran TPW hypothesis during ca. 590–560 Ma (Wen et al., 2020, 2022).

TPW hypotheses are prevalent in the Tonian Period. The paired ca. 820–800 Ma and ca. 750–700 Ma paleomagnetic poles fall along a great circle and in this circumstance India and South China moved from the pole to the equator with APW velocities of ~20 cm yr^{-1}, potentially implying a rapid and wholesale 90° rotation of all continents, i.e., a possible IITPW event (Li et al., 2004). Later, Maloof et al. (2006) obtained paleomagnetic data from a sequence of carbonates from the Akademikerbreen Group of East Svalbard, Norway, and favored two >50° shift during the Middle Neoproterozoic (ca. 810–800 Ma and ca. 800–790 Ma) probably caused by a TPW oscillation (Figure 6c). The depositional age of this carbonate sequence was determined by $\delta^{13}C$ isotopes and regional geology, where the varied $\delta^{13}C$ values ranging between –3‰ and 0.5‰ were correlated to a similar carbon isotope excursion, the Bitter Springs Stage, first identified in the Bitter Springs Formation of the Amadeus Basin of central Australia (Hill and Walter, 2000; Halverson et al., 2005). High-precision age constraints were since obtained for the Bitter Springs Stage with U-Pb dates on tuffs in the Tambien Group of Ethiopia (Swanson-Hysell et al., 2015). To test this Tonian TPW oscillation, detailed studies including stratigraphy, δ^{13}C isotopes, and magnetostratigraphy were carried out on the Bitter Springs Formation (Swanson-Hysell et al., 2012). However, the paleomagnetic direction of the Love's Creek Member of the syn-Bitter Springs Stage falls on the Cambrian portion of the Australia APW path and fails to strongly confirm the supposition; nonetheless the results are still consistent with the TPW hypothesis and cannot rule it out (Swanson-Hysell et al., 2012).

Also from South China, more geochronological and paleomagnetic data have been reported to suggest pre- and syn-Bitter Springs TPW hypotheses, especially for the period from ca. 820–800 Ma. Firstly, the Xiaofeng dykes (802 ± 10 Ma), key data for the TPW proposal of Li et al. (2004), were argued to be 20 Myr older (Wang et al., 2016). The Xiaofeng paleomagnetic pole also has been argued to be complicated by regional faulting and local rotation (Jing et al., 2019). Another ca. 824 Ma pole has been acquired from the Yanbian dykes with a positive baked contact test (Niu et al., 2016). The younger pole of ca. 800 Ma has also been obtained from the Madiyi Formation, lower Banxi Group, with tuff U-Pb ages of 802 ± 6 Ma and 805 ± 10 Ma (Xian et al., 2020). Based on the three poles, Xian et al. (2020) suggests South China was at high latitude from 825–800 Ma. Jing et al. (2019) also obtained a ca. 800 Ma pole from the Chengjiang Formation of Yunnan Province with tuff U-Pb ages of 800 ± 8 Ma, and suggested a ~63° TPW event during 825–790 Ma after combining paleomagnetic results from South China and Svalbard. In addition, Niu et al. (2016) considered that the paleopoles of the ca. 824 Ma Yanbian dykes and the Xiaofeng dykes (assuming emplacement at ca. 802 Ma) indicated a ~50° TPW rotation, and the later paleopoles from ca. 800–780 Ma indicated a ~90° TPW rotation in the opposite direction, constituting an IITPW oscillation. To address these different opinions, detailed geochronological and paleomagnetic studies have been conducted on the Xiajiang Group (816–810 Ma) of South China (Park et al., 2021). The new data support South China being located at high latitudes during ca. 821–805 Ma, which for the TPW hypothesis to be feasible, would require superimposed differential plate motion that would separate South China from supercontinent Rodinia (Park et al., 2021). Most recently, Fu et al. (2022) have obtained a ca. 832 Ma paleopole from the Fanjingshan mafic sills, and deem that the paleopoles of the Fanjingshan sills and the Xiaofeng dykes (assuming emplacement at ca. 821 Ma) indicate a ~55° TPW event immediately prior to the Bitter Springs TPW oscillation.

Similar to the Bitter Springs Stage, an earlier Neoproterozoic carbon isotope oscillation, the ca. 940 Ma Majiatun anomaly of North China, similarly coincides with an oscillation in paleomagnetic poles (according to a reconstruction of North China in Rodinia) and climate-sensitive carbonate facies that may also represent a TPW oscillation (Zhang et al., 2021), although direct evidence is lacking and more work is needed.

4.3 Mesoproterozoic–Paleoproterozoic TPW

In the late Mesoproterozoic, APW paths of Laurentia present several loops including the Logan loop from ca. 1140–1108 Ma (Robertson and Fahrig, 1971), the Keweenawan track from ca. 1108–1080 Ma (Swanson-Hysell et al., 2019), and the Grenville loop from ca. 1080–980 Ma (McWilliams and Dunlop, 1975). The Keweenawan track indicates Laurentia drifted from high latitudes to the equator. By analyses of high-resolution geochronological data and complied paleomagnetic data, it can be concluded that the motion of Laurentia exceeded 20 cm yr^{-1}, which could be caused by rapid plate tectonics or modest TPW rather than the effects of non-dipolar components (Swanson-Hysell et al., 2009, 2019). In addition, paleomagnetic data from the Nanfen Formation (<1130–945 Ma) of North China craton also indicate a systematic pole shift that indicates the craton also drifted from high to low latitudes (Zhao et al., 2019). However, lacking precise ages constraints, comparison to the paleomagnetic poles of Laurentia is tentative. Furthermore, recent petrological evidence for motion related to a hotspot track on Laurentia (Brown et al., 2022)—which must represent some large component of plate tectonics for the observed APW motion—amplifies to careful need to distinguish TPW from plate motion in this case.

For younger Mesoproterozoic time to the early Neoproterozoic, the Grenville loop was thought to be equal to the Sveconorwegian loop of Baltica (Gong et al., 2018), or the Huaibei loop of North China craton (Fu et al., 2015). Zhao et al. (2022) recently suggested a match between the Grenville loop poles and the poles newly obtained from the middle Huaibei Group in the North China craton, although the geochronologic constraints remain loose. They also mentioned the large-scale latitudinal change of these two cratons during the assembly of Rodinia could be interpreted as rapid plate tectonics or TPW. However, for both the cases of the Keweenawan track and the Grenville loop arguably recorded in both Laurentia and North China, given the two continents are also deemed to be contiguous, plate motion of a large continent remains a viable possibility. Whether they are comparable and represent TPW events requires more geochronological and paleomagnetic studies.

A ca. 1235 Ma paleomagnetic pole and a 1207 Ma virtual geomagnetic pole (VGP) from the North China craton (Wang et al., 2020) exhibit 75° of APW within 28 Myr, for an APW rate of ~30 cm yr^{-1}, which is a potential indication of TPW in the late Ectasian. However, the lack of time-averaging for the younger result precludes such an interpretation from being robust.

In the Orosirian Period of the Paleoproterozoic, the APW path of the Slave craton exhibits large sweeping loops. These data are mainly obtained from three contemporaneous basins surrounding the Slave craton: the Coronation Basin in the west, the Kilohigok Basin in the east, and the Great Slave Basin in the south. The sweeping APW path was called the Coronation loop (McGlynn and Irving, 1978), which may be caused by either regional vertical-axis rotations and/or TPW (Gong and Evans, 2022; Irving et al., 2004; Mitchell et al., 2010b). After correcting the expected minor vertical-axis rotations induced by the far-field fault systems, and excluding the possibility of large vertical-axis rotations by independent paleocurrent measurements from the Great Slave Basin, the Coronation loop could represent an interval of rapid oscillatory TPW during ca. 1960–1850 Ma (Mitchell et al., 2010b; Gong and Evans, 2022) (Figure 6d). In addition, geochronological and paleomagnetic studies on the Uatumã silicic large igneous province of the Amazonia craton also support TPW in the Orosirian, where the ca. 1877 Ma SF1 pole and the ca. 1854 Ma SF2 pole differ by an angular distance of ~85°, implying a rapid APW rate of ~40 cm yr^{-1} (Antonio et al., 2017).

4.4 Archean TPW

Detecting TPW events in the Archean is challenging given the difficulties in obtaining high-quality paleomagnetic poles that have not suffered from globally widespread Orosirian metamorphism or numerous younger tectonic events. So far, reported poles of Archean age (Evans et al., 2021) are not enough to substantiate any compelling TPW events, but some clues can be found, such as in the Pilbara craton, Australia. As plotted in Figure 4 of Brenner et al. (2020), there is a large APW shift that occurs between paleomagnetic poles of the 2772 ± 2 Ma Black Range Suite and the 2766 ± 2 Ma Fortescue Group, representing a ~47° rotation with an APW rate of ~87 cm yr^{-1} (Mitchell, 2020). Recent analyses imply TPW was possible during ca. 3340–3180 Ma (Mitchell and Jing, 2023). These hints are indications of putative Archean TPW events, but further studies are needed.

In brief, TPW is a common phenomenon in Earth history (Table 1). We note that non-uniformitarian (non-GAD) magnetic fields such as alternating equatorial and polar dipoles have been proposed as an alternative explanation to TPW for anomalous APW such as the existence of both high and low paleolatitudes in the Ediacaran for Laurentia (Abrajevitch and Van der Voo, 2010). However, poles scattered in terms of declination, like Australia in the Ediacaran and Slave craton in the Orosirian (Mitchell et al., 2010b; Mitchell et al., 2012), can be explained in terms of TPW as continental rotations near the TPW axis, but cannot be explained by the proposed alternation between equatorial and polar dipoles. Neither can intermediate directions such as Ediacaran mid-latitude poles of Laurentia (McCausland et al., 2011) be explained by such a model, but are compatible with TPW. Also, the documentation of weak magnetic fields such as the Sept-Îles intrusion (Bono and Tarduno, 2015; Bono et al., 2019; Driscoll, 2019) do not invalidate the general reliability of the Ediacaran dipole, which is supported by multiple paleomagnetic studies globally during that time interval.

5. Effects of TPW on the Earth system

As TPW is a global process, it is natural to expect global-scale effects influencing most spheres of the Earth system. Despite such expectations, in general, these topics have only been explored at a cursory level up until now. As more evidence of specific TPW events becomes available, such interdisciplinary tests of TPW can be conducted. After all, although paleomagnetic data can provide a quantitative and direct evidence of TPW, it is not the only form of data that can test and explore the TPW hypothesis.

5.1 Lithosphere and tectonics

The evolutionary history of the Earth is accompanied by the aggregation and disintegration of supercontinents, which has an important impact on the evolution of the whole Earth system (Nance et al., 2014). Statistics on the global databases of detrital zircon and monazite find that there are five main peaks in the age spectra: 2.7, 1.8, 1.0, 0.5, and 0.25 Ga (Hawkesworth et al., 2010; Mulder and Cawood, 2021), perhaps corresponding to the assembly of continental landmasses/supercontinents through time known as Kenorland (or Superia, Sclavia, etc. supercratons), Columbia, Rodinia, Gondwana and Pangea, respectively (Mitchell et al., 2021b) (Figure 7a, 7c). The supercontinent cycle, as a fundamental organizing pattern of global tectonics being related to subduction and mantle plumes, undoubtedly causes large mass redistribution in the mantle, and therefore should be expected to excite TPW events (Evans, 1998; Mitchell, 2014).

Evans (2003) proposed a model to explain the possible linkage between the supercontinent cycle and TPW, where as many as three episodes of TPW could occur during one cycle. The first TPW event is driven by a thermal plume under the supercontinent, stabilizing it on the equator. The second is driven by the drifting continental fragments during supercontinent breakup. The third is driven by the formation of the incipient new supercontinent, with TPW still occurring about the relict upwelling axis of its predecessor. This proposal reconciles the tectonic cases and assumed TPW to some degree. Numerical modeling suggested that TPW could be large and more variable during supercontinent assembly,

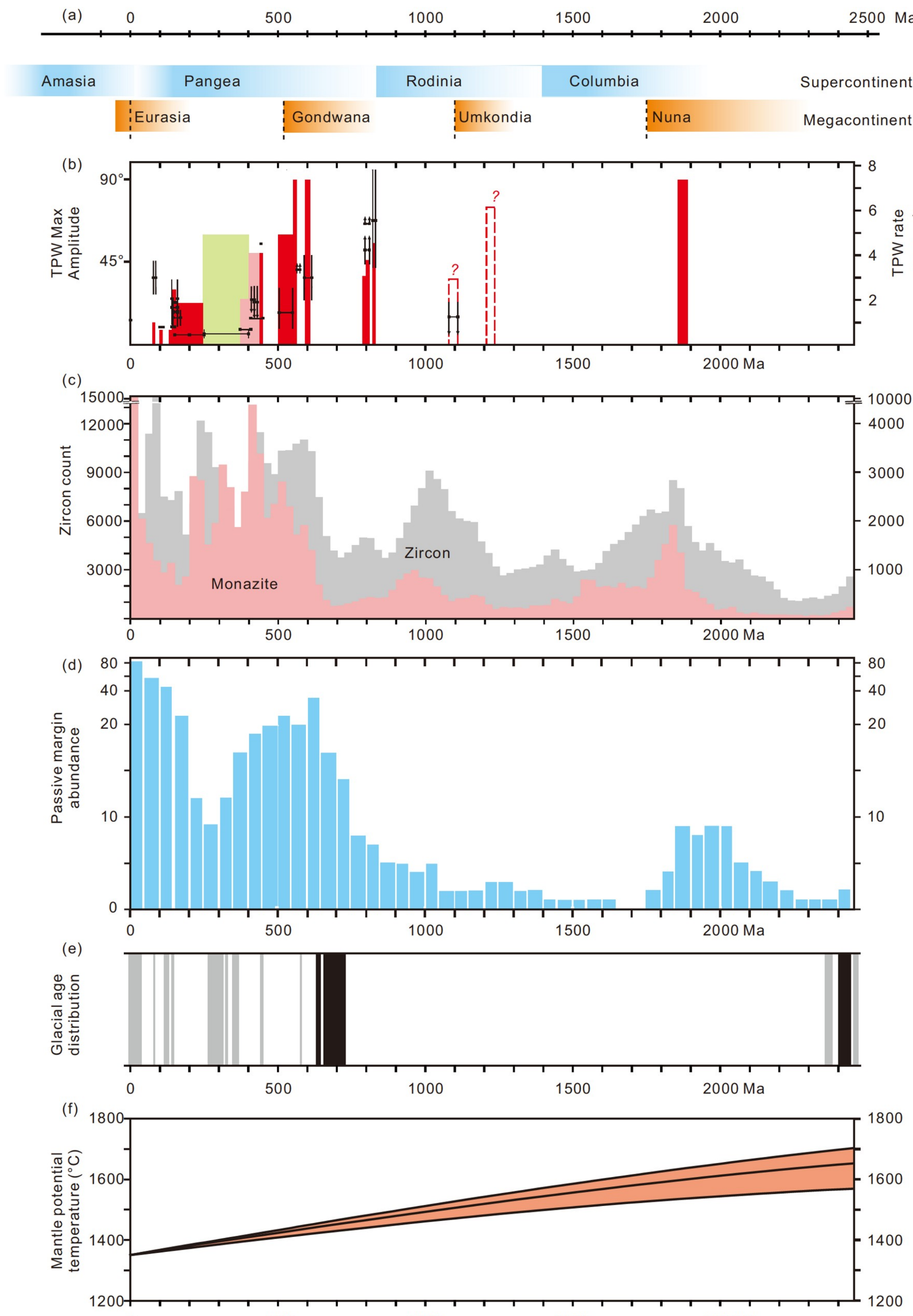

Figure 7 Temporal distribution of the supercontinent–megacontinent cycle (a) (Wang et al., 2021), TPW amplitudes and rates (b), detrital zircon and monazite counts (c) (Mulder and Cawood, 2021), abundances of passive margins (d) (Bradley, 2008), glacial ages (e) (Hoffman et al., 2017), and mantle potential temperature (f) (Herzberg et al., 2010). In (b), pink and light green rectangles represent ca. 450–370 Ma and ca. 400–250 Ma TPW hypotheses, respectively. The data of TPW rates since 1200 Ma (black squares and error bars) are from Fu et al. (2022) and Jing et al. (2022). In (e), black stripes represent snowball Earth, and gray stripes represent regional-scale ice ages.

but insignificant when the supercontinent becomes located on the equator and during breakup (Zhong et al., 2007).

Recently, according to the discrimination from the various paleogeographic reconstruction models, Wang et al. (2021) found that the assembly each supercontinent was inherited from assembly of an earlier sub-supercontinent 100 to 200 million years before that, i.e., the supercontinent Columbia was inherited from the Paleoproterozoic Nuna (Laurentia-Baltica-Siberia connection), the supercontinent Rodinia was inherited from the Mesoproterozoic Umkondia (São Francisco-Congo-Amazonia-India-Kalahari-West Africa connection), the supercontinent Pangea was inherited from the early Cambrian Gondwana, and the future supercontinent Amasia will be inherited from massive Eurasia (Figure 7a). The new concept of a "megacontinent" has been described for these precursor sub-supercontinents. In general, a megacontinent is believed to be a major and early building block of the upcoming supercontinent. To some degree, the age of megacontinent formation may overlap with the breakup of the previous supercontinent. This idea elaborates the formation stages of a supercontinent, and answers the necessary role of a megacontinent for a supercontinent (like the well-known Gondwana within Pangea).

According to the summary of TPW events in section 4 (Table 1), we compile the temporal distribution of TPW during the past ca. 2.2 Ga (Figure 7b) to explore its relationships with the supercontinent–megacontinent cycle. For the Columbia–Nuna cycle (ca. 2000–1300 Ma), the large amplitude oscillations of the Coronation loop TPW hypothesis (Mitchell et al., 2010b) occurred during the formation of megacontinent Nuna (Hoffman, 1988), and well before later sutures of supercontinent Columbia (Pourteau et al., 2018). However, no TPW has been reported during the tenured Columbia (ca. 1600–1400 Ma) and the main breakup stage (ca. 1400–1300 Ma). For the Rodinia–Umkondia cycle (ca. 1300–700 Ma), the potential TPW event at ca. 1240–1210 Ma (Ding et al., 2020; Wang et al., 2020) occurred during the formation of the Umkondia megacontinent (>1.1 Ga; Choudhary et al., 2019). If the ca. 1.11 Ga TPW event happened, it corresponds closely with megacontinent Umkondia. TPW amplitude seems to be muted during the tenured Rodinia (ca. 900–800 Ma). The Bitter Springs TPW

Table 1 Summary of proposed TPW events in Earth history a)

TPW hypothesis	Age (Ma)	Amplitude (°)	Rate ((°) Myr^{-1})	References
Late Cretaceous oscillation	86–84	12	2–6	Mitchell et al., 2021a
	84–78	12		
Jurassic monster shift	~160–145/ ~170–145	30	1.2–2	e.g., Fu and Kent, 2018; Fu et al., 2020; Kent et al., 2015
Since Pangaea assembly	250–200	22.5	0.5	Torsvik et al., 2012
	200–150	22.5	0.5	
	150–140	8	0.8	
	110–100	8	0.8	
Late Ordovician–Devonian	450–408	50	1.2	Van der Voo, 1994
	408–372	25	0.6–0.7	
Ordovician–Silurian	450–440	50	5	Jing et al., 2022
Devonian–Permian	400–250	50–60	0.4	Le Pichon et al., 2021
Early Cambrian (?)	600–505?	~90		e.g., Kirschvink et al., 1997
Early–Middle Cambrian	550–505?	60	1.2–1.5	Mitchell et al., 2010a
Middle–Late Cambrian (?)	500.5–494	57	8.8	Jiao et al., 2018
Ediacaran oscillation	615–590/571	~90	2–3.6	Mitchell et al., 2011; Robert et al., 2017, 2018
	590/571–565	~90	3.6–9	
Bitter Springs oscillation	810–800	46	≥4.6	e.g., Maloof et al., 2006
	800–790	37	3.7	
Fanjingshan–Xiaofeng	832–821	55	5.5	Fu et al., 2022
Keweenawan track (?)	1108–1080	30–40	1.4	Swanson-Hysell et al., 2019
Late Mesoproterozoic (?)	1235–1207	75		Ding et al., 2020; Wang et al., 2020
Coronation loop	~2050–1850	60–90?		Mitchell et al., 2010b
Archean Pilbara (?)	~2772–2766	~47		Brenner et al., 2020; Mitchell, 2020

a) TPW rate 1° Myr^{-1} ≈ 11.1 cm yr^{-1}; (?) indicates less certain TPW events.

oscillation and the newly reported ca. 832–821 Ma TPW event before it both arguably occurred during the transition of tenured Rodinia and initial breakup. For the Pangea–Gondwana cycle (ca. 700–100 Ma), TPW events with large amplitudes seem to be prevalent during the formation of megacontinent Gondwana (ca. 700–500 Ma). The TPW event during ca. 450–440 Ma (Jing et al., 2022) occurred 20 Myr before the closure of Iapetus Ocean and the formation of Laurussia, but Gondwana still existed with the Proto-Tethyan and Terra Australis subduction systems around it. Note that there was no significant breakup event during this period. Meanwhile, TPW occurred repeatedly during the tenure (ca. 350–200 Ma) and breakup (ca. 200–50 Ma) of Pangea, but the amplitude was less than 30°. In detail, the tenure of Pangea experienced ~22.5° TPW (Torsvik et al., 2012), which may be consistent with the TPW proposal by Le Pichon et al. (2021). The breakup of Pangea (ca. 200–50 Ma) experienced 2 to 3 TPW events with amplitudes varying from 8°–30° (Torsvik et al., 2012; Fu and Kent, 2018; Muttoni and Kent, 2019; Mitchell et al., 2021a). For the Amasia–Eurasia cycle, Eurasia at least has had an appreciable size since ca. 50 Ma after the opening of northeast Atlantic and the collision of India, although the formation of megacontinent Eurasia overlaps with the breakup of Pangea. We can observe the polar motion phenomenon during the formation of Eurasia, but it is hard to evaluate the full amplitude because this event is still ongoing.

By and large, megacontinent assembly (also being a part of the supercontinent assembly) has the potentiality to be accompanied by large amplitude TPW and even exceeding 50°. When a tenured supercontinent begins to break up, TPW may or may not occur, with various amplitudes. Based on current constraints, TPW as breakup ensues, while possibly increasing in rate (Fu et al., 2022), tends to decrease in amplitude, which is in accordance with the conclusion drawn by numerical modeling (Zhong et al., 2007). In general, megacontinents seem have a close relationship to large TPW, while supercontinents during tenure and breakup might trigger TPW of relatively smaller amplitude.

TPW rate is another proxy that reflects the dynamic balance between TPW excitation and limitation factors. We of course do not underestimate the importance of other TPW features like TPW rate, but compared to amplitude, the estimation of rate is more uncertain for various reasons, including: (i) it includes not only the uncertainties of paleopoles, but also the uncertainties of geochronological ages and (ii) it is highly dependent on the sampling resolution of a TPW event, where the maximum TPW rate during the middle of a nonlinear TPW event is probabilistically less likely to be sampled (Jing et al., 2022). Both of these issues become increasingly problematic the farther one goes back in time, due to increasingly large age uncertainties and generally lower paleomagnetic sampling resolution deeper in Precambrian time.

Recently, Fu et al. (2022) compiled TPW rates since 1200 Ma (Figure 7b), before which the above concerns become quite large. The fastest rates (4°–5.5° Myr^{-1}) occur at ca. 832–790 Ma and ca. 450–440 Ma (Jing et al., 2022). The slowest rates (0.45°–0.5° Myr^{-1}) occur from 250–150 Ma and ca. 400–250 Ma (if indeed the events proposed by Le Pichon et al. (2021) are viable). Other fast rates (>2° Myr^{-1}) occur at ca. 615–565 Ma, ca. 160 Ma, and ca. 84 Ma, while other slow rates might occur at ca. 150–140 Ma and ca. 110–100 Ma. Although there are theoretical reasons to anticipate links to geodynamic evolution, with current constraints—limited in number, certainty, and to the past 1200 Myr—it is difficult to confidently correlate patterns in TPW rates to the supercontinent–megacontinent cycle and mantle heating/cooling. Nonetheless, at present, as pointed out by Fu et al. (2022), there appear to be both trends and rhythms in TPW rates over time. Two intervals of relatively fast TPW occur at both ca. 832–790 Ma and ca. 170–80 Ma, where such temporary boosts in TPW rate may be related to relatively homogenous mantle thermal structure during the two Rodinia and Pangea supercontinent cycles, respectively. Isoviscous mantle structure has been shown to indeed promote faster TPW (Richards et al., 1999). In addition to such rhythms, the Rodinia cycle seems to have higher rates than those of the Pangea cycle. Fu et al. (2022) suggest the striking reduction in average TPW speeds from the Neoproterozoic to the Phanerozoic might be caused by the irreversible transition of secular mantle cooling—see subsection 5.4 on secular change.

Generally, TPW amplitude and rate are correlated, but the patterns discussed above may suggest a potential trade-off between the two that may relate to the supercontinent-megacontinent cycle. The Neoproterozoic offers an illustrative comparison. On one hand, the 830–790 Ma TPW events are the fastest of the Neoproterozoic and occurred during the Rodinia tenure-breakup transition. On the other hand, the 615–560 Ma TPW events that occurred during assembly of megacontinent Gondwana are the largest of the Neoproterozoic, but are slower than the earlier events. We tentatively suggest that megacontinent assembly causes large TPW and supercontinent tenure and breakup cause fast TPW.

If the 1235–1207 Ma paleomagnetic pole and VGP from the North China craton (Ding et al., 2020; Wang et al., 2020) and the ca. 1108–1080 Ma Keweenawan track of Laurentia (Swanson-Hysell et al., 2019) merely represent plate tectonic motions, then the occurrence of TPW might be absent from ca. 1.8–0.85 Ga. This protracted period roughly corresponds to "Earth's middle age" (Cawood and Hawkesworth, 2014; Zhai et al., 2014; Tang et al., 2021), also referred to as the "boring billion" (Holland, 2006), or simply the "mid-Proterozoic" (Spencer et al., 2021). Significantly, glaciations were also absent and preserved passive margins were rare during this period (Figure 7d, 7e).

Rare passive margins represent a relatively stable continental configuration, although the supercontinent cycle hypothesis underlines the distinct stages between the breakup of Columbia and assembly of Rodinia in Mesoproterozoic (Evans et al., 2016). One explanation is from Columbia to Rodinia, the configurations change relatively less than other supercontinent cycles until Rodinia breakup in the late Neoproterozoic. This process was called introversion unlike the extroversion configurations from Rodinia to Pangea (Murphy and Nance, 2003; Li et al., 2019). Extension-related magmatism at ca. 1.4–1.25 Ga is widespread and is ascribed to Columbia breakup (Evans and Mitchell, 2011; Kirscher et al., 2021). Anyway, another possibility is that both passive margins and TPW events are scarce during ca. 1.8–0.85 Ga. If continents were roughly in stable configurations during the boring billion (Roberts et al., 2022), that means the mantle did not experience large-scale mass redistribution, then TPW might have been muted. Alternatively, the lack of passive margins (Bradley, 2008) may have been emblematic of increased effective elastic thickness of the unbroken lithosphere which, in turn, could have reduced TPW amplitude (Creveling et al., 2012). Finally, balanced convection (between upwelling and downwelling flux) during the mid-Proterozoic (Mitchell et al., 2022) also supports insignificant TPW. No glacial event has been reported during this period (Hoffman et al., 2017) (Figure 7e), further indicating the remarkable stage in the Earth system.

5.2 Sea level, paleoclimate, and biodiversity

Much like plate tectonics, TPW changes the paleographic locations of continents, therefore it also carries profound implications for the evolution of Earth's surface environment. Changes in continental paleolatitude due to TPW are the most obvious driver of surface effects, and will be discussed here. Other changes such as oceanographic circulation due to continental margins changing orientation with respect to prevailing wind directions can be found in Raub et al. (2007). We will discuss changes in sea-level, paleoclimate, and biodiversity due to TPW.

Alfred Wegener, founder of Pangea and continental drift, also was the first to recognize the potential for TPW to cause systematic changes in relative sea level (Wegener, 1966). An important concept in understanding potential effects of TPW is "quadrature", where TPW breaks the world into four quadrants based on changing paleolatitudes (Figure 8a). Given the TPW axis, by definition, is equatorial and at a certain longitude, there are two types of quadrants: those moving equatorward and those moving poleward (Figure 8a). Thus, for an example where the TPW axis is at 0°E, northeastern/southwestern quadrants and northwestern/southeastern quadrants are similar. The liquid ocean responds instantaneously to TPW (i.e., maintaining constant hydrostatic figure), whereas the mantle has a delay and responds viscously to TPW. Therefore during TPW, continental margins plow through the equipotential surface of the oceans, with those continents moving poleward leaving the hydrostatic bulge and experiencing regression (like A in Figure 8a), and those continents moving equatorward driving into the hydrostatic bulge and experiencing transgression (like C in Figure 8a). Of course, the magnitude of sea-level change is a function of the paleogeographic distance from the TPW axis, with largest changes occurring 90° away from the TPW axis and inconspicuous sea-level change predicted near the TPW axis.

Numerical simulations by Mound et al. (1999) demonstrate that if an IITPW event lasted 25 Myr, a continent initially at the pole will move toward the equator, experiencing significant transgression (sea-level changes of up to 75–200 m depending on the mantle viscosity and thickness of the purely elastic lithosphere) followed by a moderate

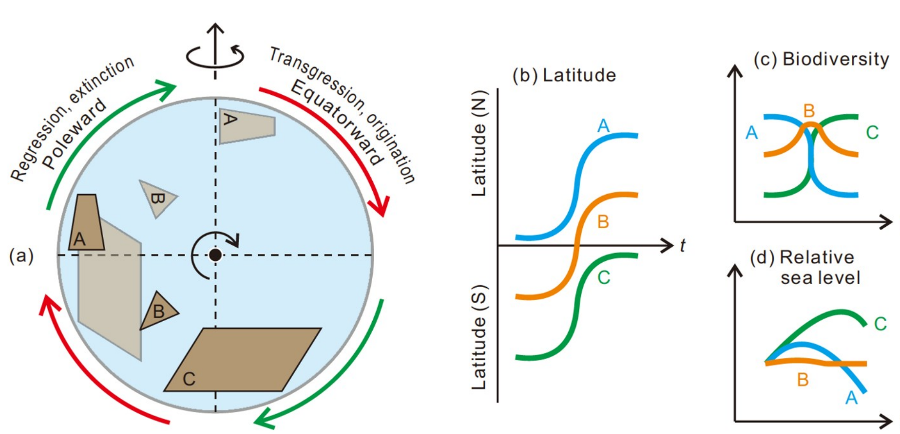

Figure 8 Schematic illustration of the motion of continents ((a), (b)), biological diversity (c), and sea level change (d) during TPW. Black dot at center of (a) represents TPW axis of clockwise rotation. Green arrows represent poleward move and red arrows represent equatorward move. Continent A moves from the equator to the pole. Continent B moves from mid-latitudes in one hemisphere through the equatorial bulge to mid-latitudes in the opposite hemisphere. Continent C moves from the pole to the equator. (d) Modified and simplified after Mound et al. (1999).

regression, but the main stratigraphic signal would be the initial transgression (Figure 8b, 8d). If a continent initially at the equator moves toward the pole, it will experience moderate transgression followed by a major regression, but the main stratigraphic signal would be the regression (Figure 8b, 8d). Sea-level change as detected by sequence stratigraphy can thus be a signal independent of paleomagnetism for testing TPW. One of the best-known cases of relative sea-level changes due to TPW are the only two sequence boundaries in the thick Neoproterozoic succession in Svalbard occurring at the two TPW events associated with the Bitter Springs TPW oscillation (Maloof et al., 2006). Another example is the large paleolatitude oscillation of Laurentia during the Ediacaran being consistent with a sequence of regression and transgression during Laurentia's trip poleward and then back to the equator, respectively (Mitchell et al., 2011). To be clear, sea-level change due to TPW quadrature only causes relative sea-level change, not eustatic change.

However, eustatic sea-level change is also a conceivable effect of TPW. For example, slow TPW over the past 40 Myr that has moved North America and Greenland poleward is thought to have caused the inception of Laurentide continental ice sheet formation ca. 3 Myr ago, corresponding also to a eustatic drop in sea level associated with northern hemisphere glaciation (Daradich et al., 2017). Modeling of Pleistocene glaciations has also explored the possibility that small amplitudes of TPW (<<1°) could be driven by glacial loading/unloading (Bills and James, 1997). Larger amplitudes in the past, either when the glacial forcing was larger (e.g., the vast peri-Gondwanan ice sheet; Caputo and Crowell, 1985) or the background nonhydrostatic figure and mantle viscosity were more prone to TPW, glacial-induced TPW may be detectable with high-resolution, high-quality paleomagnetism.

There are many conceivable changes in paleoclimate due to TPW. Changes in paleolatitude causing motion between different climate belts associated with Hadley cells should be consistent with climate-sensitive sedimentary facies such as low-latitude carbonates and coal, mid-latitude evaporites, and high-latitude glacial diamictites. Aridification of East Asian has been attributed to the Jurassic "monster shift" moving the North China craton into the arid doldrums (Yi et al., 2019). The well-known migration of glacial centers back and forth across Gondwana during the Paleozoic (Caputo and Crowell, 1985) has been attributed to oscillatory TPW (Evans, 2003), and recently confirmed (Jing et al., 2022). Stratigraphic changes from non-carbonate to stromatolite-bearing carbonate facies has been attributed to coeval changes in paleolatitude likely due to oscillatory TPW during both Neoproterozoic carbon isotope excursions, the ca. 940 Ma Majiatun anomaly (Zhang et al., 2021) and the ca. 810 Ma Bitter Springs Stage (Maloof et al., 2006; Swanson-Hysell et al., 2012).

Because TPW also causes relocation of carbon depocenters, TPW also can reorganize the global carbon cycle, causing either positive or negative carbon isotope excursions depending on the background paleogeography and the sense of TPW rotation. Both the Majiatun anomaly and Bitters Springs Stage negative carbon isotope excursions can be interpreted as the Amazon-like rivers of low-latitude supercontinent Rodinia temporary moving out of the tropics, reducing the fraction of organic carbon burial, and therefore driving both negative excursions (Maloof et al., 2006; Zhang et al., 2021). More details on the effects of TPW on carbon cycling can be found in Maloof et al. (2006). On shorter timescales, TPW could also trigger methane clathrate destabilization, potentially causing short-term warming due to methane's short residence time in the ocean and effectiveness as a greenhouse gas (Kirschvink and Raub, 2003). Because TPW would also form new methane clathrates on continental shelves moving poleward, it is also conceivable that TPW could even sustain a long-lived (>1 Myr) carbon isotope excursion due to clathrate resupply despite methane's short residence time—such excursions would be negative $\delta^{13}C$ given that methane is isotopically very light.

Last, but not least in terms of potential surface effects, TPW can also affect biodiversity. The largest effect of diversity on Earth is the latitudinal diversity gradient (LDG), with more species richness near the equator and less towards the poles (Fischer, 1960; Roy et al., 1998). Mitchell et al. (2015) present a TPW-LDG model where, much like sea level, TPW quadrature causes coordinated changes in diversity, with poleward continents experiencing extinction and equatorward continents experiencing origination (Figure 8a, 8c). The TPW-LDG model was used by those authors to explain the previously enigmatic elevated rates of both origination and extinction during the Cambrian explosion, as continents were located in both types of quadrants. Because more continents either moved into low latitudes or remained at low latitudes (i.e., near either antipode of the TPW rotation axis), origination rates won out extinction rates and drove the Cambrian radiation. Besides, recent studies consider that the TPW-LDG model can account for the protracted end-Ordovician extinction due to a 450–440 Ma TPW event (Jing et al., 2022). Testing of TPW-LDG effects during younger Phanerozoic radiations and extinctions should be conducted, but requires both strong evidence for TPW as well as collaboration with knowledgeable paleontologists, presenting a unique opportunity for interdisciplinary research. Testing for such biotic changes in the Precambrian is naturally more difficult due to the relatively enigmatic fossil record, but not impossible, and represents fertile ground for TPW research as Precambrian TPW events were relatively large amplitude compared to their Phanerozoic counterparts (Figure 7b).

5.3 Core–mantle boundary

Due to Earth's stratification, planetary reorientation (aka TPW) on Earth occurs by the solid Earth rotating about the liquid outer core. That is, it is assumed that the slip that accommodates TPW rotation occurs along the core–mantle boundary (CMB), the largest viscosity discontinuity within the planet. The characterization of TPW as "net rotation of the lithosphere" is therefore potentially misleading; although it describes well the surface kinematics of the rotational vector shared by all lithospheric plates, it incorrectly implies that TPW might be accommodated by slip at the lithosphere–aesthenosphere boundary (LAB), which it is not, as such a highly unlikely scenario would unrealistically require dipping lithospheric slabs to be plowing through the highly viscous mantle at rates commensurate with TPW.

Given that TPW occurs due to slip at the CMB, there may be potential effects on both the lower mantle above (Biggin et al., 2012) and the core-powered geodynamo below (Courtillot and Besse, 1987). Interestingly, the first two magnetic reversals after ca. 42 Myr of no reversals during the Cretaceous Normal superchron occur precisely during the two TPW events of the Late Cretaceous TPW oscillation (Mitchell et al., 2021a), possibly suggesting that rapid TPW played a role in ending the superchron and returning the core to a reversing mode. Also, a weak dipole field during the Neoproterozoic predicted by a numerical dynamo evolution model (Driscoll, 2016) also coincides with some of the fastest and largest known TPW events in Earth history (Figure 7b). Thus, potential mechanisms linking TPW to instability in the dynamo, in the form of magnetic reversals and/or weak dipolar fields, might warrant further investigation.

5.4 Secular change

It is now well established that Earth has cooled substantially (50–100 °C Gyr^{-1}) as evidenced in mantle potential temperatures estimates from primitive basalts (Herzberg and Gazel, 2009; Herzberg et al., 2010; Ganne and Feng, 2017; Herzberg, 2022; Mitchell and Ganne, 2022) (Figure 7f). Cooling is also consistent with all classes of models of Earth's thermal evolution (Davies, 1980, 2009; Korenaga, 2003, 2008). Because the mantle is very viscous and it must be deformed in order to shape-shift to match the new, reoriented hydrostatic bulge due to TPW, the rate of TPW is controlled to first order by mantle viscosity, both the average viscosity as well as the viscosity profile (as the lower mantle is particularly viscous). Although many factors control TPW rate including both the size of the forcing and the strength of TPW limitation forces (Figure 3), mantle viscosity is an important rate-limiting factor (Tsai and Stevenson, 2007). Because of this, a 2.4° Myr^{-1} (27 cm yr^{-1}) TPW "speed limit" is often cited as a feasibility test for whether paleomagnetic APW could be TPW or not. However, this speed limit is parameterized by Earth's present-day mantle viscosity and may therefore represent a conservative underestimate of TPW rates in the past, particularly in the Precambrian. For example, Neoproterozoic TPW generally being faster than most Phanerozoic TPW can be attributed to secular mantle cooling from one supercontinent cycle to the next (Fu et al., 2022). Viscosity is strongly temperature dependent, meaning that when the mantle was hotter in the past, TPW rates could have been faster due to a weaker resistance force to mantle deformation required by reorientation. But other factors than temperature also affect mantle viscosity, such as water. If the mantle has been hydrated over time due to subduction, this could offset to some degree and buffer an expected increase in mantle viscosity due to secular cooling. Garnering evidence for TPW through time provides a unique opportunity to constrain secular change independent of thermal models and igneous petrology.

6. Conclusion and perspectives

TPW is the self-adjustment of Earth's spin axis as a reaction to the mass redistribution of the solid Earth. Preliminary appraisal shows that during the past ca. 2.2 billion years large TPW events, i.e., those with amplitude >10°, occurred at ca. 2050–1800, 800, 630–500, 450–250 (?), 250–150, and 86–78 Ma. By comparison with the timing of the supercontinent-megacontinent cycle, we suggest that the assembly of megacontinents could have a close relationship with the occurrence of large TPW, whereas supercontinent tenure and breakup may be associated with fast TPW. Looking to the future, TPW observations are of vital importance for discussion. Tracking TPW in deep time relies primarily on garnering high-quality paleomagnetic data, whether high-quality and well-dated paleomagnetic poles or high-resolution sampling of well-dated volcanic or sedimentary stratigraphic section. Testing of TPW also requires global synchronicity. Beyond paleomagnetic evidence, the significance of TPW on a broader range of sub-fields within geology should be further explored.

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