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True polar wander and supercontinents

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Abstract

I present a general model for true polar wander (TPW), in the context of supercontinents and simple modes of mantle convection. Old, mantle-stationary supercontinents shield their underlying mesosphere from the cooling effects of subduction, and an axis of mantle upwelling is established that is complementary to the downwelling girdle of subduction zones encircling the old supercontinent. The upwelling axis is driven to the equator by TPW, and the old supercontinent fragments at the equator. The prolate axis of upwelling persists as the continental fragments disperse; it is rotationally unstable and can lead to TPW of a different flavor, involving extremely rapid (≤ m/year) rotations or changes in paleolatitude for the continental fragments as they reassemble into a new supercontinent. Only after several hundred million years, when the new supercontinent has aged sufficiently, will the downwelling zone over which it amalgamated be transformed into a new upwelling zone, through the mesospheric shielding process described above. The cycle is then repeated.

The model explains broad features of the paleomagnetic database for the interval 1200–200 Ma. Rodinia assembled around Laurentia as that continent experienced occasionally rapid, oscillatory shifts in paleolatitude about a persistent axis on the paleo-equator, an axis that may have been inherited from the predecessor supercontinent Nuna. By 800 Ma, long-lived Rodinia stabilized its equatorial position and disaggregated immediately thereafter. Gondwanaland assembled as its constituent fragments documented rapid, oscillatory shifts of apparent polar wander, here interpreted as TPW. The Gondwanaland–Pangea centroid migrated to the equator immediately prior to Jurassic–Cretaceous breakup. Lack of substantial TPW since 200 Ma may indicate the stabilizing effects of specific plate boundary conditions (i.e., persistent convection patterns in the Tethys–Indian Ocean region), possibly superimposed on a secular geodynamic shift governed by increased lower-mantle viscosity associated with long-term planetary cooling. TPW is a significant geodynamic process that, in terms of continental motions, may even dominate plate tectonics for certain intervals of Earth history. The effects of such rapid TPW may be found among regional tectonics and sea-level changes, and possibly global climate change and biological evolution.

Keywords: True polar wander; Supercontinents; Equator

1. Introduction

True polar wander (TPW) is the migration of the Earth's geographic reference frame relative to its spin axis. It is an inherently difficult concept to define because all large-scale elements of our planet are in relative motion, requiring approximations of processes operating at timescales encompassing several orders of magnitude. TPW was once considered an alternative to continental mobilism, to account for geological observations such as Carboniferous–Permian glacial deposits in India (e.g., Wegener, 1929) and discordant

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paleomagnetic poles from ancient rocks (e.g., Creer et al., 1954; Irving, 1956; Deutsch, 1963). Now it is considered as a companion process to plate tectonics that, when excited at the relevant timescales, should be viewed as a natural consequence of the dynamic nature of our solid Earth (Goldreich and Toomre, 1969; Gordon, 1987). TPW is measurable today at a rate of about 10 cm/year, resulting largely from the effects of Holocene deglaciation (Sabadini et al., 1982; Wu and Peltier, 1984; Peltier, 1998; Vermeersen and Sabadini, 1999). Estimates of long-term Mesozoic and Cenozoic TPW rates are typically about 1–5 cm/year (e.g., Besse and Courtillot, 1991). In recent years, however, rapid bursts of TPW have been proposed for discrete intervals of mid-Paleozoic (Van der Voo, 1994), Cambrian (Kirschvink et al., 1997), and Cretaceous (Sager and Koppers, 2000; Prevot et al., 2000) times. These proposals have arisen simultaneously with theoretical development of TPW (Spada et al., 1992, 1994, 1996; Ricard et al., 1993a; Spada, 1993; Richards et al., 1999) and geodynamic models integrated with observed histories of Mesozoic–Cenozoic plate motions (Ricard et al., 1993b; Richards et al., 1997; Steinberger and O'Connell, 1997).

The prevalence or absence of TPW throughout Earth history carries implications into the realms of geodynamics, stratigraphy, regional tectonics, evolutionary biology, long-term paleoclimate, and supercontinental episodicity. For example, if the large sweeping motions of Paleozoic Gondwanaland across the southern hemisphere, determined by paleomagnetism as well as apparent migrations of climatic zones (Caputo and Crowell, 1985), are *not* due to TPW, then the implied rates of ≥ 20 cm/year eliminate the concept of a plate-tectonic "speed limit" for large continents (Meert et al., 1993). As another example, rapid TPW should generate regional sea-level changes of decameters to hectometers (Mound and Mitrovica, 1998; Mound et al., 1999); hence, global sequence-stratigraphic correlations of a given interval may be inaccurate if TPW effects were regionally biasing the eustatic signal. This paper seeks to clarify current concepts of TPW, summarize methods used to measure TPW, present a model of TPW in the context of supercontinents, assess this model using the paleomagnetic database, and emphasize the far-reaching implications of the TPW hypotheses.

2. What is TPW?

True polar wander arises from centrifugal forces acting on mass anomalies either on the surface or within the body of a quasi-rigid planet. In simplified terms, excess masses are driven to the equator, mass deficiencies are driven to the pole, and the instantaneous pole location is determined by the integrative effects of all the planet's mass anomalies, taking into account complexities such as mantle viscosity variations (Ricard et al., 1993a). Any discussion of TPW requires first a clarification of timescales. Here, TPW is considered as a long-term (10^6–10^7 year) process by which the solid Earth shifts in a secular manner beneath its spin axis. The resulting displacement of the rotational axis relative to an established geographic reference grid gives rise to the term "polar wander." I find it easier to understand TPW in the "celestial" reference frame, in which orbital angular momentum of the Earth–Moon system is conserved, and through which the solid Earth shifts uniformly (Fig. 1). In this "celestial" reference frame, slight orbital variations (e.g., free nutation, Milankovitch cycles) are ignored because of their rapid frequency (periods $< 10^5$ year). Speculations of large-magnitude secular changes in planetary obliquity during Proterozoic–Cambrian time (Williams, 1975, 1993) are based primarily on paleoclimatological data and cannot explain the abrupt variations in paleomagnetic data that found the TPW hypotheses. For the purposes of this paper, orbital obliquity is therefore assumed roughly constant at about the present value of 23°. In this case, global climatic zones and circulation patterns will be fixed in the celestial reference frame; TPW on a cloud-enshrouded world (such as Venus) would not be visible from space. The celestial reference frame incorporates the ca. 20-km equatorial bulge, which readjusts primarily at the timescale of isostatic glacial rebound (Gold, 1955; Goldreich and Toomre, 1969), and through which TPW drives the solid Earth incrementally as if through a standing wave.

The "solid-Earth" reference frame can be considered as a thin lithospheric shell or the entire 3000-km-thick mantle (see Gordon, 1987; Courtillot and Besse, 1987). A curious set of motions is proposed by Hargraves and Duncan (1973), whereby the mesosphere (sub-asthenospheric mantle) "rolls" under-

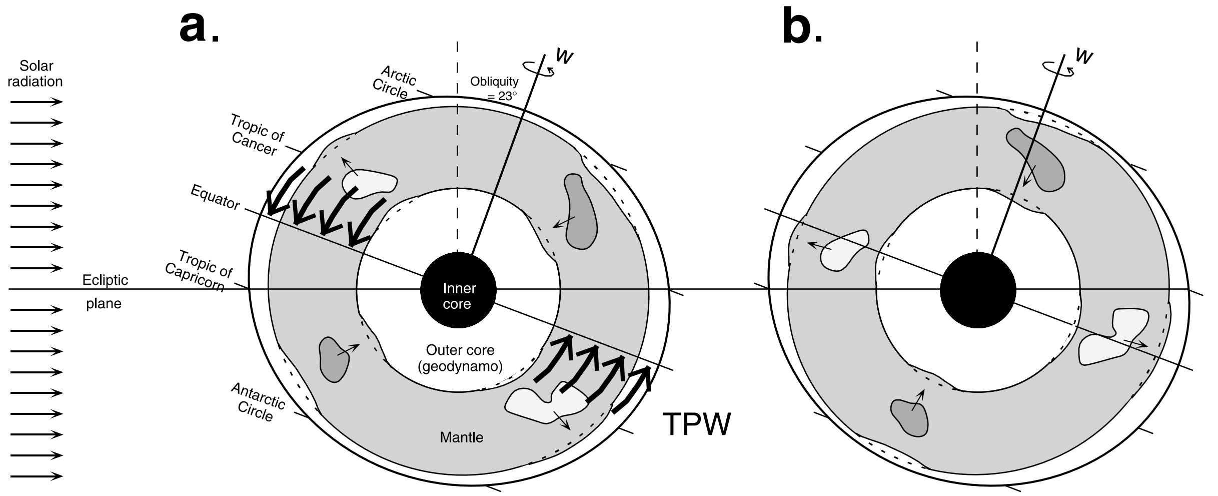

Fig. 1. Simplified concept of true polar wander (TPW) in the context of plate tectonics, the geodynamo, the equatorial bulge (exaggerated), and climate zones. (a) Mantle convection, associated with plate tectonics, incorporates rising and sinking density anomalies (light and dark gray, respectively). Due to viscosity, these vertical motions deform the upper and lower boundaries, and any internal discontinuities, of the mantle. (b) TPW turns the entire mantle, driving the upwellings to the equator, and the downwellings to the poles. The outer core-derived geomagnetic field remains aligned with the spin axis, as does the equatorial bulge and climatic zonation. Continents ride in unison on top of the migrating mantle.

neath a lithosphere which has no net rotation relative to the spin axis. Doglioni (1993) proposed a general eastward motion of the mesosphere relative to the plates; such motion may be kinematically similar to mantle roll, but it cannot be dynamically linked to TPW, which by definition involves equatorial instantaneous Euler poles only (Gold, 1955). When the "solid Earth" component of TPW is considered as some sort of deep mantle or mesospheric reference frame, it generally includes the hotspots (Morgan, 1972); however, it is likely that they themselves move independently from one another at modest rates (Tarduno and Gee, 1995; Steinberger and O'Connell, 1998).

The Earth's internal magnetic field, arising from poorly understood liquid convection cells in the Fe–Ni outer core, is to good approximation dipolar, geocentric, and aligned with the planetary rotation axis when averaged over 10^3–10^4 year (Merrill et al., 1996). Although persistent higher-order components of the geomagnetic field have been postulated to be more prevalent in Paleozoic and older times (Kent and Smethurst, 1998; Bloxham, 2000), these have always been considered subsidiary to a dominating dipole.

Given all of these first-order approximations, TPW involves wholesale migration of the entire mantle beneath a celestially constant spin axis. This secular motion passes through the equatorial bulge, under the orbitally pinned climatic zones, and over the liquid outer-core convection cells that generate the axial-geocentric, dipolar geomagnetic field. Plate-tectonic motions continue as usual before, during, and after TPW episodes.

3. Measuring TPW

Astronomical measurements have indicated an average 20th-Century TPW rate of about 10 cm/year (Vermeersen and Sabadini, 1999), occurring as a secular trend superimposed upon the larger-magnitude Chandler wobble. Mesozoic–Cenozoic TPW can be measured in a variety of ways. When all plate motions are relatively well established, a no-net-rotation lithospheric reference frame can be constructed (Jurdy and Van der Voo, 1974, 1975; Gordon, 1987). A significant, generally westward drift of this no-net-rotation lithosphere relative to the hotspots was determined by plate motions since 3 Ma (Argus and Gordon, 1991), but with the increasing likelihood of deep mantle counterflow biasing the motions of hotspots beneath the Pacific plate (Steinberger and O'Connell, 1998), it is uncertain how much that process could have influenced the result. For progressively older times, the destruction of oceanic lithosphere increasingly obfuscates any estimate of net lithospheric rotation.

Mesozoic TPW is thus measured by the motion of hotspots relative to the paleomagnetic (i.e. celestial) reference frame, either indirectly (Morgan, 1981; Courtillot and Besse, 1987), or directly (Gordon and Cox, 1980). Assuming a deep source for the hotspots with slow relative motion, these methods quantify TPW in the sense of the entire mantle rather than just a thin shell. Although the hotspots are not truly fixed, such an approach is worth describing as a thought experiment because the implications extend to the general interpretation of continental apparent polar wander (APW) paths.

Considering ${}_xV_y$ as the finite rotation describing the motion of reference frame y to reference frame x for some time interval, the relation is used:

$$ {}_{\mathrm{continent}}V_{\mathrm{spin\ axis}} - {}_{\mathrm{continent}}V_{\mathrm{hotspot}} = {}_{\mathrm{hotspot}}V_{\mathrm{spin\ axis}} \qquad (1) $$

or,

[continent's APW path] – [continent's hotspot track] = [TPW]

where APW is the paleomagnetically determined apparent polar wander path for the continent in question. Nearly all of the published estimates of Mesozoic–Cenozoic TPW by this method (see Besse and Courtillot, 1991) are of the same general character, with TPW swinging back and forth along 130° and 310° East Longitude, at rates as high as ~5 cm/year (but typically ~1 cm/year or less).

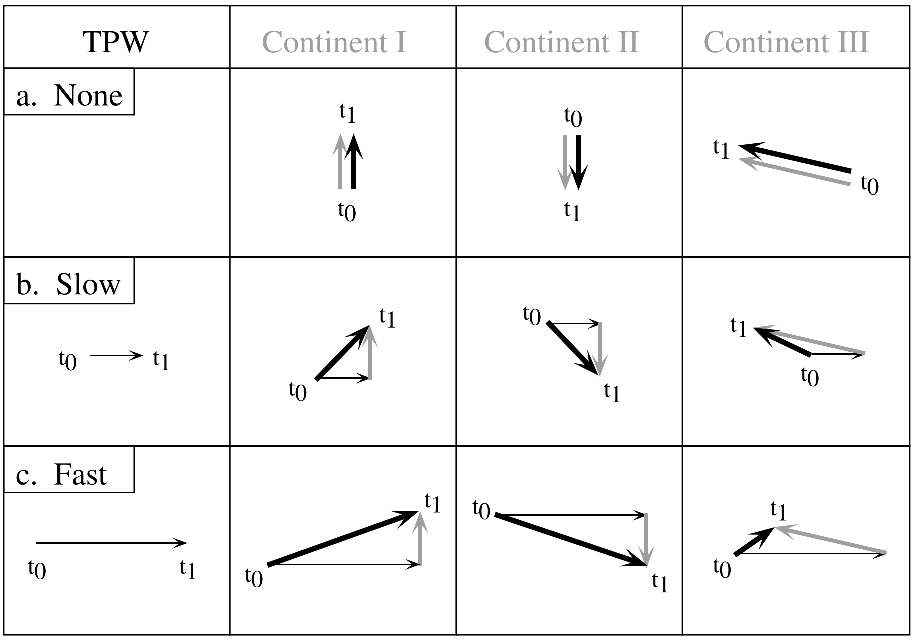

Fig. 2. Contributions of TPW to the observed motion of continents between times t_0 and t_1 (planar approximation for simplicity). Arrows may be treated as describing either motions relative to the spin axis, or components of APW paths. Gray, individual plate behavior; thin black, TPW contribution; thick black, total motion. (a) No TPW; continents' entire motions are due to plate tectonics. (b) Slow TPW; subequal contributions to the total paths, from TPW and individual plate motions. The common TPW component is not readily identified through measurements of the total vectors. (c) Rapid TPW; a common TPW path is easily deconvolved from the records of continents I and II, but largely cancelled by the opposing individual motion of continent III.

For pre-Jurassic time, TPW cannot be calculated in this way because there are only a few well-defined hotspot tracks older than 100 Ma, and none older than 200 Ma (Müller et al., 1993). Nonetheless, pre-Mesozoic TPW can be estimated in crude fashion, if it happens to have occurred at much faster rates than between-plate motions for a given interval of time. Inverting the preceding equation demonstrates that TPW, if nonzero, should form an integral component of *every* continent's APW path:

$$_{\text{continent}}V_{\text{spin axis}} = {}_{\text{continent}}V_{\text{hotspot}} + {}_{\text{hotspot}}V_{\text{spin axis}} \quad (2)$$

$$[\text{continent's APW path}] = [\text{continent's hotspot track}] + [\text{TPW}]$$

In other words, net continental motion relative to the spin axis as measured by paleomagnetic APW paths equals the sum of contributions from individual plate motion over the mesosphere and TPW. This relation holds true whether or not we can observe or measure hotspot tracks.

In general terms, the TPW will form a component of APW paths that is common to all continental blocks. The faster the TPW, the easier it is to estimate due to its contribution toward a greater proportion of each continent's APW path (Fig. 2). Slow TPW (~ 1 cm/year) would be masked by "normal" between-plate motions, and extremely difficult to detect. Even rapid TPW could be countered by equally rapid individual plate motion in a near-opposite sense, thus paleomagnetic data from a single "slow-moving" continent cannot absolutely discredit a TPW hypothesis (Fig. 2c). This unfortunate hindrance to testability will be discussed further below.

In terms of observational consequences, a pre-Mesozoic TPW hypothesis is much the same as a supercontinent hypothesis: both require matching APW paths from a majority if not all continental blocks, and both yield "absolute" reconstructions of the blocks in latitude and longitude (because paths of poles rather than individual poles are used to define the reconstructions). Important differences between TPW and supercontinental hypotheses are that a supercontinent need not contain *every* piece of continental lithosphere but for those included in the assemblage their APW paths must be precisely equivalent; conversely, TPW by definition must involve every square kilometer of the Earth's surface but its signal can be diluted by between-plate motions (Fig. 2). Because no in situ oceanic lithosphere remains from pre-Mesozoic time, proposals of TPW during times of Pangean or earlier supercontinental assembly must rely on independent observations such as the geological manifestations of subduction (e.g. Marcano et al., 1999) or tentative identifications of hotspot tracks (Higgins and van Breemen, 1998; Frimmel, 2001).

4. The Cambrian TPW hypothesis

Kirschvink et al. (1997) proposed that about 90° of TPW occurred in Early Cambrian time, a hypothesis not required by but at least consistent with the quality-filtered global paleomagnetic database. This selection of paleomagnetic results was debated (Torsvik et al., 1998; Evans et al., 1998), and the paleomagnetic community remains divided over the issue (Meert, 1999; Evans and Kirschvink, 1999). Several relevant data have arisen in the intervening years. First, numerical calibration of the Cambrian timescale has been substantially modified according to recent high-precision U–Pb zircon ages from New Brunswick and Morocco (Landing et al., 1998). The new ages have little effect on fundamental aspects of the Cambrian TPW hypothesis, which were based primarily upon biostratigraphic age constraints rather than numerical results (Kirschvink et al., 1997). Nonetheless, the absolute age of the proposed event should now be considered in the interval between about 525 and 508 Ma rather than 530–515 Ma as originally constrained (ibid.). The data still permit a rapid TPW shift occurring at any time within the allowable limits. Second, the Laurentian paleomagnetic evidence needs to be reconsidered in light of new data from Quebec and Labrador: The gabbroic–anorthositic Sept-Iles intrusion, which bears the low-latitude "A" magnetic remanence (Tanczyk et al., 1987) has been dated at 565 ± 4 Ma (Higgins and van Breemen, 1998), and the Skinner Cove volcanics, also bearing a low-latitude paleomagnetic remanence (McCausland and Hodych, 1998), have been dated at 550.5 + 3/ – 2 Ma (Cawood et al., 2001). There still remain concerns about the relative ages of the Sept-Iles "A" and "B" components (cf. Meert et al., 1994; Pisarevsky et al., 2000) and the applicability of the Skinner Cove result, possibly representing a far-travelled terrane rather than the Laurentian craton (McCausland and Hodych, 1998). There are intriguing yet unverified suggestions of high paleolatitudes for Laurentia at the Proterozoic–Cambrian boundary (Park, 1992, 1994), raising the possibility of two Eocambrian polar excursions by that continent (Evans and Kirschvink, 1999) rather than one (e.g., Torsvik et al., 1996). Finally, new paleomagnetic data from Baltica (Meert et al., 1998; Torsvik and Rehnström, 2001), Siberia (Pisarevsky et al., 1997, 2000) and Gondwanaland (Grunow and Encarnación, 2000; Randall et al., 2000) bear upon the problem but as yet do not disprove or particularly bolster the Cambrian TPW hypothesis—assessment still relies heavily on selection versus rejection of individual results.

A possible test of the hypothesis that is independent of paleomagnetic constraints is the quadrantal variation in sea level expected to result from a rapid TPW shift. Due to a relatively sluggish solid-Earth response of the equatorial bulge readjustment, transgressions are expected at sites that are driven to the equator, and regressions are predicted for sites that migrate toward one of the poles (see Wegener, 1929; Mound and Mitrovica, 1998). The magnitude of sea-level variation should depend on rheological parameters of the (primarily upper) mantle and lithosphere, with greater viscosity or lithospheric thickness leading to greater sea-level shifts (Mound et al., 1999). The Early–Middle Cambrian flooding records from Laurentia, Baltica, and Australia, at least to first-order, agree with those predicted by the hypothesized inertial-interchange TPW event (Mound et al., 1999).

5. Extension of the Cambrian TPW hypothesis

When the Cambrian TPW model was conceived, it was regarded by its proponents as the only example of an inertial interchange event, a phenomenon predicted by theoreticians decades earlier (Fisher, 1974). However, Evans (1998) noted that the geodynamic preconditions for a single inertial-interchange TPW event, and for polar instability in general, invited the possibility of multiple, oscillatory TPW about a common equatorial axis. This inertial-interchange TPW axis, the minimum moment of inertia, could also be expressed as the maximum axis of figure (neglecting the hydrostatic bulge). If such a nonhydrostatic figure were prolate, then the geographic position of the rotational axis would be highly unstable. TPW would be extremely sensitive to relatively minor mantle convective fluctuations or plate reorganizations, and would oscillate irregularly within a great circle orthogonal to the prolate axis.

Extension of the hypothesis provided an explanation for the great-circle distribution of paleomagnetic poles from each well-constrained continent in Vendian–Cambrian time (cf. Park, 1994; Torsvik et al., 1996; Schmidt and Williams, 1996) and their tendency to indicate very to extremely rapid continental velocities (Meert et al., 1993; Gurnis and Torsvik, 1994; Hoffman, 1999). The multiple-oscillatory TPW model also related the proposed Cambrian event (Kirschvink et al., 1997) to an independently proposed mid-Paleozoic TPW episode (Van der Voo, 1994); plotted in the reconstructed Gondwanaland reference frame, the great-circle oscillations of rapidly shifting Neoproterozoic–Paleozoic paleomagnetic poles shared a common axis (Evans, 1998; Fig. 3). This permitted speculation that Gondwanaland's great Paleozoic APW swaths are composed almost entirely of a TPW signal, and that the large continent was in fact drifting slowly or negligibly over the asthenosphere during that interval, constituting an approximate mesosphere reference frame.

In that scenario, the common TPW axis would have dangled curiously on one side of the Gondwanaland continent (Fig. 3). Such a position, however, makes more sense if viewed in the context of an Australian–Laurentian connection near the center of Rodinia, regardless of the precise configuration (Moores, 1991; Li et al., 1995; Karlstrom et al., 1999; Burrett and Berry, 2000; Wingate et al., in press). In this way, the alleged Neoproterozoic–Paleozoic TPW axis may have been a geodynamic legacy of the Rodinia supercontinent (Evans, 1998) in the same way that present first-order mantle heterogeneity is inherited from Pangea (Anderson, 1982; Chase and Sprowl, 1983; Davies, 1984; Richards and Engebretson, 1992). The comparison requires that Australia–Antarctica (the northwest Australian craton and Mawson-Land) drifted little over the asthenosphere following Rodinia's breakup, which is permissible according to paleomagnetic data

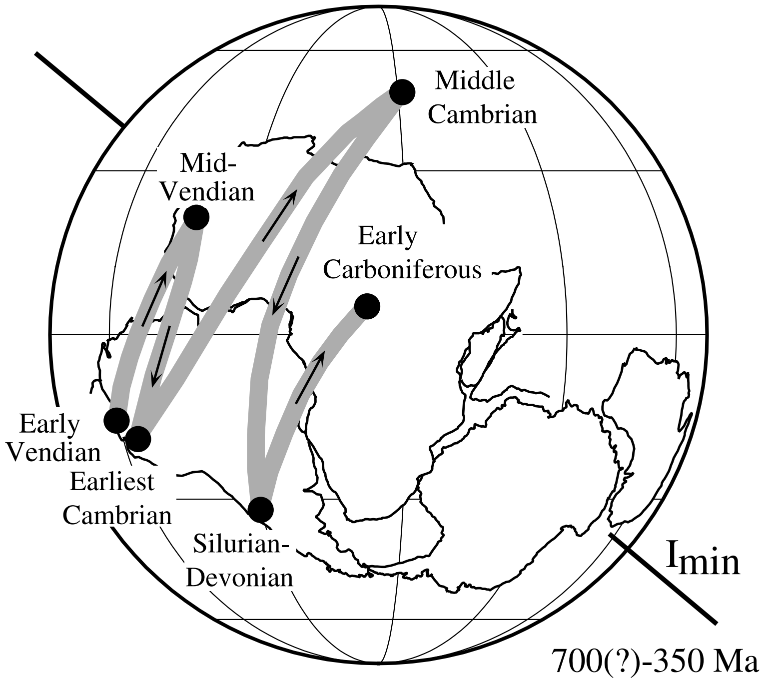

Fig. 3. Terminal Proterozoic to late Paleozoic apparent polar wander (APW) path for Gondwanaland. Individual results or groups of poles discussed by Van der Voo (1994), Kirschvink et al. (1997), and Evans (1998), with new Middle Cambrian data for Gondwanaland (Grunow and Encarnación, 2000; Randall et al., 2000). The "Early Vendian" and "Mid-Vendian" poles are unlikely to be substantially older than 600 Ma, so despite the fact that Gondwanaland was not fully assembled until Cambrian time (see Trompette, 1994), these Australian results may be considered applicable to first-order. Oscillatory APW rotations are interpreted here as TPW about a common, long-lived, minimum-inertial axis (I_{min}) near eastern Australia, which may also be regarded as the prolate axis of Earth's figure, inherited from Rodinia. The oscillations are superimposed on a gradual "northwestward" Gondwanaland plate motion relative to the mesosphere.

(Powell et al., 1993; Meert and Van der Voo, 1997; Wingate and Giddings, 2000).

6. Geodynamic topologies

Hotspots, spreading ridges, and subduction zones on the present Earth's surface might appear to belong to a simple distribution, yet a characterization in terms of simple convection models remains elusive. Various models have been proposed, with either theoretical or empirical bases, or both. They may be categorized by topology, according to first- and second-order modes of mantle convection. For the purposes of this paper, whole-mantle convective schemes rather than layered models will suffice to outline the topological planforms and their predictions for waxing and waning supercontinents. Zonenshain et al. (1991) confine their "hot-field" tectonics to lower-mantle convective patterns, which is possible as a corollary to the model presented below.

Monin (1991) adopted a useful nomenclature for single- and double-celled convection patterns inside a sphere. The topologies are "floating" within an unspecified reference frame. A single convection cell involves a point upwelling and lateral transport toward an antipodal point downwelling (Fig. 4a). This pattern is rarely invoked for the real Earth, except when supercontinental models propose complete transit of disaggregated blocks toward reassembly on the opposite side of the globe (e.g., Hatton, 1997; Veevers et al., 1997).

Two-cell convection modes have two variations. In Monin's (1991) terminology, the "open" configuration includes a girdle distribution of upwellings and bi-directional transport toward two antipodal points of downwelling (Fig. 4b). The model by Sutton (1963) invoked this pattern to achieve the simultaneous

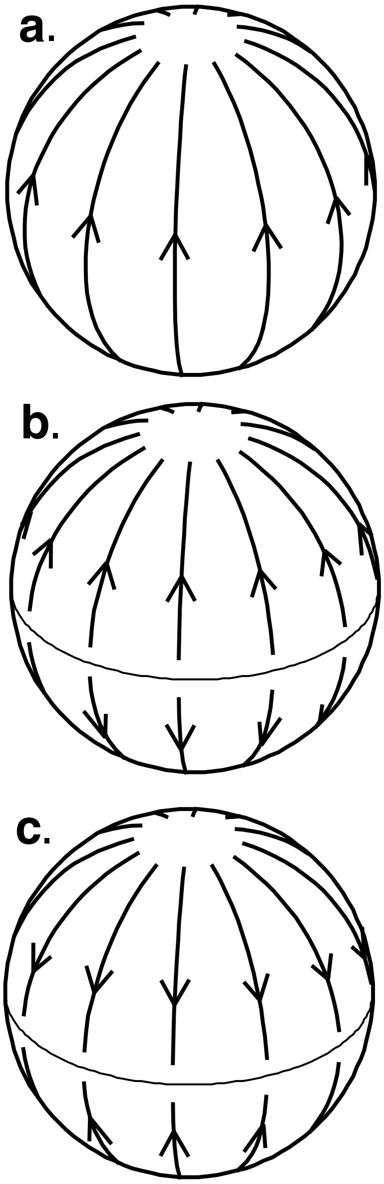

Fig. 4. Modes of simple spherical convection, as described by Monin (1991). All topologies are "floating" in unspecified reference frames. (a) One-cell configuration. (b) Two-cell, "open" configuration. (c) Two-cell, "closed" configuration.

assembly of two polar-centered megacontinents. In complete topological contrast, the "closed" two-cell configuration involves two antipolar, point upwellings separated by a girdle of downwelling (Fig. 4c). Models of supercontinental cyclicity that invoke alternate expansion and contraction of interior and exterior oceans (Worsley et al., 1984; Veevers, 1990; Anderson, 1994) fall into this category. In these models, the upwelling axis is asymmetric, driving the continents together and apart through various stages of the cycle. The model described below, following Evans (1998), also incorporates a two-cell "closed" configuration, but one that shifts its axis relative to the mesosphere by about 90° with the maturation of each new supercontinent.

7. TPW and supercontinental cycles

At present, and probably at least since the Mesoproterozoic (Hoffman, 1989), Earth's lithosphere has contained just enough continental material to occupy about a hemisphere when all elements are aggregated. Subducted slabs cannot penetrate the mantle underlying the interior region of a supercontinent that is long-lived and slowly drifting over the mesosphere; instead, slabs may descend in a great-circle "curtain" circumscribing the supercontinent (Anderson, 1994). Conservation of mass in such a long-lived convecting system produces two upwellings in a two-cell, "closed" configuration as described above. These upwellings create positive dynamic topography across major mantle density discontinuities, resulting in columns of excess inertia (Hager et al., 1985). They should then migrate to the rotational equator via TPW (Fig. 5a), and the encircling girdle of subduction zones becomes a meridional "ring of fire" such as that on Earth today (Fig. 5b). With a prolate nonhydrostatic axis thus established (the equatorial bulge ignored as justified above for these timescales of excitation; Goldreich and Toomre, 1969), polar instability may accompany supercontinental fragmentation.

Continuing around the supercontinental cycle, the disaggregated fragments of the old supercontinent may drift into the subduction-downwelling girdle but advance no further; instead, they are trapped within the downwelling zones. This concept follows Gurnis (1988) and Anderson (1994), in contrast to paleogeographic models that invoke complete transit of the disaggregated continental fragments to the opposite hemisphere (Hatton, 1997; Veevers et al., 1997). The next supercontinent assembles by colli-

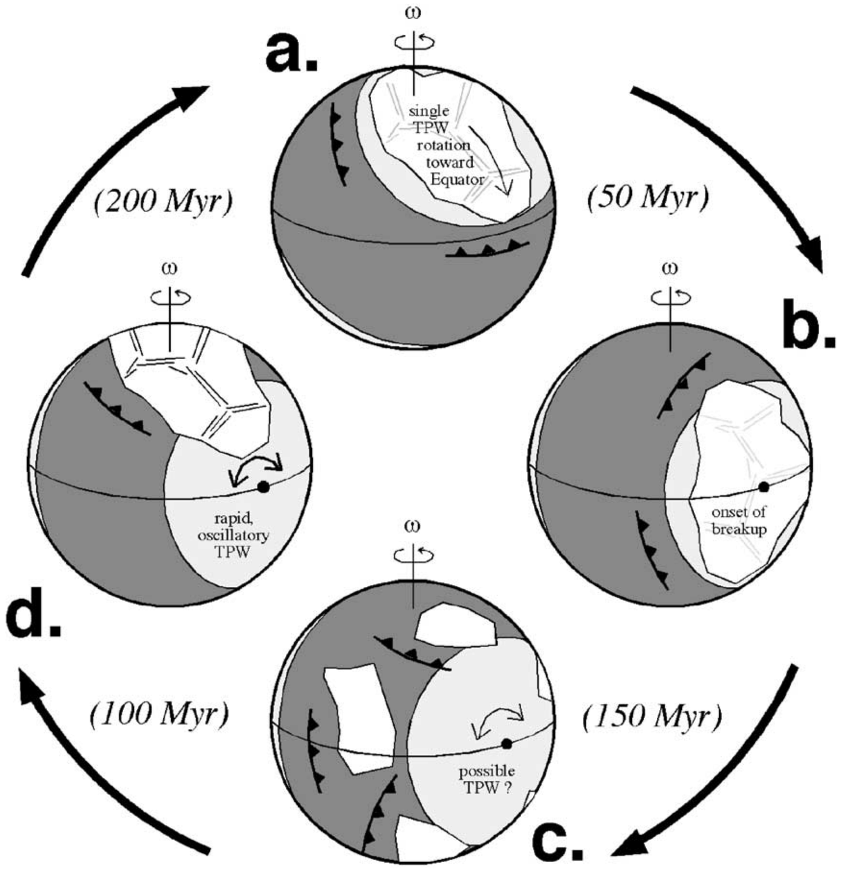

Fig. 5. True polar wander and the supercontinental cycle. (a) Prolonged slab sequestration from the mesosphere beneath an aging supercontinent causes that region of the mantle to warm; a prolate axis of upwelling develops, deforming internal boundary layers and driving the supercontinent, as well as the entire mantle, toward the equator via TPW. (b) Supercontinental fragmentation is a natural consequence of the upwelling axis. (c) Continued upwelling along the prolate axis disperses the continental fragments into the girdle of downwelling that is relict from the previous supercontinent. TPW is possible at this stage, in principle, but has not yet been described for the immediate post-Rodinian and post-Pangean intervals. (d) Reassembly of a new supercontinent may be accompanied by rapid TPW about the relict upwelling axis inherited from its predecessor. Only after several hundred million years of slab sequestration under the new supercontinent will it establish its own prolate axis, starting the cycle anew.

sions of these continental blocks within the downwelling girdle. Such a newly assembled supercontinent, before it has time to influence its own pattern of mantle convection as described above, may be subject to continuing TPW oscillations around the equatorial prolate axis inherited from its predecessor (Fig. 5c). It is only after prolonged sequestration of slabs from the deep mantle underlying an aging supercontinent, that it develops its own prolate axis, resetting the cycle (Fig. 5d). Numerical models suggest a duration of a few hundred million years for this transition (Gurnis, 1988).

8. Rodinia–Gondwanaland–SuperAsia

We may now investigate the broad-scale evolution of supercontinents and true polar wander since 1200 Ma, as indicated by the paleomagnetic record. Despite much ongoing debate regarding the precise configuration of Rodinia (e.g., Weil et al., 1998; Karlstrom et al., 1999; Burrett and Berry, 2000; Wingate and Giddings, 2000; Sears and Price, 2000; Dalziel et al., 2000; Wingate et al., 2002), Laurentia must be placed near the center because it is surrounded on all sides by terminal Proterozoic to Cambrian passive margins (Valentine and Moores, 1970; Stewart, 1972). Rodinia assembled during the "Grenvillian" orogenic peak at 1.3–1.0 Ga (Hoffman, 1991). Therefore, motion of Rodinia's central cratonic core may be estimated by the Laurentian APW path, the most completely determined of any craton for the interval between ca. 1.3-Ga initial assembly and 0.8-Ga initial breakup. During the early part of this interval, 1.2–0.9 Ga, the center of young Rodinia experienced occasionally rapid, large-magnitude shifts in paleolatitude according to the Logan, Keweenawan, and Grenville paleomagnetic swaths (see Irving and McGlynn, 1981; Weil et al., 1998). These loops and tracks oscillate nearly about the same great circle (Fig. 6), and I speculate that these swings may represent rapid TPW within the relict subduction-girdle from the preceding supercontinent Nuna (assembled by 1.8 Ga, onset of rifting by 1.5 Ga; Hoffman, 1989; 1997). Only at about 800 Ma, after an interval of 200 Myr following final Grenvillian assembly, did Laurentia stabilize its position along the equator (see Wingate and Giddings, 2000). This may represent the initiation of the prolate-equatorial mantle upwelling beneath aging Rodinia, the same upwelling that began

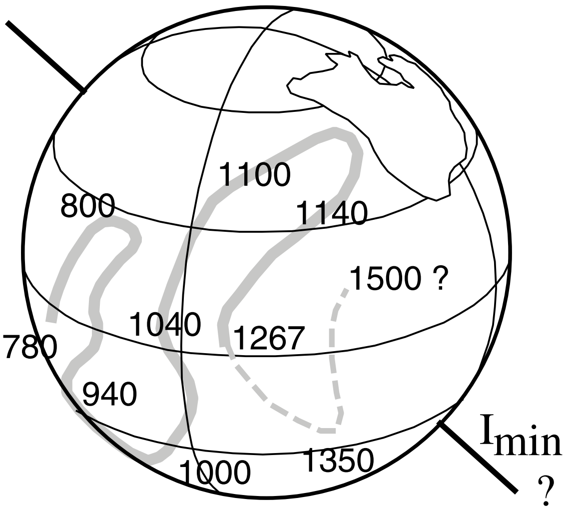

Fig. 6. Simplified Mesoproterozoic–Neoproterozoic APW path for Laurentia, after Harlan et al. (1994) and McElhinny and McFadden (2000, p. 320). Ages in Ma. Rodinia, which assembled during 1.3–1.0 Ga around Laurentia, experienced rapid and oscillatory shifts in latitude about a common equatorial axis, here suggested to be inherited from the preceding supercontinent Nuna.

to fragment the supercontinent at that time (Li et al., 1999).

Paleomagnetic constraints for the various cratonic blocks worsen considerably into the post-Rodinian epoch, between 700 Ma and the Proterozoic–Cambrian boundary (543 Ma; Grotzinger et al., 1995). Nonetheless, great-circle distributions of paleomagnetic poles characterize all of the moderately well-constrained cratonic blocks during that interval, including Laurentia and Baltica (Torsvik et al., 1996); Australia (Schmidt and Williams, 1996); and South China (Zhang and Piper, 1997). Some pairs of temporally adjacent poles appear to require very rapid rates of continental motion (Evans, 1998; Hoffman, 1999), in an oscillatory manner that is consistent with a multiple-TPW interpretation (Evans and Kirschvink, 1999). As pointed out in the original TPW-supercontinent model (Evans, 1998), these oscillations may have revolved around the relict Rodinian prolate mantle-upwelling axis, continuing into the Devonian–Carboniferous, even 400 Myr following Rodinia's breakup and 200 Myr after Gondwanaland's final Cambrian amalgamation.

Pangea completed its final assembly by Carboniferous–Permian time, along the Mauritanide–Alleghanian–Variscan–Uralian super-orogenic system (Ziegler, 1988). Thereafter, the supercontinent migrated quickly, some regions traversing roughly 35° of latitude. Such motion may have been due to TPW (Marcano et al., 1999), ultimately positioning Pangea's centroid near the equator (Le Pichon and Huchon, 1984). If this manifested the establishment of a new equatorial prolate axis under the young Pangea supercontinent, then the lack of a significant time lag between continental collisions and induced mantle upwelling (see Doblas et al., 1998) would be inconsistent with the model presented earlier in this paper. Alternatively, if the possible Permian–Triassic TPW resulted from long-lived slab sequestration beneath long-lived Gondwanaland (Evans, 1998), then the final "resting" position of Gondwanaland's centroid—significantly south of the equator—would also be inconsistent with the ideal model presented above. I propose that the early Mesozoic interval was geodynamically peculiar, in that two large megacontinents, Gondwanaland and Laurussia, had been assembled for 350 and 200 Myr, respectively (Fig. 7). These may have independently sequestered their

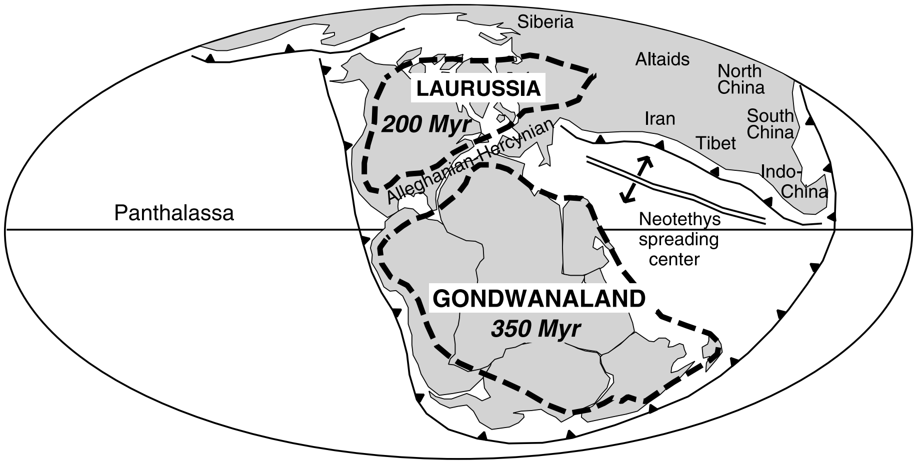

Fig. 7. Pangea at 195 Ma, the onset of initial breakup (Mollweide full-Earth projection, after Scotese, 1997). A meridional girdle of peri-Pangean subduction zones ("ring of fire") encircles the supercontinent, which includes two large, long-lived landmasses (Gondwanaland and Laurussia; shown with durations of internal stability and hence sequestration of subducted slabs from their underlying mesospheres). These "core" regions, as well as the mid-Tethyan oceanic spreading center, appear symmetrically distributed around the equator, possibly a result of early Mesozoic TPW.

underlying mesospheres from the cooling effect of subducted slabs, developing nascent upwelling zones that only merged into one axis following their unification. The resulting kinematic effect, combining TPW and continental convergence, is strikingly similar to that proposed by Holmes (1931), although the hypothesized dynamics differ. Of course, similar second-order complexities may be discovered when better resolution is achieved for the Neoproterozoic reconstructions; indeed, they may be expected within complex, quasi-chaotic systems such as Earth's convective mantle.

Jurassic–Cretaceous disaggregation of Pangea/Gondwanaland was spectacular, involving the extrusion of several large igneous provinces (Storey, 1995). Concurrently, Asia was already growing southward via accretion of Gondwanaland-derived cratons (Sengör, 1979). The Alpine–Himalayan collision is the latest development of this ongoing process. Carrying present plate motions into the future, Asia is expected to grow further via the addition of Africa, Arabia, and Australia. I name this future supercontinent "SuperAsia." According to the model presented above, we should not expect SuperAsia to develop its own mantle-upwelling axis until several hundred million years into the future. In the meantime, TPW is predicted to oscillate along the 90° meridians within the present downwelling girdle (see Richards and Engebretson, 1992), or orthogonal to Pangea's hotspot-reconstructed centroid (0°N, 40°E; Le Pichon and Huchon, 1984), along 130 and 310°E. Evans (1998) correlated the existing Mesozoic–Cenozoic TPW path (Besse and Courtillot, 1991) with the meridians encircling the relict Pangean centroid, but recognized the need for updated hotspot-based TPW estimates.

Some of these new estimates have indeed appeared (Prevot et al., 2000; Tarduno and Smirnov, 2001) and generally support less TPW during the last 100 Myr than indicated by previous studies. However, some recent work has suggested discrete bursts of TPW at 84 Ma (Sager and Koppers, 2000) and 110 Ma (Prevot et al., 2000). These proposals are contested (Cottrell and Tarduno, 2000; Tarduno and Smirnov, 2001; Mound et al., 2001), and in any case it is very unlikely that major TPW swings, analogous to the proposed Neoproterozoic–Paleozoic events, occurred since the breakup of Pangea. Why not? Perhaps a subsidiary system of mass anomalies has stabilized the rotation axis, one possible example being the long-lived, equatorially centered convective cells within the Neotethys–Indian Ocean system (Sengör and Natal'in, 1996). Alternatively, it is noted that for both the post-Nuna and post-Rodinia epochs, large and rapid APW oscillations do not characterize the paleomagnetic record until nearly complete aggregation of the successor supercontinents (nascent Rodinia at 1100 Ma, and Gondwanaland at 600 Ma, respectively). If this enigmatic observation can be generalized, then perhaps rapid post-Pangean TPW awaits a more complete assembly of SuperAsia in the future. Regardless, the small-magnitude TPW determined for recent epochs by no means limits its prevalence in more ancient times, as pointed out by Richards et al. (1997, 1999).

The TPW-supercontinent cycle proposed above can be illustrated in time as well as space (Fig. 8). For each of the long-lived supercontinents or megacontinents Rodinia and Gondwanaland, development of a broad mantle-upwelling axis followed final collisional amalgamation by ca. 300–400 Myr. Development of each prolate upwelling axis was soon (50–100 Myr) succeeded by fragmentation of the supercontinent. Assembly of each successor supercontinent occurred within the geodynamic legacy of its predecessor, such that rapid, oscillatory shifts in latitude characterized the drift histories of the nascent Rodinia (1200–900 Ma) and Gondwanaland (600–500 Ma). Hypothesized short-lived supercontinents, such as Pannotia and Artejia (Dalziel, 1997), did not endure long enough to sequester their underlying mantle regions from subduction-cooling, and so are not part of the cycle. Similarly, Pangea was an ephemeral entity that, although exerting a profound influence on the biosphere and global climate (Klein, 1994), may have had little effect on mantle dynamics.

9. Discussion

One important implication of the above model is that rapid TPW is not necessarily indicative of forcing by rapid or large-magnitude plate reorganizations. If the fundamental mode of mantle convection is dominated by an equatorial 2-cell "closed" configuration during supercontinental maturity and breakup (Fig. 5b,c), then polar instability may be greatly amplified by second- and third-order motions of convective features. These might include the formation or destruc-

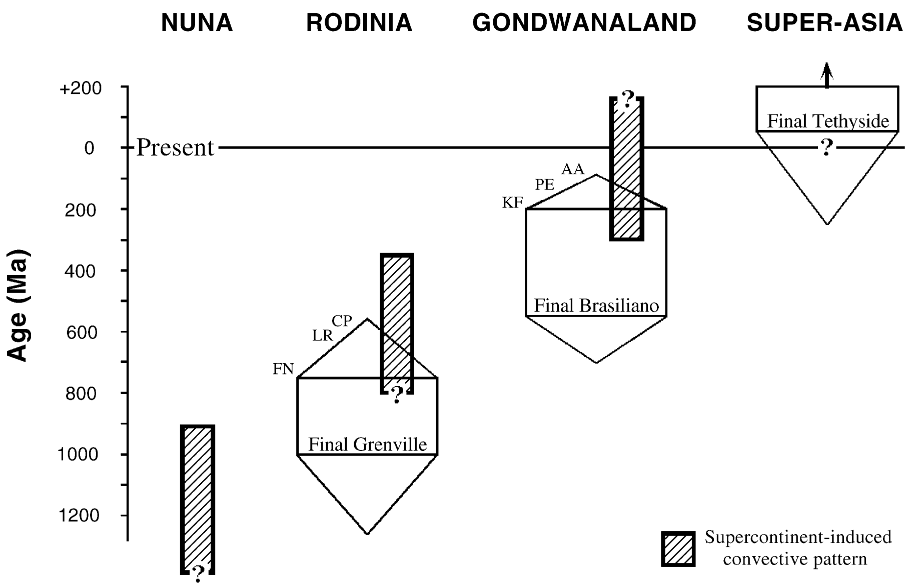

Fig. 8. Temporal progression of supercontinents and their geodynamic legacies. Growth and demise of each supercontinent is depicted according to ages of orogenic events and large igneous provinces. Age ranges for the prolate upwelling axes are inferred from either present geophysical parameters or oscillatory paleomagnetic data, as discussed in the text. Abbreviations for Rodinia: CP = Catoctin province, FN = Franklin-Natkusiak province, LR = Long Range dikes. Abbreviations for Gondwanaland: AA = Australia–Antarctica separation, KF = Karoo-Ferrar, PE = Paraná-Etendeka.

tion of an individual plume or subduction arc, or a single "avalanche" of slab penetration below the transition zone. Order-of-magnitude effects of such features upon TPW may be modeled numerically, but direct TPW causality will be extremely difficult to pinpoint from the pre-Mesozoic geological record.

Testing pre-Mesozoic TPW hypotheses is problematic. As discussed above, between-plate motions will add "noise" to the APW paths, partially or nearly completely obscuring any TPW "signal" (Fig. 2). Some plates will have components of motion that oppose the TPW direction, and continental APW paths from those plates will show limited motion. In this way, a near-stationary APW path from a single continent or craton cannot definitively reject a TPW hypothesis for that interval. This statement is logically valid for two or even more continents or cratons, although arguments in favor of rapid TPW become increasingly contrived in the face of well-determined, stationary APW paths. Circumstantial evidence, such as provided by the lithological hallmarks of continental rifting, passive margin development, and plate convergence, will assist judgments of whether a TPW hypothesis simplifies or complicates the overall picture. For example, "hairpins" in APW paths are classically attributed to continental collisions or disaggregations (Irving and McGlynn, 1981); yet we find little correlation between Neoproterozoic–Paleozoic APW oscillations and tectonic events of the Grenvillian, Pan-African, and Caledonian orogenic intervals (Figs. 3 and 6).

According to the model presented above, the prolate axis established under an old supercontinent may define a persistent reference frame for the mesosphere, during continental breakup and subsequent reassembly into a new supercontinent. After the new supercontinent matures, its new, prolate axis of mesosphere upwelling becomes converted from ca. 500 Myr of earlier downwelling; similarly, the 500-Myr-old upwelling axis relict from the preceding supercontinent is incorporated into the new subduction girdle of downwelling. Every ca. 500 Myr involves a ca. 90° shift in the fundamental convective plan of mantle upwellings and downwellings, and thus only five or so of these shifts should have occurred since the Archean. Can we search the geological record for the sites of long-vanished supercontinent-induced upwellings? Perhaps subtle isotopic variations of mid-ocean-ridge basalts may help identify not only post-Pangean/post-Gondwanaland modes of mantle convection (Anderson, 1982; Hart, 1984) but also those from older times (see Weis et al., 1987).

Numerical models of TPW indicate that its maximum possible rate is governed primarily by lower-mantle viscosity (Spada et al., 1992); specifically, a weakly yielding, nearly isoviscous mantle is required for the rapid TPW (90° in 15 Myr or less) proposed for the Proterozoic–Cambrian transition by Kirschvink et al. (1997) and Evans (1998). Presently favored models of the present Earth's mantle include at least a 10-fold viscosity difference across the transition zone (Bunge et al., 1996; Peltier, 1998; Forte and Mitrovica, 2001), which may be partly responsible for the small amount of observed Cenozoic TPW (described above). Has the Earth's viscosity structure changed through time? It is likely that pre-Mesozoic TPW estimates will provide constraints on presumed ancient viscosity structures, rather than the converse. Qualitatively, a hotter early Earth could foster more prevalent TPW through lower mantle viscosities *and* more rapid plate motions through vigorous convection. Better numerical models are required to estimate the relative sensitivity of these two phenomena to global heat flow.

Kirschvink et al. (1997) related Early Cambrian diversification of animals to abrupt changes in oceanic circulation around the continental masses, jumping frequently from quasi-stable state to another within a single ~90° TPW event. At the time of that proposal, the apparent uniqueness of the TPW episode seemed to correspond well with the equally unique and dramatic Early Cambrian animal speciation. If the oscillatory model of rapid TPW (Evans, 1998) is correct, then this one-to-one correlation vanishes. Nonetheless, the complete ramifications of multiple and rapid TPW events have not yet been fully investigated, and they may influence paleoclimate and evolution either directly or indirectly. For example, Evans (2000) proposed that rapid cycling of continents between polar and equatorial latitudes at ca. 600 Ma, may have amplified atmospheric CO_2 drawdown through alternating physical and chemical weathering of exposed silicate rocks, and that this could have contributed to the onset of widespread, low-latitude glaciations in terminal Proterozoic time. Mound et al. (1999) determined that substantial flooding and emergence of continents would occur during episodes of rapid TPW. Such an effect may have repeatedly created and destroyed physical barriers to benthic animal migrations and species interactions within the shallow marine ecosystem. Combined with likely sudden shifts of ocean currents around the rapidly moving continents (Kirschvink et al., 1997), these effects may have enhanced evolutionary turnover throughout the terminal Proterozoic to Cambrian interval.

If TPW was *not* substantial during pre-Mesozoic time, and assuming an axial-centric geomagnetic dipole field, then large Paleozoic APW swings of Gondwanaland represent oscillatory drift of that megacontinent across the southern hemisphere, at rates exceeding those of the fastest Cenozoic plates (Meert et al., 1993). Rates might have been even higher during the late Neoproterozoic, requiring specific conditions of subcontinental viscosities and plate-driving forces (Gurnis and Torsvik, 1994). In addition, there would be little correlation between Neoproterozoic–Paleozoic APW hairpins and tectonic events in Gondwanaland and Laurentia.

One may question the validity of the axial geocentric dipole hypothesis, the central tenet to paleomagnetism. A recent compilation of the Paleozoic and older paleomagnetic database has demonstrated a more significant bias toward low paleolatitudes than would be expected from random sampling of randomly drifting continents (Kent and Smethurst, 1998). One possibility to explain this observation is that significant nondipole components contributed to the geomagnetic field earlier in Earth history. Although certain patterns of heat flux across the core–mantle boundary can lead to enhanced nondipolar field behavior (Bloxham, 2000), it should be noted that several detailed paleomagnetic studies of sedimentary successions show the expected regional expressions of geomagnetic field behavior, including statistically antipolar directions and nonuniformly spaced magnetozones with consistent remanence directions across large sedimentary basins (Kirschvink, 1978; Gallet et al., 2000). An alternative explanation for the low-latitude bias of pre-Mesozoic paleomagnetic results is that TPW has driven continents preferentially toward the equator (Kent and Smethurst, 1998).

Ultimately, assessment of the TPW hypotheses and related conundra of Eocambrian paleomagnetism will require comprehensive compilations of data and their geological contexts (e.g., Van der Voo, 1990a, 1993). In addition, the criteria used to distinguish "signal" from "noise" among the paleomagnetic results (e.g., Van der Voo, 1990b) may need to be updated to accommodate new standards and developing methods in data analysis. Most importantly, patience and objectivity are required of all participants in the TPW debates, for "time...has a way of letting these issues sort themselves out" (Van der Voo, 1993, p. 143).

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