True polar wander, a supercontinental legacy

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Abstract

Paleomagnetically determined apparent polar wander (APW) paths should contain components of individual plate motions as well as true polar wander (TPW), the uniform motion of the mantle relative to the spin axis. Quantifying the TPW component for pre-Mesozoic time is hampered by the lack of a representative from the mantle reference frame; nevertheless, TPW can be estimated if all or most of the continents show similar APW paths for a given period of time. Two such estimates have been proposed recently for the early Paleozoic. Plotted relative to Gondwanaland, which may have been drifting over the mantle slowly enough to constitute an approximate mantle reference frame, these TPW swaths are oscillatory and nearly coaxial. A long-lived and stable prolateness of Earth's non-hydrostatic geoid between Cambrian and Devonian time could produce such a pattern of TPW. Similarly oscillatory APW paths exist for the late Neoproterozoic cratons, perhaps indicating TPW about the same long-lived axis during that earlier interval as well. This long-lived prolate axis of Earth's non-hydrostatic geoid, representing a stable configuration of mantle mass anomalies, may have been inherited from the vanished Rodinia supercontinent in the same way that the present non-hydrostatic geoid's prolate axis may be a legacy of Mesozoic Pangea and its peripheral subduction zones. These geoidal legacies may endure for several hundred Myr after supercontinental fragmentation, perhaps indicating a characteristic lag time between two distinct geological phenomena: global-scale surface tectonics recorded by the growth and disassembly of supercontinents; and deep mantle convective structure indicated by the long-term record of TPW. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

For a dynamic planet, true polar wander (TPW) is the migration of the geographic reference system relative to the dynamically conserved angular momentum vector or spin axis; such motion arises from secular trends of changing mass distributions within the planet's interior [1,2]. In this discussion, I refer to TPW only on time-scales longer than relaxation of the hydrostatic equatorial bulge, secular variation in Earth's geomagnetic field, and Milankovitch orbital variations (all < 10^6 yr). Whereas the existence of such long-period Mesozoic-Cenozoic ('Neozoic') TPW on Earth has been verified by several studies involving the use of hotspots as a mantle reference frame (earlier studies reviewed in [3]; updated in [4]), any effort to identify pre-Mesozoic TPW suffers from the absence of an extant mantle representative, such as well-defined hotspot tracks, for periods older than ~150 Ma.

Pre-Mesozoic TPW may be estimated in coarse
Fig. 1. Orthographic projections of portions of the Early Paleozoic South apparent polar wander (APW) path for Gondwanaland, in present African coordinates (reconstruction parameters from [39]). In each panel, $I_{\text{min}}$ is determined as the minimum eigenvector of the Bingham distribution [40] of all shown APW vertices. (a) The Cambrian TPW hypothesis of [7], using both the polar wander path and the longitudinally constrained reconstruction of Laurentia, Baltica, and Gondwanaland. Baltica’s position is queried because of its lack of data for that time [7]. ($I_{\text{min}}$ at 33°S, 076°E.) (b) The Late Ordovician–Late Devonian TPW hypothesis and resulting Laurussia–Gondwanaland reconstruction from Ref. [6], followed by the Carboniferous path of Ref. [39]. The Cambrian APW swath (light gray shading) is retained from (a) for comparison. ($I_{\text{min}}$ at 25°S, 094°E.) VC = Vendian–Cambrian; C2–3 = Middle–Late Cambrian; O3 = Late Ordovician; SD = Silurian–Devonian; D3 = Late Devonian; C1 = Early Carboniferous.

fashion by comparison of paleomagnetically determined apparent polar wander (APW) paths of continents or cratons during a given interval of time, despite the lack of any extant oceanic lithosphere from these times (entirely oceanic plates cover nearly half of the present Earth surface). Each APW path depicts the motion of the paleomagnetic dipole – and hence the planet’s rotational axis by the axial geocentric dipole hypothesis – relative to a continent or plate. An APW path for a given continent represents the summed motion of two components: the rotation of that continent’s plate over the mantle; and the TPW component of whole-mantle migration relative to the spin axis. Thus TPW and APW are not mutually exclusive; rather, TPW (if accepted as a geophysical phenomenon at these time-scales) should constitute a non-zero component of every APW path segment, common to all continents [5].

Only when TPW occurs at rates much faster than individual plate motions will it compose a significant enough amount of the continents’ APW paths to be recognized by this method alone. Two such intervals have been postulated for pre-Mesozoic time: Ordovician–Devonian [6] and Early–Middle Cambrian [7]. The proposed TPW events (Fig. 1) can account for large, rapid rotations of the enormous Gondwanaland continent, previously puzzling to plate kinematicists [8,9]. Herein I propose a simple geodynamic mechanism for these sweeping rotations, in the context of TPW and supercontinental assembly and fragmentation.

2. TPW on a prolate spheroid

The shape of the Earth is, to good approximation, an oblate spheroid with flattening $\sim 1/300$. The oblateness is due to the equatorial bulge, a hydrodynamic effect which does not contribute to long-period ($> 10^6$ yr) TPW [2,10]. The remaining variations of the planet’s surface gravity equipotential, the non-hydrostatic geoid, is an expression of the internal mass anomalies which control long-period TPW [3,11,12]. Two spheroidal figures of the non-hydro-
static geoid will lead to polar instability, both with the maximum \(I_{\text{max}}\) and intermediate \(I_{\text{int}}\) inertial moments approximately equal: a quasi-sphere and a prolate spheroid. For these figures, small adjustments in internal mass anomalies can generate large TPW much more readily than for an oblate non-hydrostatic geoid. The quasi-spherical case would result in chaotic TPW trajectories, whereas the prolate figure could be recognized by TPW confined generally to a single great circle orthogonal to the non-hydrostatic geoid’s prolate axis \(I_{\text{min}};\) Fig. 2.

If this axis were long-lived enough to host several oscillations of TPW, and if differential motions between plates were relatively small or slow compared to TPW, then we should observe the oscillations in all of the continental APW paths with simultaneous ‘turnaround’ times and equivalent rates of intervening APW. Such features, in theory, could be used to test hypotheses of pre-Mesozoic TPW [13], but several limitations of the existing pre-Mesozoic paleomagnetic database preclude explicit use of those criteria [14]. First, with rare exceptions, each continent’s pre-Mesozoic APW path is constrained only by a few reliable poles, typically separated in age by 10 Myr or more [8,15]. Second, some dynamical models of TPW allow rotations of \(\sim90^\circ\) in as fast as 5–10 Myr [12,16], necessitating a much more complete paleomagnetic database to assess the full range of geodynamically possible APW paths. Third, polarity ambiguity [17] and poor age constraints for individual paleomagnetic results, as well as the apparent lack of a plausible geodynamic mechanism to generate rapid rates (\(\geq 30\) cm/yr) of continental motion, both have traditionally spurred paleomagnetists to minimize path length in their APW constructions [18]. For these reasons, the presently favored Neoproterozoic–Paleozoic APW paths may dramatically under-represent the magnitude of actual APW motions during that interval, and the general distribution of poles is a more reliable test of TPW hypotheses than the comparison of presently favored ‘turnaround’ times of APW swaths from different continents (Fig. 3).

3. Neoproterozoic–Paleozoic TPW

Although the Paleozoic APW path for Gondwana-land has been disputed [18], the most reliable poles fall nearly within the same great circle, at times implying extremely fast velocity of as much as 30 cm/yr [9]. Models of TPW [12,16] are more easily reconciled with such fast motion of large continents than hypotheses of conventional plate motion requiring special conditions of continental roots, mantle viscosity structure, and plate-driving forces [19]. Fig. 1 shows an early Paleozoic polar wander path constructed almost entirely by the two postulated episodes of TPW [6,7]; if Gondwanaland was drifting slowly over the asthenosphere throughout that interval, then the large continent would provide an effective mantle reference frame for at least qualitative estimation of TPW. The large and rapid early Paleozoic oscillations would then suggest TPW about a long-lived prolate geoid axis intersecting the surface near the continent’s Australian–Antarctic side. Subsidiary southeastward (present African coordinates) migration of the pole may reflect slow drift of Gondwanaland or an additional, transverse TPW component.

The latitudinally and longitudinally constrained paleogeographic reconstructions generated by the two postulated TPW events show Laurentia rifting away from the Amazonian margin of Gondwanaland and then joining with Baltica, all between Late Cambrian and Late Ordovician time (Fig. 1). As it
did so, it rotated \( \sim 30^\circ \) CCW while remaining near the Equator. This explains why Laurentia’s early Neoproterozoic APW path [15], unlike that of Gondwanaland, does not fall within a single great circle (Fig. 4). Nonetheless, a progression of poorly dated, but probably Riphean and Vendian paleomagnetic poles from Laurentia, at times indicating very rapid continental motion, is, in fact, co-circular with the Vendian–Cambrian poles [20]; when treated as bidirectional data because of geomagnetic polarity ambiguity, they are evenly distributed around the great circle (Fig. 4). This is consistent with inadequate sampling of a high-frequency TPW oscillation about a prolate non-hydrostatic figure as described above.

The late Neoproterozoic paleopoles from Laurentia, although sparse, suggest the possibility that the prolate axis may have existed as early as \( \sim 700 \) Ma. A similar situation exists for Baltica, whose Riphean–Ordovician APW path swings back and forth along the same great circle [15]. Additionally, recent results from the terminal Proterozoic Bunyeroo Formation in southern Australia [21] support a Vendian APW oscillation which is co-circular with the Cambrian arc attributed to TPW [7]. A test of this sort using the other unassembled Gondwanaland cratons is not presently possible because the Riphean–Vendian APW paths from individual blocks are too poorly constrained to show any coherent patterns [22].

Overall, the limited database permits the hypothesis of predominant TPW during Neoproterozoic–Paleozoic time. If large TPW did not occur during that interval, then one must explain with conventional plate mechanisms the high-amplitude, oscillatory nature of APW paths, with implied continental velocities far exceeding today’s typical values [7]; also, as these continents sped around the globe, their relative positions changed only slightly, as appears to be the case for Laurentia and Gondwanaland (Fig. 1). The TPW hypothesis is attractive because it explains these conundra of the previous models with a simple and well-understood dynamic mechanism. In addition, it successfully reproduces Laurentia’s separation from Gondwanaland and convergence with Baltica between Cambrian and Silurian time (Fig. 1), as determined independently by geological arguments [23].

4. A supercontinental legacy

Neozoic TPW has occurred in oscillatory fashion broadly along the great circle marked by 130° and 310°E longitude [4,24,25], which lies entirely within
model (recent models are uncertain even for 85–130 Ma and completely unconstrained for earlier times [30]). Regardless, the first-order conclusion is that the present non-hydrostatic long-wavelength geoid, as well as Neozoic TPW, if verified by further study with an updated hotspot model, both seem to be geophysical legacies of the Pangean world [26,27].

I propose that the long-lived, early Paleozoic and possibly late Neoproterozoic TPW axis was inherited as a relict prolate figure from the previous supercontinent, early Neoproterozoic Rodinia [31]. Near the center of the Rodinia reconstruction is the “SWEAT” juxtaposition of ~750-Ma rifted margins preserved in Australia–East Antarctica and western North America [32]. If Rodinia had developed an enduring prolate geoid anomaly in the same sense as Pangea, then it is plausible that such an anomaly could persist into the Paleozoic Era, even 300 Myr after the supercontinent began to break apart (Fig. 5b). The prolate TPW axis would approximate the center of the vanished supercontinent. Its early Paleozoic location at the Australian–Antarctic side of the SWEAT reconstruction would suggest that East Gondwanaland did not drift appreciably over the mantle between 750 and 550 Ma, as permitted by limited paleomagnetic data [33].

A rapid apparent polar shift for Gondwanaland between Carboniferous and Permian time abruptly ends the early Paleozoic oscillatory pattern (Fig. 1b). Extending the observation by Anderson [26] that the Late Carboniferous to Late Triassic APW path for Pangea indicates migration of that supercontinent’s centroid toward the Equator, Van der Voo [6] suggested that this motion could be a TPW response to the development of a new dynamic mantle upwelling under Pangea. If true, then this places a maximum time constraint of 400 Myr on the duration of the Rodinian supercontinental geoid legacy, between the middle Carboniferous and earliest estimates (~720 Ma) of Rodinia’s breakup [23,33].

Contrary to Anderson’s [26] ‘continental insulation’ mechanism, however, mantle upwelling may be induced under a supercontinent simply because it is large enough to protect the interior region of its underlying mantle from penetration by subducting slabs. The subduction girdle around a mature supercontinent [27] thus encircles two antipodal upwellings, one beneath the supercontinent and the

the sectoral girdle defined by low values of the long-wavelength non-hydrostatic geoid (Fig. 5a). The prolate contribution of the long-wavelength (harmonic degree-2) non-hydrostatic geoid appears to have remained stable for most or all of that interval of time [11,26–28]. Enigmatically, the TPW and geoid axes are offset by about 40° longitude, similar to the offset between the present geoid and Pangea’s centroid noted and discussed by Le Pichon and Huchon [29]. As both their ‘absolute’ Pangea reconstruction and the Neozoic TPW path [4] are based on Morgan’s early hotspot compilation [24], perhaps these discrepancies could be reduced by an updated hotspot
other below the center of the exterior ocean (the present mid-Pacific geoid anomaly is in fact of higher amplitude than the antipodal Pangean geoid high). The upwellings are probably lower mantle mass excesses, as indicated by the negative sign of the geoid ‘kernel’ for those depths [34], and will be drawn toward the Equator via TPW. By this model, old supercontinents are predicted to lie on the Equator, which seems true for both Jurassic Pangea and 700-Ma Rodinia [33]. After a supercontinent fragments, the girdling subduction zones may recede laterally, but the general pattern of mantle convection, with a prolate axis of upwelling, remains stable [11,35]. In this way, the geoid, and hence TPW, becomes a supercontinental legacy, which can persist even after the next supercontinent has begun to form.

The duration of slab preclusion required to generate an upwelling under a mature supercontinent may be as short as ~100 My, the approximate length of Pangea’s existence between the Carboniferous–Permian Variscan orogeny and the Early Jurassic onset of spreading in the central Atlantic Ocean. Alternatively, the requisite timescale may be much longer; if Gondwanaland’s Paleozoic APW path largely reflects TPW, then that large landmass shielded the same region of the underlying mantle from subduction for ~400 Myr, between terminal Pan-African/Brasiliano orogenesis [31,36,37] and Cretaceous disaggregation. In either case, the timescale for development of a supercontinent-induced prolate axis is commensurate with the endurance of its post-breakup legacy. Hence the characteristic time for a fundamental turnover in mantle convection, from a downwelling over which a supercontinent amalgamates to a subsequent upwelling above which the supercontinent disaggregates, is suggested by the TPW record to be on the order of ~300 Myr, broadly consistent with previous kinematic [27] and dynamic [38] estimates for that phenomenon.

If old supercontinents generate a mantle structure that is inherently prone to polar instability, then why has there been relatively little TPW during and following the breakup of Pangea (200–0 Ma)? One explanation is provided by modelling the history of NeoZOic subducted slabs [11], which suggests that first-order mantle convective structure has
changed little since Pangea disaggregated. In addition, Earth's rotation is presently stabilized by the strong oblate component of the moment of inertia, where \((I_{\text{max}} - I_{\text{int}}) \approx (I_{\text{int}} - I_{\text{min}}}) \) [2]. Mature supercontinents and their peripheral subduction zones merely develop a prolate axis (decreasing the eigenvalue magnitude of \(I_{\text{min}}\)) with little constraint on the other two axes, whose relative magnitudes may be controlled by the distribution of individual slabs within the subduction girdle. Perhaps the late Neoproterozoic to early Paleozoic post-Rodinia subduction system was more evenly distributed than its Neozoic post-Pangean counterpart, inducing substantial TPW during the former, but not the latter time.

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References