ELSEVIER

Earth and Planetary Science Letters 157 (1998) 1–8

EPSL

True polar wander, a supercontinental legacy

David A. Evans *

Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA

Received 11 November 1997; revised version received 5 February 1998; accepted 11 February 1998

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' non-hydrostatic figure, 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.

Keywords: geodynamics; polar wandering; Gondwana; paleomagnetism; geoid; mantle; convection

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

* Tel.: +1 (626) 395-6187; Fax: +1 (626) 568-0935; E-mail: devans@gps.caltech.edu

0012-821X/98/$19.00 © 1998 Elsevier Science B.V. All rights reserved.
PII S0012-821X(98)00031-4

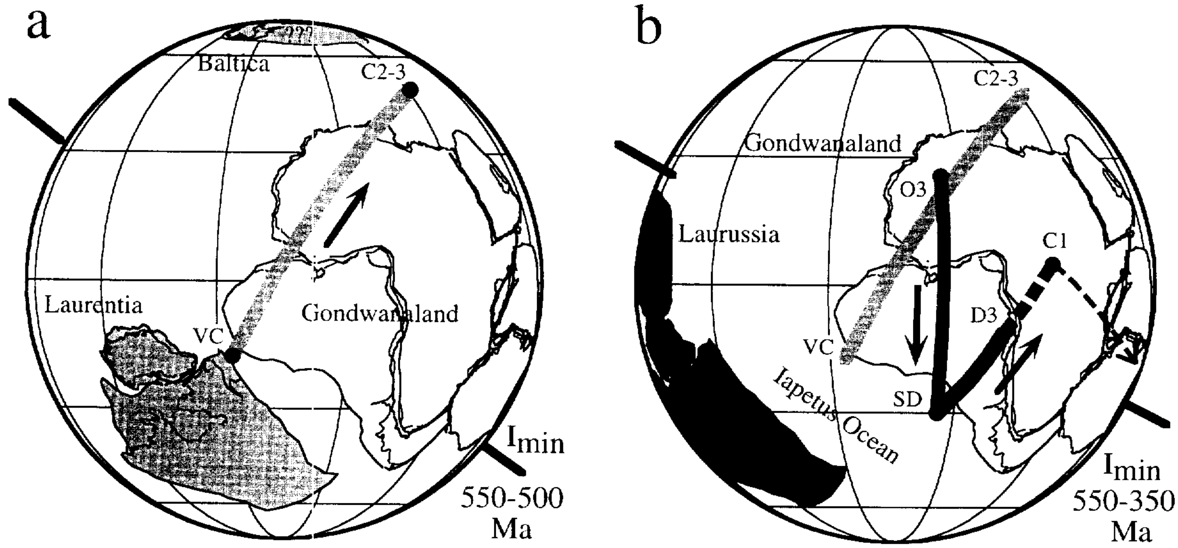

Fig. 1. Orthographic projections of portions of the Early Paleozoic South apparent polar wander (APW) path for Gondwanaland, in present African coordinates (reconstruction parameters from [39]). In each panel, I_{min} is determined as the minimum eigenvector of the Bingham distribution [40] of all shown 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_{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_{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 ~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-

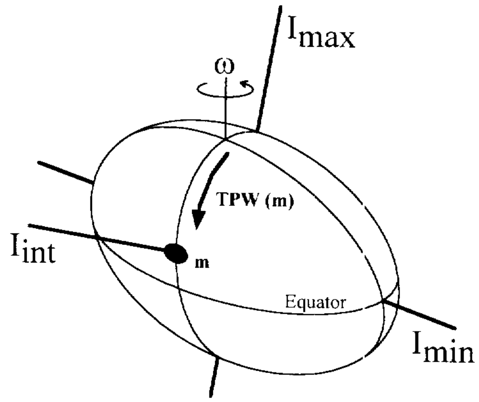

Fig. 2. Expected pattern of TPW arising from addition of small mass excess 'm' to an otherwise ideal prolate spheroid. Maximum, intermediate, and minimum moments of inertia are respectively labelled I_{max}, I_{int}, and I_{min}. $TPW(m)$ is the process by which the entire solid planet, including its geographic inertial axes, migrates relative to the angular momentum vector (Ω) as a result of the centrifugal torque on 'm'.

static geoid will lead to polar instability, both with the maximum (I_{max}) and intermediate (I_{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_{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 ~90° 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 Gondwanaland 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

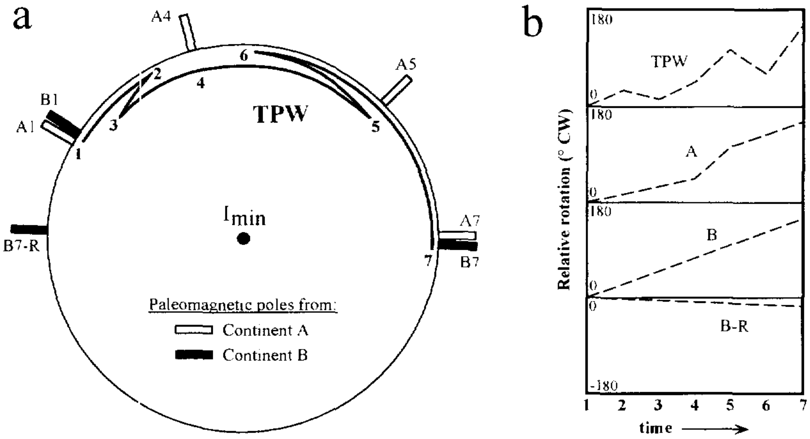

Fig. 3. Perils of parsimonious interpolation among sparse paleomagnetic data when testing hypotheses of rapid TPW. (a) cross-section of the planet in the plane of the short axes I_{max} and I_{int}, with hypothetical TPW swings as shown between times *1* and *7*. Two continents with comparatively little motion between them, *A* and *B*, have sparse paleomagnetic constraints (tick marks) throughout this interval, with ages of paleopoles exactly known (labels on the tick marks). Pole *B7-R* is the opposite-polarity interpretation of the *B7* result. (b) Interpolated APW motion during this interval according to the hypothetical TPW path and the constraints from continents A and B. The path for continent A overlooks the 'turnarounds' at times *2* and *5*, and most paleomagnetists would erroneously choose path *B–R* (using the reverse polarity of pole B7) to minimize the length of APW for continent B.

did so, it rotated ~30° CCW while remaining near the Equator. This explains why Laurentia's early Paleozoic 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 ~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 conundrums 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

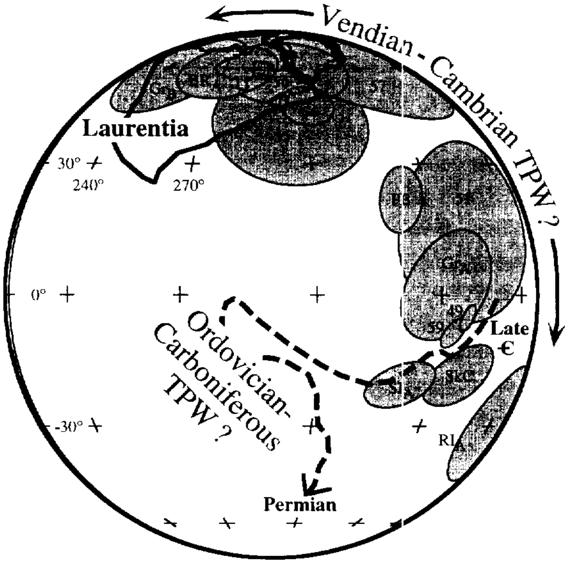

Fig. 4. An example of Neoproterozoic–Paleozoic paleomagnetic poles distributed along a great circle, from Laurentia in late Neoproterozoic to Cambrian time (~720–500 Ma). Gray ellipses delimit 95% confidence intervals; poles are numbered according to Torsvik et al. [15] or lettered according to Park [20], except those from the Grenville dikes (Gr_A, Gr_B; [41]), Sept Iles 'A' (*SIA*; [42]), and Skinner Cove Volcanics (*SkC*; [43]). Many of the ages of magnetization are not well known [15], thus the common model of a single pole-to-Equator migration for the Laurentian continent during Vendian–Cambrian time [15,20] is not a unique interpretation of the data. Polarity ambiguity for most of the Vendian–Cambrian poles permits their possible locations on the other hemisphere. A smoothed Late Cambrian–Permian South polar wander path [15], including the Late Ordovician to Late Devonian oscillation attributed to TPW [6], is shown for comparison (dashed curve). A complete discussion of the Vendian–Cambrian poles is forthcoming (D.A. Evans, in preparation). Orthographic projection.

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 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

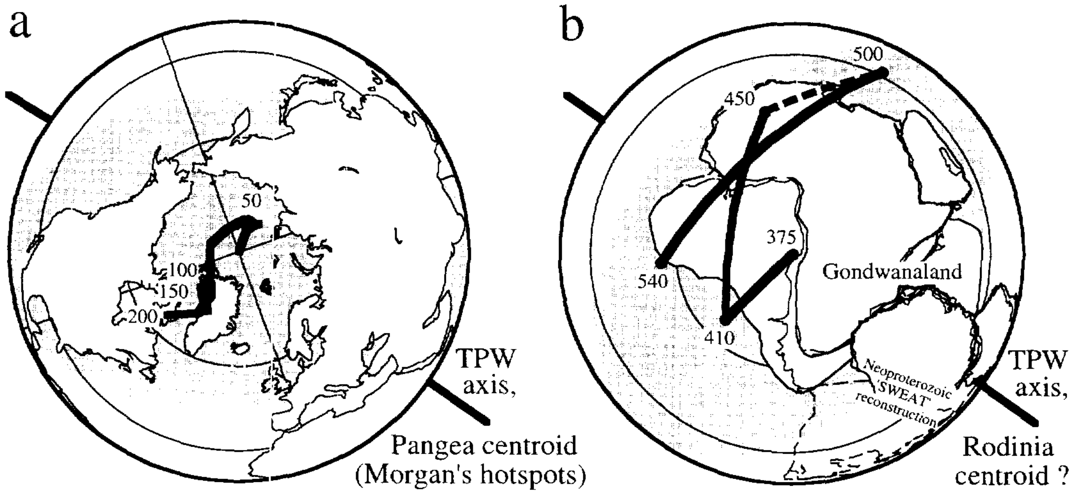

Fig. 5. Orthographic polar projections of the present (a) and Late Devonian (b) world. (a) Mesozoic–Cenozoic TPW [4] in the Morgan's hotspot reference frame [24], and its relation to the present negative non-hydrostatic geoid anomalies (harmonic degree-2 only: [44]). Ages in Ma. The TPW axis at 02°N, 039°E is orthogonal to the Bingham distribution of equally weighted paleopoles and nearly coaxial with Pangea's centroid (from Ref. [29] also using Morgan's hotspot reference frame [24]). (b) Speculative rendering of Late Devonian paleogeography and its accompanying degree-2 geoid. Gondwanaland is reconstructed to its Late Devonian position according to Ref. [6], and the APW swaths and postulated TPW axis are the same as shown in Fig. 1. To show coaxiality between the early Paleozoic TPW axis and the antecedent Rodinia supercontinent, Laurentia (dashed outline) is reconstructed to East Gondwanaland along the 'SWEAT' juxtaposition [32] according to recent reconstruction parameters [23]. For the Rodinia–Paleozoic TPW connection to be valid, East Gondwanaland must not have drifted appreciably over the mantle between 700 and 550 Ma.

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 Myr, 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 time-scale 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 time-scale 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 $(I_{max} - I_{int}) \approx (I_{int} - I_{min})$ [2]. Mature supercontinents and their peripheral subduction zones merely develop a prolate axis (decreasing the eigenvalue magnitude of I_{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-Rodinian subduction system was more evenly distributed than its Neozoic post-Pangean counterpart, inducing substantial TPW during the former, but not the latter time.

Acknowledgements

I thank D.L. Anderson, M. Billen, R.G. Gordon, M. Gurnis, P.F. Hoffman, J.L. Kirschvink, R.J. O'Connell, M.A. Richards, D.L. Stevenson, and R. Van der Voo for stimulating discussions. Some of the figures were created using the GMAP application administered by T.H. Torsvik. D.M. Jurdy and two anonymous reviewers of the manuscript prompted important clarifications. This work is supported by NSF Grant EAR94-18523 and an NSF Graduate Research Fellowship. ***[RV]***

References

[1] T. Gold, Instability of Earth's axis of rotation, Nature 175 (1955) 526–529.

[2] P. Goldreich, A. Toomre, Some remarks on polar wandering, J. Geophys. Res. 74 (1969) 2555–2567.

[3] R.G. Gordon, Polar wandering and paleomagnetism, Annu. Rev. Earth Planet. Sci. 15 (1987) 567–593.

[4] J. Besse, V. Courtillot, Revised and synthetic apparent polar wander paths of the African, Eurasian, North American and Indian plates, and true polar wander since 200 Ma, J. Geophys. Res. 96 (B3) (1991) 4029–4050.

[5] D.M. Jurdy, R. Van der Voo, A method for the separation of true polar wander and continental drift, including results for the last 55 m.y., J. Geophys. Res. 79 (1974) 2945–2952.

[6] R. Van der Voo, True polar wander during the middle Paleozoic?, Earth Planet. Sci. Lett. 122 (1994) 239–243.

[7] J.L. Kirschvink, R.L. Ripperdan, D.A. Evans, Evidence for a large-scale reorganization of Early Cambrian continental masses by inertial interchange true polar wander, Science 277 (1997) 541–545.

[8] R. Van der Voo, Paleomagnetism of the Atlantic, Tethys and Iapetus Oceans, Cambridge University Press, Cambridge, 1993, 411 pp.

[9] J.G. Meert, R. Van der Voo, C.M. Powell, Z.-X. Li, M.W. McElhinny, Z. Chen, D.T.A. Symons, A plate-tectonic speed limit?, Nature 363 (1993) 216–217.

[10] C.G. Chase, The geological significance of the geoid, Annu. Rev. Earth Planet. Sci. 13 (1985) 97–117.

[11] M.A. Richards, Y. Ricard, C. Lithgow-Bertelloni, G. Spada, R. Sabadini, An explanation for Earth's long-term rotational stability, Science 275 (1997) 372–375.

[12] B. Steinberger, R.J. O'Connell, Changes of the Earth's rotation axis owing to advection of mantle density heterogeneities, Nature 387 (1997) 169–173.

[13] T.H. Torsvik, J.G. Meert, M.A. Smethurst, Polar wander and the Cambrian (comment), Science 279 (1998) 9.

[14] D.A. Evans, R.L. Ripperdan, J.L. Kirschvink, Polar wander and the Cambrian (reply), Science 279 (1998) 9.

[15] T.H. Torsvik, M.A. Smethurst, J.G. Meert, R. Van der Voo, W.S. McKerrow, M.D. Brasier, B.A. Sturt, H.J. Walderhaug, Continental break-up and collision in the Neoproterozoic and Palaeozoic – A tale of Baltica and Laurentia, Earth-Sci. Rev. 40 (1996) 229–258.

[16] G. Spada, Y. Ricard, R. Sabadini, Excitation of true polar wander by subduction, Nature 360 (1992) 452–454.

[17] P.W. Schmidt, D.A. Clark, Late Proterozoic and late Palaeozoic reconstructions: Rodinia to Pangaea, in: 8th Scientifically of IAGA, Uppsala, 1997, 54 pp.

[18] P.W. Schmidt, D.A. Clark, S. Rajagopalan, An historical perspective of the early Palaeozoic APWP of Gondwana: new results from the Early Ordovician Black Hill Norite, South Australia, Explor. Geophys. 24 (1993) 257–262.

[19] M. Gurnis, T.H. Torsvik, Rapid drift of large continents during the late Precambrian and Paleozoic: Paleomagnetic constraints and dynamic models, Geology 22 (1994) 1023–1026.

[20] J.K. Park, Palaeomagnetic constraints on the position of Laurentia from middle Neoproterozoic to Early Cambrian times, Precambrian Res. 69 (1994) 95–112.

[21] P.W. Schmidt, G.E. Williams, Palaeomagnetism of the ejecta-bearing Bunyeroo Formation, late Neoproterozoic, Adelaide fold belt, and the age of the Acraman impact, Earth Planet. Sci. Lett. 144 (1996) 347–357.

[22] J.G. Meert, R. Van der Voo, S. Ayub, Paleomagnetic investigation of the Neoproterozoic Gagwe lavas and Mbozi complex, Tanzania and the assembly of Gondwana, Precambrian Res. 74 (1995) 225–244.

[23] I.W.D. Dalziel, Neoproterozoic–Paleozoic geography and tectonics: Review, hypothesis, environmental speculation, Geol. Soc. Am. Bull. 109 (1) (1997) 16–42.

[24] W.J. Morgan, Hotspot tracks and the opening of the Atlantic and Indian Oceans, in: C. Emiliani (Ed.), The Sea, Vol. 7, Wiley, New York, 1981, pp. 443–487.

[25] R.A. Livermore, F.J. Vine, A.G. Smith, Plate motions and the geomagnetic field – II. Jurassic to Tertiary, Geophys. J. R. Astron. Soc. 79 (1984) 939–961.

[26] D.L. Anderson, Hotspots, polar wander, Mesozoic convection and the geoid, Nature 297 (1982) 391–393.
[27] C.G. Chase, D.R. Sprowl, The modern geoid and ancient plate boundaries, Earth Planet. Sci. Lett. 62 (1983) 314–320.
[28] M.A. Richards, D.C. Engebretson, Large-scale mantle convection and the history of subduction, Nature 355 (1992) 437–440.
[29] X. Le Pichon, P. Huchon, Geoid, Pangea and convection, Earth Planet. Sci. Lett. 67 (1984) 123–135.
[30] R.D. Myller, J.-Y. Royer, L.A. Lawver, Revised plate motions relative to the hotspots from combined Atlantic and Indian Ocean hotspot tracks, Geology 21 (1993) 275–278.
[31] P.F. Hoffman, Did the breakout of Laurentia turn Gondwanaland inside out?, Science 252 (1991) 1409–1412.
[32] E. Moores, Southwest U.S.–East Antarctic (SWEAT) connection: a hypothesis, Geology 19 (5) (1991) 425–428.
[33] C.M. Powell, Z.X. Li, M.W. McElhinny, J.G. Meert, J.K. Park, Paleomagnetic constraints on timing of the Neoproterozoic breakup of Rodinia and the Cambrian formation of Gondwana, Geology 21 (1993) 889–892.
[34] B.H. Hager, R.W. Clayton, M.A. Richards, R.P. Comer, A.M. Dziewonski, Lower mantle heterogeneity, dynamic topography and the geoid, Nature 313 (1985) 541–545.
[35] G.F. Davies, Lagging mantle convection, the geoid and mantle structure, Earth Planet. Sci. Lett. 69 (1984) 187–194.
[36] R. Trompette, Geology of Western Gondwana, Balkema, Rotterdam, 1994, 350 pp.
[37] R. Unrug, The assembly of Gondwanaland, Episodes 19 (1996) 11–20.
[38] M. Gurnis, Large-scale mantle convection and the aggregation and dispersal of supercontinents, Nature 332 (1988) 695–699.
[39] C.M. Powell, Z.X. Li, Reconstruction of the Panthalassan margin of Gondwanaland, in: J.J. Veevers, C.M. Powell (Eds.), Permian–Triassic Pangean Basins and Foldbelts along the Panthalassan Margin of Gondwanaland, Geol. Soc. Am. Mem. 184 (1994) 5–9.
[40] T.C. Onstott, Application of the Bingham distribution function in paleomagnetic studies, J. Geophys. Res. 85 (1980) 1500–1510.
[41] G.S. Murthy, The paleomagnetism of diabase dikes from the Grenville Province, Can. J. Earth Sci. 8 (1971) 802–812.
[42] E.I. Tanczyk, P. Lapointe, W.A. Morris, P.W. Schmidt, A paleomagnetic study of the layered mafic intrusion at Sept-Iles, Quebec, Can. J. Earth Sci. 24 (1987) 1431–1438.
[43] P.J.A. McCausland, J.P. Hodych, G.R. Dunning, Evidence from western Newfoundland for the final breakup of Rodinia? U–Pb age and palaeolatitude of the Skinner Cove Volcanics, Proc. Geol. Assoc. Canada/Min. Assoc. Canada Ann. Meeting, Ottawa (1997) A-99.
[44] R.S. Nerem, F.J. Lerch, J.A. Marshall, E.C. Pavlis, B.H. Putney, B.D. Tapley, R.J. Eanes, J.C. Ries, B.E. Schutz, C.K. Shum, M.M. Watkins, S.M. Klosko, J.C. Chan, S.B. Luthcke, G.B. Patel, N.K. Pavlis, R.G. Williamson, R.H. Rapp, R. Biancale, F. Nouel, Gravity model development for TOPEX/POSEIDON: Joint Gravity Models 1 and 2, J. Geophys. Res. 99 (1994) 24421–24447.