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A paleomagnetic analysis of Cambrian true polar wander

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Abstract

The latest Neoproterozoic through Cambrian is one of the most remarkable intervals in geologic time. Tectonically, the period from 580 to 490 Ma marks a time of rapid plate reorganization following the final stages of supercontinental breakup and Gondwana assembly. The apparent speed at which this reorganization occurred led some to propose a link between tectonic events, biologic changes and climatic changes. One of the more intriguing proposals is that the tectonic changes were triggered by an episode of inertial interchange true polar wander (IITPW) which resulted in a rapid (6°/m.y.) shift of the spin axis relative to the geographic reference frame. IITPW is a special case of true polar wander (TPW) that makes specific demands on the length of apparent polar wander paths (APWPs) recording the motion. Specifically, each path must allow for ~90° of synchronous motion during the interval from 523 to 508 Ma. A review of paleomagnetic data for Laurentia, Baltica, Siberia and Gondwana indicates that none of the APWPs approaches the necessary length, each path is of a different length and the apparent motions are non-synchronous. Collectively, these observations negate the premise of a Cambrian IITPW event. Since the IITPW hypothesis was proposed as an alternative to rapid plate motion of Laurentia and Gondwana during the Neoproterozoic–Cambrian interval, any alternative model must account for this rapid motion. I suggest that a reasonable explanation for 'anomalously' high rates of plate motion for some continents, possibly on the order of 20–40 cm yr^{-1}, is enhanced plate motion driven by lower-mantle thermal anomalies and possibly true polar wander. In fact, the enhanced plate motions driven by these lower-mantle sources may provide a dynamic feedback triggering true polar wander.

Keywords: polar wandering; upper Proterozoic; Cambrian; paleomagnetism

1. Introduction

The Vendian–Cambrian boundary represents one of the most puzzling and intriguing transitions in earth history. It marks the first time that all major phyla are well represented in the fossil record [1–3], major transitions in seawater chemistry [4,5], plate reorganization, the breakup of the vestiges of the Rodinia supercontinent [6,7] and a possible change from a severe icehouse climate to a greenhouse climate [5]. All of these changes may have taken place over a relatively short interval of geologic time, giving rise to speculation about cause and effect among the observed changes. For example, did the breakup of the remnants of the Rodinia supercontinent lead to an icehouse climate (snowball earth) followed by a rise in $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ isotopic values [4,5]? Did this climatic change in turn trigger the rise of the metazoans? Was the rise of the metazoans stim-

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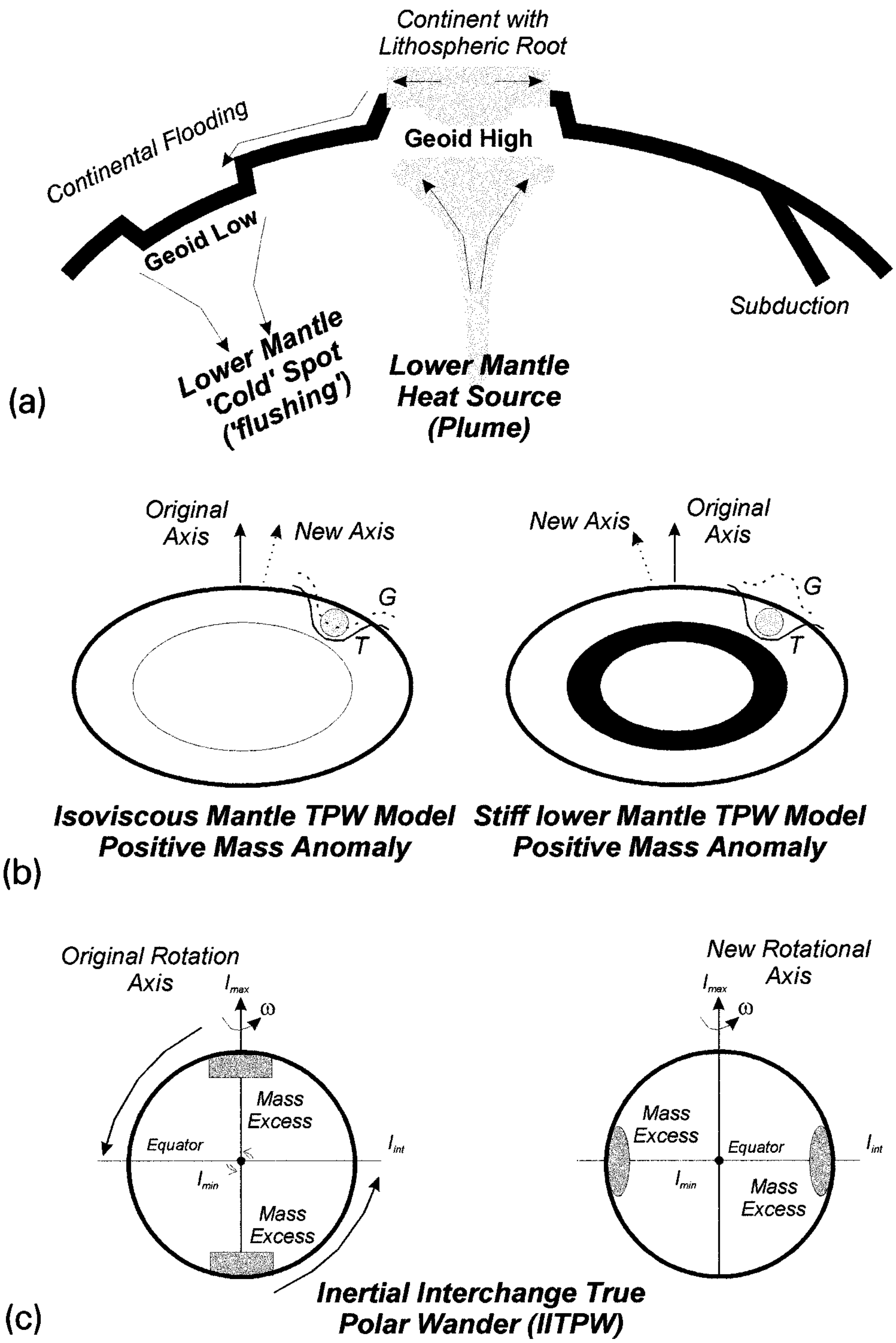
ulated by the changes in the oceanic environment due to a rapid redistribution of landmasses [5,8]? Indeed, this period in earth history may represent more than a simple time marker; it may represent a fundamental shift in the modus operandi of the earth's climatological and geodynamic systems.

Several authors [6,9,10] noted the rapid migration of continents at the close of the Precambrian. These authors remarked that the calculated minimum velocities suggested that large continents were able to move at much higher velocities than was typical of Phanerozoic time but provided no geodynamic explanation for this rapid motion. Gurnis and Torsvik [11] demonstrated that upper-mantle convection was not sufficient to drive large plates at velocities in excess of 25 cm yr^{-1} due to drag forces at the base of a thickened lithosphere. They did show, through the use of finite-element models, that such velocities could be attained provided a continent with a thick lithospheric root was pushed away from a region of elevated deep-mantle temperatures (plumes) or pulled toward a deep-mantle cold spot (Fig. 1a).

An alternative explanation [8] for this rapid continental motion is that it resulted from an episode of inertial interchange true polar wander (IITPW) during the period from Early Cambrian (late Tommotian ~523 Ma) to early-Middle Cambrian (Amgan ~508 Ma). True polar wander (TPW) is the migration of the net lithospheric and mantle reference frame relative to the spin axis (Fig. 1b). IITPW is a special case of TPW wherein the Earth's intermediate inertial axis and maximum inertial axis interchange (i.e. the maximum axis becomes the intermediate axis and vice versa, Fig. 1c). IITPW requires a 90º shift in the geographic reference frame relative to the spin axis in a relatively short amount of geologic time [8]. The exact time it takes for these axes to interchange depends on the material properties of the interior of the earth; however, time periods as short as 10–15 m.y. have been proposed [8,12,13]. The IITPW hypothesis was expanded upon by Evans [14] who proposed that TPW is a geodynamic legacy of the preceding supercontinent of Rodinia.

Paleomagnetic studies are typically used to determine the relative motion of continents with respect to the spin axis of the earth. Paleomagnetists represent this motion through the use of apparent polar wander paths (APWPs). These paths represent the motion of the continent through time in terms of latitudinal drift and rotation. Because of the assumed symmetry of the geomagnetic field, longitudinal motion is not quantifiable from paleomagnetic studies alone. However, should the motion of the entire lithosphere take place in unison and at rates exceeding typical plate velocities, then the amount of APW measured by paleomagnetic studies will reflect the amount of true polar wander (APW = TPW) and the relative longitudinal positions of landmasses can be determined [8]. Thus, in order to demonstrate an episode of rapid TPW several requirements must be met. One requirement is that APWPs from all continents show nearly the same lengths and shapes for a given time interval. This is theoretically possible to demonstrate with a complete paleomagnetic database. The second requirement is that all plates show more or less the same amount of APW for the interval of proposed TPW. Since we have no paleomagnetic record from the oceanic plates that must have existed in

Fig. 1. (a) Schematic cartoon illustrating possible enhancements to normal plate motions after Gurnis and Torsvik [11]. Motion of a continent with a thickened lithospheric root is inhibited by drag forces unless the plate driving force is deep-seated. A lower-mantle heat source may produce a long-wavelength geoid high and push the continent away from the heat source. Alternatively, a long-wavelength geoid low may be produced by a localized deep-mantle cold spot, perhaps forming as a result of mantle 'flushing' [42] which will also result in an enhancement in plate velocity. Laurentia may have been situated over a mantle plume [28] and the long-lived subduction of oceanic crust beneath parts of Gondwana may have produced a 'cold' region in the mantle. These mass anomalies may also induce an episode of true polar wander. (b) Schematic cartoon of 'normal' true polar wander after Spada et al. [12]. A positive mass anomaly represented by the shaded ball produces a depressed topography (*T*) for either an isoviscous mantle or a stiff lower mantle. The geoid (*G*) is depressed/elevated for the isoviscous/stiff lower-mantle models. The rotational axis (maximum inertial axis) will migrate toward the geoid low in the isoviscous case and away from the geoid high in the stiff lower-mantle case. (c) Schematic cartoon of inertial interchange true polar wander. If the magnitudes of the maximum inertial moment (I_{max}) and intermediate inertial moment (I_{int}) are nearly equal and a mass excess is located along the I_{max} axis, the magnitude of I_{int} will exceed I_{max} and cause the mantle and lithosphere to 'tumble' through 90º as the inertial moments 'interchange'. The result is to line the mass excess along the equatorial region in a relatively short (10–15 m.y.) time period.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Polar Wander (IITPW)
(c)

pre-Mesozoic times, any analysis of TPW prior to the Mesozoic will be incomplete.

2. Cambrian IITPW episode

Kirschvink et al. [8] examined selected paleomagnetic data available from Baltica, Laurentia, Gondwana and Siberia for the interval from latest Vendian through Ordovician time. They concluded that selected paleomagnetic data were compatible with the hypothesis of an episode of inertial interchange true polar wander beginning during the Early Cambrian (late Tommotian) until early-Middle Cambrian time (Amgan; 523–508 Ma using the revised Cambrian time scale discussed below). Both [8] and [15] noted that there were no paleomagnetic data from within the proposed interval of TPW and therefore the best analysis can only compare data that bracket the interval of proposed TPW. IITPW requires that each APWP should allow for approximately 90º of motion during the 523–508 Ma interval (approximately 66 cm yr^{-1} of APW). The total amount of APW observed in a given track might be reduced if the motion of the continent was purely antithetical to the direction of TPW. Below, I review additional paleomagnetic data from Baltica, Siberia, Laurentia and Gondwana in detail along with some previously unpublished data that have a direct bearing on the Cambrian IITPW hypothesis.

3. Cambrian time scale

The hypothesis of IITPW was forwarded in part to explain the rapid radiation that occurred during the Tommotian–Toyonian stages of the Early Cambrian [8]. A revised Cambrian time scale [16,17] places additional constraints on the IITPW hypothesis. Fig. 2 shows the revised Cambrian time scale along with the radiometric ages used to constrain the time scale [16–18]. Specifically, the new time scale shifts the end of the Lower Cambrian from ~518 Ma to ~510 Ma [16,18]. Furthermore, the Upper Cambrian–Ordovician boundary is moved from ~495 Ma to ~490 Ma. The total length of the Cambrian is approximately 54 m.y. most of which is Lower Cambrian [16].

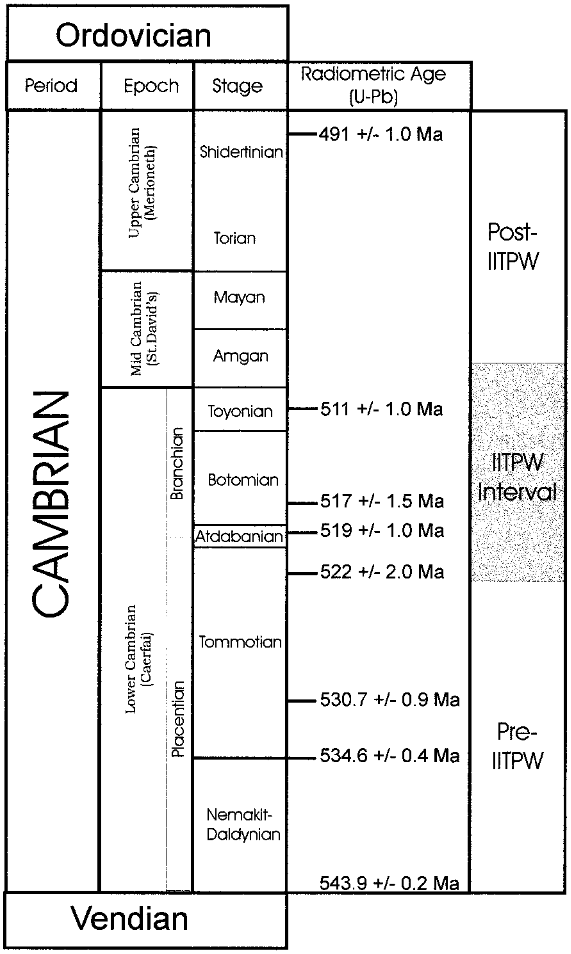

Fig. 2. A revised Cambrian time scale derived from the data of Landing et al. [16], Davidek et al. [17] and Tucker and McKerrow [18]. The interval of proposed IITPW is bracketed by the Pestrotsvet pole from Siberia [33] and the Tapeats sandstone pole from Laurentia [47].

The new time scale along with the paleomagnetic database now fixes the onset of IITPW [8] to sometime after the deposition of the Pestrotsvet Formation (Tommotian–Atdabanian ~523 Ma) and completion by the time of Tapeats sandstone deposition (Amgan ~508 Ma). The total duration of this IITPW event is approximately 15 m.y. The original IITPW hypothesis did not apply such rigid time constraints because the Lower Cambrian time scale was only loosely constrained by the available radiometric data [8,18].

The analysis described below is dependent on the choice of paleomagnetic poles used to bracket the interval of IITPW. Any alternative pole choice is discussed along with the paleomagnetic poles used by [8] so that comparisons are easily made.

4. Analysis of the paleomagnetic data

4.1. Baltica

Support for an episode of IITPW from the Baltica database was permissible because there are only two paleomagnetic results from that continent that bracket the proposed interval. Kirschvink et al. [8] used paleomagnetic results from the Fen Central Complex (FCC) at 583 ± 15 Ma [19] and the Lower Ordovician (Arenig–Llanvirn ~475–470 Ma) Swedish limestones [20] for the analysis.

Reconstructions using the IITPW model resulted in an overlap between Baltica and Gondwana using the south-pole option for the previously published Fen pole [8]. However, it is important to note that the overlap is present only if one assumes stationarity of the Baltica APWP between 583 and 523 Ma or a sense of APW during the interval that would maintain the overlap. The north-pole option was favored by [8] because it eliminated the overlap and also guaranteed a sufficiently long APWP (98º versus 62º; see Table 1, Fig. 3) to support the contention of an IITPW event in the Cambrian [8]. In a recent investigation of the FCC by [19], a south-pole option for the Fen pole was preferred for several reasons. The new age constraints and paleomagnetic pole for the Fen Complex at 583 ± 15 Ma along with a re-evaluation of Amazonia's position relative to Baltica [21], places Baltica adjacent to the Siberian craton. Secondly, acceptance of both the polarity interpretation of [8] and the Rodinia model of [7] requires a minimum drift rate for Baltica in excess of 25 cm yr^{-1} during the Vendian opening of the Iapetus Ocean (pre-600 Ma) or perhaps an additional episode of TPW during that interval [19]. It was also noted that the linking of paleomagnetic poles separated by a 100 m.y. time span is a rather tenuous position from which to argue for any TPW event midway between endpoints [19].

It is permissible to assert that the entire length of the observed Baltica APW was traversed solely during the interval from 523 to 508 Ma as suggested by [8]. This prospect leads to two options in evaluating the IITPW hypothesis. I will refer to the idea that all APW is due to TPW during the interval from 523 to 508 Ma as the liberal interpretation. The conservative interpretation assumes that APW was evenly spaced during the total interval of time between the two endpoints (average rate of APW). In order to quantify these interpretations and their associated uncertainties in a meaningful and consistent manner, the rates of APW were calculated for each set of poles according to the methods described in the Appendix A of this paper.

A recent paleomagnetic result from the Lower Ordovician (Tremadoc–Arenig ~478 Ma) St. Petersburg limestone by [22] is slightly older than the Swedish limestone results used in the analysis of [8]. Ideally, IITPW should be tested on rocks that exactly span the interval of proposed true polar wander. Therefore, the St. Petersburg limestone results [22] are preferred over the Swedish limestone results [20] in this analysis because they more closely bracket the interval in question. The great-circle angular separation between the FCC pole and the St. Petersburg limestone pole is 62 ± 9º and the poles are separated in time by 105 ± 20 m.y. The conservative rate of APW has a value of $6.6^{+2.7}_{-1.8}$ cm yr^{-1} and a liberal rate of 45.9 ± 6.7 cm yr^{-1}. I also note that use of the Swedish limestone [20] pole results in slightly higher rates of APW and a slightly longer track (Fig. 3a, Table 1). The analysis used by [8] is listed in Table 1 for comparison.

4.2. Laurentia

Both Kirschvink et al. [8] and Evans et al. [23] argue that the Laurentian paleomagnetic database is anchored by the Callander Complex pole [24] at ~575 Ma and that no motion is recorded between the Callander pole and the less well-constrained Sept Îles-B pole for which Kirschvink et al. [8] argued a 540 Ma age based on seven scattered Rb–Sr ages [25,26]. Meert et al. [27] argued for an older age based on the similarities between the Sept Îles-B pole and the 564 ± 9 Ma Catoctin-A pole. The spatial and temporal agreement between the Catoctin and Sept Îles poles suggested by [27] is confirmed by a recent U–Pb age of 565 ± 4 Ma on the Sept Îles Complex [28]. The IITPW hypothesis would then

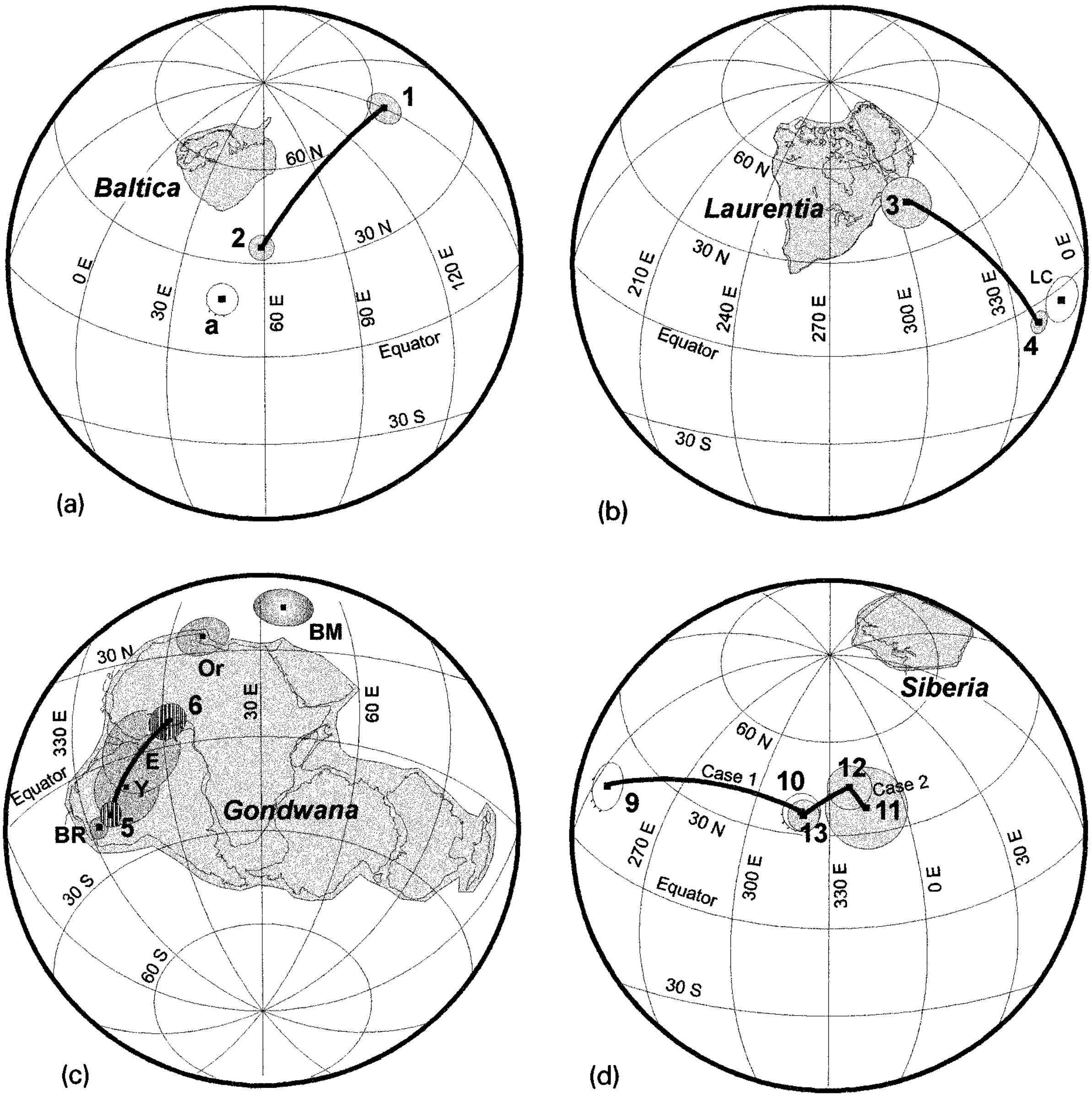

Fig. 3. All poles in this figure are considered south poles. (a) Apparent polar wander path (APWP) length for Baltica. Pole numbers are equivalent to those listed in Table 1. The total length of APW is 62 ± 9º. Pole *a* is the Swedish limestone pole of Torsvik and Trench [20]. Use of the Swedish limestone pole adds additional length to the APW (see text for details). (b) APWP length for Laurentia. Pole numbers are equivalent to those listed in Table 1. The total path length is 58 ± 11º. *LC* represents the locus of Late Cambrian poles from Laurentia as calculated by Meert et al. [27]. (c) APWP for Gondwana (see Table 1). Total path length between East Gondwana poles (*5* and *6*) is 31 ± 13º. Shaded pole *BM* is the 500–490 Ma Black Mountain pole of Ripperdan and Kirschvink [37], *OR* represents the locus of early-middle Ordovician poles for Gondwana [32], *BR* represents the Bhander-Rewa mean pole of McElhinny et al. [49] and *Y* and *E* represent the ~600 Ma Yaltipena and Elatina poles of Sohl et al. [30]. (d) APWP length for Siberia case 1 and Siberia case 2 (Table 1). Total path length for Siberia case 1 is 67 ± 12º (poles *9* and *10*) and 25 ± 25º for Siberia case 2 (poles *11*, *12* and *13*). A correction for an anticlockwise rotation of pole 10 (Moyero River) results in a shorter path length for Siberia case 1 [34].

Table 1
Paleomagnetic (south) poles used in the IITPW analysis

Pole	Pole (lat., long.)	α_{95} (°)	Age ± error (Ma)	Angular separation of poles (°)	Time separation of poles (m.y.)	Conservative APW rate (cm yr^{-1}) [a]	Liberal APW rate (cm yr^{-1}) [a]
Baltica							
1. Fen Complex [19]	56°N, 150°E	5	583 ± 15				
2. St. Petersburg ls [22]	35°N, 059°E	4	478 ± 5				
Analysis [b]				62 ± 9	105 ± 20	$6.6^{+2.7}_{-1.8}$	45.9 ± 6.7
Swedish limestones [20] [c]	18°N, 046°E	5	~475				
Analysis [d]				98 ± 9	108 ± 20	$10.1^{+3.4}_{-2.4}$	72.5 ± 6.7
Laurentia							
3. Callander, Sept Îles and Catoctin-A [27]	45°N, 305°E	8	565 ± 10				
4. Tapeats sandstone [47]	05°S, 338°E	3	508 ± 5				
Analysis [b,d]				58 ± 11	57 ± 15	$11.3^{+6.9}_{-4.0}$	42.9 ± 8.1
Late Cambrian Mean [27] [c]	03°S, 344°E	12	~500–490				
Gondwana [e]							
5. Todd River Fm. [48]	13°S, 338°E	7	535 ± 3				
6. Mean pole [31]	08°N, 001°E	6	505 ± 5				
Analysis [b]				31 ± 13	30 ± 8	$11.5^{+10.7}_{-6.2}$	22.9 ± 9.6
Yaltipena [30] [c]	09°S, 346°E	11	~600				
Elatina [30] [c]	01°S, 352°E	13	~600				
Black Mountain [37] [c]	47°N, 038°E	7	~495–490				
Analysis [d]				80 ± 14	40 ± 8	$22.2^{+10.4}_{-6.9}$	59.2 ± 10.4
Bhander-Rewa Mean [49] [c]	18°S, 334°E	6	~520				
Mean Ordovician [32] [c]	36°N, 011°E	7	~475				
Siberia-1							
9. Pestrotsvet Fm. [33]	17°N, 245°E	6	523 ± 3				
10. Moyero River [36]	37°N, 319°E	6	490 ± 5				
Analysis [b,d]				67 ± 12	33 ± 8	$22.5^{+12.5}_{-7.6}$	49.6 ± 8.9
Siberia-2							
11. Kessyusa Fm. [35]	38°N, 345°E	13	530 ± 5				
12. Erkeket Fm. [35]	45°N, 339°E	7	510 ± 2				
13. Yuryakh Fm. [35]	36°N, 320°E	5	500 ± 2				
Analysis [b]				25 ± 25	30 ± 9	$9.3^{+17.2}_{-9.3}$	18.5 ± 18.5

[a] Converted using 1° = 111 km.
[b] See Appendix A for calculation.
[c] Additional poles used in Fig. 3.
[d] Analysis based on the pole selection of Kirschvink et al. [8] according to the formulae in Appendix A.
[e] Poles are rotated to African coordinates using rotation parameters in de Wit et al. [50].

use the 575–565 Ma grouping of poles (Sept Îles-B, Catoctin-A and Callander Complex) at one endpoint and the early-Middle Cambrian (~508 Ma) Tapeats sandstone pole at the other end [8]. The minimum great-circle distance between these poles is 58 ± 11° in 57 ± 15 m.y. These figures translate to a conservative APW rate of $11.3^{+6.9}_{-4.0}$ cm yr^{-1} and a liberal rate of 42.9 ± 8.1 cm yr^{-1} (Fig. 3b, Table 1). There is little APW observed in the Laurentian path between the Tapeats pole and a sequence of Late Cambrian poles [27] suggesting that the proposed interval of IITPW was completed by early-Middle Cambrian time (~508 Ma).

A recent paleomagnetic result from Laurentia has important implications for the IITPW hypothesis. Paleomagnetic data from the 550.5^{+3}_{-2} Ma (U–Pb)

Skinner Cove volcanics of Newfoundland indicate a paleolatitude of 19 ± 9º for the Laurentian margin [29]. This paleolatitude is important since the IITPW hypothesis requires that most of the motion in the APWP take place between 523 and 508 Ma. Since the length of the APWP for Laurentia is primarily a record of latitudinal motion of the continent from the south pole to the equator, a near-equatorial position of Laurentia *prior to* the interval of proposed IITPW could considerably shorten the APW track and negate the premise of the IITPW hypothesis. Other implications of this new paleomagnetic result are discussed below.

4.3. Gondwana

Gondwana represents the largest agglomeration of landmasses that existed during the interval of proposed IITPW. Poles of variable quality populate the Gondwana paleomagnetic database and Kirschvink et al. [8] relied on two results from Australia in order to document the 90º of TPW. Torsvik et al. [15] used a more complete Gondwana database to argue against IITPW, but because of the variable quality of the data and the use of a spherical spline fit, Evans et al. [23] questioned the validity of several poles in the database and asserted that IITPW was still permissible using the Gondwana database. A careful review of the data used by Kirschvink et al. [8] along with other quality paleomagnetic data from Gondwana does not favor the IITPW hypothesis. For example, Kirschvink et al. [8] guaranteed a sufficiently long APWP by choosing the Cambrian–Ordovician Black Mountain results [8] as one endpoint of the track rather than a more logical choice as described below.

The Australian paleomagnetic database indicates little apparent polar wander for the interval between ~600 Ma Elatina–Yaltipena poles [30] and the Lower Cambrian (Nemakit-Daldynian–Tommotian, ~543–535 Ma) Arumbera–Todd River poles [8]. This quasi-static period may extend to the Tommotian–Atdabanian boundary (~520 Ma) if the less well defined Bhander-Rewa pole from India is used in the analysis [10]. Kirschvink et al. [8] chose the latest Cambrian–Early Ordovician Black Mountain results (~495–490 Ma) to anchor the younger endpoint for the interval of IITPW. As described earlier, the proposed interval of IITPW should have been completed by earliest Middle Cambrian as noted by the nearly concordant Tapeats sandstone and Late Cambrian poles from North America. Therefore a better choice of anchor poles for the end of IITPW would be early-Middle Cambrian poles from Australia or other regions of Gondwana. Klootwijk [31] documented paleomagnetic results from a number of latest Early Cambrian to Middle Cambrian age sedimentary rocks in Australia. These poles (Lake Frome, Billy Creek, Ross River, Kangaroo Island and Areyonga) yield a mean pole at 34ºN, 199ºE (8ºN, 001ºE in African coordinates; $A_{95} = 6º$). These rocks have excellent biostratigraphic age control that is now tied to an isotopically determined absolute age [16,17,31]. Since the age of these poles [31] falls precisely at the end of the proposed interval of IITPW they represent a more logical choice for determining the amount of APW in this analysis.

The Arumbera–Todd River and mean Middle Cambrian pole cited above are separated along a great circle by 31 ± 13º and 30 ± 8 m.y. The conservative rate of APW during this interval is $11.5^{+10.7}_{-6.2}$ cm yr^{-1} and the liberal estimate of 22.9 ± 9.6 cm yr^{-1}.

The Black Mountain results used by Kirschvink et al. [8] are displaced by nearly 49º from these slightly older poles and over 20º from other Gondwana [32] Early Ordovician poles (Fig. 3c, Table 1). It is possible that the Black Mountain pole reflects a rapid rotation of Australia between Middle Cambrian and Late Cambrian time, but this motion is not synchronous with the proposed interval of IITPW. The discrepancy between the Black Mountain pole and similar age poles from Australia and Gondwana needs to be reconciled in order to support this younger episode of rapid APW for Australia.

4.4. Siberia

Analysis of the Siberian APWP is problematic. There are a number of factors that must be considered when evaluating these data. This was noted by Kirschvink et al. [8] in the original analysis of IITPW. There are new data from Siberia which yield important new information regarding the length of the APWP.

There is a major discrepancy between the Pestrotsvet pole of Kirschvink and Rozanov [33], a recent compilation of Siberian data by Smethurst et al. [34] and new Siberian paleomagnetic poles of the same age [35]. Therefore, the amount of APW in the Siberian path is critically dependent upon the choice of data. However, several important points can be made with regard to the analysis of TPW offered by Kirschvink et al. [8]. The analysis uses paleomagnetic results from the Tommotian–Atdabanian age (~523 Ma) Pestrotsvet Formation [35] and the Late Cambrian (~490 Ma) Moyero River sediments [36]. These two poles are separated by an angular distance of 67 ± 12° and a time difference 33 ± 8 m.y. This yields a conservative APW rate of $22.5^{+12.5}_{-7.6}$ cm yr^{-1} and a liberal APW rate of 49.6 ± 8.9 cm yr^{-1} (Fig. 3d, Table 1). However, there is an additional complication that arises when using the Moyero River results. Smethurst et al. [34] analyzed paleomagnetic data from both north and south of the Viljuy Basin in Siberia and confirmed a suspected anticlockwise rotation of northern Siberia relative to southern Siberia during the mid-Paleozoic. The magnitude of this anticlockwise rotation may have been as much as 20° [34]. A correction of the Moyero River results for this anticlockwise rotation decreases the angular separation between the Moyero River pole and the Pestrotsvet pole and lessens the magnitude and rate of APW.

An alternative to the analysis of Kirschvink et al. [8] is provided by recent results from the Olenek River in northern Siberia by Pisarevsky et al. [35]. These results are particularly intriguing because the published age range of the sediments exactly span the proposed interval of IITPW and therefore provide a critical test of the IITPW hypothesis. The Kessyusa Formation is considered by Pisarevsky et al. [35] to be of Nemakit-Daldynian–Tommotian age (543–530 Ma), the Erkeket Formation spans from the Tommotian *regularis* zone up through the Toyonian (~525–510 Ma) and the Yunkyulyabit–Yuryakh Formation extends into the Middle Cambrian Mayan stage (~509–500 Ma). Although these paleomagnetic results are from the northern part of the Siberian craton and therefore possibly rotated, the magnitude of the rotation would be identical for each of the results such that the analysis presented herein would not require adjustment. These three poles (Fig. 3d, Table 1, Siberia-2 analysis) are separated by a combined great-circle angular distance of 25 ± 25° in a 30 ± 9 m.y. time interval. This leads to a conservative APW rate of $9.3^{+17.2}_{-9.3}$ cm yr^{-1} and a liberal APW rate of 18.5 ± 18.5 cm yr^{-1}.

5. Discussion

Inertial interchange true polar wander was introduced by Kirschvink et al. [8] to explain the apparently rapid continental motion that occurred near the end of the Neoproterozoic. The IITPW hypothesis makes specific predictions about both the magnitude and duration of APW. Specifically, IITPW requires 90° of APW in about 15 m.y. for each continent. This translates to a rate of APW of 66 cm yr^{-1}. As previously noted, this 90° of APW represents an ideal value since any plate motion may be added to the total length of APW or subtracted if the motion of the continent was purely antithetical to the direction of TPW. In both the preceding and following analysis, I assume that the magnitude of plate motions is lower than the rate of IITPW motion and therefore any additions or subtractions to the total length of the path are relatively minor.

The duration of the proposed interval of IITPW is better defined by the revised Cambrian time scale and paleomagnetic data from Laurentia, Australia and Siberia (Fig. 2). IITPW must have commenced sometime following the deposition of the Pestrotsvet Formation (latest Tommotian stage, ~523 Ma) and been completed by the time the Tapeats sandstone was deposited (Amgan stage of the earliest Middle Cambrian, ~508 Ma). The preceding analysis attempts to test the idea with the available data set. No continent has an APWP that unambiguously approaches the required length (or rate of APW) that would justify the IITPW hypothesis (Table 1, Fig. 3). Furthermore, the lengths of the APWPs and rates of APW vary widely from continent to continent in direct conflict with the IITPW hypothesis (Fig. 3). The nature of the IITPW hypothesis is such that one can always call on unidentified APW to bring the path lengths into coincidence, but such an ad-hoc explanation is of limited scientific value. Alternatively, it is possible to use the polarity ambiguity inherent in paleomagnetic studies to stretch the path lengths. However, the choice of polarity is more than a simple attempt to reduce the total path length between poles as some have intimated [14]. The parsimonious choice of polarity must take into account the tectonic and geologic implications of the choice *over* the total path length. Therefore, each polarity choice must be justified by rationale that includes total path length along with other geodynamic and paleogeographic constraints.

There are several key observations regarding the analysis of IITPW presented in this paper. The paleomagnetic data from Baltica comes closest to fulfilling the requirements of the IITPW model provided that all the APW motion is contained within the time interval from 523 to 508 Ma. The observed APW path length is 62 ± 9º and thus short of the required 90º to support the IITPW hypothesis. My analysis relies on a south-pole choice for the Fen pole that is justified by Meert et al. [19] based on tectonic models proposed for that time period. However, because over 100 m.y. separates the two endpoints, it is possible, indeed probable, that additional APW is contained within the path. Furthermore, as noted by Meert et al. [19] and reiterated by Smethurst et al. [22] the Fen paleomagnetic pole may actually represent a Permo-Triassic remagnetization. New paleomagnetic data are required to state conclusively the magnitude or timing of any additional APW for Baltica irrespective of the polarity choice for the Fen pole.

The analysis of Laurentian APW highlights several key problems with the IITPW hypothesis. First, the new age constraints (from 565 to 540 Ma) for the Sept Îles pole stretches the time interval between the two endpoints used in the analysis. For the adherents of IITPW, this does not preclude all motion taking place in the interval from 523 to 508 Ma; however, one of the reasons for proposing IITPW was to explain the apparently 'high' continental velocities documented for Laurentia that resulted using the 540 Ma age for the Sept Îles-B pole [8]. The new age constraints could conceivably lower the plate velocities from ≈40 cm yr^{-1} down to ≈11 cm yr^{-1}. An additional complicating factor for the IITPW hypothesis is the recent paleomagnetic results from the Skinner Cove volcanics [29]. These 550.5^{+3}_{-2} Ma Laurentian margin volcanics yield a paleolatitude of 19 ± 9º. Since most of the APW in the Neoproterozoic Laurentian path reflects its latitudinal motion, this result would indicate that a major component of the APW took place *prior* to the proposed interval of IITPW. However, accepting these results as representative for Laurentia means that the rate of latitudinal motion between 565 and 550 Ma could be greater than 40 cm yr^{-1}.

The Gondwana (Australian) database indicates an angular separation of poles of only 31 ± 13º. This is substantially less than the requisite 90º required by the IITPW model and represents a significant challenge to the hypothesis. This discrepancy was not noted by Kirschvink et al. [8] simply because the authors chose the Black Mountain result, a younger and more remote pole, for one of the endpoints (Fig. 2c). The Black Mountain pole (~495–490 Ma) is displaced by at least 20º (when rotated to African coordinates) from other Late Cambrian–Early Ordovician poles which tend to cluster in north-central Africa [32,37] and greater than 40º from Middle Cambrian poles from Australia [31]. Interestingly, the discrepancy between the Black Mountain results [37] and other Middle–Late Cambrian results from Australia and Gondwana [31,32] can be reconciled by considering possible vertical axis rotations of the Black Mountain directions. Admittedly, rotation of the Black Mountain region is difficult to evaluate given the paucity of paleomagnetic results from the same region. Nevertheless, Middle Cambrian paleomagnetic results from Gondwana indicate that APW motion within the interval of proposed IITPW falls far short of the required amount to validate the hypothesis. Additional high-quality paleomagnetic results from Australia and other regions of Gondwana will provide tighter constraints on the magnitude of APW and may help resolve the discrepancy between the Black Mountain pole and similar-age poles from Australia.

The Siberian paleomagnetic data are difficult to reconcile with the IITPW hypothesis. For example, use of the anomalous Pestrotsvet pole [33] yields a total angular separation of only 67 ± 12º rather than the requisite 90º. There are additional complications when using the Pestrotsvet and Moyero River [36] poles as endpoints in the analysis. The first is that the Moyero River section may have experienced up to 20º of anticlockwise rotation relative to the Pestrotsvet Fm. [34]. A clockwise correction of the Moyero River results decreases the angular separation between the two poles and lessens the magnitude of APW by as much as 20º. As demonstrated by Torsvik et al. [15] and Smethurst et al. [34] there is also an angular separation of over 90º between paleomagnetic poles derived from rocks *older* than the Pestrotsvet Formation that would require an additional episode of TPW prior to that proposed by Kirschvink et al. [8] or plate velocities exceeding 50 cm yr^{-1}.

A recent paleomagnetic investigation of Lower and Middle Cambrian sedimentary rocks from Siberia that exactly span the interval of proposed IITPW show only 25º of APW and provide a direct challenge to the IITPW hypothesis [35]. These new paleomagnetic results, along with the possibly significant rotations (up to 20º) of the results used by Kirschvink et al. [8], pose a serious challenge to the IITPW hypothesis.

While it is possible to argue about individual poles used in the analysis of IITPW, a basic observation made in this paper is that the necessary agreement between APWP lengths and rates of APW does not exist for the interval from 523 to 508 Ma. Since the IITPW hypothesis demands synchronous motion in equal amounts, the hypothesis can be rejected if it can be shown that any one of the continents in question does not meet the requirements of IITPW.

5.1. Alternatives to IITPW

One of the more vexing problems that remains in attempting to explain the global plate reorganization that took place at the close of the Precambrian is a need to account for the possible rapid motion of Laurentia during the latest Neoproterozoic to early Paleozoic. High plate velocities for Laurentia were noted by Meert et al. [9], Evans [14] and Torsvik and Trench [20], but no conclusive explanation was given to explain this motion. Gurnis and Torsvik [11] offered a possible geodynamic model that would allow for relatively short bursts of rapid plate motion; however, Kirschvink et al. [8] considered the IITPW hypothesis a better alternative to these geodynamic models. Based on the recalibration of the Cambrian time scale and the evaluation of poles in this paper, the interval of rapid apparent motion is earlier than that proposed by Kirschvink et al. [8] and it does not appear to involve all the continents.

For example, the latitudinal component of plate motion for central Africa during the latest Neoproterozoic (547 ± 4 Ma) Sinyai dike pole [38] to the Early Cambrian (522 ± 13 Ma) Ntonya Ring pole [39] exceeds 20 cm yr^{-1}. Furthermore, if the pole from the Skinner Cove Volcanics [29] is representative of the Laurentian margin, then the plate velocities for Laurentia may exceed 40 cm yr^{-1} during the latest Neoproterozoic interval from 565 to 550 Ma. Australia, on the other hand, appears to remain quasi-stationary from about 600 Ma until at least ~535 Ma.

Since the selected paleomagnetic database is at odds with the notion of an IITPW event during the Cambrian, what alternatives are left which might explain these earlier rapid bursts of continental motion for Laurentia and parts of the Gondwana continent?

Evans [14] proposes that true polar wander (TPW) may be an inherent consequence of long-lived supercontinental assembly. In contrast to IITPW, true polar wander may be of any magnitude and duration. TPW still requires that the entire lithosphere move in unison relative to the underlying mantle and therefore that all APWPs must show similar lengths during the interval of TPW. For example, Evans [14] maintains that the lengths of the Lower Cambrian paths are similar for all continents and that the amount of TPW comprises a significant portion of the APWPs. The preceding analysis indicates that TPW in this interval cannot be conclusively demonstrated using the available paleomagnetic database.

Gurnis and Torsvik [11] suggest that the motion of a continent with a significant lithospheric root can be enhanced for a short period of time. The mechanism that they proposed involves the motion away from a hot lower-mantle source which produces a long-wavelength geoid high or toward a cold lower-mantle source which produces a long-wavelength geoid low (Fig. 1a). The geodynamic models employed by Gurnis and Torsvik [11] provide no absolute bounds on the maximum speed at which continents might move when driven by these large-scale, lower-mantle buoyancy forces. They did conclude that the model could explain all the documented instances of rapid plate motion (maximum rate cited in that paper was 23 cm yr^{-1}).

I suggest that a reasonable alternative to IITPW for the observed rapid motion may comprise elements of rapid plate motion away from/toward a lower-mantle hot/cold spot and a lesser component of TPW. Gurnis and Torsvik [11] also mentioned this possibility when evaluating their geodynamic models but provided no further discussion regarding the mechanism. Meert and Torsvik [40] suggested that the rapid motion of Laurentia might have resulted as the continent moved away from a deep-seated plume during its breakup from the elements of western Gondwana (~565 Ma). Higgins and van Breemen [28] suggested, on the basis of the ages of igneous provinces in eastern North America, that at least one and possibly two mantle plumes rose beneath that region in the latest Neoproterozoic. Since these plumes penetrated the lithosphere and separated elements of Gondwana from Laurentia [7,28], they may have provided a partial driving mechanism for the rapid plate motions of both landmasses. In addition, as much as 15,000 km of oceanic crust may have been consumed beneath portions of Gondwana during the closure of the Mozambique Ocean [41]. Presumably a significant amount of this oceanic material could create a long-wavelength geoid low in the mantle and enhance plate motion [42]. These combined lower-mantle driving mechanisms may account for up to 10 cm yr^{-1} of augmented velocity for Laurentia and Gondwana [11]. Assuming that 'normal' plate velocities for large continents might reach as high as 7–10 cm yr^{-1} [43], the total velocity accounted for by this model would be 17–20 cm yr^{-1}.

Mesozoic TPW of up to 0.5°/m.y. has been suggested by some authors [44] and Van der Voo [45] suggested TPW rates of nearly 1°/m.y. for the middle Paleozoic. If the bursts in plate velocities of Laurentia and Gondwana resulted from lower-mantle sources, this might also be a time of enhanced TPW because of changes in the inertial moment of the Earth caused by mass redistribution within the mantle [8,14,46]. Since TPW requires APWPs of similar length, it is theoretically possible to provide a limit on the amount of TPW that might have occurred during the latest Vendian and Early Cambrian by analyzing the common amount of APW observed in this time period. Unfortunately, the APWPs are not sufficiently constrained to provide this limit because they cover different intervals of time or contain significant gaps. The possibility of TPW in the latest Neoproterozoic remains a viable, albeit presently intestable, hypothesis for explaining the bursts of rapid plate motion observed for some continental masses. Alternatively, the rapid motion of Laurentia and Gondwana may simply reflect the motion of those two continents away from mantle plumes during their Neoproterozoic breakup.

6. Conclusions

Kirschvink et al. [8] suggested that the rapid continental motion that occurred at the dawn of the Phanerozoic was triggered by a pulse of inertial interchange true polar wander. A careful analysis of the original paleomagnetic data used in that study, new paleomagnetic data from Laurentia and Baltica, a re-evaluation of the Siberian and Gondwana paleomagnetic database and a revised Cambrian time scale indicate that the IITPW hypothesis is not supported by the available data. Rejection of the IITPW hypothesis requires an alternative explanation for the observed rapid APW (or latitudinal motion) of Laurentia and Gondwana during the latest Neoproterozoic and earliest Cambrian. I suggest that a possible explanation for these anomalously high rates of APW results from a combination of TPW coupled with enhanced plate motion driven by lower-mantle thermal anomalies. Conceivably, the lower-mantle sources and/or sinks may provide a dynamic feedback mechanism triggering true polar wander [42]. The extent to which this rapid plate reorganization influenced global climate and evolution is not known. However I tentatively suggest, as did Kirschvink et al. [8], that the changes in oceanic circulation, landmass distribution and orogenesis that would result from this reorganization would have some influence on global climate. These changes might then require the extant organisms to adjust to the new conditions and trigger an evolutionary response.

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Appendix A. Calculation of APW rates

In an attempt to compare relative magnitudes of APW from various continental blocks and evaluate the errors associated with that analysis, the following formulae were used. Paleomagnetic poles contain error estimates in both age and position and I have attempted to account for these uncertainties in the analysis. The method is not intended to be statistically robust, but rather to allow for a useful comparison. I calculated two separate APW rates, one assumes that all the APW takes place during the 15 m.y. interval between 523 and 508 Ma. This is referred to as the liberal rate of APW. The conservative rate assumes that the APW is evenly distributed over the time interval anchored by the paleomagnetic poles. The great-circle angular separation between poles is denoted by Ω and the error associated with the angular separation is denoted by Δ. Δ is simply the summation of α_{95} errors since each pole could theoretically be $\pm\,\Delta$ displaced from its calculated position. The time separating the poles will be denoted by T and its associated error δ.

The conservative estimate was calculated using the following formulae:

$$(\Omega + \Delta)/(T - \delta) = \text{Rate 1 (high end of conservative estimate)} \quad (1)$$

$$(\Omega - \Delta)/(T + \delta) = \text{Rate 2 (low end of conservative estimate)} \quad (2)$$

$$\text{Average rate} = \Omega/T \quad (3)$$

$$\text{Error} = +(\text{eq. 1} - \text{eq. 3}) \text{ and } -(\text{eq. 3} - \text{eq. 2})$$

Note that the method results in unequal errors that yield a larger deviation at the high end of the analysis.

The liberal estimate of APW ignores errors in age by assigning all APW to a 15 m.y. interval and is given by:

$$(\Omega + \Delta)/(15) = \text{Rate 1 (high end of liberal estimate)} \quad (4)$$

$$(\Omega - \Delta)/(15) = \text{Rate 2 (low end of liberal estimate)} \quad (5)$$

$$\text{Average} = \Omega/15 \quad (6)$$

$$\text{Error} = +(\text{eq. 4} - \text{eq. 6}) \text{ and } -(\text{eq. 6} - \text{eq. 5})$$

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