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  49. We thank S. Sharpe for sample collection; K. O'Brien, J. Betancourt, W. Broecker, and R. Dorn for helpful discussions; and C. Laj and one anonymous reviewer for their comments on the manuscript. Supported by NSF, the U.S. Department of Energy (DOE), and Los Alamos National Laboratory. Part of this work was supported and managed by DOE's Yucca Mountain Site Characterization Office. The record package containing traceability information is LA-CST-TIP-96-006.

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## Evidence for a Large-Scale Reorganization of Early Cambrian Continental Masses by Inertial Interchange True Polar Wander

Joseph L. Kirschvink,\* Robert L. Ripperdan, David A. Evans

Analysis of Vendian to Cambrian paleomagnetic data shows anomalously fast rotations and latitudinal drift for all of the major continents. These motions are consistent with an Early to Middle Cambrian inertial interchange true polar wander event, during which Earth's lithosphere and mantle rotated about 90 degrees in response to an unstable distribution of the planet's moment of inertia. The proposed event produces a longitudinally constrained Cambrian paleogeography and accounts for rapid rates of continental motion during that time.

The Vendian-Cambrian transition [~600 to 500 million years ago (Ma)] is one of the most intriguing periods in Earth history. Geological evidence points to the breakup of one supercontinent, Rodinia, and the almost simultaneous assembly of another, Gondwanaland (1). The sudden appearance of virtually all the animal phyla (2) and their exponential diversification are coeval with abrupt shifts in oceanic geochemistry (3, 4). Recent calibration of this time interval with U-Pb isotopic ages (5, 6) indicates that these events occurred within a span of 30 million years (My), and the major diversification happened in only 10 to 15 My (Fig. 1). The new ages, along with paleomagnetic data, indicate that continents moved at rapid rates that are difficult to reconcile with our present understanding of mantle dynamics (7). We propose that rapid continental motions during the Cambrian period were driven by an interchange event in Earth's moment of inertia tensor. The age constraints on the geophysical data indicate that the rapid continental motions occurred during the same time interval as the Cambrian evo-

lutionary diversification and therefore the two events may be related.

The most reliable paleomagnetic data for this interval are from magnetostratigraphic studies across well-exposed stratigraphic sections that include the Precambrian-Cambrian and Cambrian-Ordovician boundaries (4, 8–10). Magnetic polarity patterns from these sections are correlated in different geographic regions, indicating that the rocks have not suffered remagnetization. The strata can be correlated by biostratigraphy, chemostratigraphy, and sequence stratigraphy, usually with a temporal precision better than 1 My. Magnetostratigraphic studies from sedimentary rocks typically span time intervals long enough to average out secular variations in the geomagnetic field. Through these studies, the paleohorizontal is defined by the bedding and sedimentary structures, and these data allow determination of Earth's paleorotation axis (11). We used biostratigraphically dated units with correlatable magnetic polarity patterns to derive our apparent polar wander (APW) paths and supplemented these with the most reliable poles from other sources (12). Averaging pole positions over time intervals of 15 to 20 My as done by some authors (13) can mask rapid shifts in apparent pole positions, even among sediment-based APW paths. We

therefore did not smooth the data.

Australia has the best constrained APW path for Vendian and Cambrian time (Fig. 2). Three key paleomagnetic poles are ranked with the highest reliability ( $Q = 7$  out of a possible 7) on the paleomagnetic quality index (12). The oldest of these is from the basal Vendian Elatina Formation of southern Australia. It was deposited during the upper Marinoan glaciation at about 600 Ma. The two-polarity remnant magnetization is carried by detrital hematite with Curie temperatures of 680°C, whereas the maximum burial temperature was less than 160°C. The magnetic directions also pass slump-fold and reversal tests, and reversals are stratigraphically bounded and consistent between parallel sections (14). Close to this pole is a group of three others from the Pertatataka, Arumbera, and Todd River formations in central Australia (8, 15). The Pertatataka and Arumbera formations contain a late-stage Ediacaran fauna, indicating an age of about 560 to 545 Ma. Unconformably overlying sedimentary rocks contain some of the earliest Cambrian fossil tracks and trails. The Todd River formation, one of the top units, contains archaeocyathids and small skeletal fossils of Atdabanian affinity. Dense paleomagnetic sampling ends in sedimentary rocks correlated with the earliest Tommotian (16). In the calibrated time scale (5, 6) (Fig. 1), these three poles span the interval of about 560 to 534 Ma. The characteristic magnetic directions for these poles pass the fold and unconformity tests, and the polarity patterns can be correlated at several other sections within the Amadeus Basin and in the neighboring Ngalia and Georgina basins (8, 15). These data show no detectable motion for Australia in the 65 My before 535 Ma.

A magnetostratigraphic study of the Australian Cambrian-Ordovician boundary interval (~500 to 495 Ma) from Black Mountain in western Queensland (10) produced a detailed magnetic polarity profile. The polarity zones were tied to the conodont and carbon-isotope ( $\delta^{13}\text{C}$ ) stratigraphies and match the polarity, biostrati-

J. L. Kirschvink and D. A. Evans, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA.

R. L. Ripperdan, Department of Geology, University of Puerto Rico, Mayaguez, Mayaguez 00681, Puerto Rico.

\*To whom correspondence should be addressed.

graphic, and carbon-isotopic variations in rocks from North China (17), indicating a two-polarity primary magnetization. The pole for this sequence is  $>80^\circ$  away from the Vendian–Early Cambrian poles, implying that Australia underwent a large rotation while remaining near the equator sometime between Tommotian and Late Cambrian time (Fig. 2). On the basis of the recent age determinations (Fig. 1), this motion started no earlier than 535 Ma and was completed sometime before  $\sim 505$  Ma. Although not based on magnetostratigraphy, other studies of Lower Cambrian rocks in central and southern Australia (18) demonstrate that Australia rotated counterclockwise during this time.

Other parts of the Gondwanaland supercontinent must have been involved in this tectonic rotation; deformation within the Pan-African and Brasiliano orogenic belts occurred mainly from 700 to 550 Ma (19), suggesting that Antarctica, India, Africa, South America, and perhaps parts of East Asia also rotated with Australia; this is supported by paleomagnetic data from these blocks (12, 20). In addition, lithofacies in

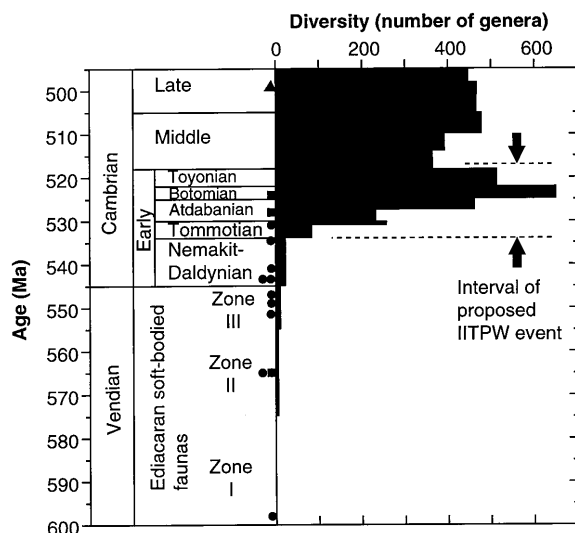
the West African and nearby cratons changed during Cambrian time as the continent moved from lower to higher latitudes (21). The Australian and Gondwanaland paleomagnetic data imply that at least half of Earth's continental lithosphere rotated nearly  $90^\circ$  between 534 and 505 Ma.

The paleocontinent of Laurentia (which included most of North America and Greenland) has the next most reliable set of paleomagnetic data in the Vendian-to-Cambrian interval. There are more than 30 published pole positions for this interval that vary in quality and age control. Several authors have reviewed these results (12, 13) (Fig. 3). Three of the poles, all from igneous intrusive complexes, fall within an overlapping group labeled Vendian to earliest Cambrian (575 to 540 Ma). The Catocin A pole is constrained in age at  $564 \pm 9$  Ma (U-Pb) (22); the Callander Complex yields Pb/Pb and K-Ar mineral isochron ages of  $575 \pm 5$  Ma; and the tilt-corrected Sept-Iles B pole has its best constrained 8-point Rb-Sr isochron at  $540 \pm 7$  Ma (23). This group of Vendian- to earliest Cambrian-aged poles is separated by nearly  $70^\circ$  from a

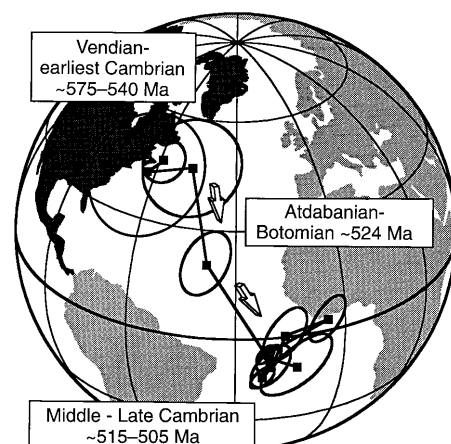
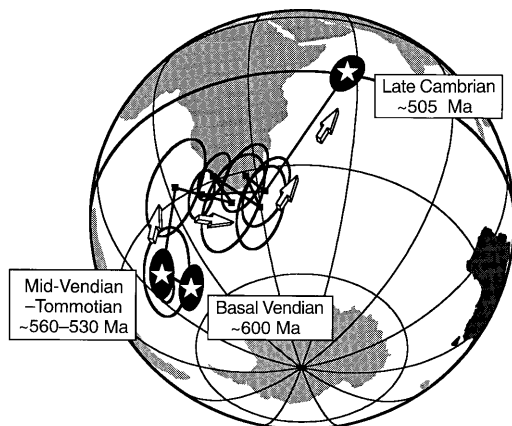
cluster of biostratigraphically dated Middle to Late Cambrian Laurentian poles, all with  $Q \geq 5$  (Fig. 3). In order of decreasing age, these include the early Middle Cambrian Tapeats Sandstone, the Dresbachian-aged Taum Sauks Limestone, the Franconian-aged Moore Hollow and Morgan Creek poles, the Franconian–Early Trempealeauan Point Peak Shale and Royer Dolomite, and the earliest Ordovician Oneota Dolomite (13). We also show in Fig. 3 the pole from the Puerto Blanco volcanic rocks, for which we now have reproduced a positive conglomerate test (24). Biostratigraphic constraints indicate that the Puerto Blanco volcanic rocks are of Atdabanian or early Botomian age (25), which agrees with the location of this pole between the Vendian and Middle-Late Cambrian pole clusters (Fig. 3). Laurentia's APW path suggests that the continent drifted rapidly from polar to tropical latitudes during Early and Middle Cambrian time, with the proto-Cordilleran margin leading and the proto-Appalachian margin trailing. This motion is consistent with the first appearance of abundant Early Cambrian carbonate rocks, where Atdabanian archaeocyathids first appeared in the Cordilleran miogeocline, followed by younger Botomian and Toyonian forms on the Iapetus shelf (26).

Comparison of the Australian and Lau-

**Fig. 1.** Isotopic age constraints and generic diversity for Vendian and Cambrian time. The time scale is from (5), with the location of the radiometric constraints indicated by solid circles (U-Pb from zircon thermal-ionization mass spectrometry, TIMS), squares (U-Pb zircon measured by super-high-resolution ion microprobe, SHRIMP), and triangles (Rb-Sr shale isochron). SHRIMP ages have been corrected for a 1 to 2% discrepancy between the TIMS and SHRIMP data (5). Data for the generic diversity (including archaeocyathids) (50) are plotted simply as the number of taxa reported in each reference time interval. The black arrows indicate the approximate time of the proposed IITPW event.



**Fig. 2.** Paleomagnetic apparent South polar wander curve from the stable cratonic areas of Australia for Vendian and Cambrian time. Ovals show the boundary of the cones of 95% confidence for the true mean directions; those containing stars are particularly well constrained both in timing and paleomagnetic reliability. Latitude and longitude grid lines are spaced  $30^\circ$  apart, from which it can be seen that the angular distance from the Late Cambrian direction to the cluster of Vendian to Tommotian poles is, within the error limits,  $90^\circ$ . Arrows show the direction of inferred pole motions, based on (18). These directions are interpreted to be South poles, on the basis of the Phanerozoic APW path for Australia.



**Fig. 3.** Apparent South polar wander path for North America. Symbols are the same as in Fig. 2. Data were compiled from (13) with data of  $Q > 4$ . Vendian poles include the Callander complex, Catocin, and tilt-corrected Sept-Iles [Laurentian poles 54, 55, and 56 of (13)], the Atdabanian–Botomian pole is from the Puerto Blanco Volcanics (24), and the Middle to Late Cambrian cluster includes the Tapeats, Taum Sauk, Moore Hollow, Morgan Creek, Royer, Point Peak, and Oneota poles [Laurentian poles 49, 44, 45, 41, 43, 47, and 40 of (13)]. Only the pole from the Buckingham Latites [pole 50 of (13), rated a “Q” of 5] was not used; the contact test only constrains the age to be older than Early Ordovician, and the pole falls in the well-defined post-IITPW group.

rentian APW paths demonstrates that nearly two-thirds of Earth's continental lithosphere experienced similar periods of stasis and motion between 600 and 500 Ma; both had little or no motion during Vendian time, and both shifted abruptly during a short time in the Cambrian. Although two fundamentally different paleogeographies exist for the width of the Cambrian Iapetus ocean between Laurentia and Gondwanaland (27, 28), even the narrow-Iapetus hypothesis includes separation of the two continents onto different plates based on Vendian to Cambrian rift-to-drift sedimentation on the proto-Appalachian margin of Laurentia (29). Thus, at least two tectonic plates, involving more than two-thirds of Earth's continental lithosphere, were involved in a rapid rotation of  $\sim 90^\circ$  relative to the spin axis. We speculate that the entire lithosphere may have been involved in this rotation. The postulated event began sometime in the first half of the Early Cambrian and ended by earliest Middle Cambrian time, for a total duration of  $\sim 15$  My. These time constraints are as follows: (i) The pole from the upper Arumbera-Todd River formation, which dates from the latest Nemakit-Daldynian or earliest Tommotian stages, plots with the Vendian group, whereas the slightly younger Early Cambrian poles of Klootwijk (18) show a shift toward the Black Mountain direction. (ii) The pole from the Atdabanian-Botomian Puerto Blanco Formation (24) is midway between the Vendian and Middle Cambrian groups. And (iii), the pole from the earliest Middle Cambrian Tapeats Sandstone (30) lies adjacent to the Late Cambrian poles from Laurentia. Consistent magnetic polarity zones from two sections of the lowermost Tapeats Sandstone suggest that it has a primary magnetic remanence, implying that the polar shift was finished by the early Middle Cambrian Glossopleura-Alokistocare trilobite zone.

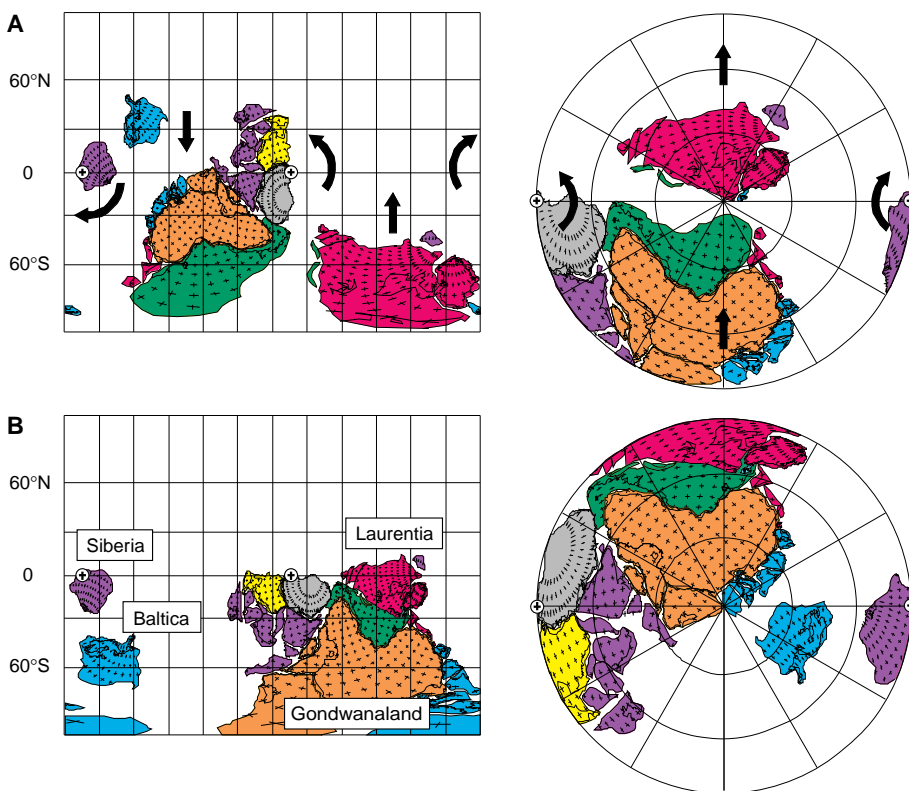
True polar wander (TPW) is the process through which quasi-rigid spheroids align their maximum moments of inertia with the spin axis, pushing positive mass anomalies toward the rotational equator (31). Normal TPW on Mars, the moon, and Earth results when small redistributions of mass lead to shifts in the location of the axis of maximum moment of inertia. The Tharsis volcanic province on Mars, with the largest positive gravity anomaly known from any planet, appears to have reoriented the martian lithosphere to place Tharsis on the equator; similarly, the lunar mascons all lie facing Earth symmetrically about its equator (32). Studies of hotspot tracks, paleomagnetic data, and post-mid Cretaceous plate motions on Earth suggest that TPW velocities of up to  $0.5^\circ/\text{My}$  were due to small

changes in crustal mass anomalies, most likely associated with growth and variation in the size of subduction zones (33) and glacial ice volume (34). A double burst of TPW has also been suggested for Silurian time, on the basis of matching similar bends on the Gondwanaland and Laurussian APW paths (35). Hence, the theory of TPW has observational support from at least three terrestrial planets, including Earth.

A variant of this mechanism, inertial interchange true polar wander (IITPW), involves discrete bursts of TPW of up to  $90^\circ$  in geologically short intervals of time if the magnitudes of the intermediate ( $I_{\text{int}}$ ) and maximum ( $I_{\text{max}}$ ) moments of inertia cross (36). This would result in a rapid movement away from the spin axis by the geo-

graphic location of the former pole with rotation of the entire solid Earth centered about the minimum moment of inertia ( $I_{\text{min}}$ ) located on the equator. Because  $I_{\text{max}}$ ,  $I_{\text{int}}$ , and  $I_{\text{min}}$  are orthogonal, the simple interchange case (with no independent plate motions) yields a  $90^\circ$  shift. Although such an event has not yet been recognized in the geologic record, the geodynamic consequences of an inertial interchange event have been considered in qualitative terms (36). These analyses predict that the  $90^\circ$  rotation of an IITPW event should happen over an interval of  $\sim 10$  to 15 My.

One way to test the hypothesized occurrence of an IITPW event is to see if it predicts an internally consistent paleogeography, with a rotation about an equatorial axis. Conventional paleomagnetic analyses



**Fig. 4.** Paleogeographic reconstructions before (A) and after (B) the proposed IITPW event, according to the Euler poles in Table 1. The pre-IITPW reconstruction in (A) was made by first rotating the four major continents (Gondwanaland, Laurentia, Baltica, and Siberia) such that their pre-IITPW poles (Vendian-earliest Cambrian) coincide at the South pole, and then rotating each of them laterally about the rotation axis such that their post-IITPW poles (latest Cambrian to early Ordovician) lie on the same longitude. The Late Cambrian reconstruction in (B) was done in a similar fashion, but by reversing the pole groups. For each reconstruction, one group of poles constrains the latitude and orientation with respect to the paleomagnetic pole, while the other constrains relative paleolongitude. Tick marks on the present latitude and longitude grid on the continental fragments are shown at  $5^\circ$  intervals, with  $30^\circ$  intervals for the Cambrian reference latitude and longitude grid (Galls Mercator and equal-area South polar projections). The large plus (+) symbols in Antarctica and Siberia on the diagrams indicate the axis of the minimum moment of inertia,  $I_{\text{min}}$ , about which Earth's entire lithosphere rotated during the proposed IITPW event. Large arrows in (A) indicate the direction of motion around  $I_{\text{min}}$  during this event. Color-coding is based on the location of Cambrian terranes within the present continents. As discussed in the text, uncertainties in these reconstructions are at least  $\sim 10^\circ$ ; hence, the apparent collision shown between Laurentia and Gondwanaland, contrary to geological evidence supporting Cambrian divergence between those two continents (29), is viewed as an artifact of an incomplete data set.

provide an estimate of the paleolatitude of a continent and its orientation with respect to the geomagnetic pole, but the paleolongitude cannot be constrained. During a large and rapid TPW event, however, motion of the geomagnetic dipole relative to the lithosphere should appear to have a common swath from all continents. It can therefore be used to predict an absolute reconstruction, including latitude and relative longitude. Variations due to the much slower normal plate motions would tend to produce only small changes in relative paleogeography at either end of the IITPW event. The IITPW reconstructions (Fig. 4) force the Appalachian margin of Laurentia to lie adjacent to the Andean margin of South America, supporting the narrow-lappetus model of a consanguineous Appalachian-Andean mountain system during Ordovician time (28, 29).

Baltica has a well-defined APW path back through Ordovician time (37), implying a confidence in the polarity interpretation of Ordovician poles. The Baltica pole closest in age to the termination of the IITPW event is from the lower Ordovician (Arenig-Llanvirn) Swedish Limestones (37). The best pole at the older end of the IITPW event is from the Fen complex, which is dated at  $578 \pm 24$  Ma by Rb-Sr on phlogopite (38). The angular gap between these directions is either  $82^\circ$  or  $98^\circ$ , depending on the polarity of the Fen pole. Ordinarily, either polarity interpretation would be possible without reliable intermediate directions; however, the IITPW paleogeographic analysis indicates that one choice is impossible: the polarity interpretation of Torsvik *et al.* (37), with the south pole at  $50^\circ\text{N}$ ,  $144^\circ\text{E}$ , places Baltica on top

of the African and Indian portions of Gondwanaland. Reversing this polarity interpretation constrains Baltica's Vendian position to lie near Siberia and Arabia (Fig. 4). This location is similar with past paleogeographic models for the Ordovician that used faunal distributions for approximate paleolongitude control (13, 27, 39).

Paleomagnetic data for Siberia are more problematic. Most Late Cambrian and earliest Ordovician results are not documented in enough detail to assess their reliability. However, two magnetostratigraphic studies of Upper Cambrian and Ordovician sedimentary rocks on the Siberian Platform provide independent constraints on the APW path (40). The Ordovician magnetic reversal patterns agree with results compiled from other cratons, providing a constraint on the polarity interpretation. Although there are no reliable paleomagnetic results of late Vendian age, the magnetostratigraphic data from the Tommotian Pestrotsvet Formation of the Lena River (9) are only slightly younger than the start of the inferred IITPW event. The magnetic polarity interpretation for these directions is constrained by paleontological and stable carbons-isotopic correlations with the *Série Lie de Vin* in the Moroccan Anti-Atlas Mountains (4), which is in turn referenced to the Gondwanaland and Australian APW paths. These two poles, with their stated polarity interpretation, are separated by about  $68^\circ$ ; together they yield a plausible tropical position for Siberia, nearly on the opposite side of the globe from Australia, in agreement with some paleogeographic reconstructions (13, 27). On the other hand, if the Ordovician

result were of opposite polarity, Siberia would be positioned adjacent to the Pacific coast of Australia, as suggested by other reconstructions (39).

Our reconstructions (Fig. 4) are a first-order analysis of a possible IITPW event, limited in several ways by the paleomagnetic and tectonic database. First, the paleomagnetic directions are each only accurate to within about  $5^\circ$ , depending on the pole. Because each Euler pole (Table 1) depends on two paleomagnetic pole determinations, positional differences of less than  $10^\circ$  ( $\sim 1100$  km) cannot be resolved. Second, no continent has reliable, biostratigraphically dated poles at both the precise beginning and end of the inferred IITPW event. Normal plate motions before and after the IITPW event will therefore modify the apparent positional change. Third, there are still ambiguities in the reconstructions used for Gondwanaland. These lead to angular differences between East and West Gondwanaland of as much as  $20^\circ$  (39), particularly when extrapolating from Australian data to the positions of northern Africa and South America. Although we maintain that between-plate motions should have been small relative to the rapid rotation associated with an IITPW event, we have allowed for these between-plate motions because of our acceptance of APW paths at face value. We view these plate motions as approximate and emphasize only the  $>1000$ -km scale features of these reconstructions. We attribute the apparent conjunction and overlap between Laurentia and Gondwanaland by Cambrian-Ordovician time (Fig. 4B) as an artifact of the several sources of error described above.

Relative to the geomagnetic reference frame, continental drift velocities of  $\geq 30$  cm/year are suggested by the well-constrained paleomagnetic data from Laurentia and Gondwanaland. This is greater than any plate velocity, continental or oceanic, observed for the past 200 My. Such high velocities of continents during the Vendian-Cambrian interval led some to question the applicability of a maximum rate of plate tectonic motions; still, conventional geodynamical mechanisms must be stretched to account for the fast motions (7). If the velocities are due to TPW, however, such geodynamical considerations are obviated because the entire mantle would have rotated along with the lithosphere. Our TPW hypothesis also accounts for the otherwise problematic absence of an orogenic belt on the leading (proto-Cordilleran) margin of Laurentia during its rapid northward motion (29).

A  $\sim 90^\circ$  lithospheric and mantle rota-

**Table 1.** Euler poles used for producing the absolute IITPW paleogeographic reconstructions shown in Fig. 4. Positions for the paleomagnetic south poles are given in order of (north latitude, east longitude), and the Euler poles for moving the continents from their present coordinates to the reconstructed positions are (north latitude, east longitude, counterclockwise angle). Euler poles used for the continental reconstructions of Gondwanaland and small pieces of Laurentia are as given in (39), except for the fit between Great Britain and northern Africa; we use a GB-AF pole of (34.2, 15.9, 51.6) to position this further west along the north African margin as indicated by Torsvik *et al.* (13). Note that the post-IITPW poles provide the relative paleolongitude constraints for the pre-IITPW reconstructions, and vice versa. SS, sandstone; LS, limestone; Fm, formation.

Continent	Pre-IITPW pole	Post-IITPW pole	Pre-IITPW Euler pole	Post-IITPW Euler pole
Gondwanaland	Arumbera SS (15), (-46.6, 337.4)	Black Mountain (10), (03.3, 054.0)	49.4, 219.7, -69.3	32.2, 185.9, 118.5
Laurentia	Callander complex (48), (46.3, 301.4)	Tapeats SS (30), (-04.9, 337.7)	14.3, 172.0, -146.5	24.9, 92.9, 96.4
Baltica	Fen complex (49), (-50.2, 324.4)	Swedish LS (37), (18.0, 045.8)	40.7, 216.2, -53.4	20.1, 183.0, 132.9
Siberia	Pestrotsvet Fm (9), (16.6, 244.5)	Moyero River (40), (36.6, 318.6)	20.1, 3.9, 117.3	24.2, 112.0, 156.8

tion associated with the inferred IITPW event would have rearranged the continents relative to global physiochemical systems, and especially oceanic circulation. Even small changes in circulation can have major effects on the dynamics of the normal equator-to-pole heat transport; for example, the Pliocene emergence of Panama caused the northward deflection of the Gulf Stream, a second-order global feature but a first-order regional feature of North Atlantic climate (41). Wholesale rotation of the lithosphere is likely to have effected major changes in oceanic circulation and, hence, regional climates.

Evidence from carbon isotopes supports the hypothesis that marine circulation was reorganized repeatedly during Early Cambrian time. Pre-Tommotian oceans probably had fairly stable circulation patterns, as evidenced by a steady rise in marine  $\delta^{13}\text{C}$  (3, 4), which imply the sequestration of isotopically light organic carbon either in the deep ocean or in sedimentary reservoirs. Peak  $\delta^{13}\text{C}$  values were reached immediately before the base of the Tommotian, heralding an interval of about 10 large oscillations of up to 6 parts per mil in  $\delta^{13}\text{C}$  starting in the late Nemakit-Daldynian, with marine  $\delta^{13}\text{C}$  values finally stabilizing in the late Botomian. As the positive swings of these oscillations are correlated with the first appearance and radiation of new faunal groups, they were first thought to be due to enlargement of the biosphere and the corresponding depletion of  $^{12}\text{C}$  from the oceanic reservoir. However, large and rapid swings in  $\delta^{13}\text{C}$  also could be produced by deep ocean ventilation produced by the circulation jumping successively from one quasi-stable pattern to another, coupled by the locally variable sea-level swings predicted for a large TPW event. Pronounced shifts in seawater Sr isotopic ratios during the Early Cambrian (42) provide additional evidence of large-scale changes in the global oceans and related physiochemical systems, including continental weathering and mid-ocean ridge activity.

The repeated reorganizations in global climatic patterns during an IITPW event should have fragmented any large-scale ecosystems that were established, generating smaller, more isolated populations and leading to a higher evolutionary branching rate among existing groups (43, 44). Comparison of evolutionary rates between Cambrian and late Paleozoic time (45), corrected for the new time scale (5, 6), indicates that the Cambrian rate was a factor of ~20 times higher. A period of accelerated speciation during the 10- to 15-My interval of the proposed IITPW event could possibly resolve disagreements between estimates of the divergence time for the animal phyla

based on molecular (46) versus paleontological (47) evidence. We suggest, therefore, that the IITPW hypothesis can explain many of the anomalous tectonic, geochemical, and biological trends that occurred during the Precambrian-Cambrian transition.

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