

Polar Wander and the Cambrian

Joseph L. Kirschvink *et al.* (1) propose that true polar wander (TPW) occurred during the Cambrian (520 to 535 Ma). This conclusion is based on (i) apparently high drift rates from Gondwana-Laurentia, (ii) an anomalous pole reading from Siberia, and (iii) reinterpretation of polarity from a Vendian pole reading from Baltica. Their interpretation of Laurentian TPW (1) relies exclusively on the contentious Sept Iles Complex result (2), which yielded two different poles and seven imprecise Rb-Sr ages (586 to 475 Ma). There are no Cambrian data from Baltica (3); a polarity switch of a Vendian pole (1) would increase apparent polar wander (APW) path length, but this exercise would have no bearing on Cambrian TPW. Kirschvink *et al.* (1) state that the Siberian data are problematic, but this conundrum stems from a single anomalous result (4). Excluding this one result, the Siberian data define a gentle APW path (Fig. 1A) from Vendian through Ordovician times (5).

A reliable analysis of continental drift-rates or APW rates (Fig. 1, B through D) requires a robust mathematical analysis, but Kirschvink *et al.* (1) only quote drift-rates between selected poles or group of poles before stating their conclusions. In arguing that spherical spline analysis (3) masks rapid shifts in pole positions, they incorrectly state that the method averages poles over 15- to 20-Ma intervals; the TPW model (1) requires that data from all continents must show the same amount of APW between 520 and 535 Ma. Phanerozoic APW rates for Laurentia average 5 cm/year, with peaks in Vendian, Siluro-Devonian, and Jurassic times (Fig. 1B). The Cambrian data show a local minimum. The gap in the Baltic record (580 to 480 Ma; Fig. 1C) requires interpolation beyond reasonable limits and does not shed light on Cambrian TPW. The Siberia data show a local Cambrian maximum (10 cm/year), but considerable higher rates are observed in the Ordovician (Fig. 1D). Analysis of a more complete Gond-

wana data set [(6) and including all the data of (1)] shows a high Cambrian APW, but the highest peak occurs in the late Cambrian, outside the proposed TPW period (Fig. 1E). None of the examples show convincing evidence for Cambrian TPW, and rather than “stretching” geodynamic mechanisms, one can fit the data better with conventional plate tectonic systematics (3, 7). Thus, the TPW idea (1), while intriguing, is not supported when the most unreliable data are removed from the database.

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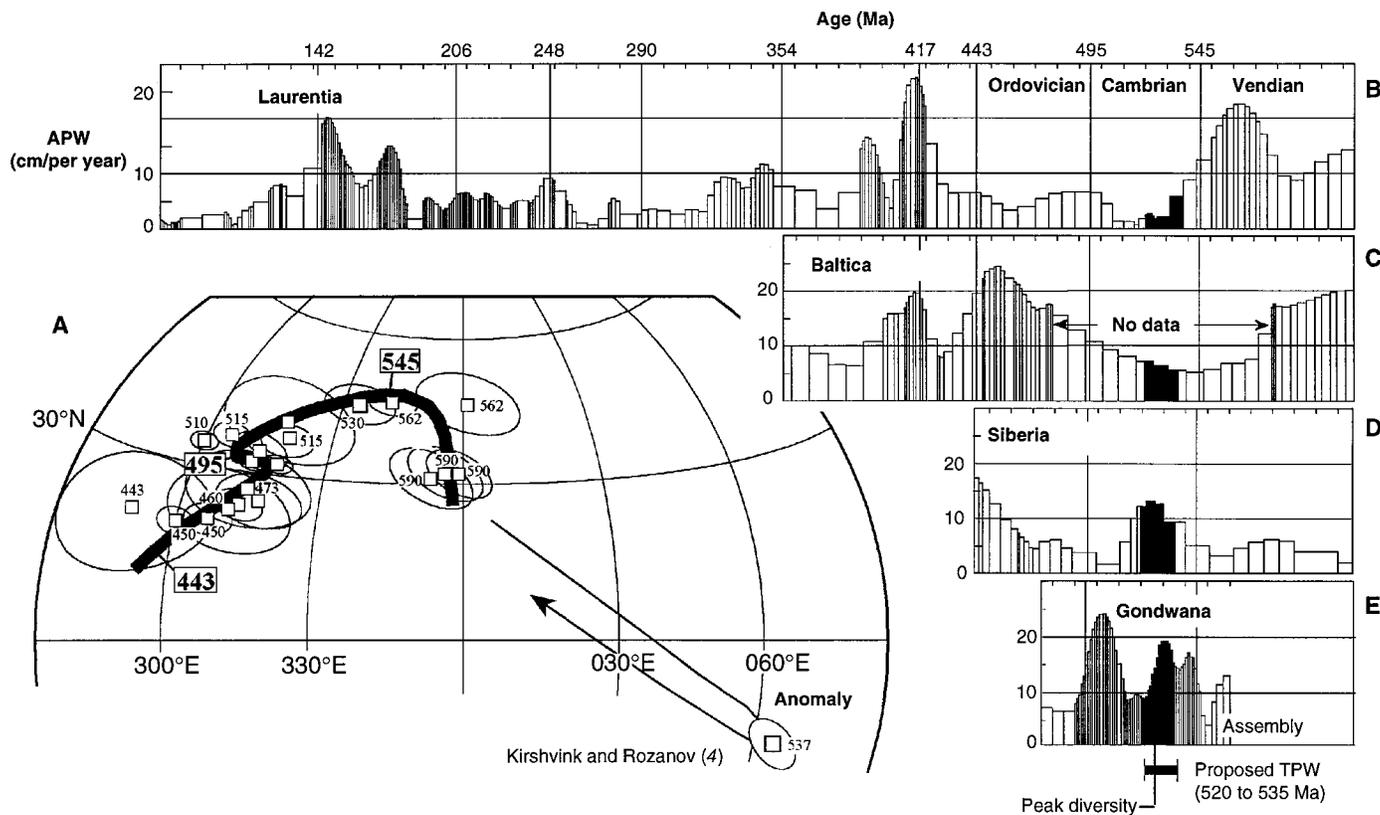


Fig. 1. Palaeomagnetic poles from south Siberia (A) plotted with confidence ovals along with a spherical spline (APW) path (5). Numbers are mean poles ages (Ma) using the time scale of Tucker and McKerrow (8). Geological boundaries are marked with bold numbers. An anomalous pole is evident (4). (B through E) Calculated APW rates (centimeters per year), based on APW paths for Laurentia, Baltica, Siberia, and Gondwana. Data sources include (3)

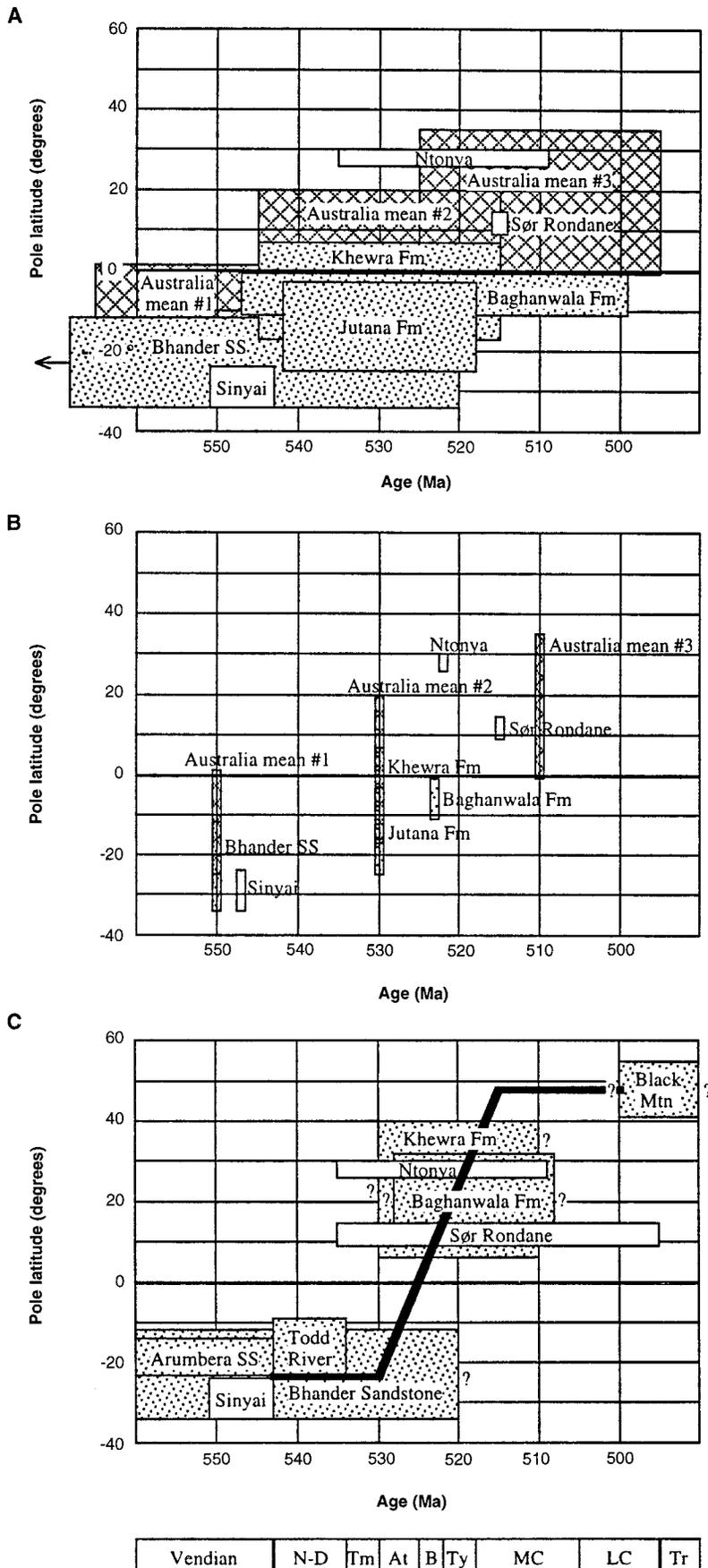
and (5–7), with Lower Paleozoic ages adjusted to the time scale of Tudor and McKerrow (8). Inadequate or no data-coverage indicated by wide APW bars and may be entirely interpolated (for example, that of Baltica between 580 and 480 Ma). APW bars within the proposed TPW interval (520 to 535 Ma), which have been said to bracket peak generic diversity (1), are shaded.

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 5. M. A. Smethurst *et al.*, *Earth Sci. Rev.*, in press. Siberian palaeomagnetic data north and south of the Viljuy basin confirm a mid-Palaeozoic counter-clockwise rotation (20 degrees) of north Siberia relative to south Siberia, and thus pre-Devonian APWP paths from north and south Siberia (Fig. 1A) must be analyzed independently. From south Siberia, there are many Vendian through Ordovician (590 to 443 Ma) palaeomagnetic poles; most sources are old and often undocumented Russian data, but more recent data on the whole confirm the earlier, and the sometimes mistrusted, old Russian data-set. Stratigraphic sections from Siberia bracket the inferred, TPW period (520 to 535 Ma) with no within-section sign of rapid APW. The Lena River pole data from a study by Kirschvink and Rozanov (4) remains an outstanding anomaly. One of us (T.H.T.) resampled part of the Cambrian Lena section (1994), but the data were of such poor quality that they were not submitted for publication.
 6. J. G. Meert and R. Van der Voo, *J. Geodynam.* **23**, 223 (1997).
 7. M. Gurnis and T. H. Torsvik, *Geology* **22**, 1023 (1994); in the Vendian data, we link high APW rates (Laurentia-Baltica) with final breakup of the Rodinia Supercontinent, driving Laurentia toward equatorial latitudes. During Cambrian and Ordovician times, Laurentia was flooded and stationary at equator; thus, there was little APW (Fig. 1B). Conversely, rapid rotation of Baltica combined with a northerly drift-component toward Laurentia is reflected by high Ordovician APW (Fig. 1C).
 8. R. D. Tucker and W. S. McKerrow, *Can. J. Earth Sci.* **32**, 368 (1995).

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Response: Torsvik *et al.* question the reliability of the paleomagnetic data used in our report (1). In discussing the Sept Iles B pole (2), which they and other workers have previously treated as one of the most reliable Vendian pole readings from Laurentia (3, 4), they disagree with our recapitulation of its 540-Ma Rb-Sr age (1). The variance in Rb-Sr ages for the Sept Iles complex was discussed thoroughly by Higgins and Doig (5), who developed a geochronologic-petrologic model of the complex that showed emplacement occurring at about 540 Ma. Their well-defined isochron (5) seems preferable to an assignment of 575 Ma that is based on comparison of a paleomagnetic pole with the better-dated Callander complex (3, 4); this latter approach seems circular. Contrary to the statement by Torsvik *et al.* that our "interpretation of Laurentian TPW ... relies exclusively on the contentious Sept Iles Complex result," we note that the angular separation of ~70° between Vendian and Middle-Late Cambrian poles remains the same, whether or not the Sept Iles pole is included [figure 3 of (1)]. Its only relevance to the TPW hypothesis is that it could provide an earliest Cambrian maximum age limit for Laurentia's motion from polar latitudes to the tropics. An older age for the Sept Iles intrusion could relax the constraint on the timing of TPW initiation, but results from earliest Cambrian strata in the Mackenzie Mountains (6) also support the Laurentian APW path that we presented (1). Torsvik *et al.* also state incorrectly that "a polarity switch of a Vendian pole [for Baltica] ... would have no bearing on Cambrian TPW." As pointed out by Kirschvink *et al.*, the new polarity interpretation of Baltica's Vendian paleopole [permissible, given the lack of Cambrian data from Baltica (1, 3)] generates strict paleogeographic implications and tests for the TPW hypothesis. Regarding the Siberian database, the result of Kirschvink and Rozanov (7) is currently the most reliable paleomagnetic study to date of the Cambrian Siberian craton: Magnetic polarity patterns from that study were found to correlate over wide distances of the Siberian platform, and independent tests of this correlation on an intercontinental scale with the use of marine carbon isotopes strongly support the primary nature of the remanent magnetization (8).

Torsvik *et al.* present histograms of APW rates for the four Cambrian continents, and use the heterogeneity of their interpolations as a key argument against a Cambrian IITPW event, but the existing Cambrian global paleomagnetic database is far from comprehensive. Torsvik *et al.* have excluded data they state are problematic



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REFERENCES AND NOTES

Fig. 1. Comparison of methods used to analyze the Vendian-Cambrian paleomagnetic database from Gondwanaland. For the sake of facility in presentation, diagrams show an oblique projection of the spherically bounded APW curve onto a purely latitudinal ordinate varying with time. Data are presented as rectangles with dimensions from quoted or employed uncertainties in both paleopole latitude (A_{95} or α_{95}) and age. Stippled boxes represent results from sedimentary rocks whose ages depend on use of a calibrated time scale of the fossil record [all boundaries as in the study by Tucker and McKerrow (13) except the Vendian-ND boundary at 543 Ma (14)]. Mean poles are cross-hatched. N-D, Nemakit-Daldynian; Tm, Tommotian; At, Atdabanian; B, Botomian; Ty, Toyonian; MC, Middle Cambrian; LC, Late Cambrian; and Tr, Tremadocian. **(A)** Data selected according to a study by Meert and Van der Voo; (15) (which are presumably the basis for the histogram in figure 1E of the comment by Torsvik *et al.*) are shown at face value. **(B)** Age uncertainties have been eliminated to reflect the nature of the spline-smoothing technique used by Torsvik *et al.* **(C)** Subset of the most reliable data is taken at face value as used in our report (1). Queried age limits for some results indicate uncertainties in the paleontological ages of the sampled units, as well as potential revisions to the numerically calibrated Cambrian time scale. Arumbera, Todd River, and Black Mountain results are preferred over the mean poles for Australia derived from a smooth interpolation between those data and others of lesser reliability (15). Khewra and Baghanwala poles have been restored to account for $\sim 30^\circ$ of Neogene CCW vertical-axis rotations in the sampled area [(16, 17), which was not done in other studies (3, 15), and 5° of uncertainty has been added to each pole's latitude. The Jutana pole is not included because rotations of its sampled region were estimated only by comparisons with a poorly defined APW path (17). Age estimates for the undated but probably Vendian-Cambrian Bhandar Sandstone are tentatively accepted from (15). The 515 ± 20 Ma age for the Sør Rondane pole is shown as a reasonable 2σ estimate from a compilation of ages (18). Thick solid curve indicates the hypothesis of Kirschvink *et al.* (1), which appropriately passes through all the uncertainty fields of the data. We (1) did not rely on the more problematic or imprecisely dated poles shown in this panel; they are merely shown here to illustrate their compatibility with our earlier conclusions (1).

[the “anomalous” Lena River pole by Kirschvink and Rozanov (7)], have misassigned ages to the Laurentian poles as described above and below (9), have relied on a 100-Myr interpolation with no data to generate conclusions about Baltica’s incremental motion during Cambrian time, and have included incorrect results from Gondwanaland (Fig. 1). We respect that Torsvik *et al.* have chosen the spline-smoothing technique as the kinematic basis for their geodynamic models (3, 10); however, given the present database, this technique is not yet applicable as a test for Cambrian TPW. Initially developing the spline-smoothing technique, Jupp and Kent explicitly stated (11, p. 45), “fitted spline paths are reasonably stable under moderate errors in the data times” [italics ours]. By assigning exact geochronological precision to imprecisely dated and undated paleopoles of low reliability, and by including already smoothed data in the form of means of poles from Australia, Torsvik *et al.* have constructed specious

APW paths that present merely one of several possible interpretations of the data (Fig. 1).

In developing the hypothesis that a single burst of Early Cambrian TPW joined the disparate poles bracketing that interval from all of the major continents, we found that it neatly explained many of the enigmatic features of the Eocambrian geologic record. The model is not a “stretch” relative to geophysical considerations of TPW (12). Until contradicted by solid, reliable paleomagnetic data, the TPW hypothesis remains a viable explanation for the dramatic changes in paleogeography and evolution that occurred during the Vendian-Cambrian interval.

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9. For example, within the 1996 study by Torsvik *et al.* (3) (presumably the main source for figure 1B of their comment), most of the Vendian-Cambrian Laurentian poles appear to be misdated [ages cited (3) in Ma; note the quoted precision of 0.1 Myr]; the Double Mer (550.0), Johnnie Rainstorm (550.0), and Long Range Dykes A (550.0) poles have permissive age constraints, whereas the Sept Iles B (575.0) and Tapeats Sandstone (525.0) should be given formation ages of ~ 540 Ma and lowermost Middle Cambrian [~ 515 Ma with the use of the time scale of Tucker and McKerrow (13), as used in our report (1) and the comment by Torsvik *et al.*], respectively.
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