LETTER

Supercontinent cycles and the calculation of absolute palaeolongitude in deep time

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Traditional models of the supercontinent cycle predict that the next supercontinent—'Amasia'—will form either where Pangaea rifted (the 'introversion'[1] model) or on the opposite side of the world (the 'extroversion'[2–4] models). Here, by contrast, we develop an 'orthoversion'[5] model whereby a succeeding supercontinent forms 90° away, within the great circle of subduction encircling its relict predecessor. A supercontinent aggregates over a mantle downwelling but then influences global-scale mantle convection to create an upwelling under the landmass[6]. We calculate the minimum moment of inertia about which oscillatory true polar wander occurs owing to the prolate shape of the non-hydrostatic Earth[5,7]. By fitting great circles to each supercontinent's true polar wander legacy, we determine that the arc distances between successive supercontinent centres (the axes of the respective minimum moments of inertia) are 88° for Nuna to Rodinia and 87° for Rodinia to Pangaea—as predicted by the orthoversion model. Supercontinent centres can be located back into Precambrian time, providing fixed points for the calculation of absolute palaeolongitude over billion-year timescales. Palaeogeographic reconstructions additionally constrained in palaeolongitude will provide increasingly accurate estimates of ancient plate motions and palaeobiogeographic affinities.

Two hypotheses have been proposed for the organizing pattern of successive supercontinents. 'Introversion' is the model whereby the relatively young, interior ocean stops spreading and closes such that a successor supercontinent forms where its predecessor was located[1]. 'Extroversion' is the model in which the relatively old, exterior ocean closes completely, such that a successor supercontinent forms in the hemisphere opposite to that of its predecessor[2–4]. A third model,

which we call 'orthoversion', predicts that a successor supercontinent forms in the downwelling girdle of subduction orthogonal to the centroid of its predecessor[5]. Hypothetical predictions for each model type can be considered for the future Asia-centred supercontinent, 'Amasia'[8], relative to the location of Pangaea in a deep mantle reference frame. (Amasia will merge the Americas with Asia, including the forward-extrapolated northward motions of Africa and Australia, and possibly include Antarctica.) According to the introversion model, the comparatively young Atlantic Ocean will close and Amasia will be centred more or less where Pangaea was (Fig. 1a). According to the extroversion model, the comparatively old Pacific Ocean will close and Amasia will be centred on the opposite side of the world from Pangaea (Fig. 1b). Finally, according to our orthoversion model, the Americas will remain in the Pacific 'ring of fire' girdle of post-Pangaean subduction, closing the Arctic Ocean and Caribbean Sea (Fig. 1c).

If any one model can be empirically demonstrated, then not only can we speculatively forecast where and how Amasia will form, but also we can extrapolate palaeogeography, including the historically elusive palaeolongitude, backwards in Earth history, from supercontinent to supercontinent. Using our orthoversion model, we find that Pangaea orthoverted from Rodinia, and Rodinia orthoverted from Nuna. Extrapolating this model into the future, Amasia should be centred within Pangaea's subduction girdle. Orthoversion helps to resolve the problems of the popular introversion and extroversion models, which have led to a "fundamental disconnection … between the geologic evidence for supercontinent formation, and the models purported to explain their assembly"[9].
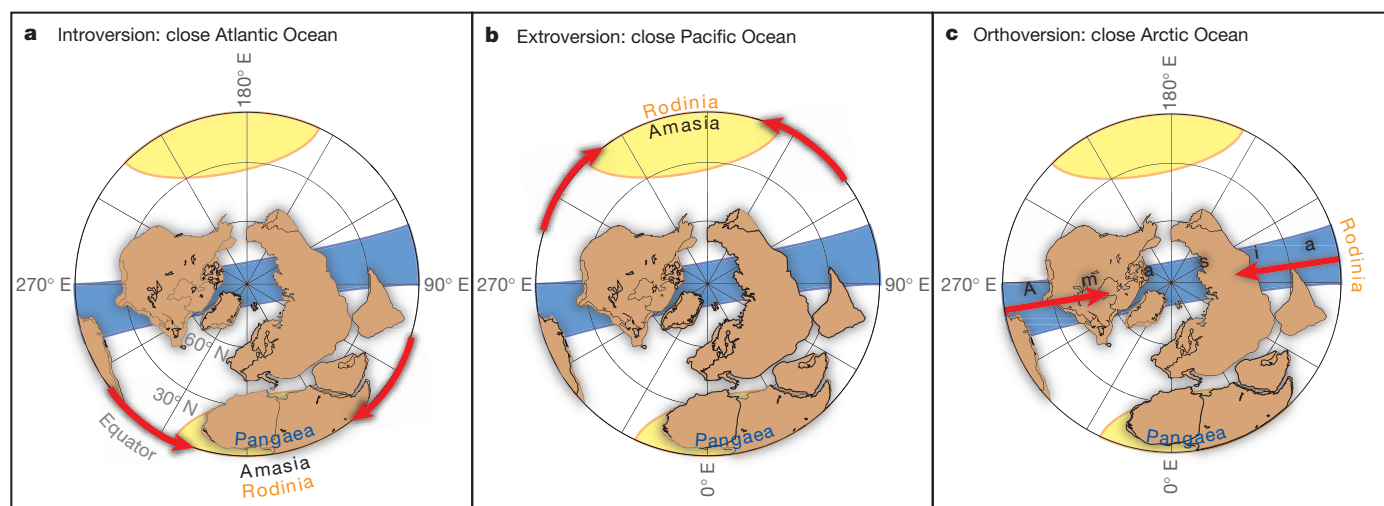
Figure 1 | Supercontinent cycle hypotheses. Predicted locations of the future supercontinent Amasia, according to three possible models of the supercontinent cycle: **a**, introversion; **b**, extroversion, and **c**, orthoversion. The labelled centres of Pangaea and Rodinia are the conjectured locations of each supercontinent's I_{min} (Fig. 2). Yellow equatorial circles represent supercontinent-induced mantle upwellings, and the orthogonal blue great circle swath represents Pangaea's subduction girdle (as in Fig. 3). In **c**, Amasia could be centred anywhere along Pangaea's subduction girdle. Red arrows indicate where ocean basins would close according to each model. Continents are shown in present-day coordinates.

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Several independent methods are available to estimate the centre of supercontinent Pangaea (see Methods). However, only the palaeomagnetic identification of ancient true polar wander (TPW)—the rotation of solid Earth about the equatorial minimum moment of inertia[10], I_{min}—allows us to measure the angle between successive supercontinents in deep time. For a long-lived (more than a hundred million years) prolate Earth for which the intermediate and maximum moments of inertia are subequal and prone to interchange, I_{min} provides a quantitative datum for the mantle convective planform beneath a supercontinent's centre (see Methods). Recently, Steinberger and Torsvik[7] determined the palaeolongitude of the Pangaean I_{min} by identifying four Mesozoic TPW oscillatory swings about nearly the same axis near central Africa.

We fitted great circles, and their orthogonal axes defining I_{min}, to the TPW-rich portion (260–90 million years (Myr) ago) of the global palaeomagnetic apparent polar wander (APW) path in a South African reference frame[7] (Fig. 2). One great-circle fit to all the 260–90 Myr-old poles does not convey the true azimuths of the individual TPW swings, which are subparallel. Because plate motions as well as the TPW signal are included in the APW paths, continental drift relative to the stationary I_{min} will appear in a continental reference frame as the TPW great-circle segments shifting with age. We therefore fitted two great circles, one to 260–220-Myr-old poles (20° N, 349° E, $A_{95} = 3°$ (error), $N = 5$ (sample)) and one to 200–90-Myr-old poles (10° N, 001° E, $A_{95} = 4°$, $N = 12$; light and dark blue, respectively, in Fig. 2). The two great circles are proposed to be caused by oscillations about the same Pangaean I_{min} axis, but are distinct geographically owing to the movement of the South African reference frame relative to the stable I_{min}.

Before these Africa-centred TPW rotations, Gondwanaland experienced early Palaeozoic oscillatory rotations around a distinctly different axis. Instead of the African region swiveling in azimuth in constantly tropical latitudes as described above, early Palaeozoic rotations involved rapid changes of palaeolatitude for the African and South American regions of the large continent. These rotations, about an axis near the Australian sector of Gondwanaland, have also been attributed to TPW[11,12] and closely match the motions produced by migrations of ice centres across the drifting supercontinent[13]. Continuing backwards in time into the Ediacaran period, additional large-magnitude rotations recorded in the Australian palaeomagnetic database[14] suggest similar TPW-dominated kinematics for that time.

In South African coordinates, the earliest Palaeozoic I_{min} (−30° N, 075° E, $A_{95} = 12°$, $N = 14$) plots near the reconstructed Australian sector of the supercontinent (Fig. 2a). The results of this calculation are similar whether only Cambrian data are considered, or only Ediacaran data, or the combined Ediacaran–Cambrian data set. The angular distance between the successive I_{min} locations from 550–490 Myr ago and 260–220 Myr ago, in the same reference frame, is 83 ± 15 degrees. In principle, this could represent the steady drift of Gondwanaland over the mantle, including a stationary I_{min} throughout Phanerozoic time[15,16]. However, the rapidity of the shift between 370 and 260 Myr ago would suggest rates of motion averaging about 10 cm yr^{-1} (see the 'alternative animation' in the Supplementary Information), which would be unusual for a continent of that size[17]. We consider it more likely that I_{min} shifted substantially relative to Gondwanaland, owing to the post-Pangaean mantle axis being created in a position orthogonal to that of its post-Rodinian predecessor. The orthoversion model of supercontinent succession neatly explains this result.

With its perimeter surrounded by Neoproterozoic rifted to passive margins, Laurentia occupies a central place in most Rodinia reconstructions[18,19], akin to Africa in Pangaea. The orthoversion model predicts that soon after Rodinia's assembly, the young supercontinent's centre could have experienced oscillatory TPW with large changes in palaeolatitude around an axis corresponding to the preceding Nuna supercontinent's[20] convection-driven I_{min}. This would be
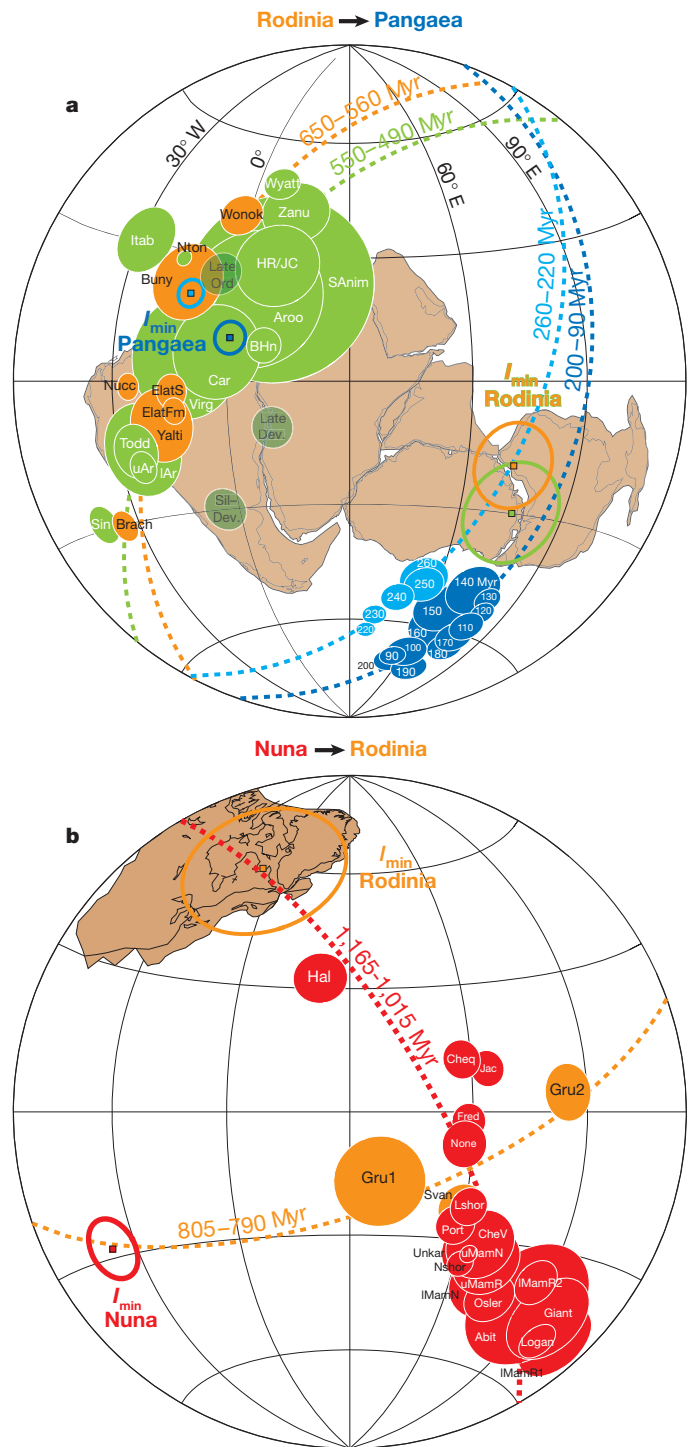
Figure 2 | Supercontinent centres. a, Successive post-Rodinia (orange and green open ellipses) and post-Pangaea (light-blue and dark-blue open ellipses) I_{min} axes are calculated as the poles to great-circle fits of palaeomagnetic poles from Australia at 650–560 Myr ago (orange solid ellipses) and Gondwanaland from 550–490 Myr ago (light-green solid ellipses), and the global running-mean apparent polar wander path for 260–220 Myr ago (light-blue solid ellipses) and 210–90 Myr ago (dark-blue solid ellipses)[24]. Dark-green poles for later Palaeozoic time from Gondwanaland are displayed but not included in any mean calculation (see text for discussion). **b**, Successive post-Nuna (red open ellipse) and post-Rodinia (orange open ellipse) I_{min} axes. Filled red ellipses are poles for Laurentia from 1,165–1,015 Myr ago. Filled orange ellipses are poles for Laurentia rotated from Svalbard at around 800 Myr ago[18] (see Methods section for discussion of rotation). All ellipses are projections of cones of 95% confidence. Pole information is listed in Supplementary Table 1, statistical parameters are detailed in Supplementary Table 2, and a version of this figure with the poles numbered to give a sense of age order is provided in Supplementary Fig. 1.

followed by mantle convective reorganization to a new super-continent-centred I_{min} location with swivel-like TPW oscillations at constantly tropical latitudes during Rodinia break-up. The palaeomagnetic record for Laurentia during Meso–Neoproterozoic time, the crossover interval between Nuna and Rodinia TPW legacies[5], shows this pattern.

The Rodinia interval is marked by rapid, oscillatory continental motions that have been interpreted as TPW during the time of super-continent amalgamation at around 1,100–1,000 Myr ago[5,21] and break-up at around 800 Myr ago[18,22]. We fitted two great circles, for 1,165–1,015 Myr ago[18] ($-28°$ N, $263°$ E, $A_{95} = 6°$, $N = 19$) and for three approximately 800-Myr-old poles from Svalbard[18,23] rotated to Laurentia ($59°$ N, $293°$ E, $A_{95} = 17°$, $N = 3$). The angle between the two successive I_{min} axes of Nuna and Rodinia is $89° \pm 23°$ (Fig. 2b).

As with Gondwanaland in Palaeozoic–Mesozoic time, the large shift in location of I_{min} relative to Laurentia can be interpreted in principle as the motion of the Rodinia supercontinent over a single, long-lived, mantle-stationary inertial axis. However, the orthoversion model also neatly explains the data, invoking a post-Rodinia I_{min} axis created $90°$ away from that of its predecessor, Nuna. Given that the two kinematically quantifiable supercontinental transitions (Nuna to Rodinia, and Rodinia to Pangaea) are both characterized by nearly ideal $90°$ shifts in location of the I_{min} axes, we conclude that orthoversion is the most parsimonious model for supercontinental cyclicity through the past billion years.

The orthoversion model of the supercontinent cycle makes palaeogeographic predictions deep into Earth history, from supercontinent to supercontinent, that include historically elusive absolute palaeolongitude constraints. Continents can be reconstructed latitudinally and longitudinally relative to supercontinent centres, as determined by a supercontinent's TPW legacy (fixed I_{min}). Figure 3 consists of five global maps in 200-million-year intervals, including simplified schematic mantle convection planforms through time. Given that the actual measured angles between supercontinent centres are within a few degrees of $90°$, we choose to assume in our reconstructions that successive supercontinents are ideally orthogonal, that is, successive I_{min} axes are offset by exactly $90°$ in palaeolongitude. Such ideality conforms to the self-organizing behaviour of mantle convection towards predominantly degree-2 spherical harmonics[6].

Absolute reconstructions are provided back to 500 Myr ago in an animation in the Supplementary Information and back to 800 Myr ago for select continents in Fig. 3. Reconstructions from 320 Myr ago to the present are identical to the configurations of ref. 24 except that our solutions additionally track the drift of South Africa relative to the long-lived Pangaean I_{min}. By aligning successive I_{min} axes from historical Pangaean TPW (260–90 Myr ago[24]) with the post-Pangaean I_{min} currently at $0°$ N, $010°$ E (ref. 25), we reconstruct all continents including South Africa with respect to present-day (or 'absolute') latitude and longitude coordinates.

Before 320 Myr ago, absolute reconstructions are limited to those continents for which TPW segments have been identified. The post-Rodinian I_{min} axis (650–490 Myr old) is ideally shifted in our model to a location $90°$ in longitude from the post-Pangaean axis (Fig. 3). Of the two possible orthoverted equatorial axes, $100°$ E and $80°$ W, we choose $100°$ E to minimize plate-tectonic drift rates of large, continent-bearing plates. We note that early Palaeozoic kimberlites and large igneous provinces, particularly widespread in Siberia and Australia, reconstruct within or near the idealized I_{min} circles in our model, consistent with their derivation from plume-generating zones in the deep mantle[16]. At 600 Myr ago, just before Gondwanaland assembly, Australia is reconstructed relative to the I_{min} axis according to its palaeomagnetic data (Supplementary Table 2), as is Laurentia, assuming that TPW is responsible for the bulk of variance in its palaeomagnetic poles[26]. At 800 Myr ago, we reconstructed Rodinia, according to ref. 19, around Laurentia, which is fixed to the I_{min} axis by its restored Svalbard palaeomagnetic data.
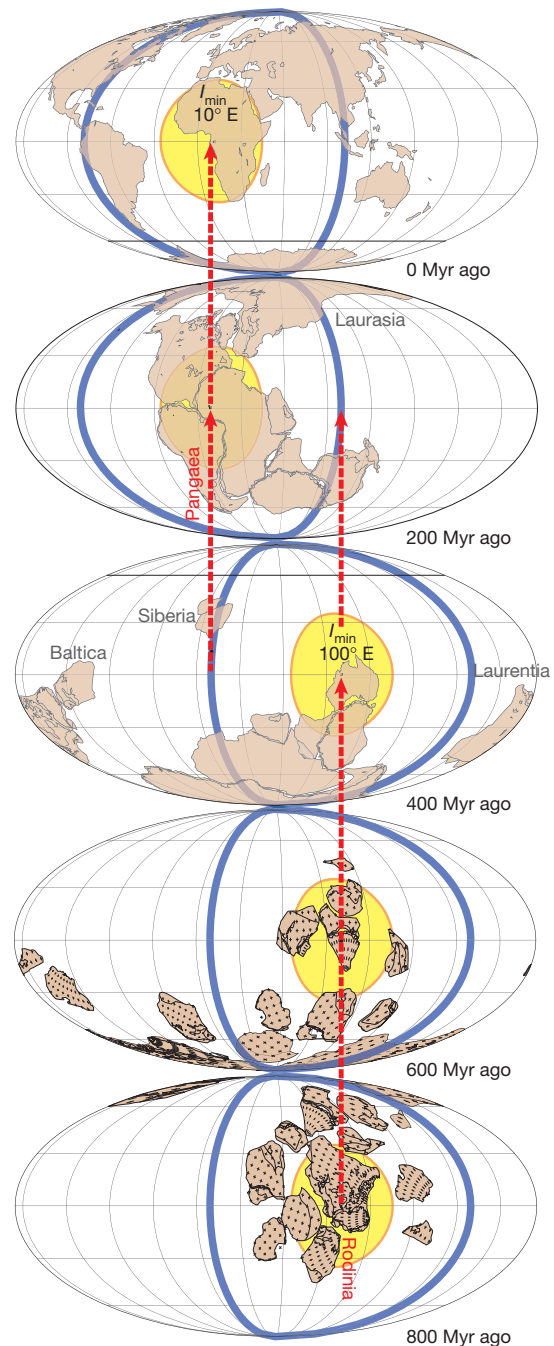
Figure 3 | Absolute palaeogeographic maps. Since 260 Myr ago, each I_{min} about which TPW occurred is pinned at $0°$ N, $10°$ E. Before 260 Myr ago, continents are rotated in palaeolongitude such that the Rodinian I_{min} is ideally 'orthoverted' at $0°$ N, $100°$ E. Yellow equatorial circles represent supercontinent-induced mantle upwellings (not showing the antipodal upwellings such as under the Pacific Ocean), and orthogonal blue great-circle swaths represent subduction girdles (as in Fig. 1). See text for details and Supplementary Tables 3, 4 and 5 for absolute reconstruction parameters. An animation for the past 500 million years is also included in the Supplementary Information.

If a supercontinent-induced two-cell mantle topology[6] drives the supercontinent cycle by orthoversion, can we predict plate motions during supercontinental transitions? Generally, orthoversion may not be expected to disaggregate a supercontinent entirely in order to form its successor because the new centroid is only a half-hemisphere away (as opposed to the extroversion model, for example). It would not be possible to predict, however, which newly rifted continent that had been peripheral to the predecessor would become the central

nucleation point for the succeeding supercontinent. The orthoversion pattern is perhaps best embodied in the present tectonic transition from Pangaea to Amasia, in which rifted fragments of Gondwanaland are reassembling in Eurasia[27]: most recently India and Arabia, imminently Africa, more distantly Australia, and possibly Antarctica (Fig. 1c). In particular, the most distant continent, Australia, advanced eastward only to the circum-Pangaean subduction girdle[28] before turning northward and accelerating towards Asia[24].

Two related implications of the orthoversion model of the supercontinent cycle concern mantle convection. First, orthoversion provides the missing geodynamic model to explain the enigmatic closure of the early Palaeozoic Rheic–Iapetus ocean system and thus resolve the Pangaea "conundrum"[9]: the Rheic–Iapetus oceanic tract originated about 90° away from Rodinia's centroid (Fig. 3) and was thus destined for continent–continent collision and a central position in Pangaea, irrespective of its young age. One can regard the Indian Ocean as a present-day Iapetus–Rheic-like young oceanic system that opens and closes in a single hemisphere, as the ring of subduction around the rifting supercontinent prevents the Indian Ocean from widening further. Rifted terranes, like Avalonia and Carolinia in the Iapetus–Rheic oceanic system, and India and the multitude of other Eurasian blocks in the Tethys-Indian oceanic system, traverse the young ocean system only to reassemble in the broad subduction girdle inherited from the Pangaean two-cell convective planform[6].

Second, the orthoversion model implies that the antipodal upwellings underneath the African and Pacific plates today have existed only since the creation of Pangaea[29,30], not earlier[15,16]. Reorganization of global mantle convection by only 90° every 700 million years is a slow enough process to distinguish long-lived geochemical tracers from separate reservoirs in mantle-derived basalts[15,31,32] and also to accommodate the observed sizes of African and Pacific large low-velocity provinces[33] in the context of reasonable amounts of entrainment by normal rates of whole-mantle convection through hundreds of millions of years.

METHODS SUMMARY

For each of the six time intervals, I_{min} is calculated as the pole to the best-fitted great circle to a swath of palaeomagnetic poles (Fig. 2; Supplementary Table 1) relative to a given reference frame during proposed intervals of TPW: 200–90 Myr relative to South Africa, 260–220 Myr relative to South Africa, 550–490 Myr relative to South Africa, 650–560 Myr relative to South Africa, 805–790 Myr relative to Laurentia, and 1,165–1,015 Myr relative to Laurentia (Supplementary Table 2). Reconstructions from 260 Myr ago to the present are taken from ref. 24, modified slightly in absolute palaeolongitude such that the I_{min} axes align with 010° E (ref. 25) throughout each of the two TPW-defined time intervals (Supplementary Table 3). For 500–370 Myr ago, the four continents Gondwanaland (reconstructed in Supplementary Table 4), Siberia, Baltica and Laurentia are constrained in palaeolatitude according to palaeomagnetic poles (Supplementary Table 1) in 20-Myr running-mean APW paths from various summary models (Supplementary Table 5), and constrained in palaeolongitude according to our idealized orthoversion model of early Palaeozoic TPW around 100° E (including an additional proposed TPW oscillation at 450–375 Myr ago[12]). The animation in the Supplementary Information from 500 Myr ago to the present uses our global rotation model, which incorporates kinematic interpolations seeking to minimize rates of absolute motions between TPW-defined intervals, while also minimizing areas of cratonic overlap and conforming to the global tectonic record. This model is formatted (Supplementary Table 6) for the GPlates freeware (www.gplates.org), which provides continuous kinematic interpolation shown at two-million-year intervals (animation in the Supplementary Information). The 800-Myr and 600-Myr reconstructions (Fig. 3) are slightly modified from ref. 19.

Full Methods and any associated references are available in the online version of the paper at www.nature.com/nature.

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1. Nance, R. D., Worsley, T. R. & Moody, J. B. The supercontinent cycle. *Sci. Am.* **259**, 72–79 (1988).
2. Hartnady, C. J. H. About turn for supercontinents. *Nature* **352**, 476–478 (1991).
3. Hatton, C. J. The superocean cycle. *S. Afr. J. Geol.* **100**, 301–310 (1997).
4. Veevers, J. J., Walter, M. R. & Scheibner, E. Neoproterozoic tectonics of Australia—Antarctica and Laurentia and the 560 Ma birth of the Pacific Ocean reflect the 400 m.y. Pangean supercycle. *J. Geol.* **105**, 225–242 (1997).
5. Evans, D. A. D. True polar wander and supercontinents. *Tectonophysics* **362**, 303–320 (2003).
6. Zhong, S. J., Zhang, N., Li, Z. X. & Roberts, J. H. Supercontinent cycles, true polar wander, and very long-wavelength mantle convection. *Earth Planet. Sci. Lett.* **261**, 551–564 (2007).
7. Steinberger, B. & Torsvik, T. H. Absolute plate motions and true polar wander in the absence of hotspot tracks. *Nature* **452**, 620–623 (2008).
8. Hoffman, P. F. in *Earth Structure: An Introduction to Structural Geology and Tectonics* (eds van der Pluijm, B. & Marshak, S.) 459–464 (McGraw-Hill, 1997).
9. Murphy, J. B., Nance, R. D. & Cawood, P. A. Contrasting modes of supercontinent formation and the conundrum of Pangea. *Gondwana Res.* **15**, 408–420 (2009).
10. Gold, T. Instability of the Earth's axis of rotation. *Nature* **175**, 526–529 (1955).
11. Mitchell, R. N., Evans, D. A. D. & Kilian, T. M. Rapid Early Cambrian rotation of Gondwana. *Geology* **38**, 755–758 (2010).
12. Van der Voo, R. True polar wander during the middle Paleozoic? *Earth Planet. Sci. Lett.* **122**, 239–243 (1994).
13. Caputo, M. V. & Crowell, J. C. Migration of glacial centers across Gondwana during Paleozoic Era. *Geol. Soc. Am. Bull.* **96**, 1020–1036 (1985).
14. Schmidt, P. W. & Williams, G. E. Ediacaran palaeomagnetism and apparent polar wander path for Australia: no large true polar wander. *Geophys. J. Int.* **182**, 711–726 (2010).
15. Burke, K., Steinberger, B., Torsvik, T. & Smethurst, M. Plume generation zones at the margins of large low shear velocity provinces on the core–mantle boundary. *Earth Planet. Sci. Lett.* **265**, 49–60 (2008).
16. Torsvik, T., Burke, K., Steinberger, B., Webb, S. J. & Ashwal, L. D. Diamonds sampled by plumes from the core-mantle boundary. *Nature* **466**, 352–355 (2010).
17. Forsyth, D. & Uyeda, S. On the relative importance of the driving forces of plate motion. *Geophys. J. Int.* **43**, 163–200 (1975).
18. Maloof, A. C. *et al.* Combined paleomagnetic, isotopic, and stratigraphic evidence for true polar wander from the Neoproterozoic Akademikerbreen Group, Svalbard, Norway. *Geol. Soc. Am. Bull.* **118**, 1099–1124 (2006).
19. Li, Z. X. *et al.* Assembly, configuration, and break-up history of Rodinia: a synthesis. *Precambr. Res.* **160**, 179–210 (2008).
20. Evans, D. A. D. & Mitchell, R. N. Assembly and breakup of the core of Paleoproterozoic-Mesoproterozoic supercontinent Nuna. *Geology* **39**, 443–446 (2011).
21. Swanson-Hysell, N. L., Maloof, A. C., Weiss, B. P. & Evans, D. A. D. No asymmetry in geomagnetic reversals recorded by 1.1-billion-year-old Keweenawan basalts. *Nat. Geosci.* **2**, 713–717 (2009).
22. Li, Z. X., Evans, D. A. D. & Zhang, S. A 90 degrees spin on Rodinia: possible causal links between the Neoproterozoic supercontinent, superplume, true polar wander and low-latitude glaciation. *Earth Planet. Sci. Lett.* **220**, 409–421 (2004).
23. Macdonald, F. A. *et al.* Calibrating the Cryogenian. *Science* **327**, 1241–1243 (2010).
24. Torsvik, T. H., Müller, R. D., Van der Voo, R., Steinberger, B. & Gaina, C. Global plate motion frames: toward a unified model. *Rev. Geophys.* **46**, http://dx.doi.org/10.1029/2007RG000227 (2008).
25. Pavoni, N. Present true polar wander in the frame of the Geotectonic reference system. *Swiss J. Geosci.* **101**, 629–636 (2008).
26. McCausland, P. J. A., Hankard, F., Van der Voo, R. & Hall, C. M. Ediacaran paleogeography of Laurentia: paleomagnetism and 40Ar-39Ar geochronology of the 583 Ma Baie des Moutons syenite, Quebec. *Precambr. Res.* **187**, 58–78 (2011).
27. Şengör, A. M. C. Mid-Mesozoic closure of Permo-Triassic Tethys and its implications. *Nature* **279**, 590–593 (1979).
28. Collins, W. J. Slab pull, mantle convection, and Pangaean assembly and dispersal. *Earth Planet. Sci. Lett.* **205**, 225–237 (2003).
29. Evans, D. A. D. Proposal with a ring of diamonds. *Nature* **466**, 326–327 (2010).
30. Li, Z. X. & Zhong, S. Supercontinent-superplume coupling, true polar wander and plume mobility: plate dominance in whole-mantle tectonics. *Phys. Earth Planet. Inter.* **176**, 143–156 (2009).
31. Deschamps, F., Kaminski, E. & Tackley, P. J. A deep mantle origin for the primitive signature of ocean island basalt. *Nature Geosci.* **4**, 879–882 (2011).
32. Gonnermann, H. M. & Mukhopadhyay, S. Preserving noble gases in a convecting mantle. *Nature* **459**, 560–563 (2009).
33. Garnero, E. J., Lay, T. & McNamara, A. K. Implications of lower mantle structural heterogeneity for existence and nature of whole mantle plumes. *Geol. Soc. Am. Spec. Pap.* **430**, 79–101 (2007).

Author Contributions R.N.M. developed the conceptual idea for the study, D.A.D.E. assembled input data and developed statistical methods, and T.M.K. executed calculations and generated reconstructions and animations. All authors contributed to discussions and the writing of the manuscript.

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METHODS

To test between introversion ($0°$), extroversion ($180°$), or orthoversion ($90°$) models of the supercontinent cycle, one must quantitatively determine the centres of supercontinents and measure the angular distance between successive supercontinent centres. Pangaea's centre can be determined by post-Pangaean seafloor-spreading reconstructions of continents and large igneous provinces, allowing for precise determination of the supercontinent's centre of mass[24] or four oscillatory rotations shared by all continents about an equatorial Euler pole (which is I_{min} according to the TPW hypothesis) in the aftermath of Pangaea[7]; this I_{min} axis closely coincides with two antipodal large low-shear-wave-velocity provinces at the core–mantle boundary underneath Africa and the Pacific imaged by present-day seismic tomography[34].

For each of the six time intervals, I_{min} is calculated as the pole to the best-fit great-circle to a swath of palaeomagnetic poles (Fig. 2; Supplementary Table 1) relative to a given reference frame during proposed intervals of TPW: 200–90 Myr relative to South Africa, 260–220 Myr relative to South Africa, 550–490 Myr relative to South Africa, 650–560 Myr relative to South Africa, 805–790 Myr relative to Laurentia, and 1,165–1,015 Myr relative to Laurentia (Supplementary Table 2). We limit our calculation of Rodinia's I_{min} to the 650–360-Myr APW path for Gondwanaland and Australia alone before the Early Cambrian period (Fig. 2a). Poles from Gondwanaland are rotated into South African coordinates (Supplementary Table 4). The Rodinian I_{min} for Laurentia (Fig. 2b) is affected by the rotation of Svalbard to Laurentia[18,35] but our results do not change significantly if geologically reasonable juxtapositions are considered. Confidence limits on the poles to great circles (Supplementary Table 1) are calculated using the software package of ref. 36 employing two alternative statistical methods[37,38]. For the 800-Myr I_{min} calculation, the method of ref. 37 cannot be used for $N < 4$ and so we use the mean angular deviation method of ref. 38, which probably overestimates error. Errors on and angular distances between successive I_{min} axes were calculated by numerical bootstrap methods following ref. 39.

Reconstructions from 260 Myr ago to the present are taken from ref. 24, modified slightly in absolute palaeolongitude such that the I_{min} axes align with $010°$ E (ref. 25) throughout each of the two TPW-defined time intervals (Supplementary Table 3). For 500–370 Myr ago, the four continents Gondwanaland (reconstructed in Supplementary Table 4), Siberia, Baltica and Laurentia are constrained in palaeolatitude according to palaeomagnetic poles (Supplementary Table 1) in 20-Myr running-mean APW paths from various summary models (Supplementary Table 5), and in palaeolongitude according to our idealized orthoversion model of early Palaeozoic TPW around $100°$ E (including an additional proposed TPW oscillation at 450–375 Myr ago[12]. The animation from 500 Myr ago to the present (in the Supplementary Information) uses our global rotation model, which incorporates kinematic interpolations seeking to minimize rates of absolute motions between TPW-defined intervals, while also minimizing areas of cratonic overlap and conforming to the global tectonic record. Minor problems with overlapping plates in Pangaea, which have generated discussion on non-dipole geomagnetic field behaviour[40] are taken 'as is' from the smoothed pole paths without correction. This model is formatted (Supplementary Table 6) for the GPlates freeware (www.gplates.org) that provides continuous kinematic interpolation shown at two-million-year intervals (animation in the Supplementary Information). An alternative animation in the Supplementary Information demonstrates that the solution where I_{min} is held constant, prompted by the model where geoid highs are stable through time[16], involves much more east–west motion than the orthoversion model. The fixed I_{min} solution requires about $60°$ of east–west motion over 60 Myr.

Kinematics before 500 Myr ago are more speculative, and the illustrated snapshots at 600 and 800 Myr ago (Fig. 3) are merely indicative of plausible global palaeogeographies. The 800- and 600-Myr-ago reconstructions are slightly modified from ref. 19. Aside from Gondwanaland and Laurentia at 600 Myr ago, other cratons are reconstructed according to a recent model for Rodinia break-up[41].

34. Becker, T. W. & Boschi, L. A comparison of tomographic and geodynamic mantle models. *Geochem. Geophys. Geosyst.* **3,** http://dx.doi.org/10.1029/2001GC000168 (2002).
35. Evans, D. A. D. The paleomagnetically viable, long-lived and all-inclusive Rodinia supercontinent reconstruction. *Geol. Soc. Lond. Spec. Publ.* **327,** 371–404 (2009).
36. Cogne, J. P. PaleoMac; a Macintosh™ application for treating paleomagnetic data and making plate reconstructions. *Geochem. Geophys. Geosyst.* **4,** 1007 (2003).
37. Mardia, K. V. & Gadsden, R. J. A small circle of best fit for spherical data and areas of vulcanism. *J. R. Statist. Soc. C* **26,** 238–245 (1977).
38. Kirschvink, J. L. The least-squares line and plane and the analysis of palaeomagnetic data. *Geophys. J. R. Astron. Soc.* **62,** 699–718 (1980).
39. McFadden, P. L. A new fold test for palaeomagnetic studies. *Geophys. J. Int.* **103,** 163–169 (1990).
40. Torsvik, T. & Van der Voo, R. Refining Gondwana and Pangea palaeogeography: estimates of Phanerozoic non-dipole (octupole) fields. *Geophys. J. Int.* **151,** 771–794 (2002).
41. Li, Z. X. & Evans, D. A. D. Late Neoproterozoic $40°$ intraplate rotation within Australia allows for a tighter-fitting and longer-lasting Rodinia. *Geology* **39,** 39–42 (2011).