Rapid Early Cambrian rotation of Gondwana

Ross N. Mitchell, David A.D. Evans, and Taylor M. Kilian
Department of Geology and Geophysics, Yale University, 210 Whitney Avenue, New Haven, Connecticut 06511, USA

ABSTRACT

Based on the history of Mesozoic–Cenozoic plate motions, as well as simple dynamical considerations, a "speed limit" for tectonic plates has been suggested at ~20 cm/yr. Previous paleomagnetic data from the Early Cambrian of Gondwana are conflicting but generally imply rapid motions approaching that limit. Herein we describe results from a continuous paleomagnetic sampling of Lower to Middle Cambrian strata from the Amadeus Basin, central Australia. We find characteristic remanence directions that show an ~60° declination shift through the section. Assuming a tectonically assembled Gondwana supercontinent by Early Cambrian time, this large vertical-axis rotation of its Australian sector corresponds to an equally large translation across paleolatitudes for its Brazilian and West African sectors. Analysis of all high-quality paleomagnetic data from Gondwana both confirms and constrains the 60° rotation to have occurred toward the end of Early Cambrian time, at rates exceeding 16 $^{+12}/_{-8}$ cm/yr. These observations suggest that either nonuniformitarian plate tectonics or an episode of rapid true polar wander occurred during the Cambrian "explosion" of animal life.

INTRODUCTION

The Proterozoic–Cambrian transition—when animal life abruptly evolved and diversified—is one of the most enigmatic periods in Earth history. The enigmas pervade well beyond the biosphere: Explanations for massive (>3‰) and sudden (<100 k.y.) carbon isotopic excursions (Kirschvink and Raub, 2003; Maloof et al., 2005) and sweeping (>60°) and rapid (<50 m.y.) motions of numerous continents (Grunow and Encarnacion, 2000; Kirschvink, 1992; Kirschvink et al., 1997; Meert et al., 1993; Trindade et al., 2006) elude concession and invite debate.

Assessing the terminal Proterozoic and Cambrian global paleomagnetic database, Kirschvink and colleagues (Kirschvink, 1992; Kirschvink et al., 1997) hypothesized a near-90° rotation of multiple continents, at rates fast enough to suggest true polar wander (TPW)—the wholesale rotation of solid Earth (mantle and crust) about the liquid outer core to reinstate inertial alignment with the rotation axis. As a geophysical mechanism, TPW has long been theoretically and mechanically understood (Gold, 1955; Goldreich and Toomre, 1969) and has been both computationally (Richards et al., 1997; Steinberger and O'Connell, 1997) and qualitatively (Evans, 2003) modeled. Three oscillatory, seemingly wholesale rotations of all continents about an equatorial Euler pole (likely TPW) have now been observed in Mesozoic to Cenozoic time, during the breakup of Pangea (Steinberger and Torsvik, 2008). Empirical evidence for large-magnitude TPW in Earth's earlier geologic record, however, is often hotly debated (Raub et al., 2007).

Recently, a study documenting evidence for a pair of TPW events during the mid-Neoproterozoic (Maloof et al., 2006) illustrates an increasingly powerful method for testing the TPW hypothesis: paleomagnetic sampling of continuous sedimentary successions. This method goes far to eliminate putative caveats, such as wholesale or partial remagnetizations and local vertical-axis rotations. In this paper we reinvestigate the Cambrian apparent polar wander (APW) path of Australia and assess the possibilities of TPW and nonuniformitarian plate motions, by presenting high-quality paleomagnetic data from a single stratigraphic succession in the Amadeus Basin of central Australia.

GEOLOGIC SETTING

In its central location on the Australian craton, the Amadeus Basin (>150,000 km^2 of areal extent) evolved over 500 m.y., from the mid-Neoproterozoic to the Carboniferous. The reference stratigraphic section along Ellery Creek (Warren and Shaw, 1995) (23.8°S, 133.1°E) includes Arumbera Sandstone, Hugh River Shale, and Jay Creek Limestone (Figs. 1 and 2B). The Ellery Creek area is unique across the 300-km-long MacDonnell Ranges, in exposing substantial portions of the recessive, valley-forming Hugh River Shale. Preliminary paleomagnetic study at this location (Embleton, 1972) documented a more simple and stable characteristic remanence than was found in age-correlative carbonate sections farther east along the MacDonnell Ranges homocline (Klootwijk, 1980).

The upper Arumbera Sandstone correlates laterally to the Todd River Dolostone, in which archaeocyathids and phosphatic small shelly fossils suggest a late Atdabanian age (Gravestock and Shergold, 2001) (ca. 520 Ma; Maloof et al., 2005). The overlying Hugh River Shale and Jay Creek Limestone have been laterally correlated to the Shannon Formation of the eastern, carbonate-rich lobe of the Amadeus Basin (Gravestock and Shergold, 2001) (Fig. DR1 in the GSA Data Repository[1]). The Hugh River Shale should accordingly have late Templetonian to Floran and late Undillan ages on either side of a late Floran to early Undillan depositional hiatus. After another short early Boomerangian hiatus, brachiopods, hyoliths, gastropods, monoplacophorans, and trilobites in the Jay Creek Limestone indicate a late Middle Cambrian (late Boomerangian) age, as young as 501 Ma (Shergold, 1986).

METHODS

Oriented cores were drilled in the field using a stratigraphic (versus site-based) sampling approach. Sun-compass observations

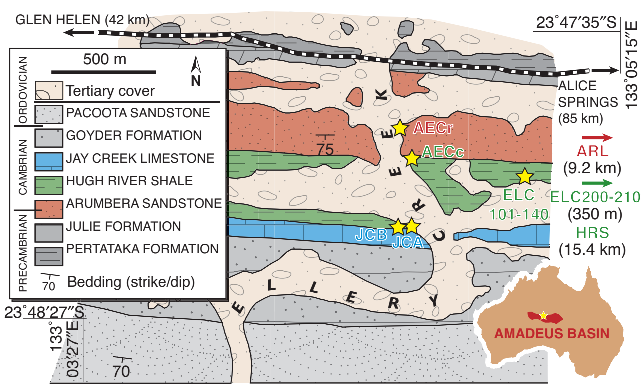


Figure 1. Ellery Creek section. Outline of Amadeus Basin of Australia in lower right. Relevant stratigraphy on left, with sampled units color-coded (same in Fig. 2). Stars indicate sampled levels within continuous Ellery Creek section. JCA and JCB are parallel sections ~100 m apart. Sections that plot east of the map are tied into the section at Ellery Creek owing to continuous lateral exposure (see detailed stratigraphy in Fig. 2B). Map modified from Warren and Shaw (1995).

[1]GSA Data Repository item 2010204, supplementary text, four figures, two tables, and references, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

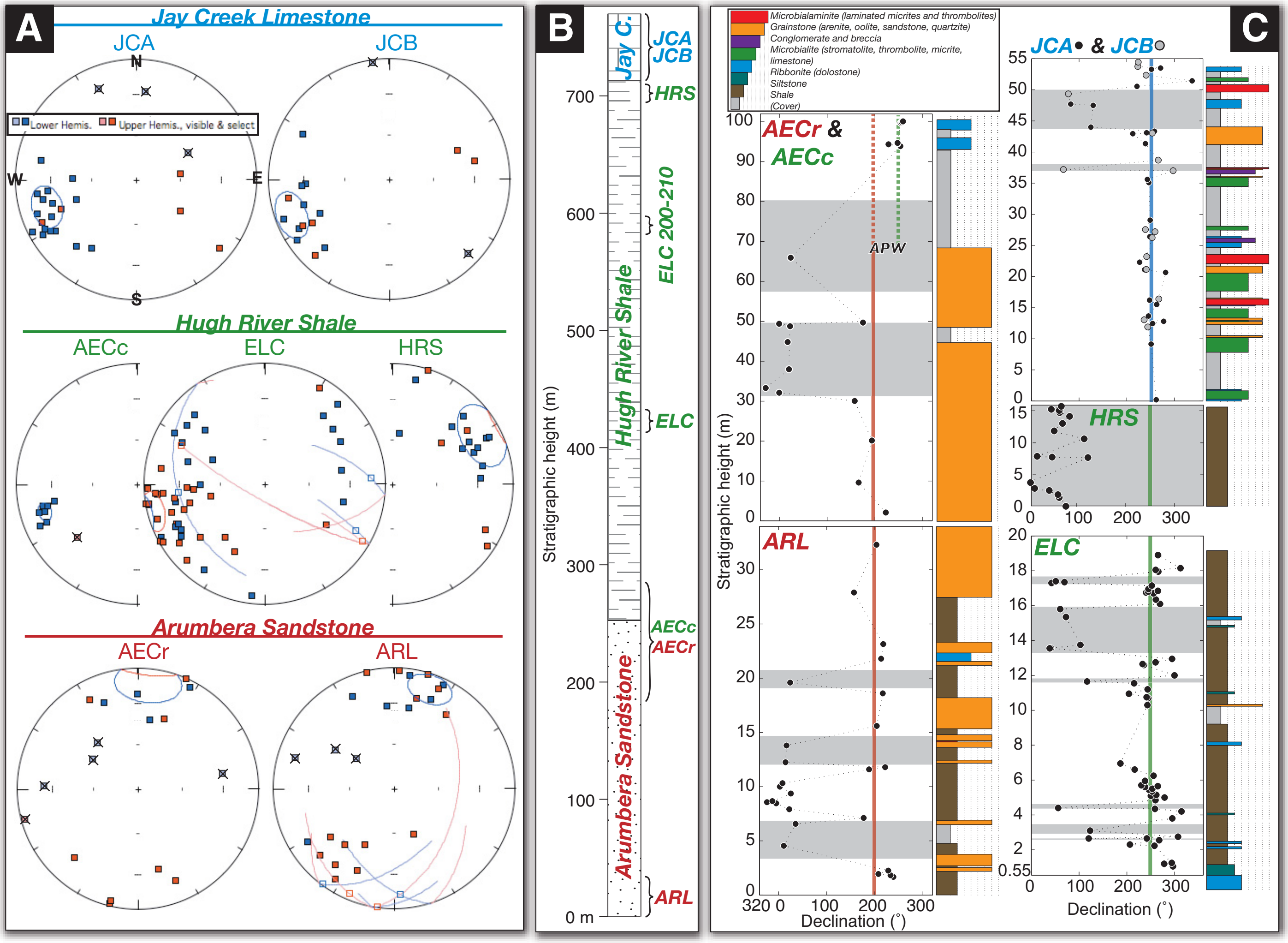


Figure 2. Paleomagnetic directions through Ellery Creek section. A: Stereonet of characteristic remanent magnetizations by stratigraphic level. Faint, crossed-out data points have not been included in calculation of Fisher mean ellipses, *P* = 0.05 (see Table DR1 [see footnote 1]). B: Sampling of Ellery Creek section. C: Combined litho- and magnetostratigraphy showing the migration of declination through the section and regular alternation between white and gray magnetochrons. "APW", apparent polar wander, indicates where ~60° shift in declination occurs, where vertical bars show mean declination values. Parallel sections JCA and JCB (Fig. 1) are plotted together with different symbols.

were made whenever possible to ensure an accurate measure of the local magnetic declination. Remanent magnetization measurements were made with a 2G-Enterprises DC SQuID magnetometer with background noise sensitivity of 5 × 10^{-12} A m^2 per axis. The magnetometer is equipped with computer-controlled, online alternating-field demagnetization coils and an automated vacuum pick-and-put sample-changing array (Kirschvink et al., 2008). Samples and instruments are housed in a magnetically shielded room with residual fields less than 500 nT throughout the demagnetization procedures.

After measuring the natural remanent magnetization (NRM) of all samples, random magnetic field components were removed from all samples with incremental alternating-field demagnetization at 2, 4, 6, 8, and 10 mT. Next, all samples were thermally demagnetized in steps of 5–25 °C up to 676 °C (or until thoroughly demagnetized or unstable, for an average of 20–25 thermal steps per specimen) in a magnetically shielded ASC furnace (±2 °C error) in a nitrogen atmosphere. Magnetic components were computed for each sample using principal-component analysis (Kirschvink, 1980) as implemented in Paleomag OS X (Jones, 2002). Paleomagnetic poles from previous work have been compiled and compared using the computer program PaleoMac (Cogne, 2003).

RESULTS

Paleomagnetic samples from all three formations—Arumbera Sandstone, Hugh River Shale, and Jay Creek Limestone—shared two broadly similar magnetic components: a low-stability component coincident with the present local geocentric axial dipole field, and a high-stability component of varying orientations. Alternating-field demagnetization removed appreciable amounts of magnetization from carbonate samples (Jay Creek Limestone [JCA, JCB] and dolostone horizons of the Hugh River Shale [AECc]; Fig. DR2A) but only small amounts from red-bed samples (Arumbera Sandstone [AECr, ARL] and Hugh River Shale [ELC, HRS]; Fig. DR2B). Sequential thermal demagnetization removed the present-field component by ~250 °C (150–300 °C range) for carbonates and by ~400 °C (150–565 °C range) for red beds (Fig. DR3). Characteristic remanent magnetizations (Table DR1 in the GSA Data Repository) were defined by fitting either a linear decay to the origin (70% of data; Figs. DR2A and DR2B), a stable end point on the equal-area plot (Fig. DR2C), or in rare cases a best-fit demagnetization plane (Fig. DR2D). All of these data fits were forced through the origin. Most of the stable end point data fits

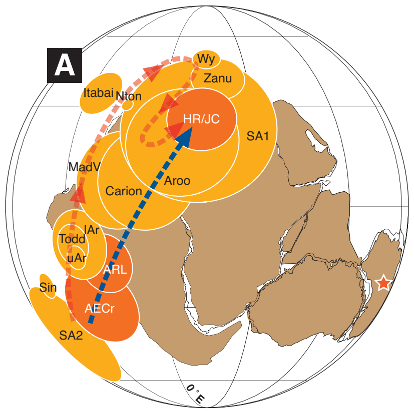
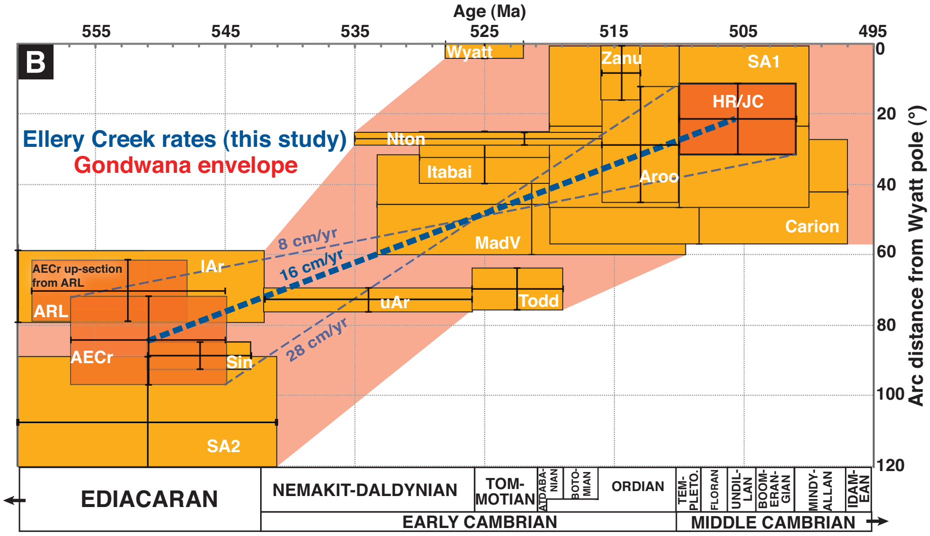


Figure 3. Polar wander of Gondwana from late Ediacaran through Early and Middle Cambrian. A: Paleomagnetic poles from Gondwana constituents, where orange are poles from this study and yellow are extant poles for Gondwana (Table DR2 and supplementary text in the GSA Data Repository). Orange star indicates sampling locality. Blue arc is great-circle fit to poles from this study. Red path modeled after Trindade et al. (2006) to satisfy all Gondwana poles. B: Arc distance motion of South Pole relative to Gondwana, measured relative to Wyatt (Wy) pole. Dashed lines indicate constant linear velocities as constrained by new data from Australia (orange). Red envelope includes all high-quality data from Gondwana (yellow and orange).



characterized highly stable >650 °C magnetic components likely carried by low-Ti hematite.

Although the characteristic remanence directions of the Arumbera Sandstone are somewhat scattered (Fig. 2A), both sections (ARL, AECr) predominantly preserve a dual-polarity magnetization (Fig. 2C) whose equatorial, nearly north-south direction is broadly similar to the classic Arumbera data from the nearby Ross River section (Fig. 3A; Fig. DR4), which are supported by reversal, unconformity, and fold tests (Kirschvink, 1978). Our data further contribute to a regional fold test for the more extensive Ross River study and support the accepted equatorial reconstruction of Australia across the Proterozoic–Cambrian transition.

In all sections, magnetic polarity changes are independent of lithology (Fig. 2C), reducing the likelihood that the characteristic remanence is a two-polarity remagnetization. Data from the Hugh River Shale (ELC and HRS), including dolostone interbeds near the Arumbera–Hugh River stratigraphic transition (AECc), preserve a dual-polarity magnetization (Fig. 2C) whose equatorial, nearly east-west direction agrees with an original, albeit very preliminary, study (Embleton, 1972) (Fig. DR4). The data from the overlying Jay Creek Limestone (JCA, JCB) are statistically indistinguishable (Figs. 2A and 3A; Fig. DR4). Directions from sections ELC, HRS, AECc, JCA, and JCB are merged to yield one mean pole for the Hugh River Shale and Jay Creek Limestone (HR/JC; Fig. 3).

DISCUSSION

The mean magnetization direction of the Hugh River Shale and Jay Creek Limestone (HR/JC) is rotated ~60° clockwise in declination from that of the underlying Arumbera Sandstone (Figs. 2A, 2C, and 3A). This discrepancy cannot be explained parsimoniously by either wholesale remagnetization or local vertical-axis rotation, because the samples derive from one, homoclinal stratigraphic exposure. Furthermore, the younger magnetization is recorded by both carbonate and red-bed lithologies, arguing against any lithologic dependence of paleomagnetic results. Finally, both remanence directions span substantial stratigraphic thicknesses and contain numerous reversals; thus neither can be explained trivially by a geomagnetic excursion.

Our results confirm the earlier observation that during Early Cambrian time, Australia rotated substantially and rapidly about its equatorial position (Kirschvink, 1992; Kirschvink et al., 1997). The angular great-circle distance between the well-constrained Todd River Dolostone (Todd) pole (Kirschvink, 1978) and the combined Hugh River and Jay Creek (HR/JC) pole of this study is 61° ± 16° (error is sum of A95 values for two given poles; Fig. 3A). In the reconstructed Gondwana reference frame (McElhinny et al., 2003), the Australian poles pass over West Africa and South America, so those sectors are inferred to cross paleolatitudes at the same rate as movement along the APW path (Fig. 3A). From our data alone we estimate minimum, maximum, and pole-to-pole linear, constant velocities: 8 cm/yr minimum, 28 cm/yr maximum, and 16 cm/yr from AECr to HR/JC pole (Fig. 3B). High-quality poles from other Gondwana constituents, however, may constrain in more detail the rate of the rapid Early Cambrian rotation of Gondwana as captured in our study.

Indeed, paleomagnetic poles from all sectors form a coplanar swath when reconstructed into a Gondwana paleogeography (McElhinny et al., 2003) (in present northwest Africa coordinates; Fig. 3A; Table DR2; see supplementary text in the Data Repository for discussion of pole list). In a non-TPW interpretation of this motion (i.e., without an equatorial Euler pole), the APW rate (and hence translational rate of motion for West African and South American sectors) represents a minimum estimate of the total rate of motion, which could include an unconstrained paleolongitudinal component. Furthermore, the total APW path length may be more convoluted, such as to satisfy every reliable paleomagnetic pole (Fig. 3), as for one example, the oscillatory path favored by Trindade et al. (2006). The red envelope in Figure 3B includes all reliable poles from Gondwana and implies rates as fast as or faster than our maximum 28 cm/yr estimate from our study of Ellery Creek. The fast rate is compatible with TPW (Tsai and Stevenson, 2007), assuming that the viscosity structure of the mantle during Cambrian time was broadly similar to that of today, when we can study glacioisostatic rebound and the geoid (Hager and Clayton, 1989).

If the existence of widespread archaeocyathid reefs in Morocco implies tropical paleolatitudes, then the 60° pole shift should have interrupted carbonate deposition as northwest Africa translated over the pole (Fig. 3A). It remains to be demonstrated, however, whether the Anti-Atlas margin is autochthonous or has a pre-Ordovician terrane history independent of Africa, thereby obviating this test. If TPW is a viable explanation for the rapid rotation of Gondwana, then its record should be found in paleomagnetic data from other Cambrian paleocontinents. Data from Siberia and Baltica are complex, but large polar shifts of ~60° are not unreasonable (Gallet et al., 2003; Llanos et al., 2005). Translation of Laurentia to higher latitudes and back in the earliest Cambrian is supported by one published result from the Backbone Ranges Formation (Park, 1992), which despite having a perfect quality (Q) rating (Van der Voo, 1990), suffers from merely marginally acceptable numbers of analyzed samples. Even if that result is not reproduced, a TPW interpretation for other continents' APW paths would not be refuted by a single plate moving nearly counter to the TPW (Evans, 2003).

A major, Neoproterozoic-like shift in inorganic carbon isotopes in the Early Cambrian occurs at ca. 525 Ma as observed most prominently in the Anti-Atlas carbonates (Maloof et al., 2005). This major isotopic shift correlates with the peak rate of the paleogeographic rotation (Fig. 3B). TPW has been identified as a potentially profound perturbation for Earth's carbon cycle largely by relocating major depocenters of organic carbon (Maloof et al., 2006; Raub et al., 2007). The same processes would take effect even if Gondwana alone experienced the rapid rotation of ~60°, due to its large length of marine sedimentary margins: Its relocation via rapid plate motion about an Euler pole near Australia could produce a similarly sized isotopic perturbation as TPW. These observations and considerations suggest that either nonuniformitarian plate tectonics or an episode of rapid TPW, or both, translated and rotated Gondwana during the Cambrian "explosion" of animal diversity.

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Online Supplementary Material for:

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This file contains:

Supplementary text

Supplementary figures (Fig. DR1, DR2, DR3, DR4)

Supplementary tables (Table DR1 and DR2)

Supplementary references

SUPPLEMENTARY TEXT

Discussion of Gondwana-Land paleomagnetic compilation. In their study of the Itabaiana mafic dikes, Trindade et al. (2006) provide a reasonably comprehensive review of the highest quality paleomagnetic poles from the Gondwana-Land constituents. Our pole list (Table DR2, Fig. 3) largely reflects theirs. We now discuss those poles included or excluded herein that are excluded or included, respectively, in their study.

A major difference between our pole list and that of Trindade et al. (2006) is their choice to include the numerous poles presented by Klootwijk (1980) from Australia (from oldest to youngest): Hawker Group, Pertaoorta Group, Kangroo Island, Billy Creek, Giles Creek, and Lower Lake Frome. We do not include the Klootwijk (1980) poles because they pre-date the application of principal-component analysis (Kirschvink, 1980), and rely on contour plots for distinguishing presumed primary versus secondary components. It is worth noting that Klootwijk's results do indicate a major declination shift, as we find.

The only result that Trindade et al. (2006) include from Antarctica is from the Sør Rondane intrusions. We exclude Sør Rondane pole because of the large uncertainty of its age, which is estimated from a compilation of U-Pb zircon, Rb-Sr biotite, Rb-Sr whole rock, and Ar/Ar biotite (Grunow, 1995). We tentatively include poles from the Zanuck granite, and from the Wyatt and Ackerman Formations and Mount Paine tonalite (Grunow and Encarnacion, 2000), although we recognize the possibility that they maybe allochthonous to Gondwana-Land at the time of emplacement (Grunow and Encarnacion, 2000; Paulsen et al., 2007). Zanuck granite is well-dated, with cooling estimates for the magnetite blocking temperature range between emplacement age of 521 ± 2 Ma (Encarnacion and Grunow, 1996) (which we use for pole age) and an argon closure age for biotite (i.e., cooling to 300˚C) by 496 ± 3 Ma (Grunow and Encarnacion, 2000). The Zanuck granite pole yields a Van der Voo (1990) reliability Q-value of 4. The combined pole from the Wyatt and Ackerman Formations and Mount Paine tonalite (Grunow and Encarnacion, 2000) yields a Q-value of 6. A Pb/Pb age of 526 ± 2 Ma on zircons from an ash bed within the Wyatt Formation provides a tight, concordant age constraint (Encarnacion and Grunow, 1996). The possibility remains that the Scott Glacier area (and by geologic correlation, north Victoria Land, East Antarctica, and possibly West Antarctica) was part of a terrane that accreted to eastern Gondwana-Land after the Early Cambrian.

We follow Trindade et al.(2006) in the selection of the Ntyona ring structure, Sinyai metadolerite, Madagascar virgation zone, and Carion granite poles for Africa.

Finally, for South America we include Itabaiana dikes pole and two from Sierra de las Animas Complex. Although Itabaiana dikes poles is highly reliable (Q=7), its baked contact test is inconclusive due to a lack of a stable host rock direction away from dike margins. We exclude poles from Equeefa dikes and Mzumbe gneiss because of large errors (524 ± 36 Ma; 2σ standard error from original data). Other Cambrian South American poles from Trindade et al. (2006) (C7, C8, C9, C11) are magmatic overprints with imprecise ages. Refer to Table DR2 for Q-values and references for all poles considered in Figure 3.

SUPPLEMENTARY FIGURES

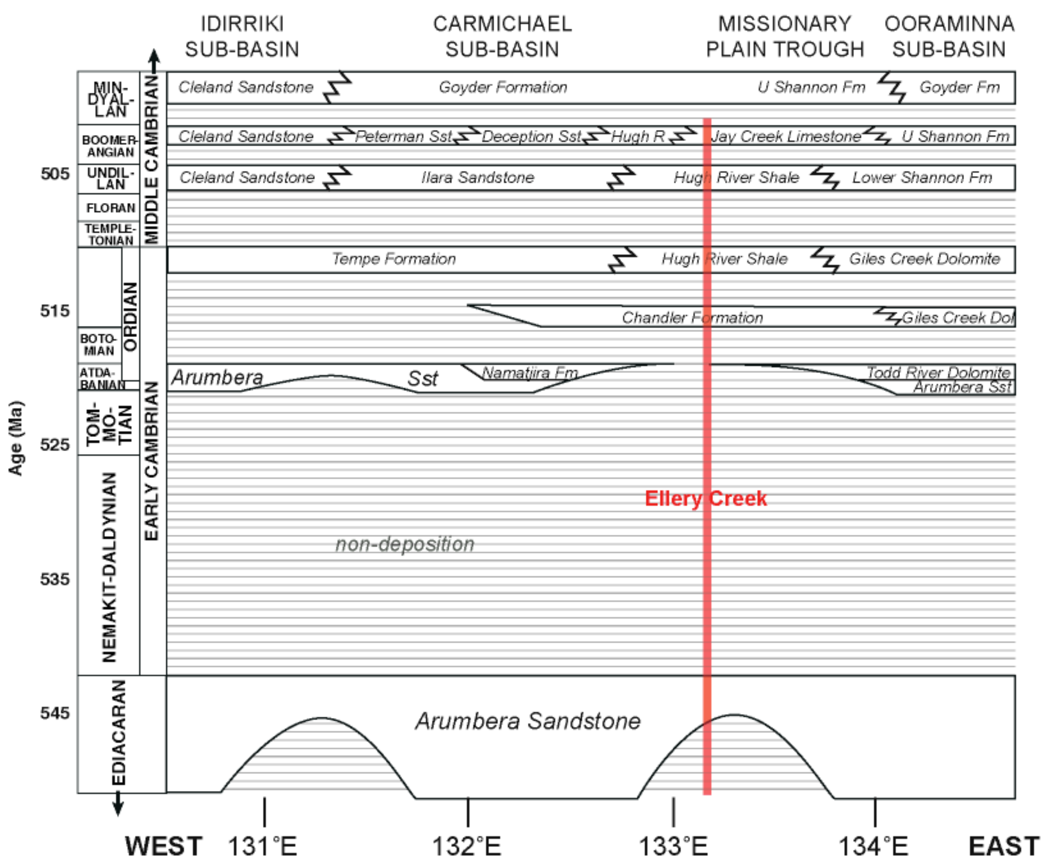

Fig. DR1 Cambrian sequence stratigraphy of the Amadeus Basin showing age ranges of units sampled: upper Arumbera sandstone, Hugh River Shale, and Jay Creek Limestone. Modified after Kennard and Lindsay (1991) and Gravestock and Shergold(2001) according to revised time scale (Maloof et al., 2005). The evaporitic Chandler Formation, although present at 133˚-133.5˚E elsewhere in the Amadeus Basin, is not exposed at Ellery Creek.

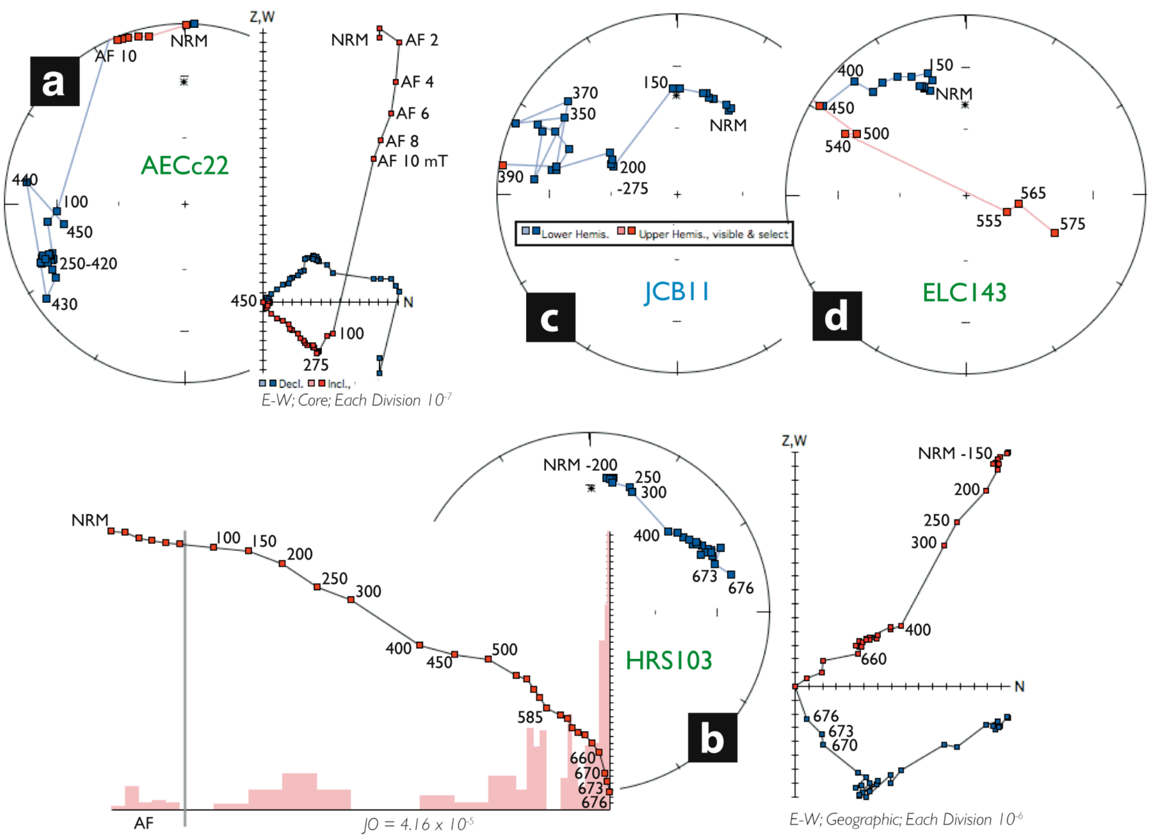

Figure DR2. Example equal area, orthogonal, and normalized intensity (J/J_o) demagnetization projections for (A, B, and D) the Hugh River Shale and (C) the Jay Creek Limestone. See text for a description of the various levels of data quality represented above and employed in the study.

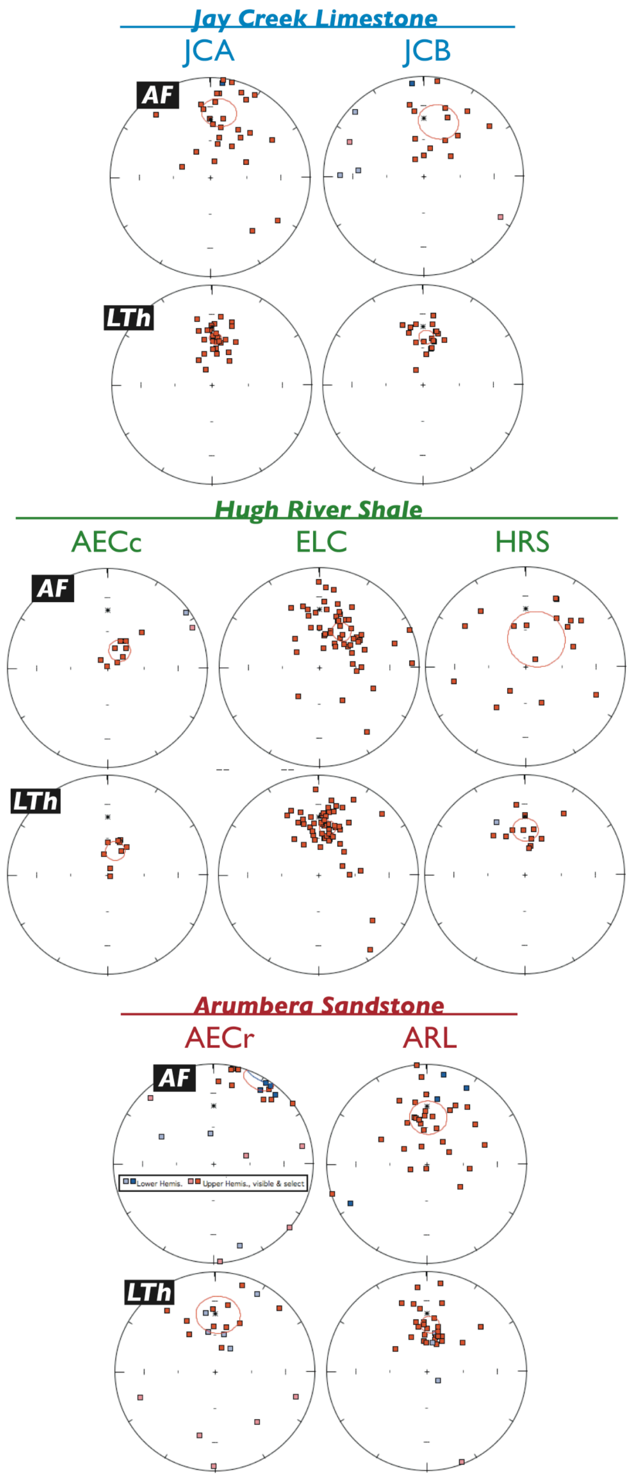

Figure DR3. Equal area projections of low-stability components determined for each site and formation. Components are determined by both demagnetization techniques (used in tandem on all samples) alternating-field (AF) and low thermal demagnetization (LTh).

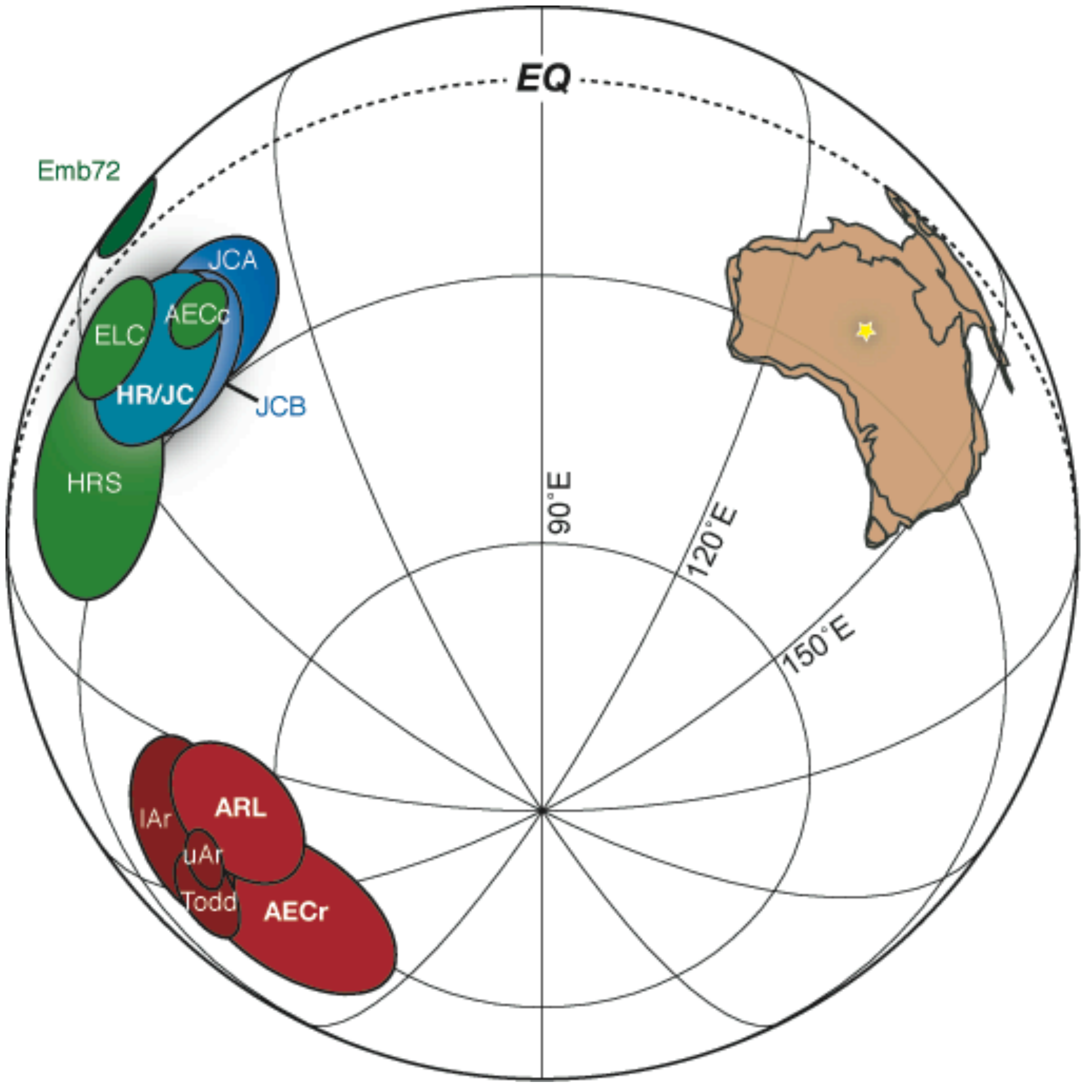

Figure DR4 Paleomagnetic poles from Ellery Creek section. HR/JC is mean paleomagnetic pole from HRS, ELC, JCB, JCA, and AECc from Hugh River Shale and Jay Creek Limestone of this study. 'Emb72' (dark green) is preliminary pole from Hugh River Shale (Embleton, 1972). lAr, uAr, and Todd are poles from lower and upper Arumbera Sandstone and Todd River Dolomite as exposed at Ross River (Kirschvink, 1978). Plot in present-day Australia coordinates. Star indicates sampling locality.

SUPPLEMENTARY TABLES

Table DR1. Calculated mean palaeomagnetic directions in this study and plotted in Fig. 3. ID = identification refers to text, Dec = declination, Inc = inclintion, a95 = radius of circle of 95% confidence, n = samples, Site = latitude and longitude of sampling site, Pole = latitude and longitude of palaeomagnetic pole, A95 = radious of circle of 95% confidence of palaeomagnetic pole, λ = palaeolatitude, ± = uncertainty of palaeolatitude.

ID	Dec (°)	Inc (°)	a95 (°)	n	Site (°N)	Site (°E)	Pole (°N)	Pole (°E)	A95 (°)	λ (°)	±
ARL	199.9	-13.1	12.1	23.0	-23.8	133.1	-53.9	348.1	8.8	-6.6	6.4
AECr	185.6	-11.4	17.6	12.0	-23.8	133.1	-59.9	324.3	12.7	-5.8	9.3
AECc*	253.3	21.5	5.2	7.0	-23.8	133.1	-19.6	46.9	4.0	11.1	2.9
ELC*	256.1	-5.3	10.0	50.5	-23.8	133.1	-11.6	34.9	7.1	-2.7	5.1
HRS*	241.3	-15.4	17.9	17.0	-23.8	133.1	-22.3	23.1	13.2	-7.8	9.7
JCA*	253.1	23.6	12.1	21.0	-23.8	133.0	-20.2	47.9	9.4	12.3	7.0
JCB*	249.8	14.5	13.0	15.0	-23.8	133.5	-21.4	42.2	9.5	7.4	6.9
HR/JC				110.5			-19.3	39.1	10		

*Averaged for HR/JC mean pole.

Table DR2. List of paleomagnetic poles according to craton and position in Gondwana-Land. ID = identification refers to text, Plat and paleomagnetic pole latitude and longitude, respectively, PlatR and Plong = rotated paleomagnetic pole latitude and longitude, respectively, into Northwest Africa Gondwana-Land reference frame according to McElhinny et al. (2003), A95 = radius of circle of 95% confidence, Distance = calculated great circle distance from Wyatt paleomagnetic pole. Ages for biostratigraphically-dated units employ time scale of Maloof et al. (2005). Q-value is paleomagnetic reliability value (Van der Voo, 1990).Explanation of paleomagnetic pole choices are explained in the supplementary text.

Rock Unit by Continent and Sector	ID	Plat (˚N)	Plong (˚E)	PlatR (˚N)	PlongR (˚E)	A95 (˚)	Distance (˚)	Subsystem (Stage)	Age (Ma)	± (Myr)	Age Range Max	Age Range Min	1234567	Q	Reference(s)
East Gondwana-Land															
Australia															
Hugh River Shale (previous)*	Emb72	11.2	37.2	56.8	12.1	6.8		Ordian-Boomerangian			520	501	1000111	4	Embleton (1972)
Hugh River shale, Jay Creek limestone	HR/JC	-19.3	39.1	26.2	13.3	10.0	21.2	Ordian-Boomerangian			520	501	1110111	6	This study
Todd River dolomite, Allua Fm., Eninta Fm.	Todd	-43.2	339.9	-10.9	332.1	5.9	69.6	Tommotian-Atdabanian			526	519	1111111	7	(Kirschvink, 1978)
Aroona Dam sediments	Aroo	-26.0	33.0	19.5	7.2	16.5	28.6	late Botomian-Toyonian			517	513	1000011	3	(Embleton and Giddings, 1974)
Arumbera sandstone (Upper)	uAr	-46.6	337.4	-14.7	332.8	3.5	72.5	early Early Cambrian			542	526	1111111	7	(Kirschvink, 1978)
Arumbera (Lower), Pertatataka Fm. (Upper)	lAr	-44.3	341.9	-11.0	334.0	10.2	68.7	upper Ediacaran			580	542	1111111	7	(Grey and Corkeron, 1998; Kirschvink, 1978)
Antarctica (Mawsonland)															
Zanuck granite	Zanu	-7.1	38.8	39.8	19.0	7.7	8.2				516	513	1110001	4	(Grunow and Encarnacion, 2000)
Wyatt Ackerman Mt. Paine tonalite	Wyatt	1.1	39.3	47.4	14.7	4.0	0.0		526, 524	2,2	528	522	1111011	6	(Encarnacion and Grunow, 1996; Grunow and Encarnacion, 2000)
West Gondwana-Land															
Africa' (Congo and Kalahari)															
Sinyai metadolerite	Sin	-29.0	319.0	-23.2	315.2	3.9	88.5		547	4	551	543	1110101	5	(Meert and Van der Voo, 1996)
Ntonya ring structure	Nton	27.8	344.9	30.4	347.7	1.8	26.8		522	13	535	509	1110111	6	(Briden et al, 1993)
Madagascar															
Carion granite	Carion	-7.0	1.0	8.2	356.9	11.0	42.0		508.5	11.5	520	497	1110011	5	(Meert et al., 2003)
Madagascar virgation zone	MadV	-7.0	353.0	7.8	348.5	14.0	45.5		521.4	11.9	533.3	509.5	1110011	5	(Meert et al., 2001)
South America															
Itabaiana Dikes	Itabai	34.9	314.6	34.7	334.8	7.3	32.2		525	5	530	520	1111111	7	(Trindade et al., 2006)
Sierra de las Animas 1	SA1	6	338	24.1	12.1	22.9	23.4		510	10	520	500	1110111	6	(Sanchez-Bettucci and Rapalini, 2002)
Sierra de las Animas 2	SA2	-17	251	-41.9	307.3	18.5	107.4		551	10	561	541	1010101	4	(Sanchez-Bettucci and Rapalini, 2002)

*Not plotted in Figure 3.

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