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Trading partners: Tectonic ancestry of southern Africa and western Australia, in Archean supercratons Vaalbara and Zimgarn

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ABSTRACT

Original connections among the world's extant Archean cratons are becoming tractable by the use of integrated paleomagnetic and geochronologic studies on Paleoproterozoic mafic dyke swarms. Here we report new high-quality paleomagnetic data from the ~2.41 Ga Widgiemooltha dyke swarm of the Yilgarn craton in western Australia, confirming earlier results from that unit, in which the primary origin of characteristic remanent magnetization is now confirmed by baked-contact tests. The corresponding paleomagnetic pole (10.2°S, 159.2°E, A_{95} = 7.5°), in combination with newly available ages on dykes from Zimbabwe, allow for a direct connection between the Zimbabwe and Yilgarn cratons at 2.41 Ga, with implied connections as early as their cratonization intervals at 2.7–2.6 Ga. The proposed "Zimgarn" supercraton was likely distinct from Vaalbara (Kaapvaal plus Pilbara) at 2.4 Ga, but both of those entities independently fragmented at ca. 2.1–2.0 Ga, reassembling into the Kalahari and West Australian cratons by 1.95–1.8 Ga.

1. Introduction

Fundamental changes across the entire Earth system during the Archean–Paleoproterozoic transition (ca. 3000–2000 Ma) are reflected in global dynamics that became more similar to modern-style plate tectonics through that interval (Condie and Kröner, 2008; Reddy and Evans, 2009), although the kinematic record from that era is currently limited by a dearth of high-quality paleomagnetic data (Evans and Pisarevsky, 2008). However, recent work using a combined paleomagnetic and geochronologic approach on mafic dyke swarms within several Archean cratons, for example Slave (Buchan et al., 2009, 2012), Superior (Evans and Halls, 2010; defining member of the Superia supercraton of Bleeker, 2003), and Vaalbara (de Kock et al., 2009), has started to change this situation, enabling us to test and quantify the original connections that may have existed between them.

The Widgiemooltha mafic dykes of the Yilgarn craton (Western Australia) constitute one of the most prominent dyke swarms of the world's Precambrian shields (e.g., Sofoulis, 1966; Parker et al., 1987). The dykes generally trend east-west and outcrop over the entire craton (Fig. 1). Most of the dykes are of picrite, olivine–dolerite or quartz–dolerite composition and have not been affected by significant metamorphic events since their formation (e.g., Hallberg, 1987).

The age of the Widgiemooltha dyke swarm is constrained by isotopic dating of its three largest dykes. Nemchin and Pidgeon (1998) reported a baddeleyite U–Pb age of 2418 ± 3 Ma for the westernmost extension of the ~600-km-long Binneringie Dyke (Fig. 1). Electron microprobe U–Pb analyses of baddeleyites from an eastern location of the Binneringie Dyke yielded a slightly younger age of 2410.3 ± 2.1 Ma (French et al., 2002). A baddeleyite U–Pb age of 2410.6 + 2.1/−1.6 Ma was also obtained for the Celebration Dyke (Doehler and Heaman, 1998). Fletcher et al. (1987) reported Rb–Sr and Sm–Nd isochron age of 2411 ± 38 Ma for the ultramafic core of the ~180-km-long Jimberlana intrusion, located south of the Binneringie Dyke (Fig. 1). These data broadly confirm the earliest geochronological study of the Widgiemooltha dyke swarm (Turek, 1966), which yielded a 2420 ± 30 Ma Rb–Sr

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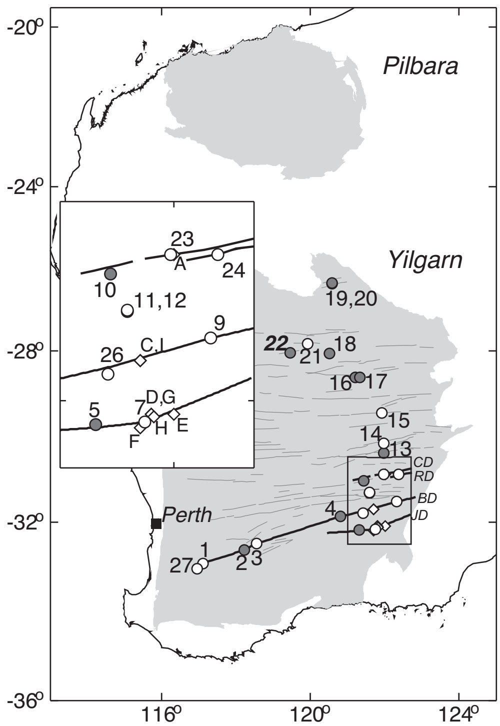

Fig. 1. Locations of sampling sites of this study (circles) and of Evans' (1968) (diamonds) sampling sites. Open (or grey) symbols show the sites used (or not used) to calculate the mean paleomagnetic directions. Shaded areas show the Yilgarn and Pilbara cratons. Thin gray lines indicate the Widgiemooltha dyke swarm; solid lines show the Binneringie (BD), Jimberlana (JD), Celebration (CD), and Randalls (RD) dykes. Inset map shows the area studied by Evans (1968).

age (using a decay constant of $1.39 \times 10^{-11}\,\mathrm{yr}^{-1}$); and the consistency of isotopic ages attests to the excellent preservation of the dykes.

Magnetic surveys show both positive and negative anomalies associated with the Widgiemooltha dykes (e.g., Tucker and Boyd, 1987), suggesting the presence of dual-polarity remanent magnetization. The only previous paleomagnetic study of the Widgiemooltha dyke swarm (Evans, 1968) found remanence directions of both polarities from four independently cooled dykes. However, that study was confined to a limited area in the southeastern Yilgarn (Fig. 1), it did not employ modern demagnetization and processing techniques, and it lacked a rigorous field test to confirm the primary origin of dyke magnetization. Here we report new high-quality paleomagnetic data from the Widgiemooltha dyke swarm, with implications for tectonic style of craton amalgamation and separation during the Archean–Paleoproterozoic transition.

2. Methods

We sampled 27 sites representing 14 separate Widgiemooltha dykes spanning most of the Yilgarn craton (Fig. 1). Five to thirty-two field-drilled oriented core samples were collected from each site. Orientation was done with both solar and magnetic compasses. Low-field thermomagnetic analyses, remanence unblocking temperature and magnetic hysteresis measurements indicate the presence of pseudosingle-domain magnetite or low-Ti titanomagnetite in most dykes (Fig. 2).

Magnetic remanence measurements were conducted at Yale University and Michigan Technological University using automated three-axis DC SQUID 2G rock magnetometers housed in magnetically shielded environments. After measurement of the natural remanent magnetization (NRM), the samples were cycled through the Verwey transition at ∼120 K (Verwey, 1939) by immersing them into liquid nitrogen for about two hours in order to reduce a viscous component carried by larger magnetite grains (Schmidt, 1993). Next, a low alternating field (AF) pre-treatment (to 100 mT in 20 mT steps) was applied to remove any remaining low-coercivity viscous or isothermal remanence. Finally, 15–20 thermal demagnetization steps were performed in an inert (nitrogen) atmosphere. Progressive demagnetization was carried out until the magnetic intensity of the samples fell below noise level or until the measured directions became erratic and unstable (typically at 580–590 °C).

The characteristic remanent magnetization (ChRM) for samples displaying nearly linear demagnetization trajectories was isolated using principal-component analysis (PCA) (Kirschvink, 1980). The best-fit line was used if defined by at least three consecutive demagnetization steps that trended toward the origin and had a maximum angle of deviation (MAD) less than 20°. For the majority of dykes, the ChRM was isolated within a narrow (10–25 °C) temperature range above 520 °C (Figs. 3–5). The mean directions were calculated using Fisher statistics (Fisher, 1953). A site mean was accepted for further calculations if it was obtained from three or more samples, the confidence circle (α_{95}) was smaller than 15°, and the precision parameter k was greater than 50.

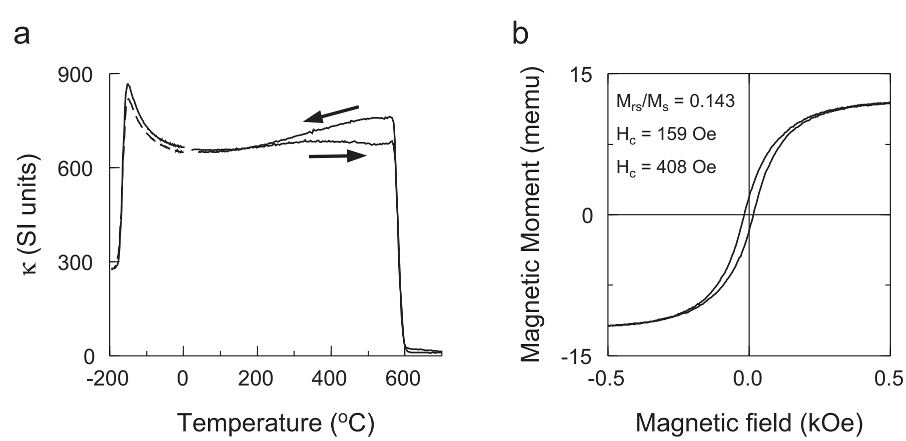

Fig. 2. (a) A typical low-field thermomagnetic curve ($\kappa(T)$) measured in argon from −192 °C to 700 °C using an AGICO KLY-4S magnetic susceptibility meter at Yale University. The $\kappa(T)$ curve indicates the presence of a single magnetic phase with a Curie temperature between 570–580 °C (low-Ti titanomagnetite or magnetite). The presence of nearly stoichiometric magnetite is further supported by a characteristic peak observed at about −153 °C, associated with the Verwey (1939) transition. (b) A typical magnetic hysteresis loop indicating pseudo-single domain behavior of the sample. Abbreviations are H_c, coercivity; H_{cr}, coercivity of remanence; M_{rs}, saturation remanence; M_s, saturation magnetization.

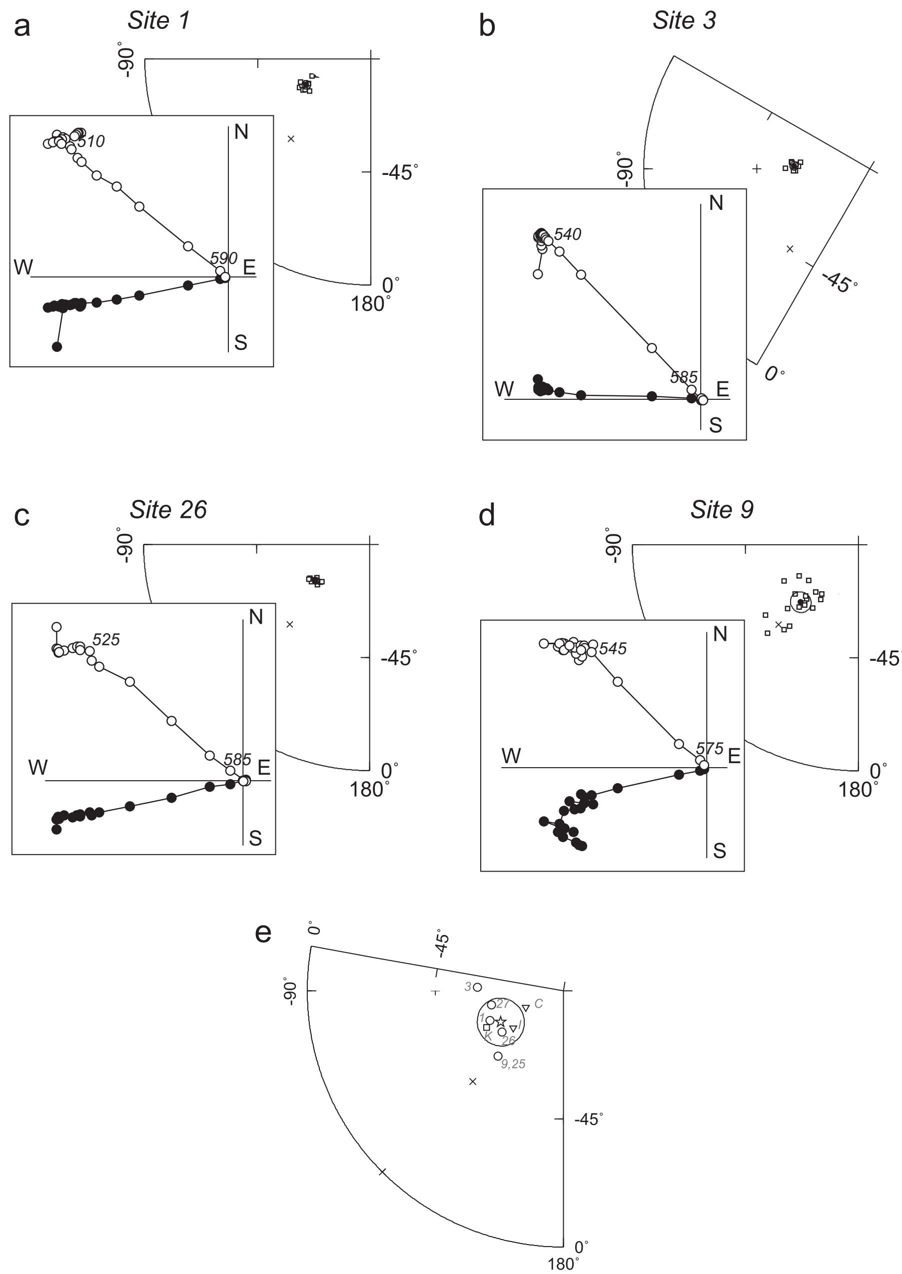

Fig. 3. Paleomagnetic results from the Binneringie dyke. (a–d) Typical orthogonal vector plots of thermal demagnetization (vertical/horizontal projections shown by open/filled symbols). Equal-area plots show the accepted paleomagnetic directions (open squares) and their mean (solid circle) with the 95% confidence circle (α_{95}). Numbers indicate temperature steps (in °C). (e) The site-mean directions from this study (circles) and from Evans (1968) (triangles) used to calculate the mean direction (star) and its α_{95} circle (solid line) for the Binneringie dyke (Table 1). Open square shows the direction from Site K (Evans, 1968) collected from baked granite about five meters from the Binneringie dyke. Although based on only two independently oriented samples (Table 1), the site *K* direction hints at the primary origin of the dyke magnetization.

3. Results

Eighteen sites from thirteen separate dykes yielded well-defined (α_{95} < 15°) site mean directions, including twelve sites (from eight different dykes) that yielded directions consistent with those reported by Evans (1968) (Fig. 6a, Table 1), and the combined dataset yields a paleomagnetic pole at 10.2°S, 159.2°E (A_{95} = 7.5°). The angular dispersion of virtual geomagnetic poles (VGPs) $S = (11.7 \pm 1.9)°$ from the Widgiemooltha dykes is lower than that of 15–17° observed at the comparable latitude band for the last 5 million years (e.g., Johnson et al., 2008). However, the low S value is consistent with the systematically low VGP dispersion values measured from other reliable paleomagnetic datasets of the Neoarchean and Paleoproterozoic age, suggesting more stable geomagnetic field at the Archean–Proterozoic boundary (Smirnov et al., 2011).

Although Evans (1968) found consistent directions between dykes and baked granite host rocks at two sites, those are not strictly positive baked-contact tests because they lack stable, different results from unbaked host rocks. We augment the aggregate Widgiemooltha dataset with positive baked-contact tests confirming the primary age of magnetization in these dykes. First is the inverse baked contact test from Narrogin quarry (Site 1) near the western end of the Binneringie Dyke, where the dyke is cross-cut by a thin, younger, east-west dyke bearing a remanence direction identical to those of the Marnda Moorn large igneous province (LIP), also known in the Narrogin region as Wheatbelt or Fraser dykes (Pisarevsky et al., 2003; Wingate and Pidgeon, 2005) (Table 2;

Table 1
Summary of paleomagnetic results from the Widgiemooltha dykes. Site ID: numbers denote the original sites collected for this study, letters denote the sites from Evans (1968). λ_s, Φ_s are the site latitude and longitude. N is the number of samples used to calculate the paleomagnetic declination (D) and inclination (I); α_{95} and k are the 95% confidence circle and the concentration parameter for paleomagnetic directions. B is the number of sites used for a between-site mean direction. λ_p, Φ_P are the latitude and longitude of the virtual geomagnetic pole (VGP). A_{95} and K are the 95% confidence circle and the concentration parameter for VGP distribution.

Site ID		λ_s (°S)	Φ_s (°E)	N	B	D (°)	I (°)	k	α_{95} (°)	λ_p (°N)	Φ_p (°E)	K	A_{95} (°)
Binneringie	27	33.0	116.95	4		258.9	−64.3	95	9.5	16.3	342.1		
	1	32.94	117.11	11		248.1	−62.3	731	1.7	08.6	339.9		
	3	32.49	118.54	8		272.3	−59.8	1212	1.6	22.1	353.3		
	26	31.80	121.42	9		236.2	−64.1	1607	1.3	2.8	336.8		
	9, 25	31.53	122.32	19		225.1	−57.6	71	4.0	−8.2	336.3		
	C	31.7	121.7	4		246.0	−75.5	26	–[e]	17.9	327.9		
	I	31.7	121.7	4		233.5	−68.0	160	–[e]	5.2	332.2		
	K[a,d]	31.6	122.1	2		244.5	−60.0	25	–[e]				
Mean – Binneringie Dyke[b]					7	245.8	−65.4	75	7.0	9.3	338.3	38	9.9
Mean – Binneringie Dyke (this study only)[b]					5	247.8	−62.7	75	8.9	8.3	341.6	35	13.1
Jimberlana	7	32.16	121.74	7		217.3	−67.1	137	5.2	−1.3	324.8		
	5[d]	32.18	121.31	7		130.4	−42.8	27	11.9				
	D	32.1	121.8	5		260.5	−69.5	166	–[e]	20.0	340.7		
	E	32.1	122.0	3		278.5	−61.0	9	–[e]	26.7	357.3		
	F	32.2	121.7	3		243.0	−66.5	119	–[e]	8.6	338.0		
	G	32.1	121.8	3		252.5	−68.0	166	–[e]	14.7	340.1		
Mean – Jimberlana Dyke					5	251.6	−67.8	71	9.2	13.9	339.8	28	14.8
Other dikes[c]													
	11	31.32	121.59	6		262.7	−65.2	562	2.8	17.9	346.6		
	14	30.18	121.97	16		242.5	−56.4	76	4.3	−1.0	347.1		
	15	29.46	121.93	8		264.8	−68.8	146	4.6	19.9	342.4		
	17[d] King of the Hill Dyke	28.63	121.33	5		354.6	−81.4	51	10.9				
	18[d]	28.06	120.52	7		299.0	−66.1	24	12.5				
	19[d]	26.38	120.59	7		335.5	40.2	500	2.7				
	20[d]	26.36	120.59	10		352.4	−54.4	145	4.0				
	21	27.83	119.92	8		228.3	−61.2	189	4.0	−7.0	333.7		
	22[d]	28.04	119.45	6		356.9	48.5	797	2.4				
	23 Celebration Dyke	30.90	121.97	5		238.1	−67.6	172	5.8	6.2	335.3		
	24 Randalls Dyke	30.90	122.38	7		266.1	−68.1	866	2.5	21.3	344.1		
	A[d,f]	30.9	122.0	3		239.0	−67	25	–[e]	6.1	335.9		
	H	32.1	121.8	7		51.0	73.5	86	–[e]	10.7	325.6		
Total Widgiemooltha mean – This study only					8	245.3	−65.5	92	5.8	8.2	336.0	27	10.9
This study plus Evans (1968), 2 polarities[g]					9	247.5	−66.6	117	4.8	10.2	339.2	48	7.5

[a] Sample from baked granite 5 m away from the Binneringie Dyke (Evans, 1968). Not used for the mean.
[b] No site mean direction was calculated for the Binneringie sites 2, 4, and 8, which yielded scattered directions.
[c] No site mean direction was calculated for Sites 12, 13, and 16, which yielded scattered directions.
[d] Site not used for calculation of the mean directions.
[e] α_{95} is not provided in Evans (1968)
[f] Site A (Evans, 1968) is equivalent to our Site 23 and was not used for calculation of the total mean direction.
[g] The Site H direction was inverted for the total mean calculation.

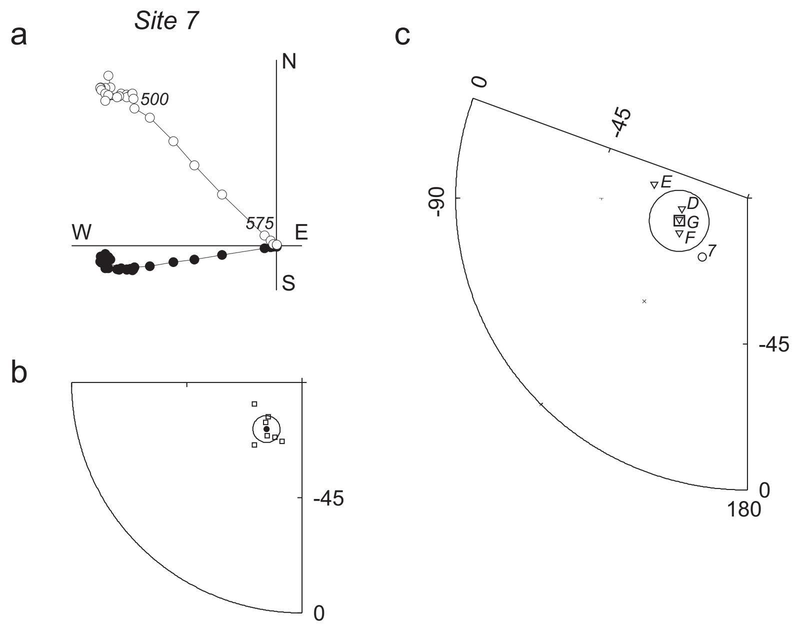

Fig. 4. Paleomagnetic results from the Jimberlana dyke. (a) A typical orthogonal vector plot of thermal demagnetization (vertical/horizontal projections shown by open/filled symbols) from Site 7. Numbers indicate temperature steps (in °C). (b) Accepted paleomagnetic directions (open squares) and their mean (solid circle) with the 95% confidence circle (α_{95}) for Site 7 (equal-area projection). (c) The mean direction for the Jimberlana dyke (open square) and its α_{95} area (solid circle) calculated from Site 7 (this study) and Sites D, E, F, and G (Evans, 1968) (Table 1).

Fig. 6b). Although the younger Narrogin dyke is undated, its orientation and paleomagnetic directions suggest a Marnda Moorn age that would imply the Binneringie remanence pre-dates 1.2 Ga.

An additional positive baked contact test that was conducted at Booylgoo Hills (Site 21) where a Widgiemooltha dyke intrudes an Archean lava sequence provides more direct evidence of a primary magnetization in the Widgiemooltha swarm (Table 2; Fig. 6c). These data indicate that the Booylgoo dyke carries a primary magnetic remanence, whose direction is identical to other Widgiemooltha dykes and thus confirms that the Widgiemooltha grand mean pole is representative of the Yilgarn craton at 2.41 Ga. The combined result from our study and that of Evans (1968) merits a perfect 7 point classification on Van der Voo's (1990) Q-scale of paleomagnetic reliability.

Six additional sites yielded site-mean directions significantly different from the Widgiemooltha grand mean (Table 1). The mean directions from three dykes (Sites 17, 18, and 20) are close to the Fraser dyke mean (Pisarevsky et al., 2003) and to the directions yielded by the intruding thin dyke at Narrogin (Table 2; Fig. 6b) thus offering a possibility that these dykes may represent an eastward extension of the Muggamurra swarm, a part of the Mardna Moorn LIP (Myers, 1990; Wingate and Pidgeon, 2005) into the northern Yilgarn. Alternatively, these sites may represent Widgiemooltha dykes that recorded transitional field directions. One of Jimberlana dyke sites (Site 5) resulted in a mean direction that is significantly different from the consistent directions obtained from the other Jimberlana sites (Table 1; Fig. 4c). We speculate that this direction may represent a local remagnetization event. Finally, Sites 19 and 22 yielded well-defined northerly directions with intermediate upward inclination possibly reflecting a recent field overprint.

4. Discussion and conclusions

A moderate to high paleolatitude for Yilgarn is directly comparable to that of the Zimbabwe craton, for which recent U–Pb dating allows reconstruction at 2.41 Ga according to the published Sebanga Poort Dyke virtual geomagnetic pole (Mushayandebvu et al., 1995; see Appendix A). The moderate uncertainties in both poles permit a variety of allowable juxtapositions between the two cratons, which we propose were joined together in a supercraton

Table 2
Summary of paleomagnetic directions used for the baked contact tests shown in Figure 6b,c. N is the number of samples used to calculate the paleomagnetic declination (D) and inclination (I); α_{95} and k are the 95% confidence circle and the concentration parameter for paleomagnetic directions.

Site ID	N	D (°)	I (°)	k	α_{95} (°)
Total Widgiemooltha mean (Table 1)	9	247.5	−66.6	117	4.8
Narrogin inverse baked contact test					
Site 1 (>5 m from the intruding dyke)	11	248.1	−62.3	731	1.7
Site 1 (<5 cm from the intruding dyke)	1	322.8	−72.5	–	–
	1	325.7	−73.2	–	–
Samples within the intruding dyke	1	326.3	−61.6	–	–
	1	331.1	−63.4	–	–
	1	355.7	−58.9	–	–
Fraser Dyke mean (Pisarevsky et al., 2003)	23	332.6	−74.1	110	2.9
Booylgoo Hills baked contact test					
Widgiemooltha dyke	3	265.4	−60.0	44	18.7
Archean lavas at 3 m form the contact	7	266.1	−64.8	54	8.3
Archean lavas at >9 m from the contact	15	333.8	−40.0	25	7.2

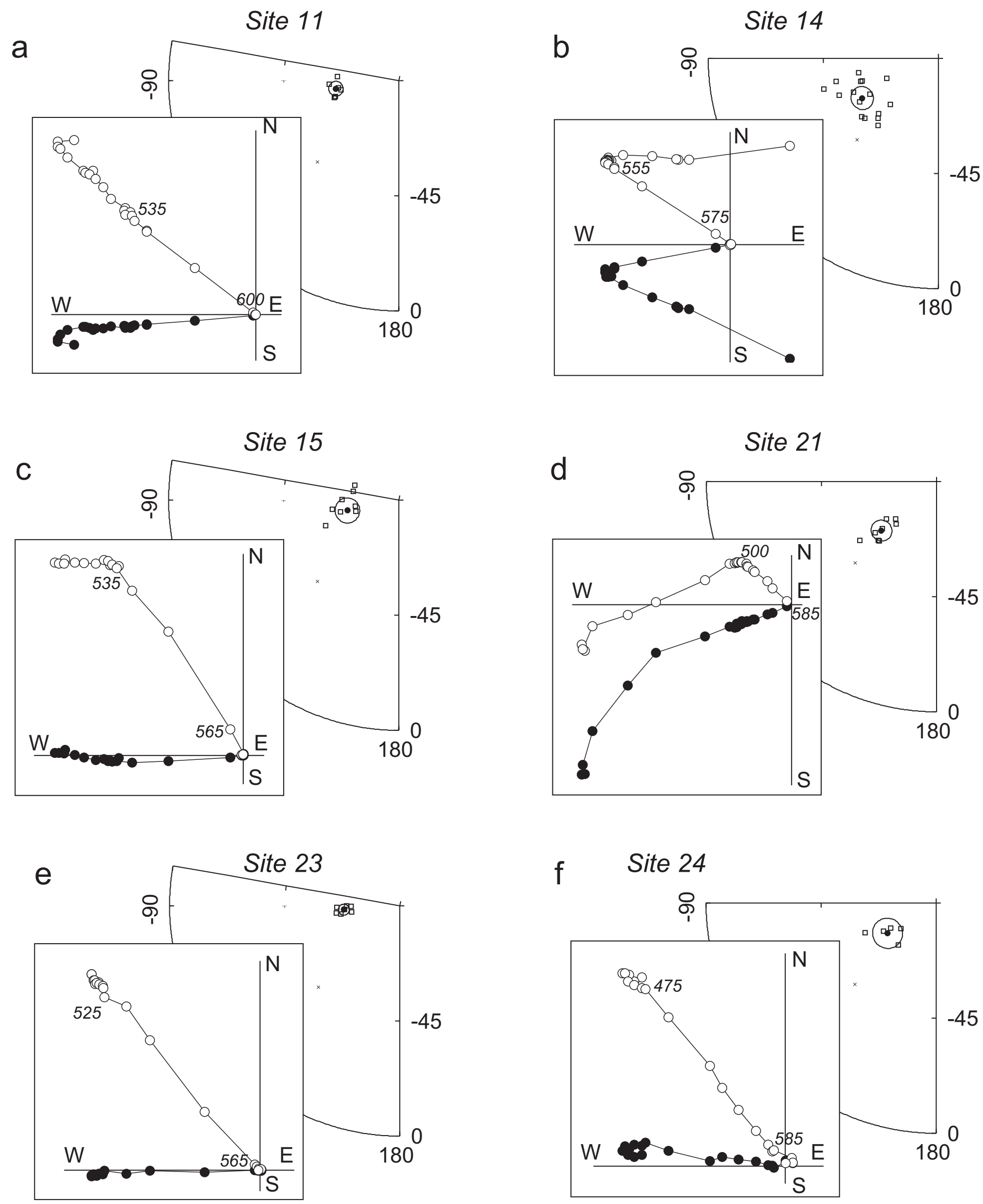

Fig. 5. Paleomagnetic results from the other dykes used to calculate the grand Widgiemooltha direction (Table 1). Typical orthogonal vector plots of thermal demagnetization (vertical/horizontal projections shown by open/filled symbols). Numbers indicate temperature steps (in °C). Equal-area plots show the accepted paleomagnetic directions (open squares) and their mean (solid circle) with the 95% confidence circle (α_{95}) for each site.

"Zimgarn" (Fig. 7). We emphasize that until additional paleomagnetic data are obtained from the two cratons, a precise model for Zimgarn will remain elusive; nonetheless, we tentatively choose a preferred juxtaposition guided by several additional geometric constraints. First, we align the Sebanga Poort Dyke approximately parallel to the Widgiemooltha dykes. Such parallelism is allowed paleomagnetically because both dyke suites have remanence declinations roughly in line with the dyke strikes. However, even after satisfying this constraint, within the uncertainties of the poles, any relative position of the two cratons is permitted (i.e., they could be translated around each other). Second, we restrict such translation so that the 2.57 Ga Great Dyke of Zimbabwe projects off the margin of Yilgarn, because it has not yet been identified in Western Australia. This constraint restricts the cratons to be either north or south of each other in paleogeographic coordinates at 2.41 Ga (Fig. 7a). Third, we choose the northern option for Zimbabwe relative to Yilgarn, because the more juvenile Neoarchean character of the eastern Yilgarn (Czarnota et al., 2010) is a better match for the sweeping pattern of younger craton stabilization from west to east across Zimbabwe (Jelsma and Dirks, 2002). Also, sinistral offset on major terrane-bounding shear zones in the eastern Yilgarn (Czarnota et al., 2010) can be restored to a proto-Zimgarn configuration (Fig. 7b) that nearly aligns the proposed Kurnalpi magmatic arc at ca. 2700 Ma with another proposed arc crossing Zimbabwe at the same time interval (Jelsma and Dirks, 2002).

Postulation of a Zimgarn supercraton presents a novel dilemma for Neoarchean reconstructions: are dyke swarms or basement provinces more diagnostic of original connections between extant cratons? Bleeker and Ernst (2006) presented the simple geometric argument that as vertical features, dykes provide piercing points whose positions are not sensitive to current exposure level; in addition, analogy with more completely preserved radiating dyke swarms (e.g., Central Atlantic Magmatic Province) shows that the rift-related dykes can show nearest-neighbor connections even among suture-bounded provinces of different age. This reasoning provides a rationale for juxtaposing cratons with distinct

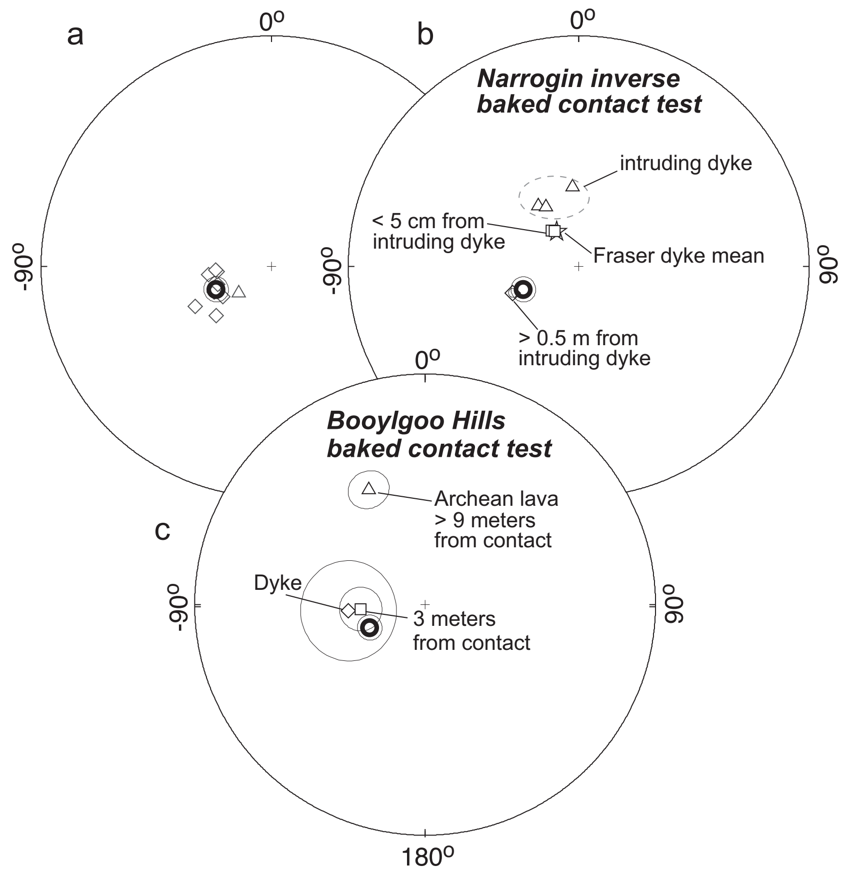

Fig. 6. (a) Stereonet of accepted site-mean paleomagnetic directions (diamonds – this study; triangles – Evans, 1968). Thick and thin circles (also in (b and c)) show the mean between-site direction and its α_{95} cone calculated from all accepted directions (Table 1). (b) The inverse baked contact test at the Narrogin quarry (Site 1; see text). Diamond shows the mean ChRM direction for Site 1 (the α_{95} is not shown). Squares show the ChRM directions for the samples taken from the Binneringie Dyke within 5 cm from the contact with the intruding dyke. Triangles show the ChRM directions yielded by the intruding dyke. The mean Fraser dyke direction (star) is calculated for Site 1 based on the paleomagnetic pole from Pisarevsky et al. (2003). (c) The Booylgoo baked contact test (see text). Square and triangle show the mean direction from the Archean lavas sampled at 3 m and >9 m from the contact, respectively.

cratonization histories, such as Yilgarn and Zimbabwe, which were previously grouped into separate supercratons (Bleeker, 2003). The distinctive 2.41-Ga age match between Widgiemooltha and Sebanga Poort dykes (Söderlund et al., 2010) may be diagnostic of their original connection despite the mismatch of cratonization ages for Yilgarn and Zimbabwe.

The Zimgarn-like assemblage might have been joined to Superia from Neoarchean cratonization to early Paleoproterozoic separation, as proposed by Söderlund et al. (2010), but precisely coeval paleomagnetic poles at 2.41 Ga are not yet available from Superior or adjoining cratons to test that hypothesis. In the Scotland sector of the North Atlantic craton, the older Scourie dykes are nearly the same age (2418 + 7/−4 Ma; Heaman and Tarney, 1989) as the Widgiemooltha and Sebanga dykes, but Scourie paleomagnetic remanences have been reset by Laxfordian (ca. 1.7 Ga) metamorphism (Beckmann, 1976; Piper, 1979). Superia lay at low paleolatitudes at 2.45 Ga, as well documented by data from the Matachewan dykes (summarized by Evans and Halls, 2010), but both Yilgarn and Zimbabwe lack paleomagnetic results from that older age.

The Vaalbara supercraton has recently been quantified for the 2.8–2.7 Ga interval (de Kock et al., 2009). It is likely that Vaalbara was paleogeographically separated from Zimgarn, for several reasons. First, basement ages and cover successions of Vaalbara substantially differ from those of Zimgarn, including extensive carbonate platform development at 2.6 Ga (reviewed by Knoll and Beukes, 2009), when Zimgarn was still undergoing final cratonic stabilization (Dirks and Jelsma, 1998; Frei et al., 1999). Second, Zimgarn and Vaalbara magmatic “barcodes” share no known matches through the interval 2.6–2.0 Ga interval (e.g., Ernst and Bleeker, 2010). Third, paleomagnetic latitudes are somewhat distinct between the two supercratons at 2.69 Ga (although uncertainties are large; Table 3).

Zimgarn probably fragmented into separately drifting Zimbabwe and Yilgarn cratons sometime between 2.2 and 2.0 Ga (Figs. 7c and 8a). Two rift- to passive-margin successions are evident: the Magondi Supergroup in Zimbabwe, which is older than 2.0 Ga (McCourt et al., 2001) and may indicate rifting as early as 2.26 Ga (Manyeruke et al., 2004); and the Yerrida Basin in northern Yilgarn, that extends from as early as ca. 2.2–2.1 Ga in a sag phase (Windplain Group) to a rift stage (Mooloogool Group) that is only constrained to be older than 1.84 Ga (Rasmussen and Fletcher, 2002; Pirajno et al., 2004). Despite the uncertainty of associating preserved epicratonic strata with a northern Yilgarn rift margin, that margin must have been established prior to accretion of the Narracoota/Dalgaringa arc (perhaps also the Pilbara craton) in the early stages of the 2.0–1.95 Ga Glenburgh orogeny (Pirajno et al., 2004; Johnson et al., 2011). Both the Yerrida and Magondi successions contain carbonate–evaporite platforms characterized by the Lomagundi carbon-isotopic excursion; according to our model, they are correlative successions along a common cratonic margin (Fig. 7c), representing rifting of Zimgarn from other, originally conjoined cratons yet to be identified (possibly Superia, according to Söderlund et al., 2010). By 1.88 Ga, Zimbabwe and

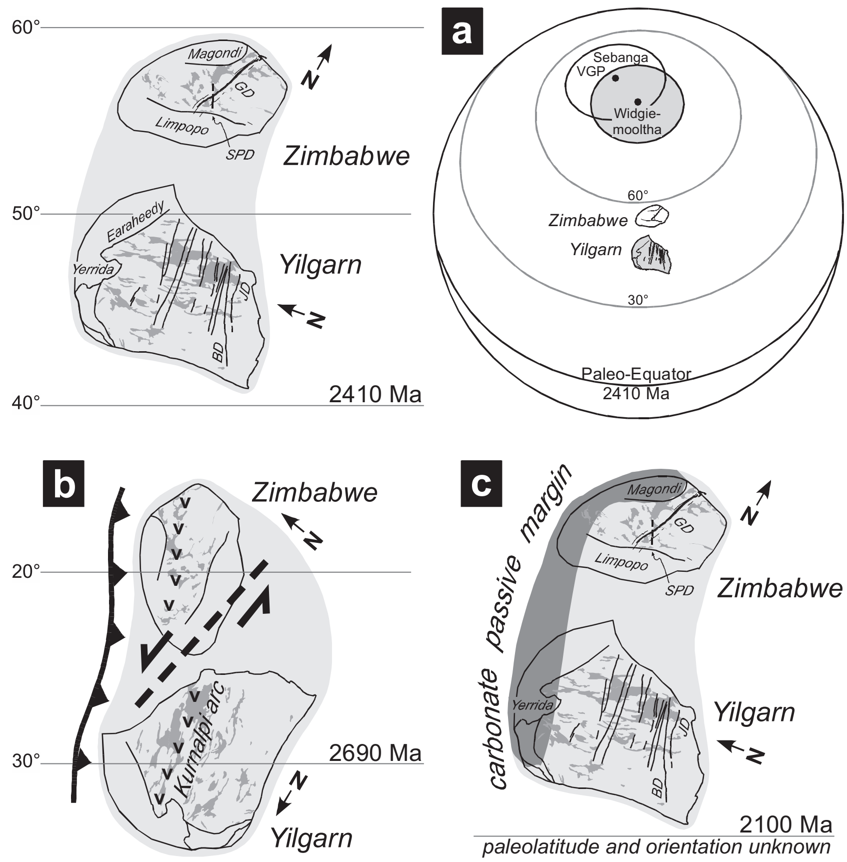

Fig. 7. (a) Zimgarn supercraton at 2410 Ma, achieved by rotation of Yilgarn to Zimbabwe according to Euler parameters (–47°, 077°, +157°), and paleogeographic restoration according to the Widgiemooltha dyke paleomagnetic pole determined herein. Greenstone belts are shaded light gray. GD = Great Dyke (paralleled by the Umvimeela and East Dykes), SPD = Sebanga Poort Dyke, BD = Binneringie Dyke, JD = Jimberlana Dyke. Younger marginal basins and orogens are labeled for reference, despite anachronism. Present north is indicated for each craton. In the right-side panel, poles are shown with their 95% uncertainty regions. VGP = virtual geomagnetic pole. (b) Tectonic elements of Zimgarn at 2690 Ma. Paleolatitudes and orientation of Zimbabwe conform to the Reliance pole (Table 3), with polarity chosen to minimize motion between 2690, 2575, and 2410 Ma. Yilgarn is displaced to restore post-2690-Ma sinistral offset on major terrane-bounding shear zones (simplified in this illustration by the generalized shear couple), thus bringing proposed 2690-Ma volcanic arcs (Jelsma and Dirks, 2002; Czarnota et al., 2010) nearer to alignment. (c) Proposed continuous passive margin extending from the Yerrida margin (Yilgarn) to the Magondi margin (Zimbabwe) at ca. 2100 Ma. Paleolatitude and orientation of Zimgarn are not constrained at that age.

Yilgarn were widely separated from each other, as indicated by the moderate versus low paleolatitudes, respectively implied by the Mashonaland and Frere poles (Table 3).

Kaapvaal and Pilbara share similar tectonostratigraphic records through much of the early Paleoproterozoic Era, such similarity providing the original basis for the Vaalbara hypothesis (Cheney, 1996). However, the Bushveld-related magmatism that is so widespread across Kaapvaal at 2.06 Ga (Reischmann, 1995; Cawthorn et al., 2006; Mapeo and Wingate, 2009; Prendergast, 2012), has not yet been recognized in Pilbara, suggesting that Vaalbara could have split prior to 2.06 Ga. If so, then the 2.2 Ga mafic events in Kaapvaal (Cornell et al., 1996) and Pilbara (Müller et al., 2005) could document their initial separation. Unfortunately, among the four cratons discussed herein, only Kaapvaal has

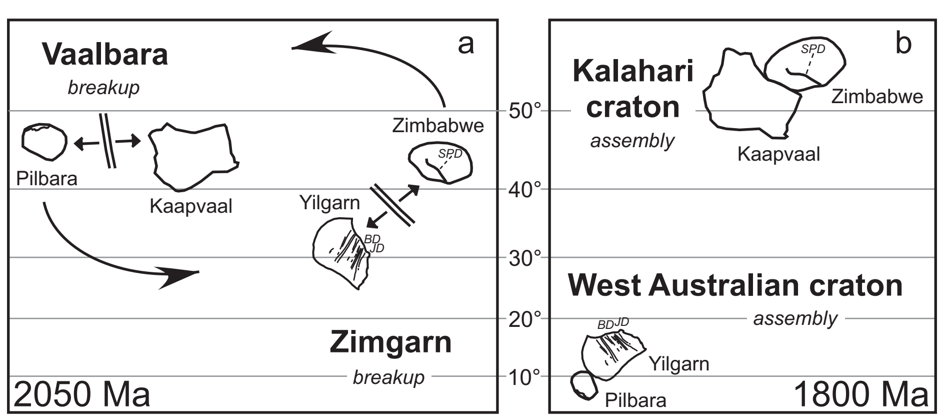

Fig. 8. Kinematic sequence of the trading cratonic partners. (a) Vaalbara and Zimgarn in the early stages of breakup, 2050 Ma. Only Kaapvaal is constrained paleomagnetically at this age (Table 3), but other cratons are positioned for consistency in the kinematic sequence. (b) Kalahari and West Australian cratons after final assembly, 1800 Ma; paleolatitudes and orientations of both cratons are consistent with the ca. 1800 Ma poles listed in Table 3.

Table 3
Paleomagnetic poles bearing on Zimgarn, Vaalbara, and their transition toward united Kalahari and West Australian cratons.

Craton/Paleomagnetic pole	Age (Ma)	λ_p (°N), p (°E)	λ_r (°N), r (°E)	A_{95} (°)	1234567 Q	Test	λ' (°)	Reference
Zimgarn:			*Zimbabwe Ref.*					
Reliance middle-temp.	2690	44, 128	44, 128	17	1011101 5	f	21	Yoshihara and Hamano (2004)
Great Dyke grand mean	2575	24, 057	24, 057	9	1111100 5	C,c	37	See Appendix A
Sebanga Poort Dyke (VGP)	2410	17, 006	17, 006	14	1001100 3	C	45	See Appendix A
Widgiemooltha dikes	2410	−10, 159	06, 013	8	1111111 7	C,c	50	This study
Vaalbara:			*Kaapvaal Ref.*					
Allanridge basalt combined	2685	−70, 346	−70, 346	6	1111101 6	G	36	de Kock et al. (2009)
Rykoppies E-W dikes only	2685	−63, 339	−63, 339	7	1111101 6	C	37	Lubnina et al. (2010)
Woongarra/Weeli Wolli	2450	−50, 220	−78, 235	5	1111100 5	g	11	Evans (2007) (abstract only)
Ongeluk lava	2220	−01, 101	−01, 101	5	1111101 6	G	17	Evans et al. (1997)
Waterberg UBS-I	2055	37, 051	37, 051	11	1111100 5	F,G	28	de Kock et al. (2006)
Bushveld complex	2050?	19, 031	19, 031	6	1111110 6	f	49	Letts et al. (2009)
Transitional poles:			*Kaapvaal Ref.*					
Waterberg UBS-II	~1950?	−11, 330	−11, 330	10	0111110 5	c,g	33	de Kock et al. (2006)
Black Hills dikes	~1900?	09, 352	09, 352	5	0111110 5	C	42	Lubnina et al. (2010)
Mashonaland + Mazowe	1880	07, 338	18, 016	7	1111110 6	C	48	Hanson et al. (2011)
Waterberg sills & Soutp. lavas	1875	16, 017	16, 017	9	1111110 6	C	50	Hanson et al. (2004)
Frere iron formation (Yilgarn)	1890	−45, 220		2	1110111 6	(f)	10	Williams et al. (2004)
Kalahari craton:								
Soutpansberg UBS-II	~1800?	25, 008	25, 008	8	0111110 5	M	39	de Kock (2007)
West Australian craton:								
Hamersley overprint HP3	~1800?	−35, 212	−35, 212	3	0110101 4	–	12	Li et al. (2000)

Note: λ_p (°N), p (°E): paleomagnetic pole in the reference frame of the sampled units.
λ_r (°N), r(°E): paleomagnetic pole rotated into the reference frame indicated above each section. Rotation parameters: Yilgarn to Zimbabwe in Yilgarn (this study; −47°, 077°, +157°), Pilbara to Kaapvaal in Vaalbara (de Kock et al., 2009; −59°, 252°, +93°), Zimbabwe to Kaapvaal in the transitional period (Hanson et al., 2011; −69°, 051°, −39°).
A_{95}(°): Fisher's (1953) confidence cone radius.
1–7 and Q: reliability criteria from Van der Voo (1990). The fourth criterion of a field stability test, if positive, is abbreviated as follows: C = baked-contact test, c = inverse baked-contact test, F = soft-sediment fold test, f = tectonic fold test, G = intraformational conglomerate test, g = conglomerate test, M = magnetostratigraphy test of stratabound reversals in sequence. In these abbreviations, uppercase symbols indicate primary paleomagnetic remanence; lowercase symbols indicate ancient remanence that might be primary but is not yet demonstrated as such.
λ' (°) = paleolatitude computed for reference localities in the Limpopo belt between Zimbabwe and Kaapvaal (−22°N, 029°E) and in the Capricorn orogen between Yilgarn and Pilbara (−24°N, 120°E).

reliable paleomagnetic poles from the 2.2 to 1.9 Ga interval (Table 3; Fig. 8a).

Following these breakup events, the four cratons "traded partners" to reassemble into their currently preserved affinities within West Australian and Kalahari cratons (Fig. 8b). Yilgarn and Pilbara collided via suturing in the Capricorn orogen, most likely at about 1.95 Ga (Johnson et al., 2011). Zimbabwe and Kaapvaal joined together across the Limpopo belt, possibly as late as ca. 1.8 Ga, by way of large-scale sinistral shearing suggested by discordant paleomagnetic data between the two cratons at 1.87 Ga (Hanson et al., 2011).

Our hypothesized tectonic model, albeit speculative given the modest number of available data, demonstrates the possibility that supercratons had rich tectonic histories of interaction prior to their amalgamations into more familiar continental associations embedded within younger supercontinents. Deciphering those histories will require continued effort to obtain precise geochronologic and reliable paleomagnetic data from the tectonically stable interiors of exposed Archean terrains. Integrated U–Pb baddeleyite dating and paleomagnetic study from earliest Proterozoic mafic dykes constitute a powerful approach toward "fulfilling Wegener's legacy" and producing a robust global paleogeography for the entire latter half of Earth history (Ernst and Bleeker, 2010).

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Appendix A.

Discussion of some paleomagnetic poles listed in Table 3.

Great Dyke and related intrusions. The Great Dyke (GD) was one of the first targets for paleomagnetic study of Precambrian rocks. The pioneering work of McElhinny and Gough (1963) on the GD generated a mean paleopole (20.7°N, 62.6°E, K = 27.5, A_{95} = 11.7°; seven sites) corroborated independently by Nairn (1963). A more regional study by Jones et al. (1975) discovered partial remagnetization on its southern and southeastern extensions. South of the GD, the Msiningira Dyke generated a mean from four site-generated VGPs at 20.4°N, 52.1°E, K = 13.6, A_{95} = 25.8° (Jones et al., 1975). Parallel to the GD, the East Dyke has also yielded robust paleomagnetic results (McElhinny and Gough, 1963; Jones et al., 1975) with a similar, assumed-primary remanence direction (mean of three low-dispersion VGPs from sites 9, *A*, and *X*), yielding a pole at 32.3°N, 52.7°E, K = 182.5, A_{95} = 9.2°. A more recent paper by Mushayandebvu et al. (1994) described paleomagnetic results from many new sites in the Umvimeela Dyke, ~15 km west of and parallel to the Great Dyke along most of its length. Although Mushayandebvu et al. (1994) computed a mean of local paleomagnetic directions (declination and inclination), the ca. 550 km dyke length indicates that a more accurate approach would be to average the VGPs calculated from each site. This yields a position of (20.8°N, 61.8°E; K = 60.3, A_{95} = 4.8°), calculated from 16 well constrained Umvimeela sites, including those from earlier studies but excluding sites US (also excluded by its authors due to location within the deformed northern end of the dyke) and UM (excluded herein due to its α_{95} value of 23.3°). This mean is regarded as a VGP in itself, i.e., not averaging out the paleosecular variation of Earth's magnetic field, because of its low dispersion of directions among sites separated by as much as 500 km. Results from the Popoteke Gabbro are cited by Wilson et al. (1987) and Mushayandebvu et al. (1994), but are not fully reported in the published literature. We therefore compute the mean paleomagnetic pole from the four dyke-mean results calculated above (23.6°N, 57.4°E, $K = 107.6$, $A_{95} = 8.9°$, $N = 4$ dyke means comprising data from 219 samples distributed among 30 sites), as the best representation of the time-averaged paleogeography for Zimbabwe craton during emplacement of the GD swarm. Jones et al. (1975) found that regional metamorphic overprinting from the Limpopo belt, to the south of the sites described above, produced a different paleomagnetic mean direction, which thus constitutes a regional inverse baked-contact test for the GD pole, which is thus older than ca. 2000 Ma (Morgan, 1985). In addition, the remanence directions from sites in the Sebanga Poort Dyke, as described below, are distinct from those of the GD swarm, despite geographic proximity. This also argues against regional remagnetization subsequent to emplacement of the Sebanga Poort Dyke at ca. 2410 Ma (Söderlund et al., 2010). The GD pole is thus considered to be "key" for the Zimbabwe craton at ca. 2575 Ma. Using the "Q"-scale of reliability (Van der Voo, 1990), the GD mean paleopole only fails to satisfy the criteria of dual remanence polarity and similarity to younger paleopoles (1.2 Ga Premier kimberlites; Doppelhammer and Hargraves, 1994).

Sebanga Poort Dyke. The type representative of the Sebanga Poort Dyke (SPD) swarm has been studied paleomagnetically by both Jones et al. (1975) and Mushayandebvu et al. (1995), and dated at 2408 ± 2 Ma, using U–Pb on baddeleyite by Söderlund et al. (2010). At more northerly sites in this intrusion, the SPD gave a southeasterly and upward characteristic remanence direction that is distinct from that of neighboring sites in the Great Dyke and East Dyke. For this reason, as well as the recognizable overprinting by a ca. 2000-Ma Limpopo overprint of nearly opposite polarity in more southerly sites (Mushayandebvu et al., 1995), we propose that the northerly SPD sites carry a primary paleomagnetic remanence. The mean of four VGPs (17.2°N, 6.1°E, $K = 42.5$, $A_{95} = 14.3°$) is itself considered to be a VGP because it derives from a single dyke. Jones et al. (1975) also reported data from the Crystal Springs and Bubi Dykes, the former of which was dated at 2512 ± 2 Ma by Söderlund et al. (2010). Unfortunately, that dyke was sampled for paleomagnetism in a southerly location that appears to have been overprinted by the Limpopo orogeny at ca. 2000 Ma. Wilson et al. (1987) grouped the Crystal Springs, Bubi, and nearby NW-striking dykes into a swarm of "Sebanga Dykes" that were supposed to be feeders to the Mashonaland sills. However, Söderlund et al. (2010) demonstrated that these dykes span a range in age of more than 100 million years. Two so-called "Sebanga" dykes were studied paleomagnetically by Bates and Jones (1996). One, near to but spatially distinct from the Sebanga Poort Dyke, yielded a paleomagnetic direction similar to overprints from the Limpopo belt (shallow southeast-upward remanence) and an inconclusive baked-contact test (site SD1). The other, located within the outcrop region of numerous Mashonaland sills, strikes NE (note this distinction from other so-called "Sebanga" dykes) and yields a remanence direction of opposite polarity relative to that of the sill which it cuts (dyke site SD2 intruding sill site MS15). A fully positive baked-contact test at that locality is indicated by a cross-over of magnetic directions at a reasonable distance of conductive heat loss from the dyke into its country rock (Bates and Jones, 1996), indicating no remagnetization of the sill since the time of dyke emplacement (positive inverse baked-contact test for the sill) and primary remanence in the dyke (positive baked-contact test). The antipodal nature of the two directions indicates likely penecontemporaneous emplacement ages between the two intrusions, separated in time by a geomagnetic field reversal but negligible plate motion.

Rykoppies Dykes. Lubnina et al. (2010) studied several areas of pre-Transvaal (pre-2.65 Ga) mafic dykes in the eastern Kaapvaal craton. In their easternmost study area, an E–W swarm of "Rykoppies" Dykes is the same as that dated by Olsson et al. (2010). In the geochronology study, U–Pb baddeleyite upper-intercept ages ranged from 2685.5 ±9.3 Ma, to 2661.9 ±7.7 Ma (decay constant uncertainties included in the quoted errors). The youngest age, however, derives from a dyke that was not sampled by Lubnina et al. (2010) for paleomagnetism; therefore the older range of ages, at ca. 2685 Ma, is preferred for the paleomagnetic pole, which includes three dykes in the Rykoppies area. The baked-contact test for one of these dykes into granitic basement appears positive, though it is not fully described with statistics of mean directions from the baked or unbaked host rocks. A fourth dyke near Barberton has similar paleomagnetic remanence to the type-Rykoppies dykes, and a strike similar to that of an ESE-WNW dyke (BCD1-04) in the same area that was dated—although with large regression errors—by Olsson et al. (2010) of approximately Rykoppies age. Although Lubnina et al. (2010) combined their Rykoppies result with that from a fifth dyke in an isolated exposure more than 300 km to the South of the type Rykoppies area, we suggest that such correlation is merely tentative, especially given the dyke's nearly E–W strike that is highly oblique to the fanning array defined by dated Rykoppies dykes (Klausen et al., 2010). Excluding the dual-polarity remanence direction from that site, we calculate a mean of four single-polarity VGPs at (−63.0°N, 338.7°E, $K = 162$, $A_{95} = 7.2°$).

Ongeluk lavas. We reject the single site of opposite polarity in the dataset of Evans et al. (1997) because it has a slightly discordant direction and an indeterminate reversals test. It also derives from an intrusion that is only speculatively correlated as a feeder dyke for the lavas.

Frere Formation. Although a positive fold test for the 'A' component is claimed by Williams et al. (2004) according to some statistical tests, inspection of the data tables and figures shows very similar levels of precision between the in situ and tilt-corrected means. The Frere Formation has more recently been dated to ca. 1890 Ma by U–Pb on interbedded volcanic ash units (Rasmussen et al., 2012).

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