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Assembly of Proterozoic Australia: implications of a revised pole for the ∼1070 Ma Alcurra Dyke Swarm, central Australia

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SUMMARY

The pole position for the late Mesoproterozoic Alcurra (formerly Kulgera) Dyke Swarm (ADS), Musgrave Block, central Australia, has been revised by adding new data from two more dykes. A palaeomagnetic fold test is positive at the 99 percent confidence level and the pole position is latitude = 2.8° S, longitude = 80.4°E ($dp = 7.2°$, $dm = 10.7°$). New ^{40}Ar/^{39}Ar determinations on single biotite grains from country-rock gneiss 20 cm from the contact with an Alcurra dyke yield ages from 1068 ± 2 Ma to 1085 ± 2 Ma (2σ). In addition, ^{40}Ar/^{39}Ar determinations on two samples of aggregates of very fine-grained biotite from the mesostasis of a Stuart Dyke (SD), Arunta Inlier, Northern Territory, yield ages of 1059 ± 2 and 1066 ± 3 Ma (2σ). These new ages are in agreement with those of the ∼1070 Ma Warakurna large igneous province, west-central Australia, indicating that both the ADS and SD belong to that suite. Palaeomagnetic poles determined by others for the ADS and SD are indistinguishable from each other but cannot be presently combined as a single pole because the published information on the SD is incomplete.

An analysis of the palaeogeography implied by the dispersed palaeomagnetic poles from members of the extended Warakurna suite shows that the present relationships between the major Precambrian cratons (West, North and South Australian), which constitute Australia west of the Tasman Line, are inconsistent with the inferred relationship at ∼1070 Ma. Nor is it apparent that internal deformations within the separate cratons are the cause of the dispersion. Our findings imply that these major Australian Cratons must have finally assembled sometime after ∼1070 Ma.

Key words: APW, Musgrave Block, palaeogeography, palaeomagnetism, Precambrian, Rodinia.

1 INTRODUCTION

The existence of Mesoproterozoic to Neoproterozoic supercontinents as precursors to Palaeozoic Pangaea is axiomatic to many workers (e.g. Bond *et al.* 1984; Moores 1991; Dalziel 1991). However, in the absence of sea-floor spreading information, there is no consensus on how the various continents were arranged or on how many supercontinents may have preceded Pangaea (Wingate *et al.* 2002). Tracking the formation and breakup of Proterozoic supercontinents is greatly dependent on palaeomagnetism. After many false starts and spurious leads, the 'key-pole approach' as advocated by Buchan *et al.* (2000) has emerged as the most promising method for reconstructing Proterozoic continental configurations. In this approach, both palaeomagnetism and geochronology are accorded equal weight and key poles are assigned if they meet the following specifications: (i) for geochronology, <20 Ma age error (2σ) for Precambrian rocks (typically U-Pb or ^{40}Ar/^{39}Ar ages meet this criterion) and (ii) for palaeomagnetism, there must be evidence that the remanence corresponds to the radiometric age (i.e. the crystallization age) and that the correct palaeohorizontal has been identified. Usually, dyke swarms that yield good palaeomagnetic information and are amenable to U-Pb zircon or baddelyite dating have proven to be the most useful (Buchan *et al.* 2000). That the remanence is primary can be demonstrated through positive contact tests (*s.s.*), by identifying secular variation between separate dykes, and by demonstrating consistent stable directions (notwithstanding secular variation) over a wide geographical area. While a fold test can constrain the timing of remanence acquisition to be prior to folding, this in itself may not be enough to invoke 'primary' magnetization. However, petrographic and rock-magnetic evidence, in addition to a positive fold test, can provide very strong evidence that the remanence dates from the time of crystallization. The key-pole approach has been more successful in high northern than in lower southern latitudes probably because outcrops of recently glaciated terrains are unweathered and thus do not suffer from the accumulated effects of lightning strikes.

Recent data from the Bangemall Supergroup Sills (BSS; Wingate *et al.* 2002), western Australia, have highlighted the potential importance of Australian mafic dyke swarms between the ages of 1000 and 1200 Ma to compare with results from Keweenawan rocks of North America and test various reconstructions involving Australia and North America (Rodinia *s.l.*) for those times. Palaeomagnetic directions from the Alcurra Dyke Swarm (ADS, formerly known as the Kulgera dyke swarm), central Australia, have previously been found to fall into two groups (Camacho *et al.* 1991). The less stable magnetizations appear to be overprints associated with the Carboniferous Alice Springs Orogeny, whereas the more stable magnetizations are similar to those from the related Stuart Dykes (SD, Idnurm & Giddings 1988). We have, therefore, revisited the issue and included new data from dykes with different orientations to establish more accurately their primary palaeomagnetic direction at the time of intrusion. Moreover, as previously established, the revised pole position is very similar to that of the SD, which calls for a reappraisal of palaeoreconstructions based on previous results and in particular the assumption that Precambrian Australian Cratons had finally assembled before 1070 Ma (Myers *et al.* 1996; Dawson *et al.* 2002).

2 GEOLOGICAL SETTING AND SAMPLING

The Tasman Line of Australia separates the Precambrian terranes from younger terranes to the east (Fig. 1). The Precambrian basement to the west of the Tasman Line comprises several distinct cratonic nuclei. The South Australian (Gawler) Craton to the southeast is late Archaean to early Palaeoproterozic in age, whereas the West Australian (Yilgarn/Pilbara) Craton to the west and northwest is Archaean and the North Australian Craton is predominantly Palaeoproterozoic. The Musgrave Block and Arunta Inlier, parts of the North Australian Craton, are Mesoproterozoic. Fig. 1 also shows locations of dyke swarms discussed below: ADS—Alcurra Dyke Swarm, BSS—Bangemall Supergroup Sills (Wingate *et al.* 2002), GB— Gawler B Dykes (Giddings & Embleton 1976) and SD—Stuart Dykes (Idnurm & Giddings 1988).

The ADS is found throughout the Musgrave Block, which is a Meso-Neoproterozoic mobile zone of metamorphic and intrusive rocks covering 120 000 km^2 in the centre of the Australian continent (Stewart 1967; Camacho & Fanning 1995). The swarm actually comprises dolerite sheets, with vertical feeders in places. The sheets/dykes are olivine-normative high-Mg tholeiites depleted in high field-strength elements and enriched in large ion lithophile

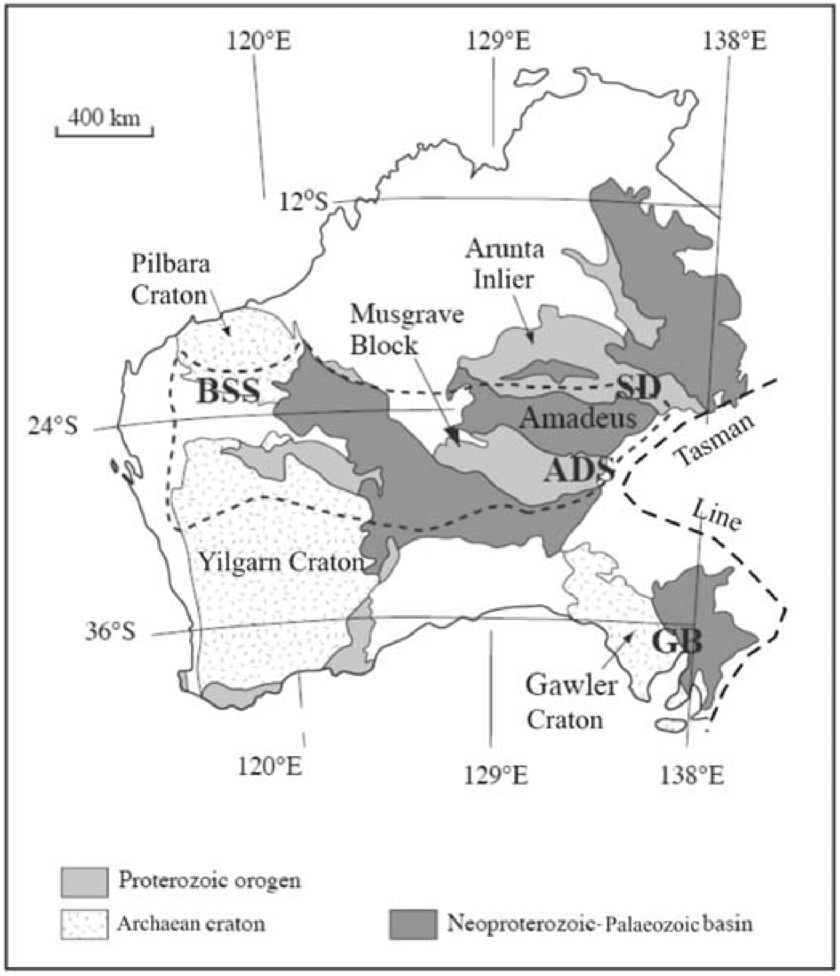

Figure 1. Major geological units showing locations of dyke swarms discussed in the text: ADS—Alcurra Dyke Swarm, BSS–Bangemall Supergroup Sills (Wingate *et al.* 2002), GB—Gawler B Dykes (Giddings & Embleton 1976) and SD—Stuart Dykes (Idnurm & Giddings 1988). The short dashed line shows the range of the Warakurna LIP, while the longer dashed line represents the Tasman Line separating Precambrian terranes to the west from younger terranes to the east.

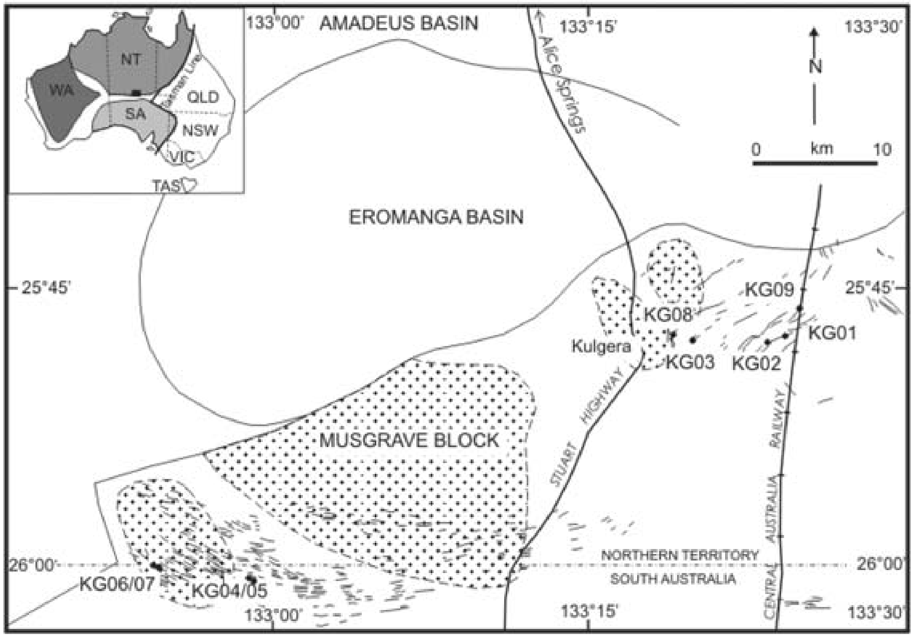

Figure 2. Generalized geological map of the Kulgera region, central Australia, showing sampling sites for the ADS. Inset shows Australian Precambrian cratons after Myers *et al.* (1996).

elements relative to mid-ocean ridge basalt, and are thought to have been derived from subduction-modified continental lithospheric mantle (Zhao & McCulloch 1993a). The Alcurra Dyke Swarm forms an east–west arcuate belt 90 km long by 10 km wide (Fig. 2), with sheets commonly 500 m long, 2 m wide, subparallel or anastomosing and shallowly dipping (5°–30°). The sheets tend to dip ESE in the east and south to SSE in the west where their greatest concentration occurs. The feeder dykes are subvertical. Sampling locations and generalized geology are also shown in Fig. 2. Petrographical investigation shows the dolerite to be pristine and completely unaltered suggesting that the Alice Springs Orogeny was no more than a mild thermal event in this area (Camacho *et al.* 1991).

3 GEOCHRONOLOGY

Previous geochronological results on the ADS include Sm-Nd and Rb-Sr isochron ages of 1090 ± 32 (2σ) Ma and 1054 ± 13 (2σ) Ma, respectively (Zhao & McCulloch 1993b; Edgoose *et al.* 1993). Correlatives of the ADS ~300 km west of Kulgera are intruded by granites having a zircon U-Pb SHRIMP age of 1071 ± 5 Ma (Scrimgeour *et al.* 1999), which, therefore, provides a lower constraint for the age of the ADS. The SD in the Arunta Inlier (Fig. 1) have yielded a Sm-Nd isochron age of 1076 ± 33 Ma (Zhao & McCulloch 1993b).

3.1 ^{40}Ar/^{39}Ar analytical methods

Biotite mineral separates and flux-monitors (HB3GR hornblende at 1071 Ma; Roddick 1983) were wrapped in aluminium foil and then irradiated with fast neutrons in position 5C of the McMaster Nuclear Reactor (Hamilton, Ontario). Groups of flux monitors were interspersed along the irradiation container and J values for individual samples were determined by second-order polynomial interpolation between replicate analyses of splits for each position in the capsule.

For total fusion of monitors and step-heating using a laser, the samples were mounted in an aluminium sample-holder, beneath the sapphire view-port of a small, bakeable, stainless-steel chamber connected to an ultrahigh vacuum purification system. An 8W Lexel 3500 continuous argon-ion laser was used. For step-heating the laser beam was defocused to cover the entire sample. Heating periods were of 3 min at increasing power settings (0.25 to 7 W). The evolved gas, after purification using an SAES C50 getter (~5 min), was admitted to an on-line, MAP 216 mass spectrometer, with a Baur–Signer source and an electron multiplier (set to a gain of 100 over the Faraday). Blanks, measured routinely, were subtracted from the subsequent sample gas-fractions. Measured argon-isotope peak heights were extrapolated to zero-time, normalized to the ^{40}Ar/^{36}Ar atmospheric ratio (295.5) using measured values of atmospheric argon, and corrected for neutron-induced ^{40}Ar from potassium, ^{39}Ar and ^{36}Ar from calcium (using production ratios of Onstott & Peacock 1987), and ^{36}Ar from chlorine (Roddick 1983). Dates and errors were calculated using formulae given by Dalrymple *et al.* (1981) and the constants recommended by Steiger & Jaeger (1977).

3.2 ^{40}Ar/^{39}Ar results

Granitoids around Kulgera (Fig. 2) yielded IDTIMS and SHRIMP U-Pb zircon ages of ~1150 Ma (Camacho & Fanning 1995) and amphibole and biotite K-Ar cooling ages of ~1140 and ~1120 Ma (Camacho 1998), respectively. Three ^{40}Ar/^{39}Ar laser step-heating experiments on single biotite crystals from a gneiss 20 cm from the contact with an Alcurra dyke exposed in the Kulgera quarry (site KG01; Fig. 2) yielded age spectra partially affected by argon loss (Fig. 3a). Dates monotonically increase from ~400 Ma in the lower-temperature steps to plateau segments with ages ranging from ~1066 to 1085 Ma (Fig. 3a), similar to a Rb-Sr biotite age of 1060 ± 10 Ma (2σ) from biotite in a pegmatite that had been

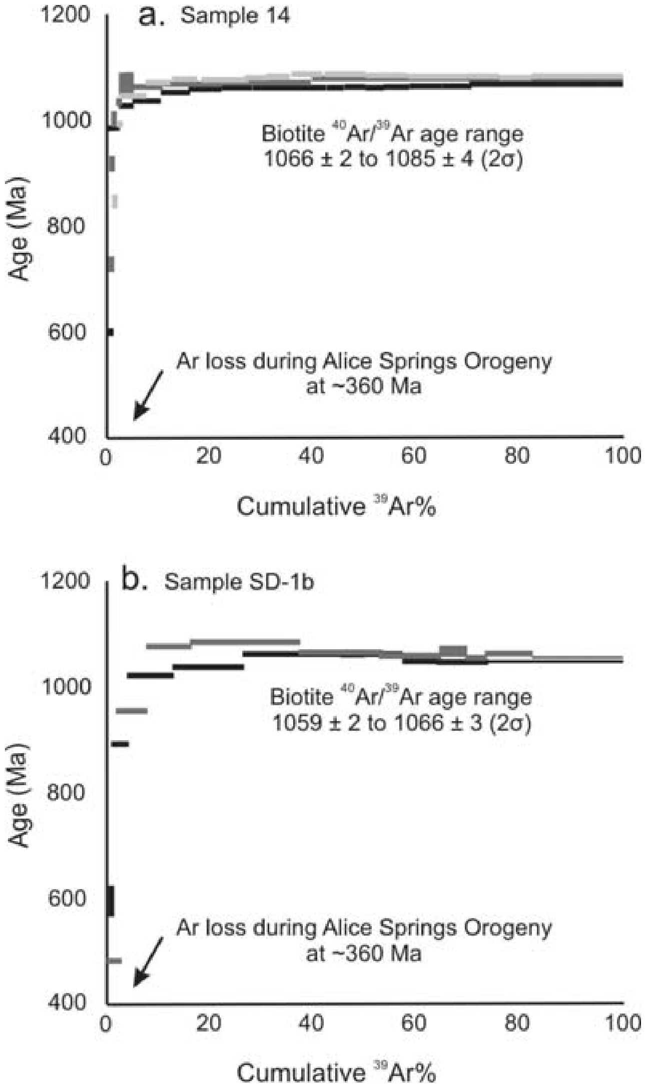

Figure 3. ^{40}Ar/^{39}Ar age spectra for: (a) single biotite grains (identified by grey-scale) sampled in the country-rock gneiss 20 cm from the contact of an Alcurra dyke in Kulgera quarry (Site KG01 in Fig. 1) and (b) two aliquots of very fine-grained biotite from the mesostasis of a SD, Undoolya quarry, Arunta Inlier.

thermally reset at the time of intrusion (Camacho *et al.* 1991). The plateau segments (representing >70 per cent of ^{39}Ar released) for all three crystals yielded a mean age of 1076 ± 6 Ma (error = standard error on the mean). These data suggest that biotite with a magmatic age of ~1150 Ma in country rocks was completely reset by the thermal pulse associated with the intrusion of the ADS and was later slightly affected during the Carboniferous Alice Springs Orogeny.

In addition, very fine-grained biotite was also dated from the mesostasis of a SD exposed in the Undoolya Quarry, Arunta Inlier, Northern Territory. Two biotite aggregates yielded ^{40}Ar/^{39}Ar age spectra (Fig. 3b) with ^{39}Ar release patterns similar to that for biotite from the gneiss in the Kulgera quarry. The plateau-like segments yield ages of 1059 ± 2 and 1066 ± 3 Ma (2σ).

The ages for both the ADS and SD are in agreement with those of the proposed Warakurna large igneous province (LIP) in west-central Australia (~1070; Wingate *et al.* 2004), indicating that both dyke swarms belong to that suite.

4 PALAEOMAGNETISM

4.1 Laboratory techniques

Routine palaeomagnetic laboratory methods (Collinson 1983; Butler 1992) were employed. Remanent magnetizations were measured using a 2G 755R three-axis cryogenic magnetometer interfaced to a PC computer using in-house software. The demagnetizers used were an in-line 2G 600 series alternating field (AF) demagnetizer and the CSIRO automated three-stage carousel furnace that is housed in a 4 m ten-coil Helmholtz set with automatic feedback maintaining zero-field (<5 nT). Samples were subjected to stepwise thermal demagnetization or AF demagnetization. If lightning effects were suspected, for example, from abnormally high magnetizations, the thermal demagnetization was preceded by low-temperature demagnetization (Schmidt 1993) using liquid nitrogen (LN_2). Components of magnetization were isolated using an interactive version of Linefind (Kent *et al.* 1983), whereby linear segments are fitted to data points weighted according to the inverse of their measured variances.

4.2 Results

Typical demagnetization behaviour for samples from the new sites KG08 and KG09 in the ADS is shown in Fig. 4. As found previously (Camacho *et al.* 1991), most samples were variably affected by lightning, calling for either AF demagnetization or low-temperature demagnetization. Fig. 4 shows examples of both treatment protocols that isolate a single component in each sample directed down to the WNW. Unlike the earlier study, no component related to the Alice Springs Orogeny was found.

Camacho *et al.* (1991) concluded that the dyke swarm was not folded because the site mean remanence directions scattered when restored to a vertical orientation. However, seven out of the nine sites are sheets whose directions converge when restored to the horizontal. This strongly suggests that the sheets were intruded subhorizontally. Therefore, for the fold test here, the remanence directions from sites in sheets have been restored to the horizontal and we have applied such tilt corrections for sheets to remanence directions for nearby subvertical dykes.

The site-mean directions for sites before and after untilting are shown in Fig. 5. We applied simple untilting about the structural strikes of sills, restoring the sampled rocks to approximate palaeohorizontal. A summary of the palaeomagnetic results from the ADS is listed in Table 1. The directions pass the fold test (McFadden 1990), showing a pronounced improvement in concentration after untilting, with 99 percent confidence, and the revised pole position lies at latitude = 2.8°S, longitude = 80.4°E ($dp = 7.2°$, $dm = 10.7°$). The positive fold test, plus the very high magnetic unblocking temperatures observed from the experiments and petrographic evidence showing that these rocks are fresh and unaltered, are strong evidence that the high temperature and high AF components isolated in the ADS date from the time of crystallization and can be confidently correlated with the ^{40}Ar/^{39}Ar ages. Although the Alice Springs Orogeny palaeomagnetic overprint was identified by Camacho *et al.* (1991), the high temperature components, now recognized as being pre-tilting, were readily distinguished.

5 DISCUSSION

Geological comparisons between Australia and North America have yielded a variety of Neoproterozoic reconstructions. However, no precisely dated palaeomagnetic poles have so far been documented

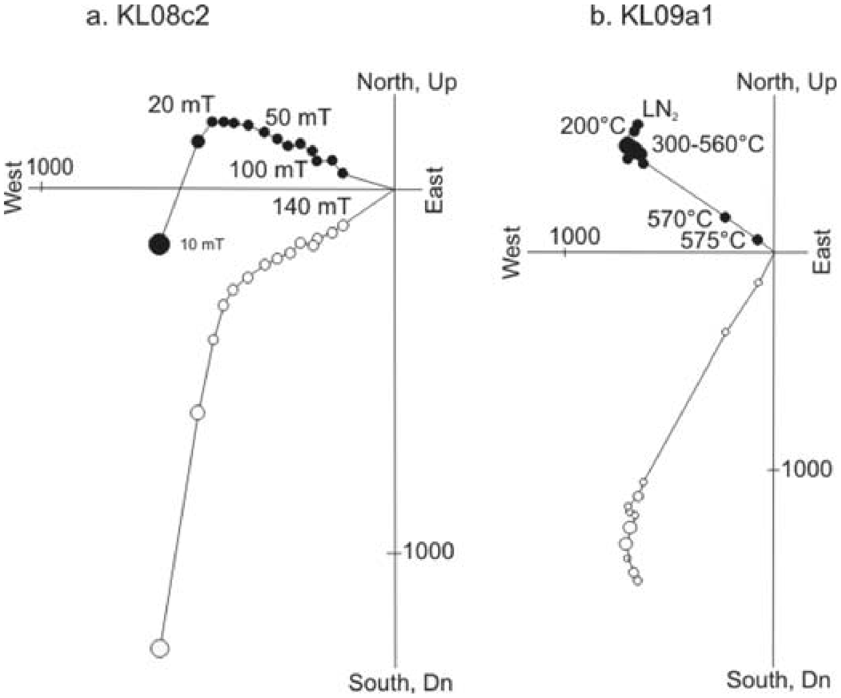

Figure 4. Orthogonal projections of remanence vectors after stepwise thermal demagnetization (°C) and stepwise AF demagnetization (mT). The LN_2 step refers to low-temperature demagnetization using liquid nitrogen. Solid circles plot on the horizontal plane and open circles on the vertical plane. The size of the circles reflects the angular standard error of the measurement. All units are mA m^{-1} (10^{-6} emu/cc).

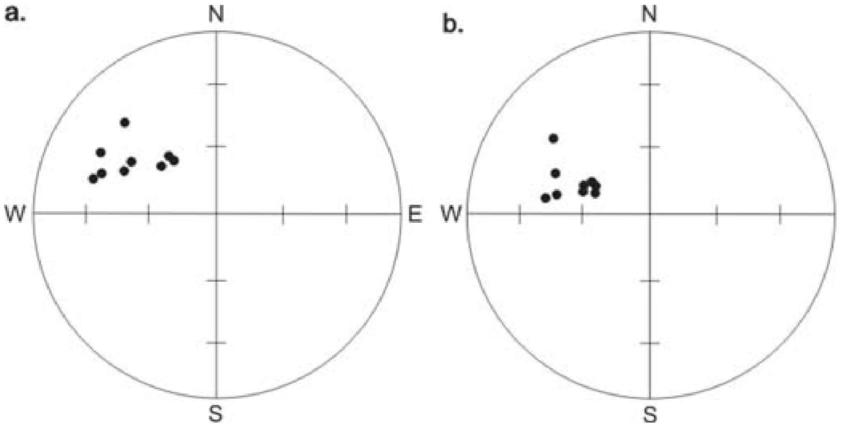

Figure 5. Stereographic projections of components for sites isolated by stepwise thermal and stepwise AF demagnetization. Solid circles plot on the lower hemisphere and open circles on the upper hemisphere. (a) and (b) are components carried by magnetite, before and after tilt-correction, respectively.

to support these reconstructions. Available data that are most relevant to compare with the Alcurra palaeopole are those from the Bangemall sills, which outcrop between the Pilbara and Yilgarn Cratons of Western Australia (Wingate *et al.* 2002) and the GB of south Australia (Giddings & Embleton 1976). The Bangemall sills are precisely dated at 1070 ± 6 Ma and yield a pre-tilting palaeopole at latitude = 33.8°N, longitude = 95.0°E ($\alpha_{95} = 8.3°$). The GB are not dated. However, the nearby Beda Volcanics have yielded a Rb-Sr whole rock age of 1076 ± 34 Ma (Webb & Coats 1980) and dolerite from the eastern Gawler Craton gave a Rb-Sr three-point isochron age of 1070 ± 74 Ma (Creaser, in Cowley & Flint 1993), suggesting igneous activity coeval with the Warakurna LIP also affected the South Australian Craton. The palaeopole from the GB, which is derived from extremely stable palaeomagnetic directions carried by single domain or pseudo-single domain magnetite (Giddings & Embleton 1976), lies at latitude = 22.8°S, longitude = 86.4°E ($\alpha_{95} = 11.3°$). The GB pole, therefore, lies in the general vicinity of the ADS and SD palaeopoles.

Redbeds of the Pandurra Formation of the eastern Eyre Peninsula, which underlies the Beda Volcanics, have yielded a preliminary pole position at latitude = 29.7°S, longitude = 59.8°E ($\alpha_{95} = 5.0°$; P.W. Schmidt & G.E. Williams, unpublished data, 2005). This is less than 25° from GB pole suggesting that the ages of the overlying Beda Volcanics and the GB may be fairly close. Similar redbeds from the western Eyre Peninsula, the Blue Range Beds, have yielded a pole at latitude = 34.3°S, longitude = 73.7°E ($\alpha_{95} = 5.0°$; P.W Schmidt & G.E. Williams, unpubublished data) that is only 15° from the GB pole, suggesting that the Blue Range Beds are more closely related in time to the Beda Volcanics, and are stratigraphically higher than the Pandurra Formation.

Table 1. Summary of palaeomagnetic results for the ADS, Northern Territory, Australia.

Site	DDA	Dip	N	D_h (°)	I_h (°)	D_b (°)	I_b (°)	K	α_{95} (°)
KG01	150	15	5	302	44	292	57	65.5	9.5
KG02	150	15	6	298	29	292	41	13.4	19.0
KG03	150	15	8	286	30	278	40	85.0	6.0
KG04	210	15	5	312	57	289	57	135	6.6
KG05	210	15	6	321	56	298	59	59.0	8.8
KG06	210	15	3	315	29	306	32	82.3	13.7
KG07[a]	210	15	3	322	59	296	61	132	10.8
KG08[a]	150	15	5	290	34	281	45	32.8	13.5
KG09	124	20	6	295	43	290	63	27.1	13.1
Mean			9	302.8	43.0	291.2	50.8	41.9	8.0

ξ_2 *in situ* 5.369 after 100 per cent unfolding 2.921 (99 per cent critical value 4.849). Pole: Latitude = 2.8°N, Longitude = 80.4°E ($dp = 7.2°$, $dm = 10.7°$). DDA- down dip azimuth.

[a] Sites from subvertical dykes; the tilt correction applied was that for the nearest sheet.

In discussing the implications of their Bangemall palaeopole, Wingate *et al.* (2002) argued that previous reconstructions of eastern Australia against either western Canada (SWEAT) or the western United States (AUSWUS) were not viable at 1070 Ma. Wingate *et al.* (2002) speculated that their results permit a reconstruction that closely aligns late Mesoproterozoic orogenic belts in northeast Australia and southernmost Laurentia (AUSMEX). However, as shown below, even this is ruled out by the disparate Warakurna poles. There now seems to be no palaeomagnetic evidence from Australia to support a Rodinia-like reconstruction during Mesoproterozoic to Neoproterozoic time. As stated by Wingate *et al.* (2002, p. 126), this implies that 'the Pacific Ocean did not form by separation of Australia–Antarctica from Laurentia, and that up to 10 000 km of late Neoproterozoic passive margins need to be matched with other continental blocks within any proposed Rodinia supercontinent'.

Given the positive fold test, the ADS pole and its precise age are considered to constitute a key pole for the Musgrave Block. The palaeomagnetic pole determination of the SD (Idnurm & Giddings 1988) did not provide enough information to allow a rigorous comparison with the revised ADS result. However, if we assume that at least ten SD were sampled then it is possible to estimate the relevant Fisher statistics to apply the McFadden & Lowes (1981) test. Assuming $N = 10$ for the SD implies $K = 24$, which yields a test statistic of 3.156 that is less than $F_{(2,34)} = 3.274$. The high degree of overlap of the confidence ovals (Fig. 6) also indicates that the SD and the ADS poles are very similar and are probably correlative.

In their synthesis of the tectonic evolution of Australia, Myers *et al.* (1996) argued that rather than having been essentially a single intact continent, with intracratonic tectonic belts, Australia comprised a number of distinct cratonic units that were assembled between 1300 and 1100 Ma. Firstly, the West Australian Craton was sutured to the North Australian Craton, followed by suturing with the South Australian Craton. The cratons themselves are thought to have formed from Archaean fragments at ∼830 Ma (Myers *et al.* 1996).

Another viewpoint is that the West Australian and the South Australian Cratons were sutured 400–500 million years earlier, during the late Palaeoproterozoic at ∼1700 Ma, soon after the cratons themselves were formed (Dawson *et al.* 2002). In addition, Wade *et al.* (2006) argued for suturing between the North and South Australian Cratons during the early Mesoproterozoic, at ∼1600 Ma.

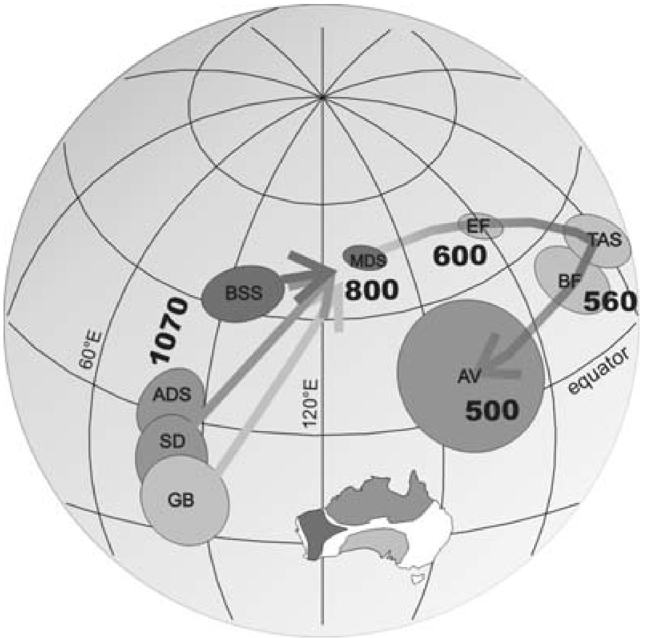

Figure 6. Palaeomagnetic poles for the Warakurna suite and other 'high-quality poles' from Australia Precambrian blocks: GB—Gawler B Dykes (Giddings & Embleton 1976), SD—Stuart Dykes (Idnurm & Giddings 1988), ADS—Alcurra Dyke Swarm (herein), BSS—Bangemall Supergroup Sills (Wingate *et al.* 2002), MDS—Mundine Wells Swarm (Wingate & Giddings 2000), EF—Elatina Formation (Schmidt & Williams 1995), Tas—Tasmanian Cambrian redbeds (Li *et al.* 1997), BF—Bunyeroo Formation (Schmidt & Williams 1996) and AV—Antrim Plateau Volcanics (McElhinny & Luck 1970).

There is palaeomagnetic evidence that the Kimberley and the eastern North Australian Cratons were assembled by 1700 Ma (Li 2000). In addition, palaeomagnetic evidence suggests that the Yilgarn and Pilbara Cratons merged at ∼1800 Ma (Williams *et al.* 2004). Li (2000) also discussed the possibility that the Yilgarn/Pilbara Cratons (West Australian Craton) and the North Australian Craton also had merged by 1700 Ma. However, the evidence presented below would argue against this, at least as a permanent merger, that is, we cannot rule out an ocean closure followed by re-opening as in a Wilson cycle. The indeterminacy of longitude adds another degree of freedom, as Li (2000) noted, making the hypothesis even more tenuous. The assembly of Precambrian Cratons was anticipated by Piper *et al.* (1973) and as such, their fig. 1(a) shows the model that may be applied to the Australian situation, where successive hypothetical apparent polar wander paths converge as cratons merge to form continents. Fig. 1(c) of Piper *et al.* (1973) applies to quasi-Wilson cycles where cratons intermittently drift apart then reform in a single entity.

Before adopting the wholesale convergence of cratons, however, we first consider a model whereby internal deformation within the cratons might account for the apparent differences. In such a situation, the magnetic declinations of the different dyke swarms might reflect the internal deformations. Given the pronounced arcuate trend of the ADS, it might be expected that the SW dykes have been rotated clockwise with respect to the NE dykes (see Fig. 2). This would correspond to the situation that has been convincingly documented for the Matachewan dykes of Canada (Bates & Halls 1991). However, when the sites are matched with their respective palaeomagnetic declinations (Table 1), it can be seen that this is not the case. There is no sign of any significant declination

Table 2. Summary of palaeomagnetic poles used in the tectonic analysis.

Formation	*N*	*D* (°)	*I* (°)	K	α_{95} (°)	Latitude (°)	Longitude (°)	*dp*[a] (°)	*dm* (°)	Reference
Gawler B Dykes	22	272.5	61.1	*b*	8.5	−22.8	86.4	11.3		Giddings & Embleton (1976)
Stuart Dykes	*b*	276.0	58.0	*b*	*b*	−10.0	82.0	10.0		Idnurm & Giddings (1988)
Alcurra Dykes	9	291.2	50.8	41.9	8.9	2.8	80.4	7.2	10.7	herein
Bangemall Sills	11	339.9	46.5	30	8.4	33.8	95.0	8.3		Wingate *et al.* (2002)
Mundine Dykes	14	14.1	32.2	*b*	*b*	45.3	135.4	4.1		Wingate & Giddings (2000)
Elatina Fm	10	197.4	7.1	9.16	16.9	51.5	166.6	7.7	15.3	Schmidt & Williams (1995)
Tasmanian seds.	11	58.3	11.1	20.2	10.4	19.4	208.9	5.3	10.5	Li *et al.* (1997)
Bunyeroo Fm	6	56.6	29.3	40.4	10.7	18.1	196.3	6.5	11.8	Schmidt & Williams (1996)
Antrim P. Vols.	14	51.0	66.0	11.0	13.0	9.0	160.0	17.0		McElhinny & Luck (1970)

[a] Where only a value under *dp* is given the value refers to A_{95}.

[b] mean directions not given in original reference or not applicable, as in Mundine dykes which outcrop over too large an area for a mean direction to be valid. To assist visualising the rotations discussed in the text, approximate directions have been calculated using a central geographical location and assuming an axial geocentric dipole.

differences, let alone differences of up to 60°. In addition, as demonstrated above, the palaeomagnetic directions of the SD, some hundreds of kilometres to the north of the ADS, are also consistent with there having been no relative (internal) deformation since their formation (Table 2). A similar argument can be made against gross rotations within the Bangemall Basin after the intrusion of the sills, insofar as the palaeomagnetic declinations of the sills do not reveal systematic rotation from one location to another (other than the tilting that yields a positive fold test). Wingate *et al.* (2002, p. 124) concluded that 'the Bangemall Basin has undergone no internal vertical axis rotation since 1070 Ma'.

The granulite facies S2 fabrics of the Musgrave Block, which formed at ∼1150 Ma, have a dominant north–south trend (Camacho & Fanning 1995) and do not appear to have been deformed subsequently (see fig. 5 in Camacho & Fanning 1995). The Petermann Orogeny and Alice Springs Orogeny are unlikely to have coherently rotated the dykes over a very large area. The Woodroffe Thrust (associated with the Petermann Orogeny) has an easterly trend, is about 300 km long, is remarkably straight and dips shallowly to the south. The rocks of the Fregon Subdomain are on the upper plate and it is difficult to see how such a configuration would permit relative rotation. Similar argument holds for the Arunta Inlier. Moreover, the Amadeus sediments have dominantly easterly trends and bedding is not rotated when viewed on a large scale. In the absence of evident internal deformations, we, therefore, must consider relative rotations between, rather than within, the cratons.

In Fig. 6, we have plotted late Mesoproterozoic to Neoproterozoic high quality poles for Australia. The Warakurna poles (BSS, ADS, SD and GB) form a trend that, given their contemporaneity, indicates some relative movement between the various blocks since their intrusion. Although insufficient data exist to say exactly when the paths converged, the point of convergence corresponds to the final assembly of the major Precambrian Cratons of Australia. This presumably occurred during the Grenville Orogeny. Notwithstanding the indeterminacy of palaeolongitude, a palaeogeographical distribution consistent with these data is shown in Fig. 7(a). A variety of palaeoreconstructions doubtless exists that satisfy the palaeopole constraints, although the chemistry and ages of the dyke swarms suggest that the different cratons were likely to be in the same general geographical area. However, it is clear that the present distribution of these Precambrian Cratons, shown in Fig. 7(b), cannot satisfy the data. The palaeomagnetic data are, therefore, inconsistent with the Warakurna LIP having been intruded into a single assembled unit. On the contrary, the palaeomagnetic data can only be interpreted in conventional terms if the West, North and South Australian Cratons were disjoint at 1070 Ma, in apparent contradiction to other geological evidence which suggests that the cratons sutured earlier. As noted above however, the other geological evidence is not self-consistent either, with some arguing for 1300–1100 Ma assembly (Myers *et al.* 1996) and others arguing for much earlier assembly at about 1600–1700 Ma (Dawson *et al.* 2002; Wade *et al.* 2006).

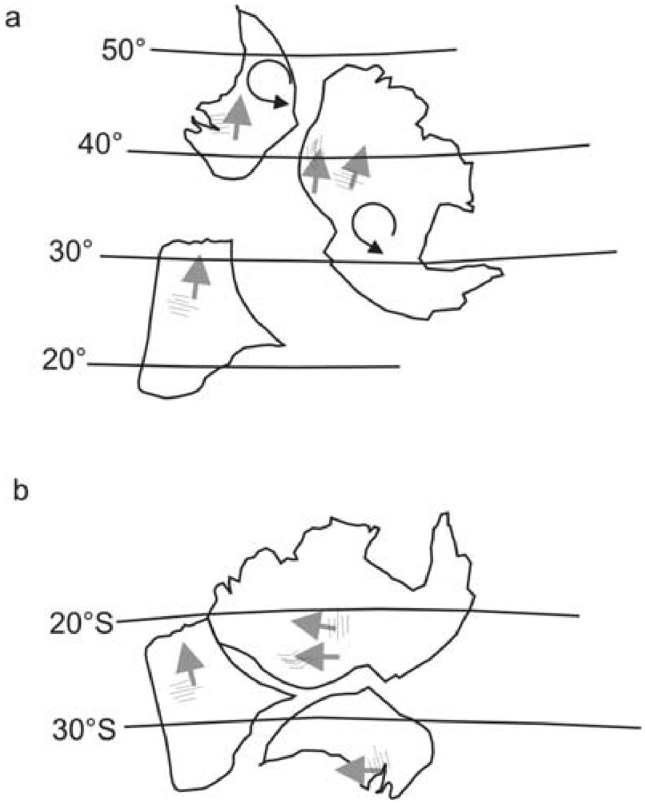

Figure 7. Distribution of Proterozoic cratons: (a) based on palaeopoles from members of the Warakurna LIP (∼1070 Ma) and (b) present day. The broad arrows represent the magnetization direction for respective dykes, the fine short lines reflect the general dyke trends, and the circular arrows indicate the notional rotation direction that occurred before collision of the cratons.

The apparent emplacement of the Warakurna LIP into distinctive and separate crustal units raises questions about the underlying mechanism for the LIP. If mantle plume activity were involved then it may be a question of how many plumes, or whether a superplume may have been active. Further palaeomagnetic and geochronological investigations are needed to resolve these issues.

6 CONCLUSIONS

(i) New palaeomagnetic and geochronological results for the ADS of the Musgrave Block, North Australian Craton, elevate the pole position to key pole status.

(ii) The age of 1070 Ma confirms that the ADS belongs to the Warakurna LIP as suggested by Wingate *et al.* (2004).

(iii) Whereas the pole position for the ADS agrees with those for the coeval SD from the Arunta Inlier, from the North Australian Craton, and the (possibly coeval) GB, from the South Australian Craton, these poles are at variance when compared to the pole from the BSS from the West Australian Craton.

(iv) The palaeomagnetic data indicate that the dykes did not intrude already assembled cratons at ∼1070 Ma. Rotation and assembly of cratons must have happened after 1070 Ma, later than previously thought.

(v) The results and the analysis presented here imply that the Precambrian Cratons comprising Australia west of the Tasman Line have not always been assembled as they are now, which accords with the ideas of Myers *et al.* (1996) although differs in timing.

(vi) While the assembly of cratons was anticipated by pioneers of Precambrian palaeomagnetism, this is the first such case documented using key poles (BSS and ADS poles are key poles, while those from the SD and the GB are not key poles but they are supportive).

(vii) Before the Rodinia riddle can be solved, however, the drift history of individual Precambrian Cratons must be defined.

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