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GR Focus Review

A review of Precambrian palaeomagnetism of Australia: Palaeogeography, supercontinents, glaciations and true polar wander

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ABSTRACT

This is the first review of the Australian Precambrian palaeomagnetic database since that undertaken by Idnurm and Giddings (1988) 25 years ago. In this period the data have almost tripled in number from about 60 to more than 170 and while some segments of the pole path are now quite well defined, overall the data are sparse. It is debatable whether the extant rock record amenable to palaeomagnetism is complete enough for full palaeogeographic histories to be reconstructed. The SWEAT connection is apparently ruled out for Rodinia as both the 1200 Ma and 1070 Ma poles from (ancestral) Australia and Laurentia disallow it. However, older palaeopoles do support a SWEAT-like configuration for the pre-Rodinia supercontinent Nuna but the geological reasoning for SWEAT applies to Rodinia so a Nuna SWEAT is less than gratifying. The concept of a “grand-pole” is introduced here, which includes all the “key-pole” features but is predicated on the condition that two or more independent laboratories are in agreement.

Precambrian data from Australia include the oldest palaeopole yet defined, the record of one of the oldest geomagnetic polarity reversals, the most definitive evidence for low-latitude Neoproterozoic glaciation, the first study of BIFs and the timing/nature of iron-ore genesis, the most unusual ‘field test’ (impact melt rock and ejecta horizon host rocks), some of the best examples of complete contact tests and the timing of craton assembly. Some old caveats that can no longer be ignored, such as corrections for inclination flattening and the permitting of rotations between contiguous intracontinental cratons to bring conflicting palaeopoles into alignment are required. Care should be exercised when inferring palaeolatitudes from sedimentary derived palaeoinclinations. TPW should only be considered if there is evidence from more than one, and preferably more, independent continents. Future work identified includes a complete magnetostratigraphic study of ~300 my Adelaidean succession, better age constraints for the Adelaidean and Officer Basin successions and a better age for the Gawler Craton GB dykes.

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1. Introduction

The first palaeomagnetic study of Australian Precambrian rocks was undertaken during the early years of palaeomagnetism by Irving and Green (1958). They studied oriented samples of the Nullagine Lavas, now called the Fortescue Volcanics (Mount Roe Basalts), from the Pilbara, the Edith River Volcanics (now the Plum Tree Creek Volcanics, part of the Edith River Group) from the McArthur Basin and the Buldiva quartzite (now part of the Tolmer Group) from Arnhem Land. While the palaeomagnetism of the Mount Roe Basalt and the Plum Tree Creek Volcanics has been re-studied since, and their ages better defined stratigraphically and geochronologically, the original observations have stood the test of time in the sense that the early pole positions remain valid. Briden (1967) undertook a palaeomagnetic study of Late Precambrian Adelaidean strata from the southern end of the Adelaide Geosyncline (fold belt) but was frustrated by Mesozoic and Tertiary overprinting evidenced by negative fold tests.

McElhinny and Embleton (1976) reviewed the Proterozoic to Early Palaeozoic (2500 Ma to 400 Ma) palaeomagnetic data from Australia and introduced their somewhat less stringent version of ranking poles than that proposed by Stewart and Irving (1974). The scheme designed by the latter workers ranked poles between 1 and 3 based on the palaeomagnetic and age data, and also the timing of remanence relative to rock age (a perfect score would be 9, although no North American pole made that grade). McElhinny and Embleton (1976) relented on the third criterion, the timing of remanence, in a pragmatic step to retain enough Australian data for postulation and debate. They showed that the polar motion for the Late Proterozoic–Early Palaeozoic period averaged about 1°/My. They also showed that results from other Gondwana continents were consistent with the Australian pole path and therefore argued that the Pan-African (550 ± 100 Ma) orogenic belts were of ensialic origin. It was also argued that the Australian data are consistent with a common apparent polar wander (APW) path back to 2500 Ma, with an average wander rate of 0.3°/Myr, indicating that the mobile belts separating the Precambrian cratons of the Australian shield are ensialic like the Pan-African belts.

The next significant advance in establishing a Precambrian palaeomagnetic framework for Australia focused on the Neoproterozoic (McWilliams and McElhinny, 1980). That study showed that the sigmoidal structural trends of the Adelaide Geosyncline are original and indicated low latitudes for the late Precambrian glacial deposits in South Australia, all findings that remain valid today.

A complete review of extant Australian Precambrian palaeomagnetism was provided by Idnurm and Giddings (1988), after they had undertaken an extensive palaeomagnetic investigation of Mesoproterozoic units in Northern Australia, particularly the McArthur Basin and the Pine Creek Inlier. That study included discussions on the validity of the Geocentric Axial Dipole (GAD) hypothesis for Precambrian time, the structural unity of the Australian Precambrian cratons since their amalgamation, global reconstructions during the Precambrian and finally the authors questioned uniformitarianism with regard to Precambrian palaeoclimates and palaeolatitudes. All these aspects are revisited in this current review.

Since 1988 various groups, namely the Australian Geological Survey Organisation (AGSO), the Tectonics Special Research Centre (TSRC) of the University of Western Australia, and the Commonwealth Scientific and Industrial Research Organisation (CSIRO), have continued to make many contributions to the Precambrian palaeomagnetism of Australia. In addition, several groups from the USA, Canada, the Netherlands and Japan have added to the data base. Idnurm (2004) updated the Precambrian palaeolatitudes of Australia, incorporating pre-2004 AGSO and TSRC data although not the late Neoproterozoic data mainly from CSIRO. It is timely to undertake a new review of Australian Precambrian palaeomagnetic results.

The Australian content of the Global Palaeomagnetic Database (GPMDB; McElhinny and Lock, 1996; Pisarevsky, 2005) has been updated to the end of 2011 (Sergei Pisarevsky, pers. comm., 2012) and can be downloaded from www.magresearch.org. These data and data published later in 2012 form the basis of this review (Supplementary data).

2. Distribution of Precambrian outcrop and sampling localities

Australia is divided into a number of tectonic cratons with the Archaean and Proterozoic in the western two-thirds and Phanerozoic terranes in the east (Fig. 1). The boundary between the Precambrian and the Phanerozoic is referred to as the Tasman Line. This boundary is mostly obscured by younger rocks and is inferred from gravity and magnetic lineations. The exact location and geological nature of the Tasman Line is a source of much debate with some disputing that it is the margin of Precambrian Australia (Direen and Crawford, 2003; Kennett et al., 2004).

The Pilbara and Yilgarn cratons were sutured during a series of orogenies beginning with the ca. 2.2 Ga Ophthalmian Orogeny, followed by the 2.0–1.96 Ga Glenburgh Orogeny and the 1.83–1.78 Ga Capricorn Orogeny to form the Western Australia Craton which exhibits tectonic features as old as 3.65 Ga to less than 2.0 Ga (Betts et al., 2002). The Bangemall Basin formed just after the Capricorn Orogeny during the Meso–Neoproterozoic. Granite–greenstone belts of the Yilgarn, the largest Archaean craton in Australia, attest to continental accretion between 3.73 Ga and 2.55 Ga. The Hamersley Basin of the southern Pilbara contains banded iron-formations (BIF) and shale units from 2.6 to 2.45 Ga deformed during the Ophthalmian Orogeny (Betts et al., 2002).

The McArthur Basin, Kimberley, Arunta and Mt Isa cratons of northern Australia were assembled into the North Australia Craton (Fig. 1) during the 1.82 Ga Halls Creek Orogeny. The Pine Creek Inlier is partly of Archaean age (Betts et al., 2002).

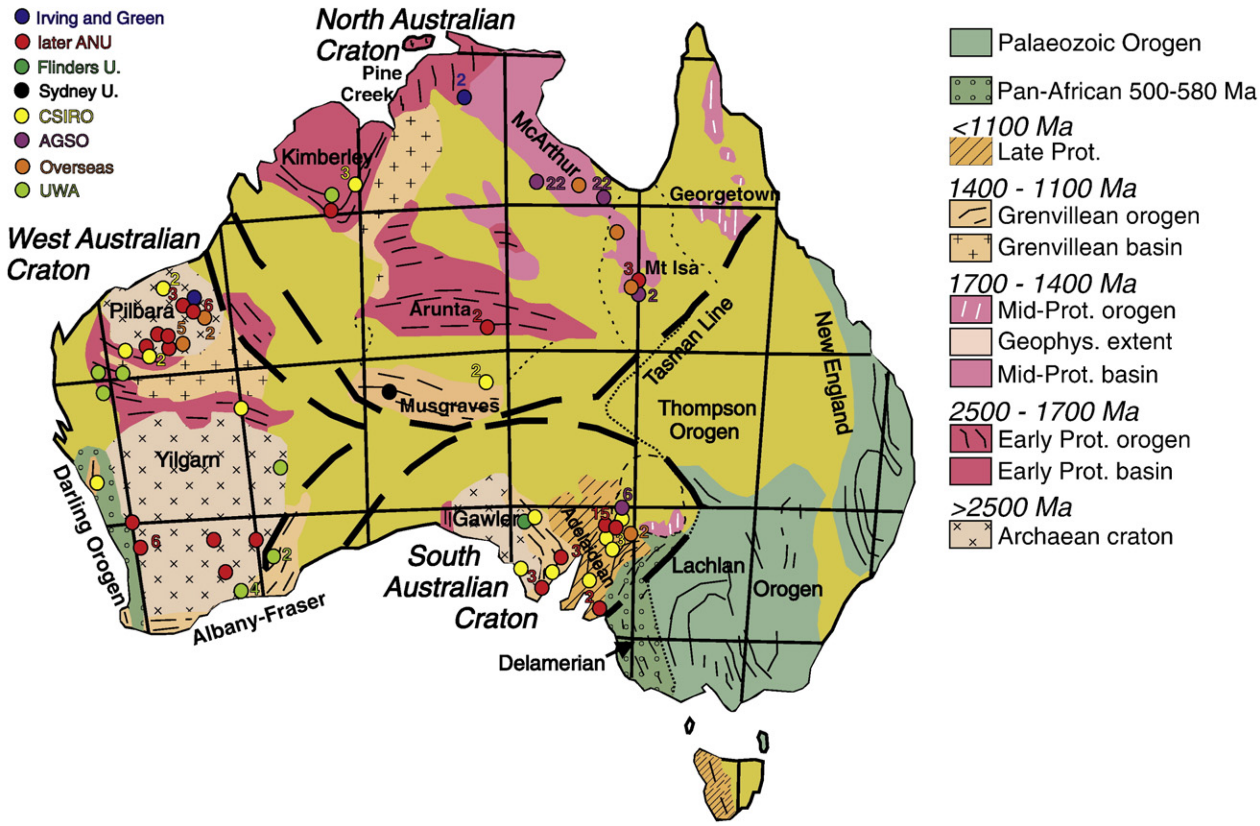

Fig. 1. Structural framework of Australia. Adapted from Betts and Giles (2006) with modifications following Schmidt et al. (2006), Musgrave and Rawlinson (2010), Cawood et al. (2011). The coloured dots represent individual palaeomagnetic studies of Precambrian rock formations. The colours refer to different institutions as shown in the legend. The numbers accompanying some dots refer to the number of formations studied.

The Gawler Craton, the Coompana Craton, the Adelaidean successions and the Curnamona Craton comprise the South Australia Craton, thought to be a dismembered part of the Gondwana pre-breakup Mawson Craton, the remainder of which today comprises the East Antarctic Shield (Giles et al., 2004).

The West Australian and North Australian cratons (WAC and NAC) were thought to have amalgamated by 1.8 Ga. The Albany–Fraser Orogeny and Musgrave Craton (Fig. 1) of Grenvillian age are thought to represent the collision zone between the south (SAC) and the west/north cratons (N/WAC). However, palaeomagnetic evidence suggests this merger may have either post-dated 1.07 Ga or there were some significant late stage readjustments after 1.07 Ga (Schmidt et al., 2006; Li and Evans, 2011).

Since unification of the major cratons, central Australia has suffered a protracted period of tectonism, beginning with the Petermann Orogeny at Proterozoic/Palaeozoic boundary time (550–535 Ma), and continuing into the Palaeozoic with metamorphism of the Arunta Craton at 450 Ma and the Alice Springs Orogeny which lasted from 400 Ma to less than 300 Ma (Haines et al., 2001).

The cause of these intraplate orogenies is a contentious issue but it is clear that they have produced the uplift of the Musgrave and Arunta cratons from beneath the Centralian Basin, of which the Amadeus, Officer, Ngalia and Georgina basins are relics. The fact that such a large basin formed in central Australia is probably evidence of some crustal weakness (Haines et al., 2001), maybe related to the palaeomagnetically derived post-1.07 Ga late stage tectonism, and partial rifting, before a final assembly of the cratons.

Precambrian palaeomagnetic sampling locations are shown in Fig. 1 and colour coded according to the schools that undertook the studies. ANU (Australian National University) is separated into 'Irving and Green (1958)' versus later workers. In addition, the various institutions from overseas are combined as a single colour code.

3. Palaeomagnetic studies of the Archaean

When Irving and Green (1958) reported results from the Nullagine Lavas it was thought the lavas were perhaps Sturtian in age (ca. 750–700 Ma), based on evidence of glaciation. These lavas are now known to be 2.7 Ga being part of the Archaean Fortescue Volcanics, underlying the Hamersley Group of the Pilbara. The results from Irving and Green (1958) are now a piece of history being part and parcel of the triumphant case in favour of the 'continental drift' question in the late 1950s and 1960s (Frankel, 2012). This is the reason I have separated the Nullagine sampling location, and other Irving and Green (1958) sites from later ANU studies in Fig. 1, and plotted the pole from this early study in Fig. 2. Other poles plotted in Fig. 2 are listed in Table 1.

3.1. Palaeomagnetism of Palaeoarchaean rocks

The oldest rocks in Australia to yield apparently reliable palaeomagnetic information are from the 3.45 Ga Duffer Formation, Pilbara, Western Australia (McElhinny and Senanayake, 1980). These workers presented a positive palaeomagnetic fold test on basaltic and dacitic lavas where folding was thought to have occurred at 3.0 Ga. Their interpretation was that because the magnetisation survived the tectonic event responsible for the folding, in all likelihood the magnetisation dated from the time of original cooling in the Earth's field, and was therefore strong evidence for the existence of the Earth's field at that time.

Usui et al. (2009) have raised a number of concerns with this study. They point out (p. 12) that more recent geochronological investigations have assigned ages of 3.3–3.2 Ga for emplacement of the plutonic complex "interpreted as the main cause of the folding". While these workers rightly point out that the age inferred for a pre-folding magnetisation is only relative to folding, they incorrectly state that while the "age of folding is uncertain, it is younger than that inferred by McElhinny and Senanayake (1980)". McElhinny and Senanayake (1980, p. 3523) state "there have been two intervals of granite emplacement… a main one at around 3000 Ma… the folding is presumed related to the main period". Thus it seems the main event has been pushed back in time indicating the age of magnetisation of the pre-folding component may be all the more tightly constrained.

On the basis that the dacite is "red" in colour, Usui et al. (2009) also suggested problems with severe weathering. While the present author in particular is aware that weathering can be a problem throughout Australia (Schmidt and Embleton, 1976; Idnurm and Schmidt, 1986; Schmidt and Williams, 2008), severe weathering is not such a problem that careful site selection cannot minimise. After all, many palaeomagnetic studies have successfully avoided the effects of weathering in this area (Fig. 1). Tight, impermeable, igneous rocks are particularly resilient against weathering in northern Australia which is generally very dry and only inundated during the monsoon season. Also dacites are quite often reddish from an originally oxidised magma. Usui et al. (2009, p. 12) may have a point regarding the "highest unblocking temperature component should be the most reliable… but, the highest unblocking temperature magnetisation from the dacite fails the fold test". While not defending the Duffer Formation fold test, per se, it is worth remembering that the most stable components

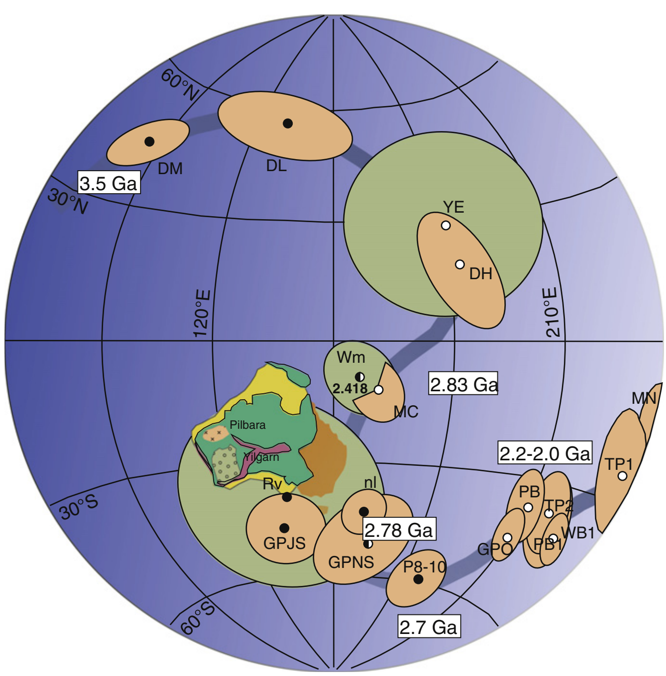

Fig. 2. Archaean–Palaeoproterozoic apparent polar wander path for Australia. Mnemonics are DM — Duffer Formation (medium); DL — Duffer Formation (low); DH — Duffer Formation (high); YE — Yilgarn 'E' dykes; Wm — Widgiemooltha dykes; MC — Millindinna Complex; Rv — Ravensthorpe dykes; nl — Nullagine Lavas of Irving and Green (1958); GPNS — Grand Pole Nullagine Supersequence; GPJS — Grand Pole Mount Jope Supersequence; P8-10 — Package 8–10 (Strik et al., 2003); GPO — Grand Pole Ophthalmian overprint; PB — Paraburdoo BIF; WB — Wittenoom BIF; TP1, 2 — Mount Tom Price iron ore; PB1 — Paraburdoo iron ore; MN — Mount Newman iron ore (Table 1). Note that the significant age difference between the Widgiemooltha dykes and the Millindinna Complex may suggest coincidental pole positions or that the Yilgarn and Pilbara cratons were separate entities at these times. Without a 2.8 Ga pole from the Yilgarn or a 2.5 Ma pole from the Pilbara however, there is not enough data to differentiate between these possibilities. For pole positions solid circles indicate normal polarity while open circle indicate reverse polarity. Half-Moon circles indicate mixed polarity.

found by some studies are demonstrably secondary overprints (Schwartz and Buchan, 1989; Schmidt, 1993). Although Usui et al. (2009) have cast aspersions on the 3.5 Ga pole position from the Duffer Formation, the Duffer Formation pole is retained here (Fig. 2) mainly because Usui et al. (2009) have only provided prima facie rather than hard evidence against its veracity, such as a repeat palaeomagnetic study, to show that the Duffer Formation pole position is erroneous. Bradley et al. (2008) have presented results that support the Duffer Formation directions from the ca. 3.34–3.37 Ga overlying Euro Basalt and Double Bar Formation. After tilt correction the Euro Basalt direction is indistinguishable from the tilt-corrected ca. 3.46 Ga Duffer Formation direction.

Usui et al. (2009, p. 12) also doubt other Archaean palaeomagnetic results from the ca. 3.46 Ga Marble Bar chert (Suganuma et al., 2006), expressed as regrets that there is "no specific evidence that the chert magnetisations are primary, and the rock magnetic data presented indicate the presence of multidomain grains which would again be expected to carry overprints related to the later metamorphism". If a rock formation is so vulnerable to remagnetisation it will almost always acquire a drilling induced remanence (DIR; Pinto and McWilliams, 1990). Since the drill hole of Suganuma et al. (2006) was oriented with a plunge of 40° toward 230°, any DIR should be acquired upward to the NE along the drill barrel axis closest to the local Earth's field, which is directed northerly and upward. The directions observed (before untilting) are very shallow to the west, indicating little or no DIR. While there are some misgivings regarding the presentation of their results (e.g. no pre-untilting, or in situ, data are specifically tabulated or plotted) the implied shallow westerly in situ directions observed are sufficiently unique and interesting to warrant attention. For these reasons, and until more tangible evidence comes to light, the palaeomagnetic results from Marble Bar chert results are worth retaining. There is a caveat though, that if the Euro Basalt direction of Bradley et al. (2008) is taken at face value, implying little (latitudinal or rotational) relative motion of the Pilbara Craton from ca. 3.46 Ga to ca. 3.34 Ga, then the Marble Bar chert result of Suganuma et al. (2006) is inconsistent. This contradiction requires further palaeomagnetic investigation.

3.2. Palaeomagnetism of Mesoarchaean rocks

The Millindinna Complex gabbro has been dated by Korsch and Gulson (1986) using Sm–Nd at 2830 ± 20 Ma (their older Pb–Pb date of 2960 ± 20 Ma is attributed to minimal dispersion of isotope ratios). The palaeomagnetic pole (Schmidt and Embleton, 1985) is based on extremely stable remanent magnetisations with coercivities of remanence exceeding 80 mT. Rock magnetic parameters indicate single domain to pseudo-single domain (SD–PSD) grain-sized magnetite carries the characteristic remanent magnetisation (ChRM), with $J_{rs}/J_s = 0.4$–0.5 and $H_{cr}/H_c < 1.7$. Although two sections were sampled with different attitudes and different in situ mean directions, which agreed much better following tilt correction, the attitude of the second section could not be accurately established and the results from the second section were not used for the final mean direction. The evidence is strong though, that the magnetisation pre-dates tilting. Despite the rock magnetic evidence, the likelihood that the magnetisation is pre-folding and the tight radiometric age, Evans and Pisarevsky (2008) chose to reject the Millindinna Complex pole position on the grounds of "poor age constraints and lack of field stability tests". To those that are familiar with rock magnetism it is clear that the Millindinna Complex gabbro could not have been remagnetised without heating to high temperature, above 550 °C, or through complete chemical alteration, neither of which is evident in any way. While lightning effects were detected, the dual treatment of AF followed by thermal demagnetisation was able to easily erase these spurious components. On balance the Millindinna Complex pole is robust compared to many other Precambrian pole positions and is herein retained (Fig. 2).

Table 1
Summary of Archaean and early Palaeoproterozoic palaeomagnetic data for Australia.

Formation	Age (Ga)	Dec. (°)	Inc. (°)	α_{95} (°)	λ_p (°)	φ_p (°)	dp (°)	dm (°)	1	2	3	4	5	6	7	Q	Result#
a. Pilbara Craton																	
Mt Tom Price iron ore	2.2	308.8	−9.3	11.3	−37.4	220.3	5.7	11.3	×	√	√	×	×	×	√	3	7542
Paraburdoo iron ore	2.2	304.7	−23.0	8.3	−36.4	209.9	4.7	8.8	×	√	√	×	×	×	×	2	7540
Wittenoom BIF	2.2	307.5	−10.5	9.0	−36.4	218.9	4.6	9.1	×	√	√	√	√	×	√	5	7541
Paraburdoo BIF	2.2	314.0	−4.7	5.8	−40.9	225.0	2.9	5.8	×	√	√	√	√	×	√	5	7539
GPO[a]	2.0	311.1	−27.0	5.7	−43.7	208.9	3.4	6.3	×	√	√	√	√	×	√	5	Herein
GPJS	2.72	156.6	75.1	5.9	−46.4	133.8	17.9	10.1	√	√	√	√	√	√	√	7	Herein
GPNS	2.76-2.74	132.3	67.0	3.6	−42.7	159.0	4.4	6.1	√	√	√	√	√	√	√	7	Herein
Millindinna Complex	2.83	265.0	−65.1	5.2	−11.9	161.3	6.8	8.4	√	√	√	√	×	×	×	4	308
Duffer Fm DM	<3.45	335.5	31.8	8.4	43.9	86.3	7.2		√	√	√	√	√	×	√	6	182
Duffer Fm DL	<3.45	6.8	23.5	14.8	55.4	132.2	12.5		×	√	√	×	√	×	√	4	184
Marble Bar chert	3.46	326.9	−35.8	9.3	59.0	26.3	6.3	10.8	×	√	√	×	√	×	√	4	9351
Duffer Fm DH	3.47	243.5	−29.7	14.0	18.7	182.9	14.5		×	√	√	×	√	×	×	3	183
b. Yilgarn Craton																	
YE dykes	2.5-2.7	232.1	−8.1	46.1	28.3	180.4	31.0		×	×	√	√	√	×	√	4	1947
Ravensthorpe dykes	2.4-2.6	114.3	82.9	13.2	38.3	316.2	25.5		×	×	√	×	√	×	√	3	49
Widgiemooltha dykes	2.418	242.0	−67.0	6.0	8.0	337.0	7.5	9.0	√	√	√	√	√	√	×	6	1889

Dec. = declination, Inc. = inclination, α_{95} = the half-angle of the cone of confidence (Fisher, 1953), λ_p = the pole latitude, φ_p = the pole longitude, dp, dm, semi-axes of the polar error ellipse (Fisher, 1953); where only one entry is given under dp, dm the value is for A_{95}; 1–7 and Q, reliability criteria of Van der Voo (1990). It should be noted that the seventh quality factor described by Van der Voo (1990), the lack of similarity to younger poles, does not carry the same weight for Precambrian data as for Phanerozoic data due to the fact that Precambrian paleomagnetic poles of distinctly different ages may commonly fall close to each other on the globe (Veikkolainen et al., 2013). Moreover, "similarity" is subjective and in reality difficult to apply. Note Result# 7540 is described in the GPMDB as Paraburdoo Banded Iron Formation where in fact it is Paraburdoo iron ore. Result# refers to the Result number listed in the GPMDB5 www.magresearch.org.

[a] GP refers to Grand Pole after combining results from studies by two or more investigations.

3.3. Palaeomagnetism of Neoarchaean volcanics and feeder dykes

Late Archaean rocks that have been investigated include the Fortescue Volcanics of the Pilbara Craton, probable feeder dykes of the volcanics, outcropping in basement granite domes, and the overlying Hamersley BIF. While the radiometric age of the Black Range dyke was taken as 2329 ± 89 Ma when studied palaeomagnetically (Embleton, 1978), it has now been precisely dated using SHRIMP at 2772 ± 2 Ma by Wingate (1999) and is clearly Archaean. Embleton (1978) argued that a single pole path could be constructed using poles from the Black Range dyke and the sub-parallel Cajuput dyke, plus others from the Pilbara and Yilgarn Cratons, without violating the known chronological constraints. This was taken as further support for the idea that younger mobile belts between the granite–greenstone terrains are ensialic, reminiscent of ideas about the Pan-African mobile belts (Kröner, 1976).

Giddings (1976) studied 54 dykes from the Yilgarn Craton and found five distinct groupings. Radiometric age dates suggested that there were in fact seven age clusters, with two groups being duplicated at different times. Cross-cutting relationships agree with the radiometric ordering of the intrusive events. The dykes were given mnemonics of YA–YF corresponding to ages of 2.5 to 1.7 Ga, plus the Ravensthorpe dyke (2.5 ± 1.0 Ga) that possesses very steep downward directed remanence similar to the YA dykes. The younger YB dyke is discussed in Section 6.3.

A new investigation of the Archaean Fortescue volcanics and intrusions of the Pilbara Craton was undertaken by Schmidt and Embleton (1985). Although lightning-affected magnetisations were a factor it was found that AF followed by thermal demagnetisation was an effective remedy and pre-folding magnetisations were identified at most volcanic sites, including those that had been specifically selected for fold tests. Poles were determined from pre-folding components for the Mount Roe Basalt (the old Nullagine Lavas of Irving and Green, 1958) and the overlying Mount Jope Volcanics (as well as the basement Millindinna Complex mentioned above). A second, synfolding, component was identified in the Mount Jope Volcanics, which was interpreted as having been acquired during the Ophthalmian Orogeny at ~2.2 Ga. Metamorphism of the Hamersley Basin shows four zones (Smith et al., 1982) reflecting depth of burial. Metamorphic grades increase from north to south, beginning with the shallowest burial assemblage Z1: prehnite–pumpellyite, then Z2: prehnite–pumpellyite + epidote, Z3: prehnite–pumpellyite + epidote + actinolite, and the deepest burial assemblage Z4: prehnite–epidote–actinolite. The Mount Roe Basalt samples came from Z1, while the Mount Jope Volcanics samples came from Z4, which is consistent with the synfolding component so prevalent in the latter. The folding was accompanied by uplift and supracrustal cooling, blocking the burial thermoviscous remanence. Indeed it is remarkable that primary pre-folding thermoremanent magnetisation have been retained by these rocks. The similarity of Mount Jope pre-folding directions with the pre-folding Mount Roe magnetisations from Z1 indicates a high degree of reliability of the results.

Following the work of Schmidt and Embleton (1985), Strik et al. (2003) re-sampled the volcanics stratigraphically and while confirming the earlier work they also constructed a polar wander path based on the ca. 60 Myr stratigraphic interval covered by the succession. Perhaps the most significant finding of that study is the sharp change in palaeolatitude of ca. 30° in a very short period, maybe a few Myr. The implications of this rapid shift remain to be determined but may have a bearing on stratigraphic correlation at least. These results have been rationalised with the earlier results from Schmidt and Embleton (1985) in Appendix A, to provide three overarching grand-poles listed in Table 1 and plotted in Fig. 2.

3.4. Palaeomagnetism of the Neoarchaean Hamersley BIF and iron ores

Western Australian hematitic ore bodies studied by Porath and Chamalaun (1968) include the Mount Goldsworthy deposit in the Archaean of the Pilbara craton, the Mount Tom Price and Mount Newman deposits in the Hamersley Basin (also part of the Pilbara craton) and the Koolyanobbing deposit from the Yilgarn craton. Three distinctly different directions were found in the Mount Goldsworthy deposit, two at Koolyanobbing, while a single mean direction was found in each of Mount Tom Price (TP1) and Mount Newman (MN). An aim of Porath and Chamalaun (1968) was to place some age constraints on the formation of the iron ores. Although they suggested a Palaeoproterozoic age for the largest Koolyanobbing ore body, because of the lack of Proterozoic poles from Australia at the time it was not possible to give more accurate estimates for the other deposits other than a general Proterozoic age and not Mesozoic as some had suggested.

Schmidt and Clark (1994) carried out a more comprehensive survey of Hamersley Basin BIF and iron ores, including rock magnetism and anisotropy of magnetic susceptibility as well as palaeomagnetism. The iron ores included the Paraburdoo deposit (PB) and the Mount Tom Price (TP2) deposits, while the BIF studied were from Paraburdoo (PB1) and Wittenoom (WB1). Their study concluded that the directions determined from the BIF are pre-folding while those from the iron ores are post-folding. For the first time the magnetic anomalies over BIFs of the Hamersley Basin could be explained in terms of measured magnetic properties, including AMS (Clark and Schmidt, 1994). The spread in pole positions from the iron ores (TP1 and MN from Porath and Chamalaun, 1968, and PB and TP2 from Schmidt and Clark, 1994) covers 30° of longitude, suggesting some polar motion took place during iron ore formation. There is evidence, however, that folding and ore formation followed soon after BIF magnetisation, since there is little difference between the PB/TP2 and PB1/WB1 pairs of poles. The BIF was apparently magnetised just before folding, through chemical remanent magnetisation (CRM) during formation of magnetite from primary hematite during deep burial. The synfolding overprint identified in the Mount Jope Volcanics that was interpreted as having been acquired during the Ophthalmian Orogeny (see above) is very similar to the PB/TP2 and PB1/WB1 pairs of poles (Fig. 2) suggestive of their approximate contemporaneity.

4. Palaeomagnetic studies of the late Palaeoproterozoic–Mesoproterozoic

Apart from the palaeomagnetism of the Yilgarn Widgiemooltha dykes (Evans, 1968), dated at 2370 ± 30 Ma, and that of the Yilgarn Ravensthorpe dykes (Giddings, 1976), dated at 2450 ± 10 Ma, there is a considerable gap between results from the well dated Neoarchaean succession in the Pilbara and those of the late Palaeoproterozoic in the Kimberley region and the Palaeo–Mesoproterozoic in the McArthur Basin and Pine Creek Inlier. Some of the overprint results from the Pilbara described in Sections 3.3 and 3.4 may bridge the gap but without better dates on the overprints considerable uncertainty remains.

4.1. Palaeomagnetism of the Kimberley Craton and the Yilgarn Craton at ~1.8Ga

Palaeomagnetic results from the late Palaeoproterozoic (ca. 1.8 Ga) Elgee Siltstone of the upper Kimberley Group in the northeastern Kimberley Basin and the conformably overlying Pentecost Sandstone were obtained by Schmidt and Williams (2008) and combined with results for the Elgee Siltstone in the southeastern Kimberley Basin (Li, 2000) to perform a fold test. This yielded a basin-wide positive fold test with 99 percent confidence which argues for an early magnetisation acquired close to the time of deposition prior to late Palaeoproterozoic initial folding of the Kimberley Group. This finding implies a low palaeolatitude (8°) for the ca. 1.8 Ga King Leopold glaciation in NW Australia (Williams, 2005).

Red beds from the Lansdowne Arkose of the Speewah Group were studied also, but only directions related to Cenozoic regolith weathering processes were found. This is similar to the OP2 and OP4 results for the late Palaeoproterozoic McArthur Basin, described below, supporting the contention that a number of sedimentary units in northern Australia record Cenozoic regolith processes (Schmidt and Williams, 2008).

Williams et al. (2004) studied redbeds of the Frere Formation in the Eraheedy Basin, and found prefolding remanence indicating a probable magnetisation close to the age of deposition at ~1.8 Ga. The Frere pole plots adjacent to, but is still significantly different from, late to post-Capricorn Orogeny overprint poles from the Hamersley Province of the southern Pilbara.

The overprint poles from the southern Pilbara Craton. A vertical-axis relative anticlockwise rotation of 10–15° aligns the Frere with the Pilbara overprint poles implying that the Earaheedy Basin (± the Yilgarn Craton) underwent clockwise rotation of 10–15 relative to the Pilbara Craton during Stanley folding (Williams et al., 2004).

A palaeomagnetic investigation of the 1790 ± 4 Ma Hart Dolerite (U–Pb zircon age; Ozchron, 2004) in the Kimberley was reported by McElhinny and Evans (1976). Although the directions after AF demagnetisation remained abnormally scattered, McElhinny and Evans (1976) viewed the remanence as primary and ascribed the scattered directions to a weak geomagnetic field at the time of intrusion. Schmidt and Williams (2008) undertook another palaeomagnetic investigation of the Hart Dolerite and its extrusive equivalent, the Carson Volcanics, finding the directions for both dolerite and volcanics were scattered. In the field Schmidt and Williams (2008) found extreme effects of lightning that deflected the magnetic compass by >10°, and in the laboratory many samples exhibited high Koenigsberger ratios in excess of 100. However, many samples also exhibited normal Koenigsberger ratios (<3) so not all the scatter could be ascribed to lightning. It is thought that pervasive spilitisation (Plumb and Gemuts, 1976; Griffin and Grey, 1990) is also responsible, whereby original thermoremanent magnetisation would have been replaced by a CRM at later times possibly involving time scales long enough to encompass geomagnetic polarity reversals which would lead to demagnetisation and random resultant net magnetisation directions. Thus spilitisation may be responsible for the scattered and very weak magnetisations displayed by the Hart Dolerite.

4.2. Palaeomagnetism of the Palaeo–Mesoproterozoic McArthur/Mt Isa/Pine Creek Systems

Idnurm and Giddings (1988) presented new data from the McArthur Basin and Pine Creek Inlier. These include the ca. 1.88 Ga Plum Tree Volcanics (updating the Edith River volcanics result of Irving and Green, 1958), the Kombolgie Formation from the west McArthur Basin, the Hobblechain Rhyolite/Packsaddle Microgranite and several overlying sedimentary units. The age of a volcanic unit within the Kombolgie Formation is 1650 ± 30 Ma and the formation overlies the Oenpelli Dolerite which is 1690 ± 30 Ma. They report a sequence of six poles that are stratigraphically ordered and reasonably well constrained in absolute time, from the Kombolgie Formation through to the Myrtle Shale/Emmeruga Dolomite.

The McArthur Basin study was augmented by a number of other reports (Giddings and Idnurm, 1993; Idnurm et al., 1995; Idnurm, 2000) that added new results and looked more closely at some of the implications of magnetic overprinting, particularly as tracers of fluid passage. The Kombolgie Formation in particular proved to be sensitive to remagnetising fluids, yielding several dual polarity groups superseding the result for the Kombolgie Formation given by Idnurm and Giddings (1988). Applying the palaeomagnetic fold test of McFadden (1990) enabled Giddings and Idnurm (1993) to determine the relative timing of overprints some of which they also argued were related to Oenpelli dolerite intrusions in the region through comparing overprint directions with negative magnetic anomalies.

Polarity reversal stratigraphy was the focus of a synthesis by Idnurm et al. (1995), although they also improved on previous palaeomagnetic poles and produced several new poles from younger strata. Idnurm (2000) continued to refine the APWP, adding seven new poles, primary and overprint, and defining a path from ca. 1770 Ma to ca. 1500 Ma. One of the salient features of this path is the termination of some linear segments in sharp bends, or cusps. The cusps are defined by a preponderance of overprint poles (OP), two of which, OP2 and OP4, are quite near the present pole while OP1 and OP3 fall elsewhere. Idnurm (2000) favoured a Precambrian origin for all the overprint magnetisations, presenting statistical arguments and tests for folding and common mean directions. However, the description of many locations does suggest weathering is present, and sediments in northern Australia are known to have been remagnetised in the late Cenozoic (Luck, 1970; Schmidt and Williams, 2008, and this Section above), so the possibility remains that OP2 and OP4 are biased towards the present or a late Cenozoic pole position. Therefore some caution is advised when incorporating OP2 and OP4 into the pole path. This caution is depicted in Fig. 3 as a dashed APW path. It may be significant that when compared to the relevant segment of the North American path this deep cusp is discordant with the North American path showing a less pronounced excursion (Idnurm and Giddings, 1995, their Fig. 2 and Section 7.4). Table 2 lists the McArthur Basin/Lawn Hill poles after combining the similar poles to simplify them following Schmidt and Williams (2011). Other Mesoproterozoic to Neoproterozoic poles are also listed in Table 2.

The status of the OP1 and OP3 groups of poles reflecting periods of overprinting in the McArthur Basin and the Lawn Hill Platform is convincing and these poles are useful as markers for the Australian Mesoproterozoic pole path, with the Lawn Hill Platform results at the older part of the path (Idnurm 2000, p. 424). Note that the age of the OP3 overprints are younger than ca. 1500 Ma (Idnurm 2000).

The rock magnetism and palaeomagnetism of three ore systems from the McArthur/Mt Isa systems have been studied by Symons (2007), Kawasaki et al. (2010) and Kawasaki and Symons (2011). These include the HYC Zn–Pb SEDEX deposit in the McArthur Basin, the Century Zn–Pb–Ag SEDEX deposit from the Lawn Hill platform and the Mt Isa-George Fisher Zn–Pb–Ag deposits of the Mt Isa area. Results from the HYC deposit yield negative conglomerate and fold tests indicating that the magnetisation postdates lithification and folding (Symons, 2007). The McArthur Basin APWP was used to infer an age of 1636 Ma for the magnetisation although this correlation is diminished if this section of the APWP is significantly biased by recent weathering as discussed above.

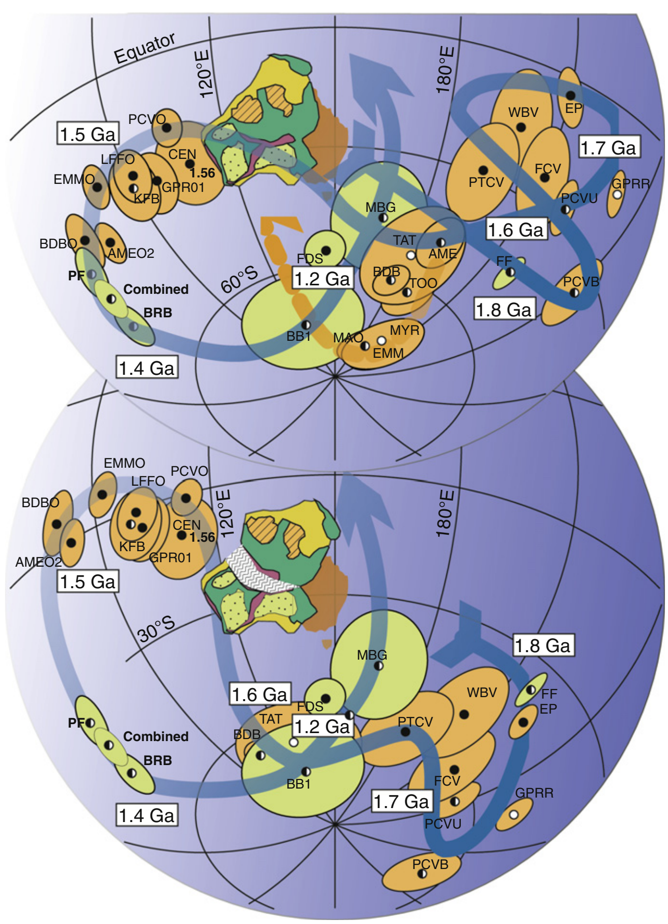

Fig. 3. Mesoproterozoic apparent polar wander path for Australia. Mnemonics are as listed in Table 2. For pole positions solid circles indicate normal polarity while open circle indicate reverse polarity. Half-Moon circles indicate mixed polarity.

Study of the Mt Isa/George Fisher deposits isolated a stable characteristic remanent magnetisation thought to be carried by single- or pseudosingle-domain pyrrhotite for Zn–Pb–Ag ore specimens and pyrrhotite and/or titanomagnetite for Cu ore specimens (Kawasaki and Symons, 2011). However, the magnetisation postdates the D3 deformation of the ca 1595 to 1500 Ma Isan orogeny as shown by a paleomagnetic fold test and again the age of magnetisation is inferred by comparison with the McArthur Basin APWP. As for the HYC results, this correlation is diminished if this section of the APWP is significantly biased by recent weathering as discussed above.

The paleomagnetic study of the Century deposits isolated a stable characteristic remanent magnetisation only from samples of ore. The main remanence carriers found were single- or pseudosingle-domain inclusions of titanomagnetite in sphalerite and gangue, and pyrrhotite in galena with modern goethite and/or hematite from the weathering of siderite. The magnetisation directions of the ore samples yielded a positive fold test showing that the ore magnetisation predates the D2 deformation of the Isan Orogeny that folded the main-stage mineralisation at ~1595 to 1500 Ma. The ore therefore yields a Mesoproterozoic paleopole at 1558 Ma (Kawasaki et al., 2010). This pole falls near a cluster of overprint poles found throughout the McArthur Basin (Fig. 3), which provides an absolute age constraint and is taken as evidence for the causal mechanism for these overprints.

5. Palaeomagnetic studies of the Mesoproterozoic

5.1. Palaeomagnetism of the Middleback Ranges

Hematite ore bodies from South Australia were palaeomagnetically studied by Chamalaun and Porath (1968). The ore bodies from the Middleback Ranges include the Iron Duke, the Iron Prince, the Iron Monarch and some other lithologies including jaspilites, amphibolite, dolerite dykes and ore contact zone. The Iron Duke ore, dolerite and contact zone failed to yield intelligible data but the other samples were found to possess consistent remanence directions from which poles were calculated. The amphibolite yielded a similar direction to the reverse directions of the Iron Monarch ore, supporting suggestions that the amphibolite dyke pre-dated ore formation but had been remagnetised by the same ore-forming processes. The ages of the poles from the Middleback Ranges ore bodies are still not well defined and are usually bracketed as 1.5–1.6 Ga.

5.2. Palaeomagnetism of the Mesoproterozoic of the Gawler Craton

Giddings and Embleton (1976) studied Precambrian dykes that intrude the Gawler Craton in South Australia, which disclosed two groups (Gawler 'A' and 'B', or GA and GB) of directions after AF cleaning. Rb–Sr radiometric ages indicated that the dykes constituting group GB were intruded at 1700 ± 100 Ma and those that yielded group GA were intruded at 1500 ± 200 Ma. They found that the GA and GB palaeomagnetic poles coincide with the poles obtained by Chamalaun and Porath (1968) from the Middleback Ranges hematite ore bodies, thereby providing age constraints on the time of formation of the ore-bodies.

Palaeomagnetic results for the 1585–1595 Ma Gawler Range Volcanics were obtained by Chamalaun and Demsey (1978), who employed AF demagnetisation to isolate a ChRM moderately upward-directed to the NE. A few selected specimens representing different lithologies were subjected to thermal demagnetisation which showed that the magnetic carrier was magnetite. XRD studies on representative lithologies revealed only magnetite diffraction lines. The XRD data are thus consistent with the thermal demagnetisation results. Dual polarity directions were not found and field tests were not performed.

Table 2
Summary of selected late Palaeoproterozoic to early Neoproterozoic poles for Australia.

Formation	Age (Ga)	Dec. (°)	Inc. (°)	α_{95} (°)	λ_p (°)	φ_p (°)	dp (°)	dm (°)	1	2	3	4	5	6	7	Q	Result#
a. Yilgarn Craton																	
GP Mundine dykes	0.75	14.8	31.1	5.0	45.3	135.4	4.1		√	√	√	√	√	√	√	7	8561
Hussar Formation	0.80	163.3	4.6	14.6	62.2	85.8	7.3	14.6	×	√	√	×	√	√	√	5	9315
Browne Fm	0.83	193.4	−33.8	7.9	44.5	141.7	5.1	9.0	×	√	√	×	√	√	×	4	9314
Edith Riv. Volc.	0.90	90.0	48.0	18.0	6.0	14.0	15.0	24.0	√	√	√	×	√	√	√	6	1832
BB1	ca. 1.2	178.2	67.0	8.9	−74.4	123.8	12.2	14.7	×	√	√	×	√	√	√	5	8980
MBG	ca. 1.205	124.0	68.8	8.2	−46.6	167.4	11.9	13.9	×	√	√	×	√	√	√	5	8981
FDS	ca. 1.212	152.6	74.1	2.9	−55.8	145.7	4.7	5.2	√	√	×	+C	√	√	√	6	8982
b. Gawler Craton																	
Blue Range Beds	>1.1 < 1.6	233.9	50.2	4.0	−45.2	59.0	4.7		×	√	√	×	√	√	√	5	a
Pandurra Fm	>1.1 < 1.6	248.3	46.7	4.4	−33.6	64.5	4.9		×	√	√	×	√	√	√	5	a
BRB & PF comb.	>1.1 < 1.6	242.6	48.3	3.1	−38.4	62.4	3.5		×	√	√	+F	√	√	√	6	a
c. North Australian Craton																	
Alcurra dykes/sills	1.07	291.2	50.8	8.0	2.8	80.4	7.2	10.7	√	√	√	√	√	×	√	6	9301
Bangemall sills	1.07	339.9	46.5	8.4	33.8	95.0	8.3		√	√	√	√	√	√	√	7	8781
Mt Isa dykes (IAR)	1.14	322.8	82.5	9.6	9.5	311.1	17.4		√	×	√	√	√	×	√	5	9749
Century ore (CEN)	1.56	249.1	73.8	5.7	−26.5	107.0	9.2	10.3	√	√	√	+F	√	×	√	6	b
Amelia Dol. AMEO2	ca. 1.5	242.8	51.7	3.6	−32.2	74.8	4.4		×	√	√	×	√	×	√	4	6099
Balbirini Dol.BDBO	ca. 1.5	247.6	44.7	5.1	−27.8	68.8	5.4		×	√	√	×	√	×	√	4	6104
Emmerugga Dol.EMMO	ca. 1.5	256.6	56.3	3.4	−21.9	81.8	4.4		×	√	√	×	√	×	√	4	6102
Kombolgie Fm. KFB	ca. 1.6	245.5	65.6	4.8	−27.1	93.7	6.8		×	√	√	×	√	√	√	5	c
Lynott Fm LYNO		*255.7*	*54.4*	*5.3*	*−21.5*	*78.3*	*5.9*		×	×	√	×	√	×	√	*3*	*d*
Lawn Hill Fm.LWNO1		*234.7*	*66.9*	*4.8*	*−37.1*	*97.3*	*7.7*		×	×	√	×	√	×	√	*3*	*d*
Fish R.Fm.FSHO2		*262.1*	*70.5*	*5.6*	*−18.9*	*101.5*	*9.3*		×	×	√	×	√	×	√	*3*	*7043*
LLFO (last 3)	ca. 1.5	253.0	65.0	3.8	−24.5	93.4	3.4		×	√	√	×	√	×	√	4	a
Gunpowder Ck.GPRO1	ca. 1.5	250.0	66.8	4.4	−27.4	97.1	6.5		×	√	√	−F	√	×	√	5	d
Percy Ck.Fm.PCVO	ca. 1.5	265.6	72.7	2.5	−17.5	105.3	4.2		×	√	√	×	√	√	√	5	d
Mallapunyah Fm.MALO		*351.3*	*−38.2*	*8.9*	*−80.7*	*193.4*	*9.8*		×	×	√	×	√	×	√	*3*	*6098*
Amelia Dol.AMEO1		*350.2*	*−40.9*	*5.7*	*−78.7*	*184.0*	*6.9*		×	×	√	*+F*	√	×	√	*4*	*6099*
MAO (last 2)	ca. 1.5	350.6	−39.8	4.8	−81.7	172.5	5.0		×	√	√	+F	√	×	√	5	a
Emmerugga Dol.EMM	1.64	349.1	−36.4	5.7	−79.1	202.6	6.1		×	√	√	+F	√	×	√	5	6102
Myrtle Fm.MYR	1.64	346.5	−38.6	8.2	−75.9	197.4	7.7		×	√	√	+F	√	×	√	5	6103
Tooganinie Fm.TOO	1.65	334.3	−50.1	5.2	−61.0	186.7	6.1		×	√	√	+F	√	√	×	5	6100
Balbirini Dol.BDB	1.6	336.1	−55.6	3.3	−60.6	176.1	4.3		×	√	√	+F	√	√	×	5	6104
Lunch Ck.Gabbro LCG	1.6	152.0	50.0	7.2	−63.0	201.0	9.0		×	√	√	×	√	√	√	5	1615
Tatoola Sst.TAT	1.65	326.5	−56.4	9.9	−52.7	182.2	10.7		×	√	√	+F	√	×	×	4	6100
Amelia Dol.AME	1.65	318.0	−55.1	4.9	−47.4	188.8	6.1		×	√	√	+F	√	×	√	5	6099
Plum Tree Ck. V. PTCV	1.88	116.1	48.8	9.3	−29.0	195.0	14.0										e

See footer for Table 1 for explanation of column headings; +F positive fold test, −F negative fold test, sF synfolding, +C positive conglomerate test; a, Schmidt and Williams (2011), b, Kawasaki et al. (2010), c, Giddings and Idnurm (1993), d, Idnurm (2000), e, Idnurm and Giddings (1988); some rows in italics have been combined in the immediately following row so the minimum values for criterion number 2 of Van der Voo (1990) (N > 24, k > 10, α < 16°) are met.

Further sampling of the Gawler Range Volcanics (Schmidt and Clark, 2011) included a steeply dipping section, near Uno, to allow the execution of a fold test. The magnetisations are most likely overprints as they post-date the tilting. Rock magnetic measurements revealed that the magnetic carriers are multi-domain magnetite grains and unlikely to retain original thermoremanent magnetisation. In addition, apatite fission track analyses have shown that the Gawler Craton cooled below the apatite fission track retention temperature (100 ± 20 °C) at ca. 300 Ma (Kohn et al., 2002), and shattered Yardea Dacite from the Acraman impact site has yielded an apatite fission track age of 319 ± 19 Ma (Williams, 1994). The Late Devonian age of the magnetic overprinting is somewhat older than the Carboniferous apatite fission track ages, which is interpreted to reflect the slightly higher blocking temperatures for the magnetic remanence (Schmidt and Clark, 2011). Although the pole position has been considered a 'key pole' for Australia at ca. 1500 Ma (Idnurm and Giddings, 1988), the negative fold test and the secondary nature of the remanence dictates that a 'key pole' status for the Gawler Range Volcanics pole must be abandoned.

Schmidt and Williams (2011) provided a pole from the Mesoproterozoic fluvial Pandurra Formation and Blue Range Beds, South Australia. The results from each unit were combined since they are thought to be the same age and together provide a positive fold test. The mean pole position for the Pandurra Formation and Blue Range Beds plots after the 1.56 Century pole and the <1.5 Ga OP3 group of overprint poles for the McArthur Basin and Lawn Hill Platform and before the ca. 1.2 Ga Albany–Fraser orogen poles described in Section 5.5 below (Fig. 3). The pole position therefore implies an age of between 1.5 and 1.2 Ga, which is consistent with the inferred Mesoproterozoic age for these sediments based on stratigraphy and geochronology of bedrock and component clasts.

5.3. Palaeomagnetism of the Warakurna Large Igneous Province

Wingate et al. (2004) proposed the term Warakurna large igneous province (WLIP) for a large number of igneous rocks from predominantly NW Australia (WA) but stretching to central Australia (northern SA and NT) and perhaps to southern SA. Wingate et al. (2002) reported results from 1070 ± 6 Ma dolerite sills from the Bangemall Supergroup and Wingate et al. (2004) extended this work to cover the Glenayle Dolerite, the Prenti Dolerite, and dykes of the NW Yilgarn and SW Pilbara cratons. These western WLIP results are internally concordant, but conflict with similarly aged eastern WLIP components, the Stuart dykes (Idnurm and Giddings, 1988) and Kulgera dykes and sills (Camacho et al., 1991). The Kulgera dykes/sills have been re-named the Alcurra Dolerite (Edgoose et al., 2004) but the term Kulgera will be retained herein to refer to the Camacho et al. (1991) palaeomagnetic results, while the term Alcurra will be used to refer to the updated positive fold test result of Schmidt et al. (2006). These results are discussed more fully under Section 7.3 on Australia and Rodinia.

5.4. Palaeomagnetism of the Albany–Fraser Belt

The late Mesoproterozoic of the Albany–Fraser Belt in southwestern Australia has yielded several poles for ca. 1.2 Ga from the Mount Barren Group and Bremer Bay–Whalebone Point metamorphics and from a dyke of the Fraser Dyke Swarm (Pisarevsky et al., 2003). Each of these provided similar dual-polarity directions with inclinations ca. 70°, placing SW Australia at high palaeolatitudes at this time. Pisarevsky et al. (2003) discussed the relevance of these results in the context of ancient supercontinents which is examined below (Section 7.3). These poles are incorporated with other data in a Mesoproterozoic pole path for Australia spanning the interval ca. 1.6–1.2 Ga (Fig. 4).

6. Palaeomagnetic studies of the Neoproterozoic

6.1. Palaeomagnetism of the Northampton/Mundine Dyke Swarm, WA

Wingate and Giddings (2000) combined the palaeomagnetic results from dykes within the Northampton inlier (Embleton and Schmidt, 1985) with results from related dykes to the north, within the Bangemall Basin and the Pilbara Craton, including a convincing contact test. The combined dykes were called the Mundine Dyke Swarm. Wingate and Giddings (2000) also found a U–Pb zircon and baddeleyite age of 755 ± 3 Ma, in agreement with the 748 ± 8 Ma K–Ar age reported by Embleton and Schmidt (1985), further justifying combining the results to yield the grand-pole for 750 Ma — GPMD (Table 2).

6.2. Palaeomagnetism of central Australian successions

Kirschvink (1978) investigated late Precambrian to early Cambrian sediments of the Amadeus Basin, Central Australia. Three stratigraphic units were sampled, the Lower and Upper Arumbera Sandstone and the Todd River Dolomite, which yielded two stable directions of magnetisation. The ChRM component satisfied a fold test and the well-defined polarity zonation led to the definition of a new field test, the unconformity tests. A secondary component in some of the non-red sediments appeared to be associated with the Alice Springs orogeny (ASO).

Swanson-Hysell et al. (2012) undertook a palaeomagnetic investigation of the Heavitree and Bitter Springs formations of the Amadeus basin and apart from finding ASO remagnetisations they determined prefolding components that yielded a new pole for the ca. 770 Ma Johnnys Creek Member of the Bitter Springs Formation. Although that pole is close to the 1070 Ma Alcurra Dolerite pole, it is in apparent disagreement with the more contemporary 755 Ma Mundine Dyke Swarm pole. These conflicts are returned to later (see Section 7.3 below).

6.3. Palaeomagnetism of dykes of the Yilgarn Craton, WA

Halls and Wingate (2001) have re-evaluated the 700–750 Ma YB pole of Giddings (1976) on the basis that it disagrees with the 755 Ma MDS pole. Their repeat study of the YB dyke and its contact shows that the remanence is secondary. There are two components also found in the (unbaked) host YC gabbro. One is a low stability component (A) carried by goethite, probably of recent or Cenozoic age and related to weathering in the area, and the other is a high stability component (B) found throughout the dyke and the host, irrespective of distance from the contact. From the location of the B pole, Halls and Wingate (2001) correlated the B component with late Palaeozoic–Mesozoic remagnetisation and attribute it to the breakup of Gondwana. They therefore advocate that the YB pole no longer be used for APW paths or Rodinia reconstructions.

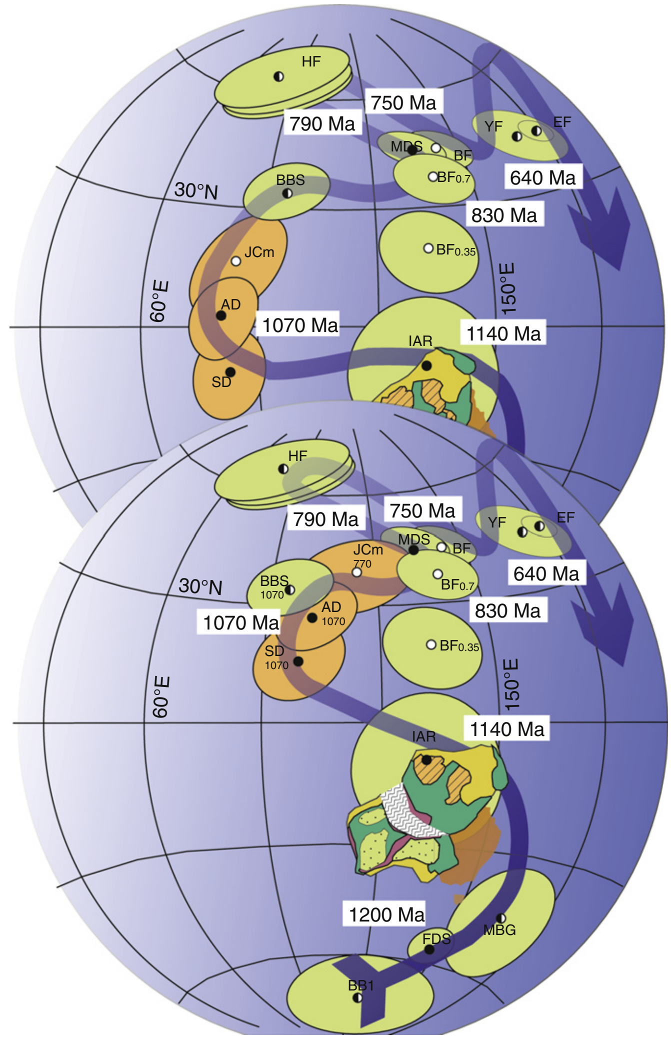

Fig. 4. Late Mesoptoterozoic–early Neoproterozoic apparent polar wander path for Australia. Mnemonics are as listed in Table 2. For pole positions solid circles indicate normal polarity while open circle indicate reverse polarity. Half-Moon circles indicate mixed polarity. The 0.7 and 0.35 associated with the Browne Formation (BF) pole indicate notional poles corrected for inclination flattening, $f = 0.7$ (for arenaceous rocks) and $f = 0.35$ (for argillaceous rocks). The Hussar Formation (HF) has also been recalculated similarly to the Browne Formation but as the original inclination is very low there is little change in pole position, (a) poles plotted without correcting for the "late (>1070 Ma) amalgamation" model in present geographical coordinates, and (b) NAC rotated 40° clockwise about an Euler pole at 20°S, 135°E according to Schmidt et al. (2006), Schmidt and Williams (2008) and Li and Evans (2011) (see Section 7.3).

6.4. Palaeomagnetism of South Australian successions

The study by McWilliams and McElhinny (1980) (see Section 1) of Australian Neoproterozoic rocks pre-dated the now mandatory use of linear-planar analysis of data structure (Kirschvink, 1980; Kent et al., 1983). While orthogonal projections of complete demagnetisation of pilot samples ensured components were accurately identified, most samples were subjected to an 'optimum' bulk treatment and directional groupings subsequently separated using density contouring. Also, because of the reconnaissance nature of the study, McWilliams and McElhinny (1980) executed few (statistically significant) positive fold tests although many formations yielded better grouped direction after tilt correction. One of their main conclusions was general support for low-palaeolatitude Late Precambrian glaciations, reversing the trend at that time which favoured Late Precambrian circum-polar glaciation (Crawford and Daily, 1971; McElhinny et al., 1974). This gave rise to more recent palaeomagnetic studies to better constrain the timing of magnetisation of the Adelaidean strata, particularly with respect to the Cryogenian glacial deposits.

In a series of papers (Schmidt et al., 1991; Schmidt and Williams, 1995, 1996, 2010, 2013; Schmidt et al., 2009), palaeomagnetic results were obtained from the Elatina Formation (including the critically important tidal rhythmites exhibiting soft-sediment deformation structures from Pichi Richi Pass — see Section 7.1 for more discussion), the disconformably–unconformably overlying Nuccaleena Formation (cap carbonate), the Bunyeroo Formation (including melt rock from the Acraman impact, the ejecta blanket which is 80 m above the base of the 400 m thick Bunyeroo Formation; Williams and Gostin, 2005), the Brachina Formation and the Wonoka Formation. Positive fold tests were found for all these formations, and since their ChRM directions are all distinctive the evidence is overwhelming that the formations all preserve early acquired remanent magnetisations. The suggestion of McWilliams and McElhinny (1980) that the Bunyeroo Formation may be overprinted is refuted not only by the positive fold test but also by the agreement in direction between the Acraman melt rock and the ejecta-bearing Bunyeroo host (Schmidt and Williams, 1996; Williams et al., 1996). Some of the tepee structures of the Nuccaleena Formation have provided positive fold tests, although the magnetisation appears to have variably lagged deposition, causing identified magnetostratigraphic horizons to appear bedding-transgressive (Schmidt et al., 2009). Raub et al. (2007) have also recognised a magnetostratigraphic "bar-code" and the early acquisition of the Nuccaleena remanence, although not the bedding transgressive nature of reversals or whether it pre- or post-dates tepee formation However, positive fold tests (Schmidt et al., 2009) of disrupted tepee limbs with steep dips militate against the tepee-like structures in the Nuccaleena Formation being giant ripples whether generated by extreme wave conditions (Allen and Hoffman, 2005) or the consequence of an unusual mode of carbonate precipitation (Lamb et al., 2012).

Other differences between newer work (Schmidt and Williams, 2010) and that of McWilliams and McElhinny (1980) involves the Brachina Formation, for which both studies found a positive fold test, yet the mean directions appear to be significantly different. Schmidt and Williams (2010) determined a mean direction (N = 11 sites) of D = 179.7°, I = −20.9° (k = 26.0), whereas the mean direction (N = 8 sites) given by McWilliams & McElhinny (1980) is D = 189°, I = −44° (k = 13.4). Schmidt and Williams (2010) showed statistically that these are different and argued that this reflected the earlier practice of employing 'bulk' cleaning.

The tidal rhythmites of the Elatina Formation from Pichi Richi Pass (Williams, 2000) deserve a special mention. Positive soft-sediment fold tests at high levels of confidence (Schmidt et al., 1991; Schmidt and Williams, 1995) from the rhythmites have quelled all opposition to the veracity of terminal Cryogenian Elatina glaciation in South Australia having occurred in near-equatorial palaeolatitudes. Sohl et al. (1999) also argued for early timing of magnetic remanence in the Elatina Formation based on reversal stratigraphy. Important as they are, the rhythmite results only contribute a virtual geomagnetic pole (VGP) that should not be construed as palaeomagnetic pole. To establish a grand-pole (GPEF) for the Neoproterozoic Elatina glaciation, Schmidt et al. (2009) combined data from 205 specimens for the Elatina Formation from Schmidt and Williams (1995) and Sohl et al. (1999) for a pole at latitude = 43.7°S, longitude = 359.3°E with confidence semi-axes dp = 2.1° and dm = 4.2°. Note that the "mean pole" of Li and Evans (2011) at latitude = 49.9°S, longitude = 344.4°E with confidence semi-axes A_{95} = 13.5° differs greatly from the more conservative mean of Schmidt et al. (2009) because Li and Evans (2011) weighted VGPs from the Pichi Richi tidal rhythmites (Embleton and Williams, 1986; Schmidt et al., 1991) the same as complete stratigraphic studies (Schmidt and Williams, 1995; Sohl et al., 1999). Also, Schmidt et al. (1991) were focused on the soft-sediment fold test and went to some effort to emphasise the VGP nature of their pole. In fact Schmidt et al. (1991) avoided calculating another VGP and instead listed the extant VGP from Embleton and Williams (1986), although a separate VGP has been illegitimatey entered into the GPMDB with a latitude = 54.3°S, longitude = 326.9°E and dp = 0.9° and dm = 1.8°. Therefore Li and Evans (2011) have used two VGPs in their "mean pole" of four, which severely biases the result. Neoproterozoic pole positions from the above investigations are listed in Table 3 and plotted with a Neoproterozoic pole path for Australia in Fig. 5.

7. Discussion

7.1. The Australian Precambrian pole path and palaeolatitudes

Palaeomagnetic data are used to infer palaeolatitudes through application of the Geocentric Axial Dipole (GAD) hypothesis. While it is healthy that the status of the GAD is challenged occasionally with ideas such as non-dipole fields and non-axial fields (Van der Voo and Torsvik, 2001; Abrajevitch and Van der Voo, 2010), no compelling evidence has yet undermined the fundamental validity of the GAD (see Section 7.2). Palaeolatitudes for Australia are shown for selected times in Fig. 6.

Palaeomagnetic evidence for Neoproterozoic low-palaeolatitude glaciation from successions around the North Atlantic was first presented by Harland and Bidgood (1959) and Bidgood and Harland (1961). However, low-palaeolatitude Proterozoic glaciations were generally not accepted until the 1990s, even though some preceding palaeomagnetic studies provided strong evidence (McWilliams and McElhinny, 1980; Kröner et al., 1980). The evidence amassed since 1980 is overwhelmingly in support of low palaeolatitudes, far in excess of a random (uniform) distribution (Evans, 2003). The inference is that glaciations formed preferentially at low latitudes in the Proterozoic. The strongest and most convincing evidence to date was derived from palaeomagnetic studies of red beds from the Elatina Formation in the Adelaide Geosyncline, as described above (Section 6). Indisputable confirmation of early remanence acquisition was derived from positive soft-sediment fold-tests on slumping in tidal rhythmites found at Pich Richi Pass (Schmidt et al., 1991; Schmidt and Williams, 1995).

Williams (1993) proposed that Proterozoic glaciations occurred preferentially in low palaeolatitudes whereas Phanerozoic glaciations were circumpolar. A comparative review of palaeomagnetic results for Proterozoic and major Phanerozoic glacial deposits (Evans, 2003) confirmed that Proterozoic glaciogenic sediments were deposited predominantly in low palaeolatitudes, as opposed to the high latitude Phanerozoic counterparts. Evans (2003, p. 353) stated "Whereas high depositional latitudes dominate all Phanerozoic ice ages, exclusively low palaeolatitudes characterise both of the major Precambrian glacial epochs". A recent review (Eriksson et al., 2013) contrasts the low palaeolatitudes of early and late Palaeoproterozoic and Neoproterozoic (pre-Ediacaran) glaciations and the circum-polar distribution of Palaeozoic, Mesozoic and Cenozoic glaciations. Despite the high palaeolatitudes of Australia at different times (e.g. 1500 Ma and 1200 Ma, Fig. 6c and d) no glaciations occurred then. These patterns are reflected globally. No glacial deposits have been found from ca. 825 Ma on any continent although parts of Rodinia were thought to occupy high-latitudes then, e.g., in South China and Australia (Li et al., 2013). However, the palaeolatitude of Australia at ca. 820 Ma is equivocal and is revisited in Section 7.3.

Low-latitude glaciations occurred in Australia in the late Palaeoproterozoic (Williams, 2005; Schmidt and Williams, 2008) and the late Neoproterozoic (Embleton and Williams, 1986; Schmidt et al., 1991; Schmidt and Williams, 1995; Williams et al., 2008, 2011), and early Palaeoproterozoic glaciation of North America occurred in low palaeolatitudes when the Superior Craton moved across the palaeoequator (Williams and Schmidt, 1997; Schmidt and Williams, 1999; Bindeman et al., 2010).

The mechanisms proposed to explain the counter-intuitive Precambrian palaeoclimatology include the high obliquity hypothesis

Table 3
Summary of reliable late Cryogenian to post-Delamerian Orogeny poles for late Neoproterozoic and early Palaeozoic rocks, South Australia (quality factor Q at least 5/7).

Formation	Age (Ma)	Dec. (°)	Inc. (°)	α_{95} (°)	λ_p (°)	φ_p (°)	dp (°)	dm (°)	1	2	3	4	5	6	7	Q	Result#
Black Hill Norite	498	231.1	19.7	3.8	−37.5	34.4	3.0	6.0	√	√	√	√	√	×	√	6	7736
Lake Frome (basal)	500	232.3	−0.5	10.1	−31.4	36.9	5.1	10.1	√	√	√	×	√	√	√	6	1401
Kangaroo Is red beds	520	224.5	−4.4	12.3	−33.8	15.1	6.2	12.3	√	√	√	×	√	√	√	6	1405
Billy Ck Fm	520	224.1	−1.2	14.4	−37.4	20.1	7.2	14.4	√	√	√	×	√	√	√	6	1403
Hawker Group	535	233.4	−27.8	11.4	−21.3	14.9	6.8	12.5	√	√	√	×	√	√	√	6	1402
Wonoka Fm	560	255.9	−23.7	6.4	−5.2	30.5	3.6	6.8	×	√	√	+F	√	√	√	6	a
Bunyeroo Fm	580	236.6	−29.3	10.7	−18.1	16.3	6.5	11.8	×	√	√	+A	√	√	×	5	8114
Brachina Fm	590	178.2	−22.6	4.4	−46.0	315.4	2.4	4.6	×	√	√	+F	√	√	√	6	a
Nuccaleena Fm	625	208.3	−34.9	3.4	−32.3	350.8	2.2	3.9	×	√	√	+F	√	√	√	6	9323
GP Elatina Fm	635	208.3	−12.9	4.2	−43.7	359.3	2.1	4.2	×	√	√	+F	√	√	√	6	b
Yaltipena Fm	640	204.0	−16.4	11.0	−44.2	352.7	5.9	11.4	×	√	√	+F	√	√	√	6	8514

See footer for Table 1 for explanation of column headings; +F positive fold test, +A indicates a unique field test whereby the Bunyeroo Fm contains the Acraman ejecta blanket and the directions of the Acraman meltrock and the untilted Bunyeroo Fm agree (the Bunyeroo Fm also satisfies the fold test); a, Schmidt and Williams (2010); b, Schmidt et al. (2009).

(Williams, 1975, 2008; Jenkins, 2003) and a number of variations on the Snowball Earth theme (Hoffman and Schrag, 2002; Domack and Hoffman, 2011). Williams (2008) documented the development of ideas and palaeomagnetic evidence concerning low-palaeolatitude pre-Ediacaran glaciations, arguing cogently for a high obliquity as the most efficacious, or parsimonious, explanation for the accompanying strong seasonal changes of temperature near the palaeoequator, open seas and widespread unglaciated continental regions.

Evans (2006) conducted a comparative analysis of major global evaporite deposits and found they formed predominantly in the subtropics, including occurrences in the Proterozoic. However, none of the palaeolatitudes of sedimentary formations has been corrected for inclination flattening so it is possible that the real palaeolatitudes were higher. For instance, Harlan et al. (2008) reported palaeopoles from 1.45 Ga Proterozoic mafic dikes in southwestern Montana, USA. While these are similar to palaeopoles of ca. 1.45–1.4 Ga from intrusions elsewhere in North America, they are discordant with palaeopoles from sedimentary rocks of equivalent age from the Mesoproterozoic Belt Supergroup, which have been used by Evans (2006) to infer evaporite palaeolatitudes. Red beds of the Belt Supergroup have yielded inclinations of ca. 30°, which if corrected for flattening typically found in argillaceous lithologies (Schmidt and Williams, 2013), where $f = 0.35$, would become steeper at ca. 60°. This corresponds to the inclinations of ca. 1.45–1.4 Ga intrusions of North America (Harlan et al., 2008) and a moderate palaeolatitude of 45°. Until sedimentary derived palaeomagnetic directions are corrected for inclination flattening their inclinations should not used to infer palaeolatitudes.

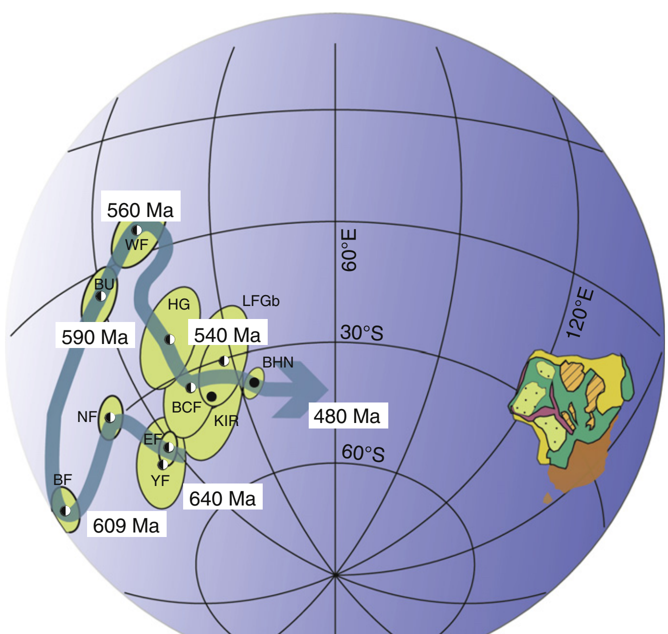

Fig. 5. Neoproterozoic apparent polar wander path for Australia (after Schmidt and Williams, 2013 and Table 3). Mnemonics are YF — Yaltipena Formation; EF — Elatina Formation; NF — Nuccaleena Formation; BF — Brachina Formation; BU — Bunyeroo Formation; WF — Wonoka Formation; HG — Hawker group; BCF — Billy Creek Formation; LFGb — Lake Frome Group (basal); KIR — Kangaroo Is Redbeds; BHN — Black Hill Norite (Table 3). The pole positions of sediments have been recalculated according to anisotropy results (Schmidt and Williams, 2013). In particular the palaeopoles of the more argillaceous facies (Brachina, Bunyeroo and Wonoka formations) are significantly different to the uncorrected poles and open the Neoproterozoic APW path into a clockwise loop that can be partially matched to the Neoproterozoic APW path for Laurentia that may reflect limited TPW. If two pole paths from different continents show similarities, although the continents maybe quite separate, then TPW is an obvious candidate. Nevertheless much more evidence, perhaps from one or two other continents, is necessary before the evidence might be considered anything more than plausible.

Li et al. (2013) also point out that widespread evaporites were deposited at high latitudes in several basins ca. 825 Ma, including the Officer Basin in central Australia, and the Mackenzie Mountains and the Amundsen Basin in northern Canada. In addition, the two poles closest in age poles in their Table 1 are the ca. 810 Ma Browne Formation, which does contain evaporites and a palaeolatitude as low as 18°, and the 848 Ma Hunnedalen Dykes pole, which places Baltica in very high latitudes, instead of equatorial position shown in Li et al. (2013) 825 Ma reconstruction. These inconsistencies imply that the Li et al. (2013) 825 Ma reconstruction model is incorrect. Li et al. (2013) further speculated that this "can also be resolved if the ca. 800 Ma TPW [true polar wander] event, rather than being a one-way trip as initially surmised (Li et al., 2004), was in fact an oscillatory pair of events, whereby Rodinia transited from the low latitudes to middle–high latitudes and back again (Maloof et al., 2006; Swanson-Hysell et al., 2012)." Apparently TPW can be brought to bear whenever the geology and palaeomagnetically determined latitudes are in conflict. However, it does not seem to be very edifying to appeal to TPW without coeval palaeomagnetic evidence from other continents.

7.2. Low-inclination bias of the Preambrian geomagnetic field

The frequency distribution of the absolute value of magnetic inclinations has been examined by many as a means to test the Geocentric Axial Dipole (GAD) hypothesis (Evans, 1976; Piper and Grant, 1989; Kent and Smethurst, 1998; Tauxe and Kodama, 2009; Veikkolainen et al., 2013b). Veikkolainen et al. (2013a) show that even a small axial octupolar term of the same sign as $g^0{}_1$ causes a bias in inclinations to lower values. This "low-inclination bias" has been recognised as a source of non-uniqueness and previous analyses (Piper and Grant, 1989; Kent and Smethurst, 1998; Tauxe and Kodama, 2009) optimised values of G2 and G3 to fit the Precambrian distributions, obtaining values between 10% and 25% for both parameters. Fig. 7 compares

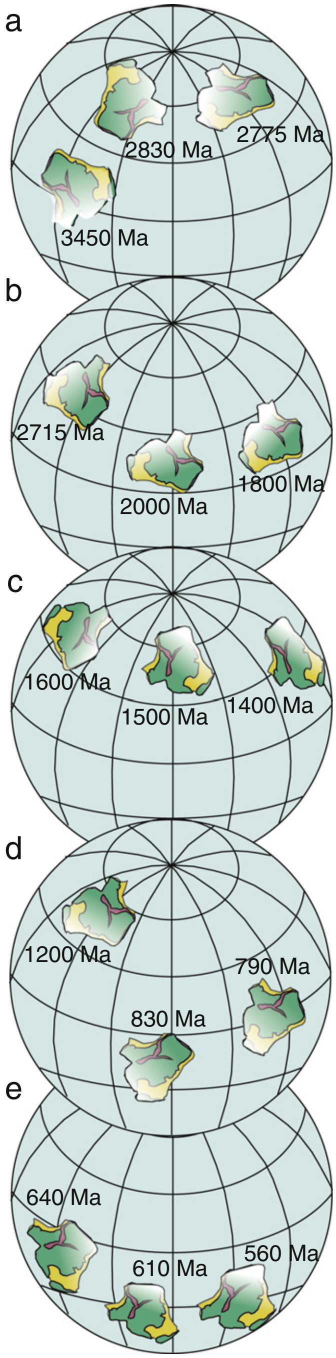

Fig. 6. Australian palaeolatitudes for different times throughout the Precambrian. The highlighted zone represents the regions from where the relevant data has been derived (see Section 7.1).

distributions found previously with the Preambrian data from Australia. As for the other data sets the Australian Precambrian shows a strong bias towards low latitudes. Globally, Mesoproterozoic data appear to be biased towards low inclinations as a direct result of continents occupying low to moderate paleolatitudes at these times (Veikkolainen et al., 2013a). Ironically, this is not the case for Australia which occupied moderately high to high palaeolatitudes during the Mesoproterozoic (Fig. 6). The bias towards low latitudes for Australia may arise from the low latitudes during the Neoproterozic and perhaps inclination shallowing in sediments from mid-palaeolatitudes that remain to be corrected. Analyses that omit results from sedimentary rocks and results of low reliability show minimal bias. Veikkolainen et al. (2013a) have found for the most reliable results, and avoiding results from unaltered rock types, the apparent support for the GAD hypothesis is remarkable and there is no reason, based on inclination distribution, to doubt its veracity.

7.3. Australia and Rodinia

Piper (1975, 1982) has long proposed a pre-Pangaea supercontinent but has not received due acknowledgement for his role in formulating this concept. This may be partly because the quality of data at his disposal was too poor, with regard to age or palaeomagnetic reliability, to be convincing (but see Section 7.4). In the past two decades significant inroads have been made to improve the quality of Precambrian palaeomagnetic data and this has revived interest in the concept of Precambrian supercontinents. The search for supercontinents that may have existed before Pangaea is an exercise in inductive thinking. The evidence is inferred from the younger geological record, as in “the less ancient past is the key to the more ancient past,” reminiscent of Lyell's famous dictum. Having established the existence of Palaeozoic Pangaea beyond reasonable doubt and the kinematics of the plate tectonics model, and having gone some way to understanding its dynamics, the question of the existence of earlier supercontinents is reasonable to pose. But it is an inductive approach especially because, except for a few traces, the all important sea-floor that led to establishing the theory, if not the reality, of plate tectonics, has disappeared ipso facto. An inductive solution is a high-risk/high-reward strategy and so far efforts have reflected more of the risk side of the equation than the reward. However, every now and then there is glimmer of hope, when several pieces of the jigsaw seem to mesh, as with the apparent resolution regarding the disagreement of palaeopoles and the contradictory evidence of the timing of Rodinian breakup between Australia–East Antarctica and Laurentia (Wingate et al., 2002; Schmidt et al., 2006; Li and Evans, 2011).

An overview of the evolution of Rodinian ideas was given by Li et al. (2008), who presented a multidisciplinary synthesis on the assembly and break-up of Rodinia, and the subsequent formation of Gondwana. Li et al. (2008) used palaeomagnetic constraints, geology of basement provinces, orogenic histories, sedimentary provenance, evidence of continental rifts and passive margins and mantle plume events.

Li et al. (2008) envisaged orogenic events from ca. 1300 Ma to ca. 900 Ma involving virtually all continental cratons as evidence of Rodinia being assembled through the accretion or collision of continental cratons around the margin of Laurentia. Similarly to Pangaea, these workers thought Rodinia lasted about 150 Myr before breakup. They proposed that some 40–60 Myr after assembly the sinking of foundered slabs which accumulated at the mantle transition zone surrounding the

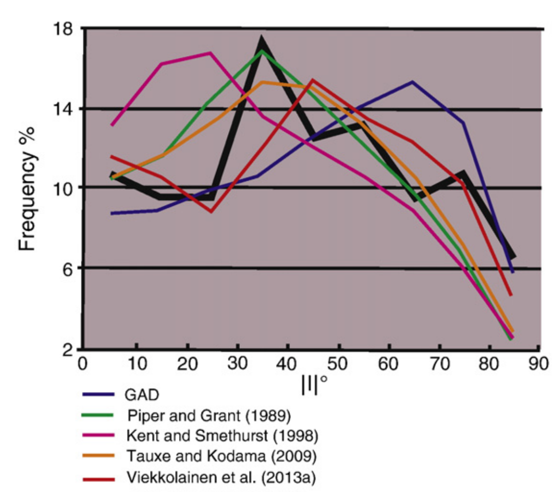

Fig. 7. Frequency plot of (absolute) inclinations from the Australian Precambrian (N = 172 GPMDB5) compared with other compilations as shown (see Section 7.1).

supercontinent led to mantle avalanches. This coupled with thermal insulation by the supercontinent led to a superplume beneath Rodinia and widespread continental rifting from 825 to 740 Ma, with episodic plume events at 825, 780 and 750 Ma. Both the assembly and the break-up of Rodinia were thought to be diachronous (Li et al., 2008).

Possibly as early as 750 Ma a major break-up event occurred along the present western margin of Laurentia followed by break-up between the southeastern margin of Laurentia and Amazonia after ca. 600 Ma. At about this time most of the western Gondwanan continents had united, although the complete formation of Gondwana did not eventuate until ca. 530 Ma.

Precambrian Australia has played a central role in the quest to define Rodinia. A variety of models have been advanced, beginning with the archetypal SouthWest (united) States–East Antarctic (SWEAT) model (Fig. 8a) of Moores (1991), based on a comparison of Neoproterozoic stratigraphies of eastern (ancestral) Australia and the western margin of Laurentia (first recognised by Eisbacher (1985) and Bell and Jefferson (1987).

Next came the "missing-link" model of Li et al. (1995) (Fig. 8b), with south China set between Australia and western Laurentia, which answered questions of the SWEAT model such as mismatches of crustal elements between Laurentia and Australia–East Antarctica and a western provenance, among several possible sources, of late Mesoproterozoic detritals of the Laurentian Belt Basin. The "missing-link" model also exploited similarities in the Neoproterozoic stratigraphies of South China, eastern ancestral Australia and western Laurentia (noted by Eisbacher, 1985) and crustal similarities between the Cathaysia Craton of southeastern China and southern Laurentia. Available palaeomagnetic data permit such a "missing-link" model for 820–800 Ma (Li et al., 2008). Previously Li et al. (2004) opted for a TPW event to explain the sudden jump from high to low latitudes although Li et al. (2008) prefer break-up with 780–750 Ma poles becoming widely dispersed. If TPW is allowed arguments can be made that all considered models are permitted, not only the "missing-link".

The AUstralia–SouthWest United States (AUSWUS) model (Fig. 8c) is based on aligning linear fractures allegedly related to the break-up of Rodinia between ancestral Australia and western Laurentia (Brookfield, 1993). The AUSWUS model was further advanced by correlating sediment provenances and basement provinces between southwestern Laurentia and eastern ancestral Australia (Karlstrom et al., 1999; Burrett and Berry, 2000). One of the supposed problems with AUSWUS is the lack of a dyke swarm, which Australia in such a configuration would be expected to host as the complement to the 780 Ma Gunbarrel radiating dyke swarm(s) of western Laurentia. While the "missing-link" and AUSMEX models obviate the need to make such a link, the AUSWUS and SWEAT models predict that any contemporaneous volcanism or plume activity should give rise to features such as radiating dyke swarms in surrounding cratons. In this regard there is an age mismatch between the ca. 825 Ma Gairdner–Amata dyke swarms in eastern ancestral Australia and the ca. 780 Ma Gunbarrel dyke swarms in western Laurentia (Park et al., 1995).

The palaeomagnetic evidence is somewhat ambivalent. While the Gunbarrel dykes would predict that the Gairdner–Amata dykes (and the Willouran plume centre in South Australia) occurred in low-palaeolatitudes (Park et al., 1995, Fig. 4), the admittedly sparse palaeomagnetic data from the Gairdner dykes (Schmidt and Clark, 1992) point to very high palaeolatitudes. Demagnetisation plots given in Schmidt and Clark (1992, p. 44) for Gairdner dyke samples show extremely stable ChRM, only partially demagnetised at 100 mT AF, directed steeply downward to the NW, indicating they were acquired within ca. 15° of the pole (VGP). Unpublished palaeomagnetic data from other

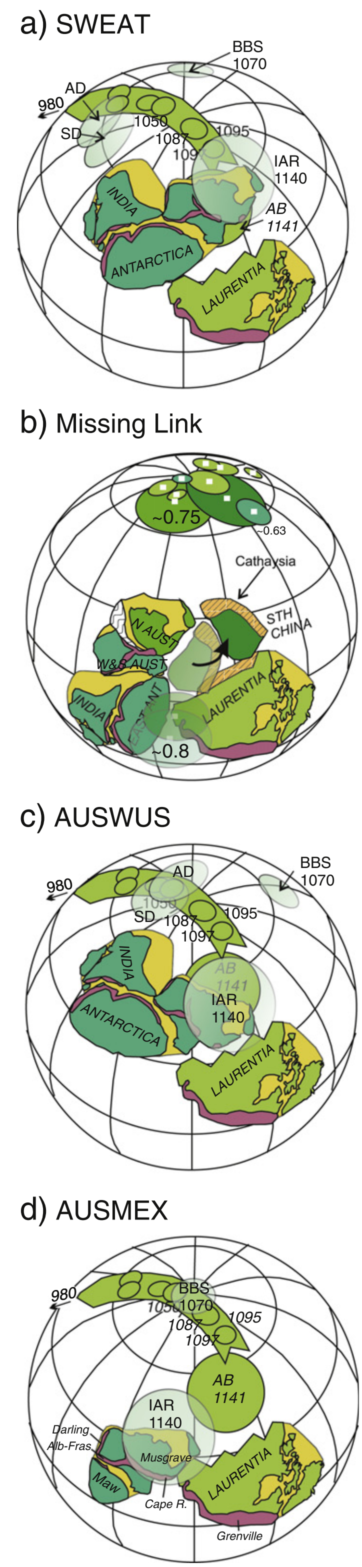

Fig. 8. Palaeogeographic reconstructions (a) SWEAT (after Moores, 1991; Euler rotations after Wingate et al., 2002), Euler poles are: Laurentia to reference frame, 42.6°N, 222.1°E, rotation = −109.7° (negative is clockwise viewed outside globe); Australia to reference frame, 35.8°N, 53.5°E, rotation = 112.1°, Antarctica to reference frame, 28.0°N, 57.0°E, rotation = 138.7°, India to reference frame, 73.0°N, 22.7°E, rotation = 94.8°. (b) Missing-link (after Li et al., 1995, with modifications after Li and Evans, 2011). Euler rotations are: Laurentia to reference frame, 42°N, 184°E, rotation = −131° (negative is clockwise viewed outside globe); West&South Australia/Antarctica to reference frame, 17°N, 56°E, rotation = 44°, North Australia to reference frame, 12°N, 9°E, rotation = 57°; Sth China to reference frame, first position 59.5°N, 161.4°E, rotation = 77°, second position 43.9°N, 150.4°E, rotation =139.9°. (c) AUSWUS (after Brookfield, 1993), Euler rotations: Laurentia to reference frame, 42.6°N, 222.1°E, rotation = −109.7° (negative is clockwise viewed outside globe); (d) AUSMEX (after Wingate et al., 2002).). Euler poles are: Laurentia to reference frame, 42.6°N, 222.1°E, rotation = −109.7°; Australia to reference frame, 41.5°N, 34.5°E, rotation = 79.5° (positive is anticlockwise viewed outside globe).

Gairdner dykes (James Austin and the present author) support these earlier results and suggest that the Gairdner–Amata dykes were intruded at high palaeolatitudes, contrary to their correlation with the Laurentian Gunbarrel swarms, but not inconsistent with their now established different ages. The Wooltana Volcanics pole (McWilliams and McElhinny, 1980), although not highly rated but used by Li and Evans (2011), is also consistent with high palaeolatitudes at this time (ca. 820 Ma). It is noteworthy that, despite this apparent high palaeolatitude, glaciation at ca. 825 Ma is unknown in Australia but occurred at low palaeolatitude in the late Palaeoproterozoic and is widespread in low palaeolatitudes during the Cryogenian (see Sections 6 and 7.1).

These apparent high palaeolatitudes are in conflict with the results of Pisarevsky et al. (2001, 2007) from the Officer Basin, central Australia, which show consistent low palaeolatitudes from ca. 830 Ma to ca. 600 Ma. However, if the 800–830 Ma Browne Formation result is corrected for inclination flattening these low palaeolatitudes may become moderate palaeolatitudes, depending upon the lithologies (Fig. 4). Schmidt and Williams (2013) found a correction factor, *f*, as low as 0.35 (*f* is varies inversely to the amount of correction) for argillaceous rocks in Adelaidean successions, and applying this correction to the Browne Formation yields a somewhat steeper inclination that would place central Australia within 45° of the pole, but not at ~70° as in the Li et al. (2013) 825 Ma reconstruction or as high as the very preliminary results from the Gairdner–Amata dykes suggest.

Other palaeomagnetic data that place Australia in high palaeolatitudes while Laurentia occupied low palaeolatitudes are the ca. 1200 Ma palaeomagnetic poles of Pisarevsky et al. (2003). To reconcile the Bangemall Basin Sills pole with a Rodinia-like reconstruction, Wingate et al. (2002) advocated the AUStralia–northwest MEXico (AUSMEX) model where there is only a tenuous connection between northernmost Australia and western Laurentia (Fig. 8d). The 1200 Ma poles of Pisarevsky et al. (2003) are not compatible with either an AUSWUS or an AUSMEX fit at that time. However, the Pisarevsky et al. (2007) 790 Ma Hussar Formation pole from the Officer Basin is in better agreement with the ca. 780 Ma Laurentian poles in the AUSMEX model than with the 755 Ma Mundine Dyke Swarm pole of Wingate and Giddings (2000) (Fig. 9b).

The Mundine Dyke Swarm (Wingate and Giddings, 2000) pole also contradicts the geological evidence for the timing of the breakup between Australia–East Antarctica and Laurentia. In the context of the Rodinia configuration of Powell et al. (1993), the Mundine Dyke Swarm pole position implies that Australia and Laurentia were adrift at 755 Ma and presumably for some time prior to 755 Ma. Wingate and Giddings (2000, p. 353) concluded that in turn "this would require continental breakup… before 755 Ma… (which) is ≥30 million years older than the 700 to 720 Ma age proposed by Powell et al. (1993), and ~200 million years older than the 560 Ma age of breakup suggested by Veevers et al. (1997)".

The 1070 Ma Bangemall Basin Sills pole (Section 5.2) of Wingate et al. (2004) and its mismatch with other WLIP palaeopoles from the Kulgera Dykes and the Stuart Dykes led Schmidt et al. (2006) to propose a rotation between the North Australian Craton and the West Australian Craton, that must have occurred after 1070 Ma. The proposed rotations restored the poles to their original relative positions. Wingate et al. (2002) had dismissed the poles from the Stuart and Kulgera dykes as being unreliable and although the age constraints and attitude of the Kulgera dykes/sills might have been tighter, the mismatch was nevertheless disconcerting. Schmidt et al. (2006) published precise ^{40}Ar–^{39}Ar ages of 1068 ± 2 to 1085 ± 2 Ma and a positive fold test for the Alcurra Dolerite, reassuring the skeptics that the problem is one of internal inconsistency of results from the WLIP, not a particular problem with any single study. In addition, ^{40}Ar–^{39}Ar ages of 1059 ± 2 and 1066 ± 3 Ma on two samples of a Stuart dyke were determined. These new ages are consistent with those of the 1070 Ma WLIP.

Schmidt et al. (2006) also incorporated the pole from the Gawler B dykes (GB; Giddings and Embleton, 1976) from South Australia, on the basis that Wingate et al. (2004) included the Beda Volcanics in their Fig. 1 as a possible WLIP member. While the GB Dykes are not dated, they are contenders to be feeders for the nearby Beda Volcanics which are dated by a whole rock Rb–Sr age of 1076 ± 34 Ma (Webb and Coats, 1980) and, in addition, dolerite from the eastern Gawler Craton at Olympic Dam yielded a three-point Rb–Sr isochron age of 1070 ± 74 Ma (R. Creaser, in Cowley and Flint, 1993). These ages suggest that the South Australian Craton was a centre of igneous activity contemporaneous with the WLIP. The palaeopole from the GB Dykes is at latitude = 22.8°S, longitude = 86.4°E (A_{95} = 11.3°), while the Stuart Dykes and Alcurra Dolerite palaeopoles are at latitude = 10.0°S, longitude = 82.0°E (A_{95} = 10.0°) and latitude = 2.8°S, longitude = 80.4°E (dp = 7.2°, dm = 10.7°), respectively. Therefore the radiometric ages for the Beda Volcanics and dolerite at Olympic Dam, and the palaeopole from the GB dykes suggest they all may be distal components of the WLIP and are coeval with the Alcurra Dolerite and Stuart Dykes. Clearly a more reliable radiometric age is required for the GB dykes as the tectonic implications are significant.

Li et al. (2008, p. 188) accepted that there was a significant problem with the internal consistency of WLIP results stating that "it appears probable that either the 1070 Ma Bangemall Basin sills, or the central

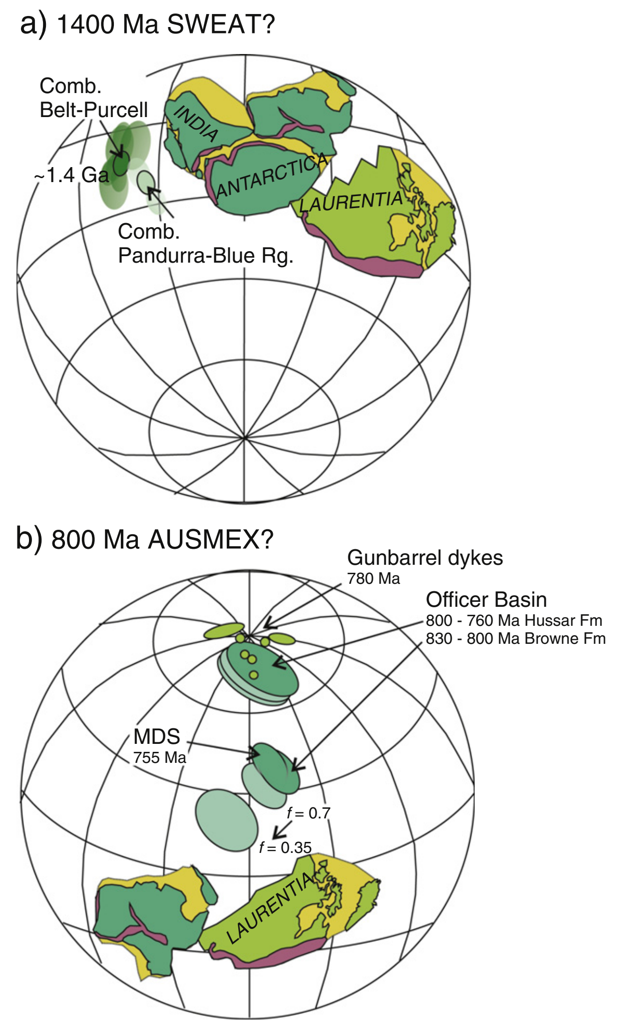

Fig. 9. (a) SWEAT at about 1400 Ma, comparing the Blue Range Beds–Pandurra Formation poles (Schmidt and Williams, 2011) and the combined Belt–Purcell (Goodge et al., 2008) poles and (b) AUSMEX Gunbarrel dykes after Harlan et al. (2003, 2008), Browne and Hussar formations (Pisarevsky et al., 2007) and the Mundine Dyke Swarm (Wingate and Giddings, 2000). The Mundine Dyke Swarm pole and the Hussar Fm pole disagree, although the former and the somewhat older Browne Fm pole agree (unless the latter is inclination corrected). These results suggest that the ages of Officer Basin sediments may require adjusting (see Section 7.4).

Australian data, have suffered vertical-axis rotations, during… the southern Capricorn Orogen… in the case of the Bangemall sills, or the late Neoproterozoic Petermann or Phanerozoic Alice Springs orogenies in central Australia" in the case of the latter. Schmidt and Williams (2008) noted that while palaeomagnetic inclinations for the Frere Formation of the Earaheedy Group (Williams et al., 2004) and the Elgee–Pentecost of the Kimberley Group are similar, the 45° separation between the Frere and Elgee–Pentecost poles (Table 2, Fig. 3) reflects this difference in declination and represents relative rotation about a vertical axis. Schmidt and Williams (2008, p. 276) drew attention to the similarities between the Frere/Elgee-Pentecost pair of poles and those of the 1.07 Ga Warakurna Igneous Province Bangemall Supergroup sills from the West Australian Craton (Wingate et al., 2002) and the Stuart Dykes and Alcurra Dyke Swarm from the North Australian Craton (Schmidt et al., 2006), suggesting that "a merger of the cratons at 1.79–1.76 Ga was temporary and followed by separation before final assembly after 1.07 Ga".

Nevertheless Evans (2009) maintained that any conclusion that Australia was not fully assembled by 1070 Ma should be "treated with caution", perhaps unaware of the corroborating evidence from the Frere and Elgee-Pentecost formations. Later, Li and Evans (2011) accepted the evidence for late amalgamation between the NAC and the W/SAC and added a third pair of "dislocated" palaeopoles that could be brought into alignment by a relative rotation between WAC + SAC and NAC. Thus, there are three sets of poles, the ca. 1800 Ma Elgee-Pentecost (NAC) and the ca. 1800 Ma Frere Formation (WAC), the 1066 to 1087 Ma Alcurra Dolerite pole (NAC) and the 1070 ± 6 Ma Bangemall Basin Sills pole (WAC) and the 755 ± 3 Ma Mundine Well Swarm pole (WAC) and 710 to 635 Ma Walsh Tillite cap dolomite (NAC), that can be reconciled by an Euler pole at 23°S, 135°E and a rotation of −40° such that NAC rotates clockwise (as viewed from above) away from WAC bringing poles into alignment, i.e. a 40° gap between the NAC and the WAC closed sometime after 1070 Ma dispersing the poles.

Further new evidence from the 770 Ma Johnnys Creek Member of the Bitter Spring Formation, central Australia (NAC), also provides support for the late amalgamation model which more closely aligns the new pole with the 755 Ma Mundine Dyke Swarm pole (Swanson-Hysell et al., 2012) (Fig. 4).

Interestingly, the Mundine Dyke Swarm and Johhnys Creek Member poles are not too far displaced from the 1070 Ma Warakurna poles, suggestive that the Australian APWP includes a loop similar to the Laurentian "Grenville Loop".

The introduction of inter-cratonic rotations does introduce more degrees of freedom in analyses of palaeopoles, as lamented by Swanson-Hysell et al. (2012), but if a number of discrepancies can be rectified as a result, as is the case here, it would appear justified.

7.4. Australia in Nuna?

Idnurm and Giddings (1995) compared their 1700–1600 Ma palaeopoles from the McArthur Basin, northern Australia, to the equivalent segment of the Laurentian Proterozoic APW path using an Euler pole at 38°N, 100°E and a clockwise angle of 117°. This superimposes the two paths and shows the segments to be similar. The same rotation connects the Pacific margins of the North American and Australian cratons, as maintained by the SouthWest (United States) East AnTarctic (SWEAT) hypothesis. The configuration is consistent with a western (off-shore) sediment source for detritals of the Belt–Purcell Basin of the Laurentia, with isotopic signatures of basement provinces, and with the alignment of major lineaments. Idnurm and Giddings (1995) concluded that the sparseness of palaeopoles on the Australian path for younger Proterozoic times, which cannot be closely matched with the relevant North American segments, might be compensated for by transferring the well-defined 1400–900 Ma North American palaeopoles to the Australian APW path for correlation and dating. This is essentially what various workers have been attempting, as described in Section 7.3.

Goodge et al. (2008) drew a comparison between the Mesoproterozoic Pandurra Formation–Blue Range Beds of the Gawler Craton and Belt–Purcell succession of the North American fold and thrust basin as proximal and distal deposits with a common provenance of the 1590 Ma Gawler–Hiltaba terrain in South Australia. SHRIMP U–Pb ages of detrital zircons from the Pandurra Formation yield a dominant 1620–1580 Ma component (Fanning and Link, 2003, 2004) from which it was concluded that the nearby Gawler Range Volcanics and Hiltaba Granite Suite were the major source of detrital zircons. This and stratigraphic constraints are consistent with a Mesoproterozoic age for the Pandurra Formation (see Section 5.2). The Mesoproterozoic Belt–Purcell basin of Laurentia also contains a detrital zircon population with ages of 1610 to 1490 Ma. The ca. 1590 Ma population has no known source from Laurentia and is inferred to have a western provenance.

On the basis of the Gawler–Hiltaba terrain being the source for detrital zircons from the Belt–Purcell sediments, Goodge et al. (2008) proposed a SWEAT-like configuration between (ancestral) Australia and Laurentia for ca. 1.4 Ga. A comparison of the available palaeopoles from the Pandurra Formation–Blue Range Beds (Schmidt and Williams, 2011) and the Belt–Purcell Supergroup (Elston et al., 2002) gives a configuration (Fig. 9a) that is compatible with this suggestion. Both the Pandurra–Blue Range and the Belt–Purcell Supergroup exhibit stable hematite magnetisations of both polarities which pass fold tests, adding confidence to the reconstruction. Zhang et al. (2012) also adopt a SWEAT-like configuration between Laurentia and Australia in their Nuna supercontinent. The breakup of their Nuna may have commenced after ca. 1.4 Ga, which would be consistent with the Pandurra–Blue Range and Belt–Purcell configuration suggested by Goodge et al. (2008).

The possibility of an AUSMEX reconstruction at about 800 Ma (Fig. 9b) seems to be supported by the palaeopoles from the 800–760 Ma Hussar Formation of the Officer Basin (Pisarevsky et al., 2007) and the 780 Ma Gunbarrel dykes of western Laurentia (Harlan et al., 2003, 2008). The palaeopole from the 755 Ma Mundine dykes does not accord with this however. Moreover this 755 Ma palaeopole appears to be in agreement with the older 830–800 Ma palaeopole from the Browne Formation of the Officer Basin (Fig. 4) which suggests that the ages of the Officer Basin sediments may be over estimated. Figs. 4 and 9b also explore the implications of inclination corrections for the Officer Basin sediments based on the finding of Schmidt and Williams (2013) that concluded that flattening factors $f = 0.7$ and $f = 0.35$ are probably appropriate for arenites and argillites respectively (the lower f translates to a greater correction). The inclinations for the Officer Basin formations have been recalculated for flattening factors, $f = 0.7$ and $f = 0.35$, and the resultant notional palaeopoles are plotted in Figs. 4 and 9b. The pole for the Hussar Formation shows only a small correction because its inclination is very low. However, the pole for the Browne Formation moves considerably, especially for $f = 0.35$, assuming the lithologies are mostly argillaceous. If this is correct then the Browne Formation implies Australia was in moderate to high palaeolatitudes at 830–800 Ma, not the low latitudes as depicted in Fig. 6d.

Pisarevsky et al. (2013) present a set of global paleogeographic reconstructions for the 1770–1270 Ma time interval based on reliable paleomagnetic data and geological constraints. Their synthesis suggests that the supercontinent Nuna/Columbia amalgamated by 1650–1580 Ma from the combination of two 1700 Ma continents, West Nuna (Laurentia, Baltica and possibly India) and East Nuna (North Australian Craton (NAC), West and South Australia Craton (WAC and SAC), the Mawson craton of Antarctica and North China). The 1770 Ma reconstruction is shown in Fig. 10a. The poles shown a from Table 1 of Pisarevsky et al. (2013). Pole 9 is from the Frere Formation (WAC) and pole 10 is from the Elgee-Pentecost formations (NAC). This reconstruction takes into account the late (post 1070 Ma) amalgamation between NAC and WAC and SAC without which poles 9 and 10 would be dispersed. Clearly these data are consistent with this 1770 Ma reconstruction.

The amalgamation and break-up ages of the Palaeoproterozoic supercontinent Nuna and Mesoproterozoic supercontinent Rodinia were analysed using palaeomagnetic and isotope age data by Pesonen et al. (2012). These workers also investigated palaeolatitudes and the frequency distribution of inclinations. It was found that generally Nuna and Rodinia were predominantly in moderate to low paleolatitudes, although both India (Dharwar) and Australia (Yilgarn) occupied polar latitudes in the Paleoproterozoic. In addition, Pesonen et al. (2012) note that there were unexpected low palaeolatitude glaciations in the Palaeoproeterozoic.

The 1.63 Ga reconstruction given by Pesonen et al. (2012) and reproduced as Fig. 10b, uses palaeomagnetic data from Laurentia, Baltica, Amazonia, Australia and Kalahari. The data from Australia however, includes those results that are suspected of being biased due to deep tropical weathering. In Section 4.1 (also see Schmidt and Williams, 2008) the evidence for significant bias of magnetisations towards Cenozoic directions due to pronounced tropical weathering in northern Australia is discussed. The Australian Palaeoproterozoic–Mesoproterozoic APWP presented by Idnurm et al. (1995) and Idnurm (2000) shows two excursions into present-day high latitudes. Schmidt and Williams (2008) observed similar excursions in their study of the Kimberley region but queried the antiquity of high-latitude poles. They noted that the Pentecost Sandstone yielded two distinct groupings of magnetisation, one pre-folding and another post-folding that yielded a pole similar to Cenozoic poles for northern Australia and close to the present-day pole. Australia's placement in Fig. 10b at 1630 Ma may therefore require reassessment.

The two reconstructions for the time periods 1800–1500 Ma and 1200–800 Ma (Fig. 10c and d) compare the palaeomagnetic results with the two principal Palaeopangaea reconstructions of Piper (1987, 1990, 2000, 2003, 2007, 2010). Piper recognises a pre-1100 Ma configuration (proto-Palaeopangaea) and a post-1100 Ma reconfiguration. This latter reconfiguration involves the more peripheral components, including Australia. Hence Australian Precambrian palaeomagnetic data might be expected to reflect the different configurations.

The data used in Fig. 10c is tabulated by Pisarevsky et al. (2013, Table 1), and here in Table 2. Palaeopoles and notional pole paths are colour coded to each of the three continents involved, North America, Baltica and Australia. The ages are shown in Ga for each of the datasets. There seems to be little support for this reconstruction although there are two areas where poles show some agreement, at 1.8 Ga between North America and Baltic, and at 1.5 Ga between North America and Australia. The conventional interpretation would deduce that these three landmasses were in relative motion with respect to each other throughout this period. It is noteworthy that Piper (2010)'s model,

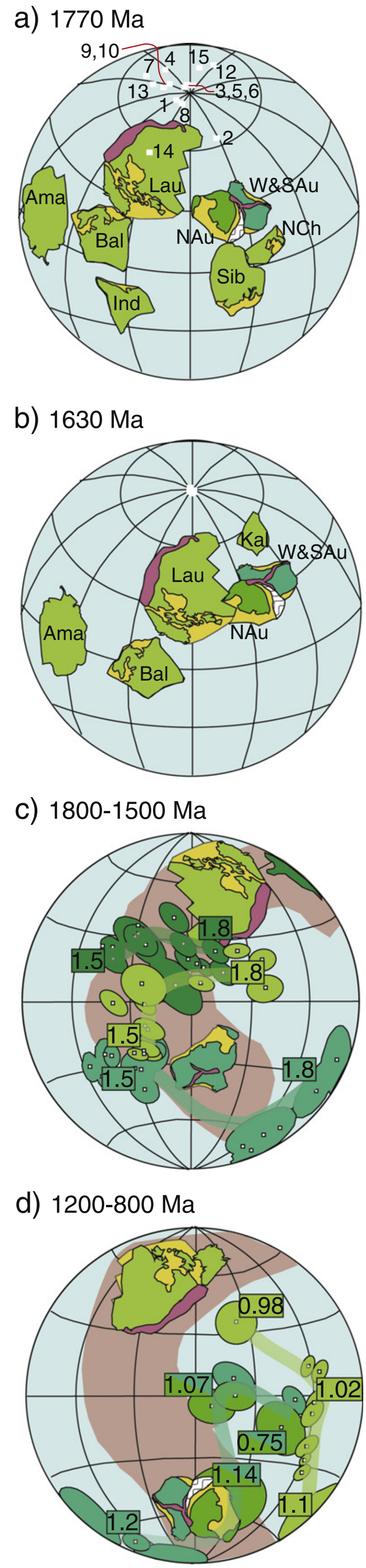

Fig. 10. (a) palaeoreconstruction for 1770 Ma according to Pisarevsky et al. (2013); poles numbered 1 to 15 are for Pisarevsky et al. (2013, Table 1), 1 — late Svecofennian rocks, 2 — Småland intrusions, 3 — Shoska Fm, 4 — Hoting gabbro, 5 — Ropruchy sill, 6 — Korosten pluton, 7 — Dubawnt Gp, 8 — Jan Lake granite, 9 — Frere Fm, 10 — Elgee-Pentecost fms, 11 — Xiog'er Gp, 12 — Taihang dykes, 13 — Basic dykes II, 14 — Colider vols, 15 — Avanavero intrusions. Euler rotations to reference frame are: Laurentia −52.0°N, 60.0°E, rotation = 215.2°; Baltica −66.3°N, 26.8°E, rotation = 199.9°; Sarmatia/Volgo-Uralia −57.9°N, −10.8°E, rotation = 172.8°; India −24.8°, 132.4°, rotation = 208.1°; North Australian Craton −33.2°N, −0.6°E, rotation = 206.8°; West Australian Craton −17.0°N, 9.3°E, rotation = 190.7°; South Australian Craton −1.9°N, 18.3°E, rotation = 178.0° (see Section 7.4). (b) palaeoreconstruction for 1630 Ma according to Pesonen et al. (2012); this reconstruction is essentially palaeomagnetically based to the extent that the continental fragments are located according to palaeomagnetic pole position, which therefore all plot precisely at the pole. Euler rotations to reference frame are: Laurentia 8.0°N, 174.3°E, rotation = 86.8°; Baltica 34.2°N, 117.1°E, rotation = 79.3°; Amazonia 65.0°N, 168.6°E, rotation = 95.6°; Australia 4.6°N, 128.2°E, rotation = 167.0°; Kalahari 45.3°N, 352.0°E, rotaion = 135.4° (see Section 7.4). (c) palaeoreconstruction for 1800–1500 Ma according to Piper (2010, Palaeopangaea A); Euler rotations to reference frame are: Laurentia fixed reference; Baltica 21.0°N, 8.0°E, rotation = 41.0°; Australia −84.5°N, 120.0°E, rotation = −119.9°. Poles from North America and Baltica (Pisarevsky et al., 2013, Table 1), and Australia Table 2 (herein) (see Section 7.4). (d) palaeoreconstruction for 1200–800 Ma according to Piper (2010, Palaeopangaea B); Laurentia fixed reference; West and South Australia Craton −63.5°N, 180.0°E, rotation = 158.3°; North Australia Craton 50.0°N, 19.0°E, rotation = −135.0°. Poles from North America (Wingate et al. 2002, Table A4), and Australia Table 2 (herein) (see Section 7.4).

and indeed his forerunners, represent a paradigm shift so it would not be surprising if he were to reject the conventional analysis above. Piper (2010) contends that "APW was evidently a continuously migrating feature prior to ~750 Ma… and no degree of radiometric precision is able to guarantee contemporaneous poles of such antiquity in a dynamic regime with continental crust migrating continuously with respect to the poles…" and the selection of poles for their reliability "although intrinsically preferable (Buchan et al., 2000), would completely fail to identify a unified APW path moving relative to a coherent crust". This is not consistent with the concept of a prolonged Palaeopangaea whose core elements were more or less fixed relative to one and other for much of the Precambrian, for which such a highly selective approach would be well suited and would work ideally. Piper (2010)'s Figs. 1 and 2 depict APW paths, such as The Garder Track (1300–1140 Ma) and the Keeweenawan Track and Grenville-Sveconorwegian Loop (1140–800 Ma), features first identified following the conventional approach. It seems that Piper's versions differ only in the scatter of poles which might simply be the result of erroneous reconstructions and the uncritical incorporation of many and varied data points.

Much of the Australian data for this period is from the McArthur Basin (NAC) which implies another rotation, with respect to the WAC and SAC, as discussed in Section 7.3. The rotation would not materially change the conclusion though, that this palaeoreconstruction is unsupported by palaeomagnetic data independently assessed as the most reliable available.

For Palaeopangaea B the data used (Fig. 10d) is tabulated by Wingate et al. (2002, Table A4), and here in Table 2. Palaeopoles and notional pole paths are again colour coded, this time to the two continents involved, North America and Australia. The ages are shown in Ga for each of the datasets from 1.1 Ga to 0.98 Ga for North America and 1.2 Ga to 0.75 Ga for Australia. North America. Here the rotation between the NAC and the WAC/SAC has been implemented since this rotation moves the NAC poles closer to the North America pole path. However, there is little comparison between these paths in this configuration. On the basis of the best palaeomagnetic data it is difficult to find supporting evidence for either of these palaeoreconstructions.

7.5. Late Neoproterozoic APW or TPW?

The early days of palaeomagnetism saw vigorous debate concerning the relative merits of true polar wander (TPW) and apparent polar wander (APW) (see historical account by Frankel, 2012). This led to theories that established the possibility of TPW (Gold, 1955; Goldreich and Toomre, 1969) with the demonstration that a hydrostatic bulge has an insignificant long term effect on planetary rotational stability. Consequently, there was a period of uncertainty whether TPW was the explanation for palaeopoles meandering or whether it was evidence against a steady dipolar field (Runcorn, 1955, 1956). After Irving and Green (1958) published results from Australia it was clear that plate motion velocities and APW vastly overwhelmed rates of TPW. To many, the solution had to be one or the other, the continental drift debate was at times heated and a compromise was simply unacceptable (Frankel, 2012). In reality, of course, polar wander almost certainly contains elements of both APW and TPW. While the former won the day regarding the post-Gondwana dispersal, the situation is not so clear regarding the more distant past.

Alleged rotations of ca. 90° at high rates ascribable to TPW have simultaneously affected multiple continents in the Cambrian (Kirschvink et al., 1997). Although the time interval proposed post-dates the Precambrian, the advent of this hypothesis is important as the inaugural "Pandora's Box" event. The proposed 90° rotation is significant because it appeals to the interchange of the Earth's two major axes of inertia, and is thus referred to as 'inertial interchange' TPW or IITPW. This is a special case of TPW that specifies ca. 90° of synchronous motion. Meert (1999) challenged this IITPW event by careful analysis of the original palaeomagnetic data and showed that the amount of TPW is significantly less than 90°. This and a revised Cambrian time scale devalued the IITPW hypothesis and led Meert (1999) to suggest that a possible explanation for the anomalously high rates of APW is a combination of TPW plus enhanced plate motion.

Having sown the IITPW seed makes it easier for more generic TPW events to spring forth. Recently, Maloof et al. (2006) presented evidence for a TPW oscillation event during the mid-Neoproterozoic to explain stratigraphically systematic dispersed palaeomagnetic poles from Svalbard's ca. 800 Ma Akademikerbreen succession. The age of the succession is inferred only by stratigraphic and carbon isotope correlations with two Australian sub-basins, so the rapidity of the TPW oscillation event, 2 × 55°, is uncertain but was estimated as less than 15 Myr. Li et al. (2004) have also invoked TPW to explain highly divergent palaeopoles from south China for the high palaeolatitude 802 Ma Xiaofeng dykes and low palaeolatitude 748 Liantuo glacials. Unfortunately, the large uncertainties in the ages of the Svalbard succession preclude correlation with the alleged south China TPW event. The Ediacaran APW path for Laurentia places it in high palaeolatitudes at 590–575 Ma, transitioning to low palaeolatitudes during the late Ediacaran, which has also been interpreted as the signature of TPW (McCausland et al., 2007). In a comparison of Ediacaran Laurentian APW with the equivalent Australian APW, Schmidt and Williams (2010) found little commonality and were therefore sceptical of this TPW 'event'.

It comes as no surprise that other TPW 'events' have been proposed for the Ediacaran of Australia with large-magnitude rotations and large swings in the pole path (Mitchell et al., 2012). However, Schmidt and Williams (2013) argued that this is no longer viable after corrections are made for significant inclination flattening in argillaceous rocks to the Australian APWP. The poles included by Mitchell et al. (2012) in their TPW analysis are from the Yaltipena Formation (Sohl et al., 1999), the Elatina Formation (Schmidt and Williams, 2010), the Nuccaleena Formation (Schmidt et al., 2009), the Bunyeroo Formation (Schmidt and Williams, 1996; Williams et al., 1996) and the Wonoka Formation (Schmidt and Williams, 2010). Palaeopoles from the argillaceous Brachina, Bunyeroo and Wonoka formations are shifted significantly on inclination correction and the new APWP for the Australian Ediacaran cannot be entirely aligned with a single great circle, a prerequisite of the analysis of Mitchell et al. (2012).

While the identification of TPW may establish a rotation axis (of minimum inertia) about which TPW occurs, and is common to all continents defining a shared reference frame that allows the longitudes of continents to be fixed relative to each other, the weakness in the method is in the arbitrary definition of the periods of TPW. The revised array of Australian late Cryogenian–Ediacaran poles disallows the inclusion of the Yaltipena, Elatina and Nuccaleena poles with the Brachina, Bunyeroo and Wonoka poles on a great circle generated by a single TPW 'event', these poles now form a distinctive loop, which ironically now show some similarities to the Laurentian Ediacaran to Cambrian path of McCausland et al. (2007). If there is a significant component of TPW in the Ediacaran loops for Laurentia and Australia it would seem to have a small circle signature rather than a great circle signature. The recent study of Mutton Bay (McCausland et al., 2011) show two equally reliable components at 585 Ma, one with steep inclinations and the other with shallow inclinations. Thus TPW candidates from the Ediacaran of North America are burgeoning and the possibility that the Australian Ediacaran path harbours elements of TPW seems increasingly likely.

8. Conclusions

This review of Australian Precambrian palaeomagnetism is based largely on the Precambrian palaeomagnetic database updated by Sergei Pisarevsky for Australia (GPMDB5 www.magresearch.org) with later additions. It is clear that some segments of the Australian pole path are now quite well defined, but overall the data remain sparse and it is debatable whether enough of the rock record amenable to palaeomagnetic investigations exists to enable complete palaeogeographic histories to be reconstructed. The factors that work against unravelling the mysteries of 'deep time', such as alteration of older rocks, the numerous gaps in the stratigraphic record, particularly for the Precambrian, and the sheer vastness of geological time, must reach the point where some gaps are insurmountable and will always be there. The difficulty, debates and disputes that accompany the defining of pre-Pangaean continental distributions suggests that this point may not be as remote as some had hoped. The "key-pole" concept introduced by Buchan et al. (2000) has proved to be an effective quality control for palaeomagnetic poles derived from Precambrian rock formations and employed in palaeogeographic reconstructions. Nevertheless, APWPs remain valuable as visual summaries of palaeopole 'ages' and locations. The concept of a "grand-pole", which includes all the "key-pole" features but encompasses the extra prerequisite that two or more independent laboratories are in agreement, is introduced here.

Some developments such as corrections for inclination flattening and the permitting of rotations between contiguous intracontinental cratons to bring conflicting palaeopoles into alignment have been useful. Indeed as a general caveat on using palaeomagnetic results for palaeoreconstructions and palaeolatitudes deals with sedimentary derived palaeomagnetic directions, until these are examined for inclination flattening their inclinations should not be used to infer palaeolatitudes. Based on experimental evidence, Schmidt and Williams (2013) concluded that flattening factors $f = 0.7$ and $f = 0.35$ are appropriate for arenites and argillites respectively (the lower f translates to a greater correction). The rampant proliferation of great circle TPW 'events' is a 'Pandora's Box' for palaeomagnetism. TPW is probably real, but it is abused as an explanation for otherwise contradictory observations without independent global evidence.

Reservations about introducing inter-cratonic rotations may be justifiable but the implications are that there are an insufficient number of key poles from any one craton to permit confident palaeogeographic reconstructions. As concluded by Buchan et al. (1994), some segment of polar wander paths for various cratons may be very precise and detailed but until similarly constrained paths are available for other cratons in the Precambrian it will not be possible to determine the timing and magnitude of displacements between individual cratons with confidence.

The reality of low-latitude glaciation at sea-level and of continental extent has been verified beyond reasonable doubt by the palaeomagnetic results from the Elatina Formation and the soft-sediment slumps of its tidal rhythmites (Section 6.4). Results from the Elatina Formation have passed all tests, not just the "slump" fold test but also inclination flattening tests (Schmidt and Williams, 2013).

In terms of future, better constrained results for the Archaean Pilbara craton are required to disentangle some of the uncertainties regarding the timing of magnetisations that have been isolated in the Duffer Formation, the Marble Bar and the Euro Basalt. The palaeolatitude of Australia at 800–820 Ma needs to be determined to resolve issues surrounding Rodinia and glaciations, or the lack of glaciations, at that time. It is noteworthy that a nominal correction for inclination flattening for the Hussar Formation places Australia in moderate to high palaeolatitudes at 830–800 Ma, not the low latitudes reported.

After corrections for inclination flattening, there may be a component of TPW in the Ediacaran paths for Australia in common with that proposed for Laurentia. However, rather than a great circle signature it would seem to correspond more to a small circle loop suggesting a more complicated mechanism.

The SWEAT connection could have existed once, but it could not be for Rodinia as both the 1200 Ma and 1070 Ma poles disallow it. On the other hand, older poles do support a SWEAT-like configuration for the pre-Rodinia supercontinent Nuna. This configuration disintegrated in the late Mesoproterozoic and then formed the "Missing Link" configuration by ca. 900 Ma or one of the other viable models.

Possibly the main conclusions of this review is the need for more palaeomagnetic work on rock units of similar ages across all of the major cratons of Australia to further constrain their relative palaeopositions. To determine to what extent the Southern Australian Craton may have moved with respect to the Western Austalian Craton, a more reliable radiometric age is required for the GB dykes. Better ages are needed for the Adelaidean and Officer Basin successions, especially the Elatina Formation of the former and the Hussar and Browne formations of the latter. A continental drilling project to study the magnetostratigraphy of the entire ~300 my succession of the Adelaidean sequence is a goal that should be achievable in the foreseeable future.

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Appendix A. Rationalising palaeomagnetic results of the Fortescue Volcanics and feeder dykes

Schmidt and Embleton (1985) and Strik et al. (2003) have both studied various units of the Fortescue Volcanics and their feeder dykes. This section compares these studies and recombines results to form Grand Poles. The study of Strik et al. (2003) was plagued by the effects of lightning but curiously neglected the dual AF/thermal demagnetisation recommended by Schmidt and Embleton (1985). Strik et al. (2003) identified a component prevalent in their southernmost sites that is similar to the synfolding component found in the Mount Jope Volcanics by Schmidt and Embleton (1985). The bedding attitudes of the affected sites of Strik et al. (2003) are shallow and apparently did not allow testing of the components for a synfolding origin, as this aspect is not mentioned. However, Strik et al. (2003, para. 58) did suggest that if the overprint component was caused by burial/uplift then it should be expressed not only in the upper units (where it was found), but also in the lower units. This can easily be explained by the geographical distribution of their sampling sites. The northern sites, where the lower units outcrop, have not been as deeply buried as the southern sites, where they encountered significant secondary overprinting. This is what Schmidt and Embleton (1985) found and what is expected from the metamorphic zonations Z1–Z4 mapped by Smith et al. (1982), which shows increasing burial depths and metamorphism to the south. If samples from the Mount Roe Basalt were available from deep drill core in the southern areas they would probably possess significant magnetic overprints.

Strik et al. (2003) also claim the oldest magnetic reversal, between the Mount Roe Basalt and overlying Hardey Sandstone "quartz-plagioclase porphyry". While Schmidt and Embleton (1985) report a reversal within the Mount Roe Basalt itself, which therefore pre-dates the overlying polarity reversal of Strik et al. (2003), Layer et al. (1996) reported a polarity reversal between the margin and centre of the 3214 ± 4 Ma Kaap Valley tonalite, Barberton greenstone belt, which is clearly older.

Given the similarities between the Schmidt and Embleton (1985) and the Strik et al. (2003) studies it is best to incorporate the results to provide superior overall mean directions (the aforementioned studies are below referred to as S&E and SBZWL, respectively). For instance, while SBZWL place paramount importance on the positive fold test that they found for their Mount Roe Basalt sites (their Package 1), this being their only fold test, while their sites are entirely of one polarity. The Mount Roe Basalts sites of S&E satisfy a fold test and are 50:50 normal and reverse, having been collected in quite disparate localities. It is expected that secular variation would be better averaged by

Table A1
Combined directions for Grand Poles NS, JS and O from Schmidt and Embleton (1985) and Strik et al. (2003). See text for discussion.

Formation	N	Dec. (°)	Inc. (°)	R	k	α_{95}
Mt Jope o/p†	14	303.9	−18.6	13.771	56.6	5.3
MT8-10	12	320.0	−37.1	11.788	52.0	6.1
Mean (GPO)	26	311.1	−27.0	25.016	25.4	5.7
Mt Jope basalt	5	154.1	79.6	4.919	49.4	11.0
P4-7	8	157.5	72.2	7.864	51.5	7.8
Mean (GPJS)	13	156.6	75.1	12.758	49.6	5.9
Mt Roe basalt‡	12	140.0	53.8	11.756	45.1	6.5
P1-2 + Black Range Suite‡	16	132.0	68.3	15.930	214	2.5
Black Range Dyke*	16	115.0	72.0	15.614	38.9	6.0
Cajuput Dyke*	9	145.0	71.0	8.520	16.7	13.0
Mean (GPNS)	53	132.3	67.0	51.287	30.4	3.6

α_{95} and k are the half-angle of the cone-of-confidence and the precision parameter of Fisher (1953).
† 35% unfolding (acquired at 65% folding implied by maximum k); ‡ mixed polarities; * from Embleton (1978).

amalgamating the results, yet SBZWL (para. 47) express concern regarding the 'misfit of site means after tilt correction'. This is to be expected when sampling lava flows and is gratifying that secular variation is recorded between the flow events indicating significant time between flow event, which is not always the case. Consequently, the results from the S&E's Mount Roe Basalt and SBZWL's P1 and P2 sites (plus the Black Range and Cajuput dykes from Embleton (1978), since SBZWL had incorporated a Black Range result in their Package 1) are combined here into a 'grand-pole' for the Nullagine Supersequence (GPNS). The pole is 'grand' in the sense that similar results from more than one laboratory are combined. Likewise, S&E's Mount Jope Volcanics and SBZWL's P4–7 sites are combined into GPJS (Mount Jope Supersequence), and S&E's Mount Jope Volcanics overprints with SBZWL's MT810 overprints are combined into GPO (Ophthalmian) (Table A1). One question that SBZWL did not ask, and for which there is no clear answer, is whether their polarity reversal between P1 and P2 near Nullagine can be correlated with the S&E polarity reversal observed entirely within the Mount Roe Basalt sampled over 300 km to the west, south of Dampier.

Fold tests (McFadden, 1990) on GPNS, GPJS and GPO are shown in Tables A2 to A4. The ξ_2 statistic for GPNS components falls from 26.248 to 1.455 on unfolding, where the significance point ($p = 0.95$) for $N = 53$ is 8.47, strongly supporting a pre-folding origin for this component (Table A2). Rock magnetic measurement by S&E show these rocks possess coercivities of remanence in excess of 30 mT (their Fig. 9) and are therefore very likely original thermoremanent magnetisations. For the GPJS components ξ_2 exceeds the significance points for $N = 13$ of 4.20 ($p = 0.95$) in both their in situ and unfolded orientation (Table A3). This fold test is therefore indeterminate. For the overprint component (GPO) ξ_2 also exceeds the significance points for $N = 26$ of 5.93 ($p = 0.95$) in both their in situ and unfolded orientation (Table A4), but has a minimum value of 0.008 at 24% unfolding implying acquisition at 76% of folding. The maximum k occurs at 37% unfolding (63% folding) which compares well with S&E's value at maximum k of 35% unfolding (65% folding). It is really not critical which of the partial unfolding values is adopted since the important point is that the overprint was acquired during the Ophthalmian Orogeny that led to exhumation and uplift, with supracrustal cooling that blocked and stabilised this thermoviscous component.

Table A2
Fold test based on GPNS results in Table 1.

GPNS	N	Dec. (°)	Inc. (°)	k	α_{95}	ξ_2[a]
In situ	53	143.0	71.6	21.1	4.3	26.25
Unfolded	53	132.3	67.0	30.1	3.6	1.46

[a] Significance points for N = 53 at the 0.95 level = 8.47, and at the 0.99 level = 11.97 (McFadden, 1990).

Table A3
Fold test based on GPJS results in Table 1.

GPJS	N	Dec. (°)	Inc. (°)	k	α_{95}	ξ_2[a]
In situ	13	173.1	63.0	9.40	14.2	9.92
Unfolded	13	156.6	75.1	49.6	5.9	4.77

[a] Significance points for N = 13 at the 0.95 level = 4.2, and at the 0.99 level = 5.86 (McFadden, 1990).

Table A4
Fold test based on GPO results in Table 1.

GPO	N	Dec. (°)	Inc. (°)	k	α_{95}	ξ_2[a]
In situ	26	311.5	−26.1	21.5	6.2	3.613
Unfolded[b]	26	311.1	−27.0	25.4	5.7	0.008

[a] Significance points for N = 26 at the 0.95 level = 5.93, and at the 0.99 level = 8.39 (McFadden, 1990).
[b] Minimum ξ_2 = 0.008, 24% unfolding (acquired at 76% folding implied by minimum ξ_2).

Appendix B. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.gr.2013.12.007.

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