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Ediacaran palaeomagnetism and apparent polar wander path for Australia: no large true polar wander

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SUMMARY

We report new palaeomagnetic data for red beds from the Ediacaran Brachina and Wonoka formations in the Adelaide Geosyncline, South Australia, and discuss their place with previously determined poles in the Ediacaran apparent polar wander path for Australia. Both formations behave similarly on thermal demagnetization, displaying high-temperature components that decay to the origin at 680 °C, consistent with haematite being the only magnetic mineral present. Restoring the strata to the palaeohorizontal yielded positive fold tests for both units at 99 per cent confidence, indicating that acquisition of magnetization occurred before the early Palaeozoic Delamerian Orogeny. For the Brachina Formation (N = 91 specimens) the mean direction after unfolding is declination $D = 178.2°$, inclination $I = –22.6°$ (α_{95} = 4.4°), indicating a palaeolatitude $\lambda = 11.8 \pm 2.5°$ and a pole position at latitude $\lambda_p = 46.0°$S, longitude $\varphi_p = 315.4°$E, with confidence semi-axes $dp = 2.4°$ and $dm = 4.6°$. The mean direction for the Wonoka Formation after unfolding (N = 70) is $D = 255.9°$, $I = –23.7°$ (α_{95} = 6.4°), indicating $\lambda = 12.3$ +3.8/–3.4° and a pole position at latitude $\lambda_p = 5.2°$S, longitude $\varphi_p = 30.5°$E ($dp = 3.6°$ and $dm = 6.8°$). The mean directions for these units and other Ediacaran units in the Adelaide Geosyncline are significantly different from each other, which excludes blanket remagnetization of the units before Delamerian folding and therefore gives strong preference to their magnetization dating from close to the time of deposition. The late Cryogenian–Ediacaran–Cambrian apparent polar wander path for South Australia spans 150 Myr from ∼635 to 490 Ma and places Australia in low palaeolatitudes throughout the interval studied. The poles differ significantly from each other, suggesting Australia underwent continual drift during that time. Whereas the directional difference between the late Cryogenian Elatina Formation and early Ediacaran Nuccaleena Formation is mainly in inclination, for most other contiguous stratigraphic units the differences are mainly in declination with minor inclination differences, indicating Australia was rotating about a nearby Euler pole in low palaeolatitudes. The large and perhaps rapid polar shifts at 615–590 and 575–565 Ma in the Laurentian apparent polar wander path are not evident in the Ediacaran apparent polar wander path for Australia. Because true polar wander should be recorded globally, in the absence of evidence for any major stratigraphic break in the South Australian succession we conclude that large true polar wander did not occur during the Ediacaran.

Key words: Magnetostratigraphy; Palaeomagnetism applied to geologic processes.

1 INTRODUCTION

Adelaidean strata in South Australia (Preiss 1987, 1993) constitute one of the most complete Neoproterozoic successions in the world and encompass two of the most intriguing periods in geological history, the Cryogenian and the Ediacaran. The Cryogenian is marked by the Sturt glaciation at ≥659 Ma (Fanning & Link 2008; Preiss *et al.* 2009) and the Elatina glaciation at ≤635 Ma (Williams *et al.* 2008, 2009), both of which occurred in low palaeolatitudes (Embleton & Williams 1986; Schmidt *et al.* 1991; Schmidt & Williams 1995; Sohl *et al.* 1999; Schmidt *et al.* 2009). Both Cryogenian glacial successions are sharply overlain by marine 'cap carbonates' (Williams 1979; Kennedy 1996; Giddings & Wallace 2009; Schmidt *et al.* 2009). The Ediacaran contains a unique fauna, with large, soft-bodied organisms representing the oldest definitive animals (Jenkins 1992; Narbonne 2005) whose appearance preceded the Cambrian radiation. Late Adelaidean strata thus provide a rich record of climatic swings and the early evolution of animals.

Palaeolatitudinal changes recorded by late Cryogenian and Ediacaran strata are of particular relevance to understanding the environmental changes in South Australia and globally. Intriguingly, large and apparently rapid polar shifts have been identified in the Ediacaran record of Laurentia, whereby continents evidently moved from low to high palaeolatitudes at 615–590 Ma and back to low palaeolatitudes at 575–565 Ma. Palaeomagnetic results for the Sept-Îles complex, Québec (Tanczyk *et al.* 1987), exemplify the problem of interpreting polar motions of Laurentia during the Ediacaran (Kirschvink *et al.* 2005). Anorthosites of the Sept-Îles complex carry a high-temperature low-inclination component whereas consanguineous cross-cutting basic dykes are steeply magnetized. In another palaeomagnetic study of the Sept-Îles complex, Raub *et al.* (2009) confirmed the low-inclination component but cast doubt on the previously determined high-latitude pole from the basic dykes, suggesting it reflects viscous remagnetization. However, they isolated a 'moderately' high palaeolatitude component so the problem of large and rapid polar motion persists.

Mechanisms that have been considered to explain these large and rapid polar shifts include unrecognized breaks in deposition, magnetic excursions and non-dipole effects (Maloof *et al.* 2006). Additionally, Davidson *et al.* (2009) highlighted the possibility of misidentification of some dykes within differently aged though subparallel dyke swarms as a possible source of apparent rapid polar shifts. Nonetheless, the large and rapid polar shifts inferred from Laurentian records commonly have been interpreted in terms of true polar wander (TPW) (Evans & Kirschvink 1999; Raub & Evans 2004; Maloof *et al.* 2006).

McCausland *et al.* (2009a) stated, provocatively, that polar shifts during the Ediacaran of other continents also are ambiguous. Here we present results from late Cryogenian and Ediacaran strata in South Australia showing that substantial polar wandering occurred but that large TPW is not required to explain the observations.

2 CRYOGENIAN AND EDIACARAN STRATIGRAPHY AND GEOCHRONOLOGY

The stratigraphy of Cryogenian and Ediacaran strata in the central Flinders Ranges of South Australia is summarized in Fig. 1. The Ediacaran System and Period are named after the Ediacara Range immediately west of the Flinders Ranges, with the Golden Spike plaque marking the Global Stratotype Section and Point (GSSP) placed near the base of the Nuccaleena Formation in Enorama Creek in the central Flinders Ranges (Knoll *et al.* 2004; Preiss 2005;Knoll *et al.* 2006; Williams *et al.* 2008, 2009).

The terminal Cryogenian glaciogenic Elatina Formation is disconformably to unconformably overlain by the thin (commonly <10 m), transgressive Nuccaleena Formation cap carbonate at a basin-wide sequence boundary marking the base of the Ediacaran Wilpena Group (Preiss 2000; Williams *et al.* 2008, 2009). This sequence boundary may represent a break in deposition of several million years (Schmidt *et al.* 2009).

The succeeding formations of the Wilpena Group constitute two major upward-shallowing/coarsening cycles (Preiss 1987; Haines 1988; Haines 1990; Preiss 1993, 1999, 2000; Grey & Calver 2007). The lower cycle is up to 2200 m thick and commences with transition beds of mudstone and dolostone at the top of the Nuccaleena Formation that pass upwards to red brown and olive green siltstone and mudstone and local reddish sandstone of the Brachina Formation (500–1200 m), which accumulated in a marine-shelf setting. The Brachina Formation coarsens upwards to the deltaic and shallow-marine ABC Range Quartzite (>2000 m in the west, but mostly ∼500 m) at the top of the cycle. The Brachina intertongues with the ABC Range Quartzite, suggesting 'deltaic progradation from a westerly source into an eastward and northward-deepening basin' (Forbes & Preiss 1987, p. 225). The Bunyeroo Formation

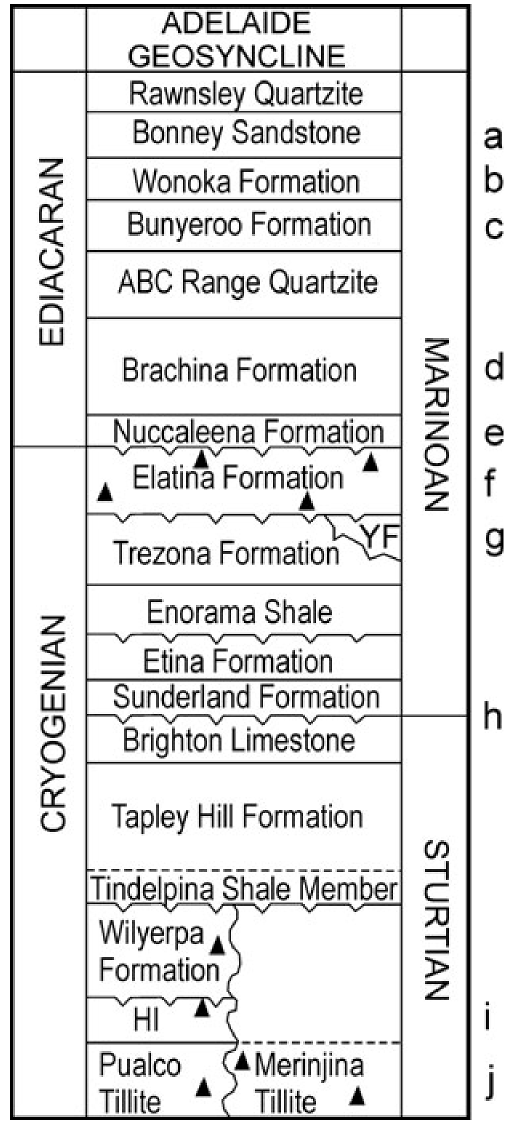

Figure 1. Generalized stratigraphy of Cryogenian and Ediacaran strata in the Adelaide Geosyncline (Central Flinders Zone), South Australia. Glaciogenic formations are shown with solid triangles. YF, Yaltipena Formation; HI, Holowilena Ironstone. Adapted from Preiss *et al.* (1998) and Williams *et al.* (2008). The letters indicate previous and pending palaeomagnetic studies: (a) Bonney Sandstone (Embleton & Giddings 1974; McWilliams & McElhinny 1980; Schmidt & Williams, in preparation); (b) Wonoka Formation <575 Ma (herein); (c) Bunyeroo Formation 593 ± 32 Ma (McWilliams & McElhinny 1980; Schmidt & Williams 1996); (d) Brachina Formation 609 ± 64 Ma (Karner 1974; McWilliams & McElhinny 1980; herein); (e) Nuccaleena Formation (Schmidt *et al.* 2009); (f) Elatina Formation ∼635(?) Ma (Embleton & Williams 1986; Schmidt *et al.* 1991; Schmidt & Williams 1995; Sohl *et al.* 1999; Schmidt *et al.* 2009); (g) Yaltipena Formation (Sohl *et al.* 1999); (h) Sunderland Formation/Angepena Formation (Schmidt & Williams in preparation); (i) Holowilena Ironstone (Schmidt & Williams in preparation) and (j) Merinjina Tillite (Schmidt & Williams in preparation).

(400–700 m) marks the marine transgression at the start of the second major upward-shallowing/coarsening cycle, with deposition of red and minor green mudstones below wave base in a low-energy marine-shelf environment. An impact ejecta horizon of shock-deformed felsic volcanic rocks related to the Acraman impact structure on the Gawler Craton occurs ∼80 m above the base of the Bunyeroo Formation (Williams & Gostin 2005). The regressive Wonoka Formation (∼500–700 m) is a storm-dominated grey, green, brown and reddish mixed carbonate/siliciclastic unit of middle- to inner-shelf origin (Haines 1988, 1990). The Wonoka Formation is conformably followed by the marginal-marine and estuarine Bonney Sandstone (255 m), and the mostly shallow-marine Rawnsley Quartzite (413 m) at the top of the Wilpena Group completes the second major cycle.

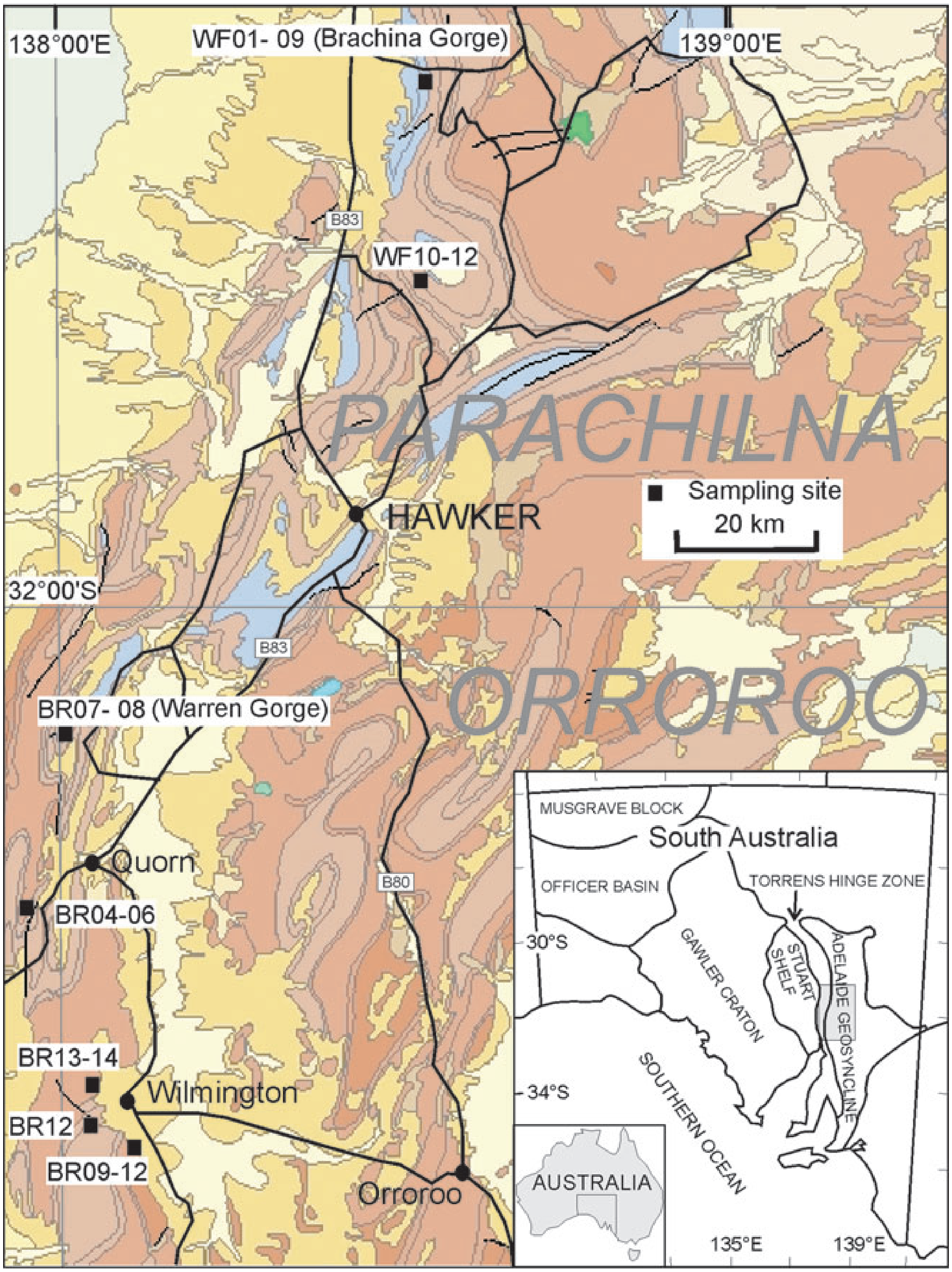

Figure 2. Locality map showing palaeomagnetic sampling sites in the Brachina and Wonoka formations, Flinders Ranges, South Australia. Site details are given in Appendix A. Background geological outline downloaded from Surface Geology of Australia 1:1 000 000 scale, South Australia © Commonwealth of Australia (Geoscience Australia) 2010 (released under the Creative Commons Attribution 2.5 Australia Licence). Parachilna and Orroroo 1:250 000 geological maps can be downloaded from http://www.geoscience.gov.au/bin/mapserv36?map=/public/http/www/geoportal/250/index.map&mode=browse&layer=map250&queryon=true. The inset shows the principal tectonic features of South Australia.

Cambrian deposits overlie the Wilpena Group with disconformity or very low-angle unconformity. The Neoproterozoic and Cambrian strata in the Adelaide Geosyncline were deformed during the early Palaeozoic (514–490 Ma) Delamerian Orogeny (Drexel & Preiss 1995; Foden *et al.* 2006).

A system of kilometre-deep canyons initiated in the Wonoka Formation cuts down through the Bunyeroo Formation, ABC Range Quartzite and into the Brachina Formation. The origin of the canyons is uncertain (von der Borch *et al.* 1989), with a submarine setting favoured by Giddings *et al.* (2010). During Wonoka deposition the Bunyeroo Formation and equivalents were exposed for 600 km along the cratonic platform (Stuart Shelf) at the eastern margin of the Gawler Craton west of the Adelaide Geosyncline (Fig. 2, inset) and subsequently were overlain unconformably by Cambrian strata, and extensional faulting in the Adelaide Geosyncline accompanied canyon incision (Williams & Gostin 2000; Foden *et al.* 2001). Correlative canyons were incised in the Officer Basin 600–700 km to the northwest, and the cratonic platform at the northwestern margin of the Gawler Craton also was exposed (Calver & Lindsay 1998; Williams & Gostin 2000). Late Ediacaran tectonism in Wonoka times evidently involved regional uplift of the Gawler Craton that exposed platforms on opposite margins of the craton and triggered canyon incision in bordering basins (Williams & Gostin 2000). However, no regional unconformity or disconformity has been observed within the Wonoka Formation in the Adelaide Geosyncline (Giddings *et al.* 2010) or at any other horizon within the Wilpena Group (Forbes & Preiss 1987; Preiss 1993), implying that no significant stratigraphic hiatus exists within the Ediacaran succession of the Adelaide Geosyncline.

Radiometric ages for late Neoproterozoic strata in South Australia are meagre. Fanning & Link (2008) obtained a U–Pb zircon age of ∼659 Ma for a tuff bed in the Sturtian Wilyerpa Formation, and Kendall *et al.* (2006) a Re–Os age of 643.0 ± 2.4 Ma for black shale from the Tindelpina Shale Member. A U–Pb age of 657 ± 17 Ma for a single zircon grain from the Marino Arkose Member of the interglacial Wilmington Formation (Ireland *et al.* 1998), a partial equivalent to the Enorama Shale, may record penecontemporaneous volcanism (Preiss 2000). Mahan *et al.* (2010) reported a Th–U–total Pb age of 680 ± 23 Ma for authigenic monazite from sandstone from the Enorama Shale. This diagenetic age for the Enorama Shale is compatible within errors with the age of 657 ± 17 Ma for the Wilmington Formation and possibly with the age of ∼659 Ma for the Wilyerpa Formation, but it conflicts with the age of 643 ± 2.4 Ma for the Tindelpina Shale Member.

The succeeding Elatina glaciation has yet to be dated directly. A U–Pb zircon age of 635 ± 1.2 Ma for volcanic rocks associated with the glaciogenic Ghaub Formation in Namibia was applied also to the Elatina glaciation (Hoffmann *et al.* 2004). Zhou *et al.* (2004) gave a maximum age of 663 ± 4 Ma and Condon *et al.* (2005) a minimum age of 635.2 ± 0.6 Ma for the Nantuo glaciation in China, which they equated with the Elatina glaciation. Zhang *et al.* (2008) reported a SHRIMP U–Pb zircon age of 636 ± 4.9 Ma for a tuff near the base of the Nantuo Formation. Kendall *et al.* (2006) noted that their age of 643 Ma for the Tindelpina Shale Member is essentially incompatible with an age of 635 Ma for the Elatina glaciation because together they require excessive rates of sedimentation for the >4 km interglacial succession in the central Flinders Ranges. Although it is unclear whether Cryogenian glaciations correlate worldwide (Allen & Etienne 2008), an age for the Elatina glaciation near 635 Ma seems favoured by available data although further work is required to corroborate this.

Ages for the Ediacaran succession in South Australia are limited to Rb–Sr whole-rock shale isochrons and ages for detrital grains. Compston *et al.* (1987) obtained a Rb–Sr isochron of 609 ± 64 Ma for the Brachina Formation and a Rb–Sr isochron of 593 ± 32 Ma for the Yarloo Shale, the equivalent to the Bunyeroo Formation on the Stuart Shelf. Chemostratigraphy suggested to Walter *et al.* (2000) that an age of ∼580 Ma for the Bunyeroo Formation may be a better estimate. Haines *et al.* (2004) provided 11 ^{40}Ar–^{39}Ar ages for detrital muscovite from the Bonney Sandstone, the youngest being 601 ± 17 Ma. A U–Pb age of 556 ± 24 Ma for a single zircon grain from the Bonney Sandstone (Ireland *et al.* 1998) possibly records penecontemporaneous volcanism and provides a maximum age for the overlying Rawnsley Quartzite (Preiss 2000).

The earliest Ediacaran biota in South Australia are found in the Wonoka Formation (Jenkins 1992) and the famous metazoan fossil assemblage occurs in the Ediacara Member near the base of the Rawnsley Quartzite (Preiss 1987, 2000). The oldest radiometrically dated Ediacaran fauna is the Avalon Assemblage in Newfoundland,

Table 1. Palaeomagnetic summary for the Brachina Formation.

Site	N	D_h (°)	I_h (°)	k_h	α_{95} (°)	D_b (°)	I_b (°)	k_b	α_{95} (°)
BR04	3	174.5	23.3	25.2	25.1	184.6	14.6	25.2	25.1
BR07a	15	333.9	5.8	11.5	11.8	355.0	26.3	12.6	11.2
BR07b	7	154.9	−11.3	12.4	17.8	186.1	−31.0	12.4	17.8
BR07c	13	339.7	−2.9	10.7	13.3	353.3	21.8	10.7	13.3
BR10	7	183.5	−7.8	15.3	15.9	178.3	−8.1	15.5	15.8
BR11	7	356.8	21.1	224	4.0	341.6	14.6	224	4.0
BR12a	11	177.4	−10.0	10.0	15.1	184.5	−28.0	9.94	15.2
BR12b	13	174.6	4.4	15.4	10.9	177.4	−21.3	14.9	11.1
BR12c	3	182.5	−5.4	6.78	51.6	188.7	−29.1	6.00	55.5
BR13	6	180.4	2.0	88.3	7.2	182.7	−21.8	88.3	7.2
BR14	6	178.1	−17.5	82.6	7.4	187.4	−38.5	82.6	7.4
Mean	$N = 91$	169.8	−5.0	11.1	4.7	178.2	−22.6	12.4	4.4

Notes: Mean Site $\lambda_s = 32.2°$S, $\varphi_s = 138.0°$E.
Dip corrected pole position: $\lambda_p = 46.0°$S, $\varphi_p = 315.4°$E, $dp = 2.4°$, $dm = 4.6°$. N, number of samples showing ChRM; α_{95}, half-angle of the 95 per cent confidence cone for the mean direction; D_h and I_h, *in situ* declination and inclination; D_b and I_b, declination and inclination with respect to bedding; k_h and k_b, precision parameter of Fisher (1953) distribution for mean directions *in situ* and with respect to bedding, respectively; dp, dm, semi-axes of error ellipse around the pole of probability of 95 per cent.

Canada, which is bracketed by U–Pb zircon ages of 575.4 ± 0.4 and 565 ± 3 Ma for volcanic ash beds (Narbonne 2005; Gehling 2007). This implies that the Wonoka Formation is <575 Ma. Volcanic ash interstratified with Ediacaran fossil-bearing shallow marine strata in the White Sea region of Russia yielded a U–Pb zircon age of 555 ± 0.3 Ma (Martin *et al.* 2000). The close comparison of taxa of the 'White Sea Association' and of the type Ediacaran in South Australia suggests they are coeval (Martin *et al.* 2000), which implies an age of ∼555 Ma for the Ediacara Member of the Rawnsley Quartzite.

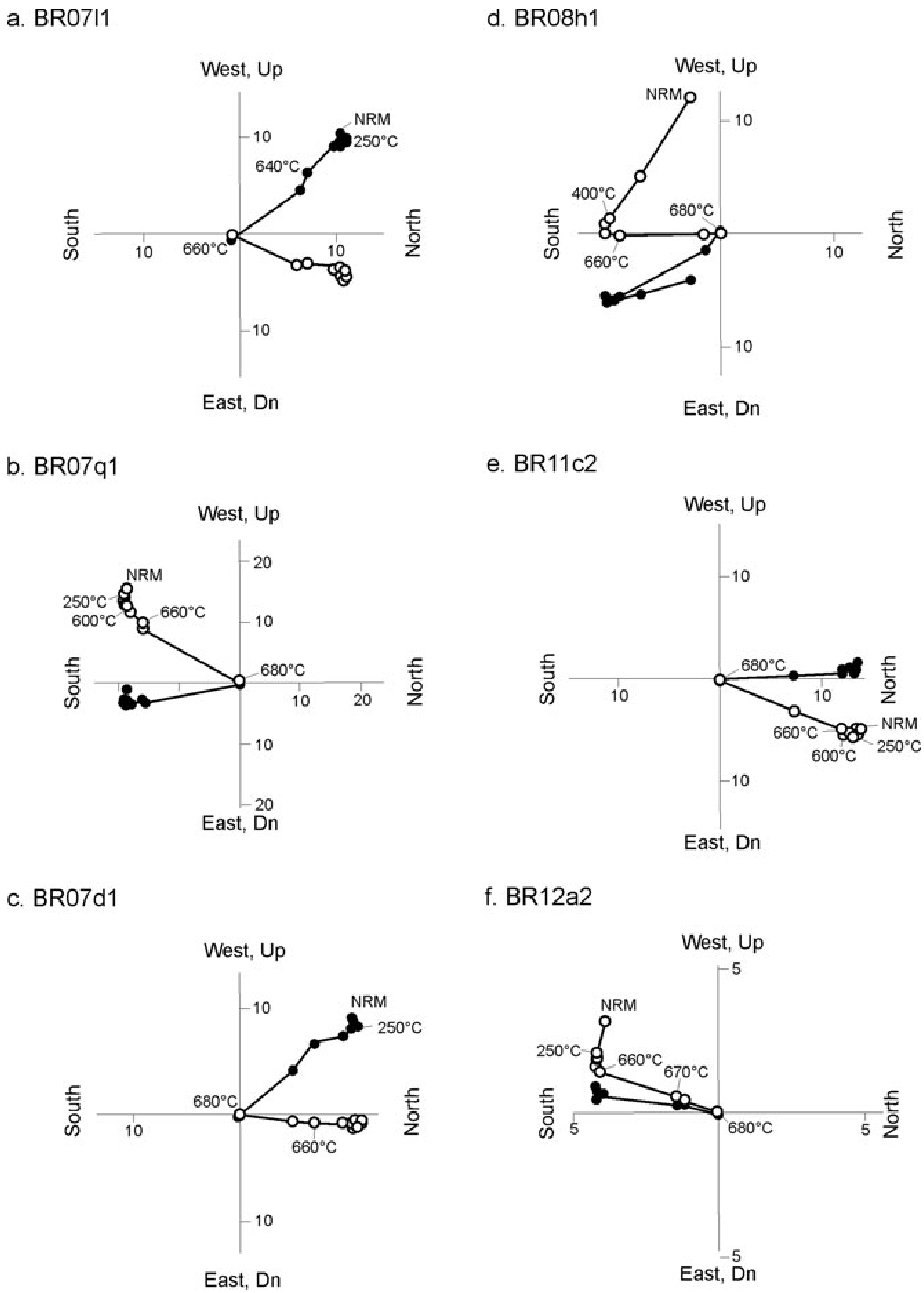

Figure 3. Orthogonal projections of remanence vectors for specimens from the Brachina Formation after stepwise thermal demagnetization. Solid circles plot on the horizontal plane and open circles on the vertical plane. Axes are m Am^{-1} (10^{-6} emu cc^{-1}), temperature in °C. See text for details.

3 PREVIOUS PALAEOMAGNETIC STUDIES

Fig. 1 indicates the various palaeomagnetic studies that have been conducted and are pending on Cryogenian and Ediacaran strata in South Australia. Previous studies of the Ediacaran succession are summarized here.

Embleton & Giddings (1974) studied the lower red sandstone of the Pound Quartzite, now termed the Bonney Sandstone. After some pilot thermal demagnetization, specimens from 38 samples were 'bulk cleaned' at 590 °C. However, the directions for 33 specimens from within those samples were random at the 0.05 probability level. The remaining five samples, plus some hand-picked directions from specimens of the 33 randomly directed samples, yielded 10 'cleaned' sample-means that nevertheless gave an indeterminate fold test. In a new study, McWilliams & McElhinny (1980, p. 18) found that both within-site and within-sample directions from the Bonney Sandstone were random at the 0.05 probability level and observed 'no systematic grouping of specimen direction'. This accords with our own findings from 99 block samples collected from 33 sites in the Bonney Sandstone from Brachina Gorge in 2006. Natural remanent magnetization (NRM) directions were highly scattered and, apart from a bias towards the local present field direction, showed no obvious clusters. After thermal demagnetization of two specimens per block, some directions moved away from the present field direction but overall they remained highly scattered. The coarser grain of the Bonney Sandstone, compared with other fine-grained units from which high-quality palaeomagnetic results have been obtained, may have allowed fluids to circulate during orogeny or weathering and may explain the poor results. All Bonney Sandstone results to date are therefore discarded.

McWilliams (1977) and McWilliams & McElhinny (1980) reported on the first systematic palaeomagnetic study of the Neoproterozoic succession in South Australia. They showed that the characteristic sigmoidal structural trends in the Adelaide Geosyncline reflect the original form of the basin and that the glacial strata were deposited in low palaeolatitudes. Although their study was necessarily of a reconnaissance nature and sampling was not focused on field tests (e.g. fold test, reversal test), their results greatly refined and clarified the Neoproterozoic apparent polar wander path (APWP) of Australia. Bulk treatment at 540°C for 24 specimens from eight sites in the Brachina Formation yielded a structurally corrected mean direction of declination $D = 189°$, inclination $I = –44°$ ($\alpha_{95} = 16°$), with a pole at latitude $\lambda_p = 33°$S, longitude $\varphi_p = 328°$E (confidence semi-axes d$p = 12°$ and d$m = 20°$).

Karner (1974) studied the Brachina Formation at Hallett Cove south of Adelaide, where it shows tight folding and strong cleavage. From 44 samples demagnetized at 450°C he obtained a mean direction of $D = 205°$, $I = –5°$ ($\alpha_{95} = 10°$), and gave a pole (his table 10) at latitude $\lambda_p = 46°$S, longitude $\varphi_p = 356°$E (d$p = 5°$ and d$m = 10°$; these errors are recalculated by us to comply with the stated α_{95}). McWilliams & McElhinny (1980, their table 2) listed Karner's pole as latitude $\lambda_p = 45°$S, longitude $\varphi_p = 334°$E, (d$p = 4°$ and d$m = 7°$), similar to their own result, but it appears to be a typographical error. Whereas McWilliams & McElhinny (1980) and Karner (1974) both claim a positive fold test (McElhinny 1964) on their cleaned directions, their mean directions are significantly different, prompting our study to resolve this conflict and perform a more rigorous fold test (McFadden 1990).

McWilliams & McElhinny (1980) reported results for the Bunyeroo Formation that showed an increase in precision by a factor of 1.65 after unfolding, which is not significant at the 0.05 probability level. To determine a definitive fold test, and to compare results for the Bunyeroo Formation—and by implication the Acraman impact ejecta horizon—with results for Acraman melt rock, Schmidt & Williams (1996) provided the result for the Bunyeroo Formation listed in Table 3. The fold test from their Bunyeroo result is positive at the 99 per cent level of confidence and the (instantaneous) direction for the Acraman melt rock is not significantly different from the Bunyeroo cluster.

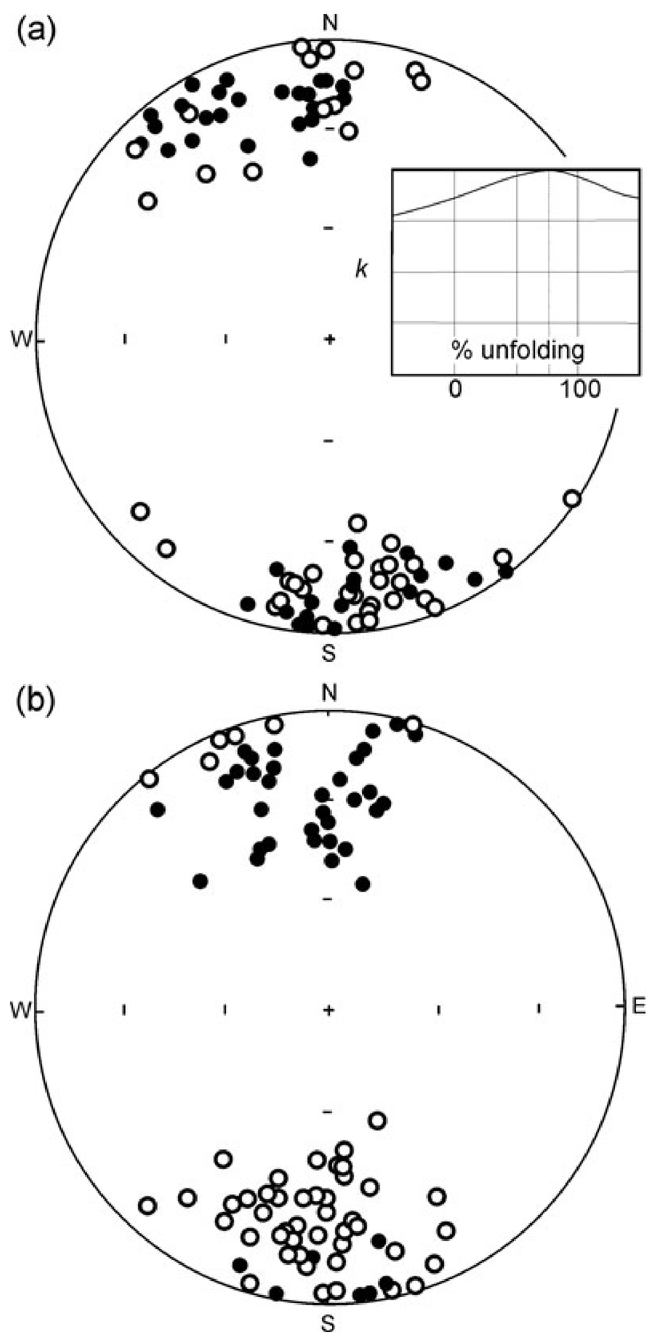

Figure 4. Stereographic projections of characteristic remanent magnetization (ChRM) directions for the Brachina Formation isolated by stepwise thermal demagnetization. Solid circles plot on the lower hemisphere and open circles on the upper hemisphere: (a) present-day coordinates and (b) after structural correction. The tighter cluster of the latter reflects a positive fold test at 99 per cent confidence and indicates that the magnetization was acquired prior to the early Palaeozoic Delamerian Orogeny. The inset shows the precision parameter, k, increase on unfolding.

Results of a palaeomagnetic and rock magnetic study of the Nuccaleena Formation, undertaken to determine palaeolatitude but also to investigate possible compaction-related inclination shallowing (Schmidt *et al.* 2009), are listed in Table 3. A fold test was positive at the 99 per cent level of confidence. Through a study of the anisotropy of saturation isothermal remanent magnetization and application of the inclination–elongation method of Tauxe & Kent (2004), it was found that although some inclination shallowing is probable, because the inclinations are genuinely low the corrections are small.

No previous palaeomagnetic study has been reported for the Wonoka Formation.

4 NEW PALAEOMAGNETIC DATA

4.1 Sampling sites

A portable rock drill was used to take 2.2-cm diameter cores from most sites and sections, although block samples were collected from National Parks and where water for drilling was unavailable. Strata at sites typically have moderate dips and cleavage is absent. Site details are given in Appendix A.

The Brachina Formation was sampled at 14 sites (Fig. 2), which included traverses across two stratigraphic sections 200 and 400 m thick (sites BF07–08 and BF12, respectively). These traverses enabled construction of magnetostratigraphic columns. The Wonoka Formation was sampled at 12 sites (Fig. 2), the first nine of which spanned a stratigraphic section 500 m thick that allowed a magnetostratigraphic column to be constructed (sites WF01–09). Altogether, 82 core and block samples were collected from the Brachina Formation and 36 block samples from the Wonoka Formation.

4.2 Laboratory techniques

Between three and nine specimens 2.2 cm high × 2.5 cm in diameter were machined from the cores and block samples, and at least two specimens per block were processed. Routine palaeomagnetic laboratory methods (Collinson 1983; Butler 1992) were employed. Remanent magnetization was measured using 2G 755R three-axis cryogenic magnetometers at the University of Western Australia and at CSIRO, North Ryde, NSW. The demagnetizers used were in-line 2G 600 series alternating field (AF) demagnetizers and Magnetic Measurements MMTD80 shielded furnaces. All specimens were subjected to stepwise thermal demagnetization with 10–15 steps.

Magnetization components were isolated using an interactive version of Linefind (Kent *et al.* 1983), in which linear segments are fitted to data points weighted according to the inverse of their measured variances. The highest temperature to which any particular component remains stable, that is, the highest unblocking temperature observed, was generally taken as an indication of the Curie temperature of the mineral carrying that component.

4.3 Results for the Brachina Formation

Our results for the Brachina Formation are summarized in Table 1, while Fig. 3 shows orthogonal projections of NRM and after thermal demagnetization up to 680 °C. Generally the structure is simple, with what appears to be a viscous component eliminated after 250–300 °C, leaving a well-defined characteristic component that decays to the origin.

Directions before and after structural correction are shown in Fig. 4. The observation of mixed polarities within some specimens agrees with chemical remanent magnetization (CRM) acquired over a protracted interval of time, and in such circumstances it is appropriate to employ specimen directions, rather than site directions, to provide an overall formation mean direction (Schmidt & Williams 1995). The structurally corrected mean direction for $N = 91$ specimens is $D = 178.2°$, $I = –22.6°$ ($\alpha_{95} = 4.4°$), indicating a palaeolatitude $\lambda = 11.8 \pm 2.5°$ and a pole position at latitude $\lambda_p = 46.0°$S, longitude $\varphi_p = 315.4°$E ($dp = 2.4°$ and $dm = 4.6°$).

A fold test (McFadden 1990) is positive with the correlation statistic decreasing from $\xi_2 = 39.6$ to $\xi_2 = 7.15$ on unfolding (*cf*. 0.05 and 0.01 significance points for $N = 91$ of 11.1 and 15.7, respectively). The fold test therefore is positive at 99 per cent confidence and indicates that the magnetization was acquired prior to the early Palaeozoic Delamerian Orogeny.

A reversal test (McFadden & McElhinny 1990) has been applied to the Brachina Formation directions after ascertaining that the normal and reverse groups share a common kappa. The reverse and normal kappas have a ratio of 1.1, which is exceeded at $p = 0.32$,

Table 2. Palaeomagnetic summary for the Wonoka Formation.

Site	N	D_h (°)	I_h (°)	k_h	α_{95} (°)	D_b (°)	I_b (°)	k_b	α_{95} (°)
WF01	6	245.5	6.4	8.33	24.7	243.5	−18.1	8.33	24.7
WF02	6	258.2	29.3	38.7	10.9	261.1	−0.8	38.7	10.9
WF03	6	269.0	5.5	3.07	46.0	268.3	−24.2	3.07	46.0
WF04	6	270.3	2.4	9.58	22.8	270.7	−28.5	9.58	22.8
WF05	6	270.4	4.7	30.6	12.3	266.9	−28.2	30.6	12.3
WF06	6	267.1	−12.3	50.6	9.5	266.1	−42.2	50.6	9.5
WF07	6	252.0	2.2	40.7	10.6	249.6	−24.4	40.7	10.6
WF08	6	270.3	1.5	8.19	24.9	269.7	−25.4	8.19	24.9
WF09	6	235.6	20.1	8.17	24.9	238.3	−4.6	8.17	24.9
WF10	5	261.5	−69.7	7.00	31.1	246.7	−31.1	7.00	31.1
WF11	5	113.6	−77.4	6.57	32.3	227.0	−42.2	7.07	30.9
WF12	6	264.5	−62.2	60.0	8.7	255.3	−13.2	60.0	8.7
Mean	$N = 70$	259.7	−9.1	3.70	10.3	255.9	−23.7	8.10	6.4

Notes: Mean Site for WF01–09: $\lambda_s = 31.3°$S, $\varphi_s = 138.6°$E; Mean Site for WF10–11: $\lambda_s = 31.6°$S, $\varphi_s = 138.5°$E.
Dip corrected pole position: $\lambda_p = 5.2°$S, $\varphi_p = 30.5°$E, $dp = 3.6°$, $dm = 6.8°$.
See Table 1 for explanation of column headings.

that is, $p >> 0.05$, so the hypothesis of a shared kappa is accepted. The shared kappa is estimated as 13.012. For $N = 91$ and kappa = 13.012, the critical angle ($p = 0.05$) between the normal and reverse axes, γ_c, is 8.6°. The observed angle, γ_o, is 11.7°, which is greater than γ_c and corresponds to a $p = 0.044$. The reversal test is therefore marginally negative. It is possible that the assumption of circular symmetry is strictly invalid (see Tauxe & Kent 2004), which may cause the reversal test to break down in marginal cases.

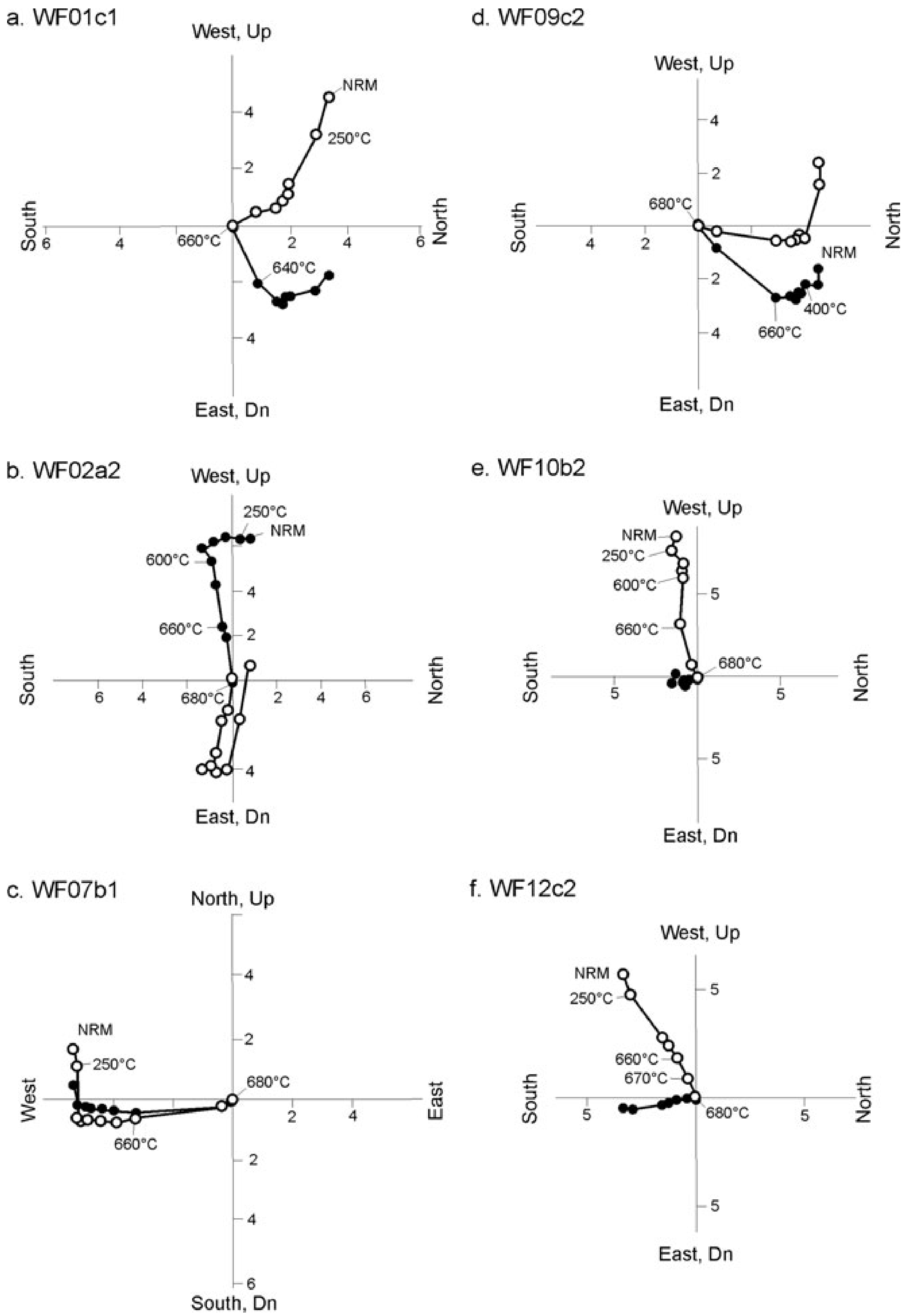

Figure 5. Orthogonal projections of remanence vectors for specimens from the Wonoka Formation after stepwise thermal demagnetization. Solid circles plot on the horizontal plane and open circles on the vertical plane. Axes are m Am^{-1} (10^{-6} emu cc^{-1}), temperature in °C. See text for details.

4.4 Results for the Wonoka Formation

Results for the Wonoka Formation are given in Table 2, while Fig. 5 shows orthogonal projections of end points of NRM and after thermal demagnetization up to 680 °C. As we found for the Brachina Formation, the magnetic structure is simple, with what appears to be a viscous component eliminated after 250–300 °C, leaving a well-defined characteristic component that decays to the origin.

Directions before and after structural correction are shown in Fig. 6. The structurally corrected mean direction for $N = 70$ specimens is $D = 255.9°$, $I = –23.7°$ ($\alpha_{95} = 6.4°$), indicating a palaeolatitude $\lambda = 12.3$ +3.8/–3.4° and a pole position at latitude $\lambda_p = 5.2°$S, longitude $\varphi_p = 30.5°$E ($dp = 3.6°$ and $dm = 6.8°$).

A fold test (McFadden 1990) is positive with the correlation statistic decreasing from $\xi_1 = 39.4$ to $\xi_1 = 0.43$ on unfolding (*cf*. 0.05 and 0.01 significance points for $N = 70$ of 9.73 and 13.8, respectively). The fold test therefore is positive at 99 per cent confidence and indicates that the magnetization was acquired prior to the Delamerian Orogeny.

A reversal test (McFadden & McElhinny 1990) has been applied to the Wonoka Formation directions after ascertaining that the normal and reverse groups share a common kappa. The reverse and normal kappas have a ratio of 1.3, which is exceeded at $p = 0.17$, that is, $p >> 0.05$, so the hypothesis of a shared kappa is accepted. The shared kappa is estimated as 9.4257. For $N = 70$ and kappa = 9.4257, the critical angle ($p = 0.05$) between the normal and reverse axes, γ_c, is 15.2°. The observed angle, γ_o, is 30.9°, which is much greater than γ_c. We note that only 13 of the 70 directions are easterly, so compared to the westerly group the easterly group is undersampled and may appear biased.

4.5 Magnetostratigraphy of the Brachina and Wonoka formations

Two traverses each spanning most of the exposed section of the Brachina Formation were sampled at sites BR07–08 (Warren Gorge) and site BR12 80 km to the northeast across Hancocks Lookout Road near Wilmington (Fig. 2). The Warren Gorge section spans about 200 m and the section at Hancocks Lookout Road about 400 m. The changes of cleaned directions with stratigraphic height are plotted in Fig. 7. The directions fall into two groups; because of low inclinations only the declinations are shown with groupings around 0° and 180°. The lower parts of both sections show several polarity transitions that may be correlative. However, the upper halves of the sections have little in common, suggesting that most of the upper parts at these localities were magnetized at different times, between which the geomagnetic field changed polarity. The CRM probably does not date from the time of deposition but rather is diagenetic in nature and became blocked at some time after deposition. Also, it is possible that these sections were deposited at different times through diachronous deposition on a prograding deltaic complex.

The change of direction with stratigraphic height through the 500-m thick section of the Wonoka Formation exposed at sites WF01–09 is shown in Fig. 8. The other sites sampled in this formation (sites WF10–12) span only a short section, being sampled more for the execution of a fold test than for magnetostratigraphy. It is noteworthy that for a stratigraphic interval of ~300 m the Wonoka Formation shows a single magnetic polarity, with a declination centred near 230°.

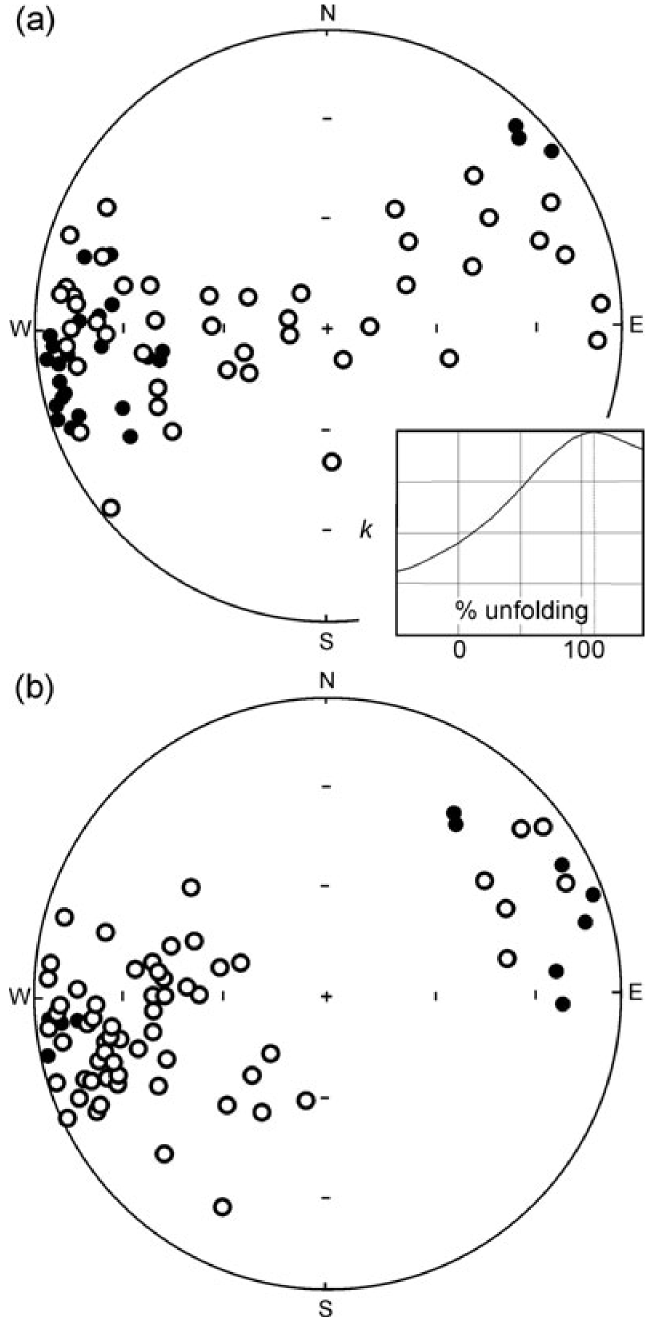

Figure 6. Stereographic projections of ChRM directions for the Wonoka Formation isolated by stepwise thermal demagnetization. Solid circles plot on the lower hemisphere and open circles on the upper hemisphere: (a) present-day coordinates and (b) after structural correction. The tighter cluster of the latter reflects a fold test at 99 per cent confidence and indicates that the magnetization was acquired prior to the early Palaeozoic Delamerian Orogeny. The inset shows the precision parameter, *k*, increase on unfolding.

Magnetostratigraphic studies of late Neoproterozoic formations in the Adelaide Geosyncline (Sohl *et al.* 1999; Schmidt *et al.* 2009; herein) have shed little light on the precise timing of polarity transitions with respect to the time of deposition. Schmidt *et al.* (2009) concluded that the remanent magnetization of the Nuccaleena Formation was largely diagenetic, being acquired at a similar time to the formation of tepee-like structures in those carbonates. We speculate that the blocking of remanence in the red beds studied here

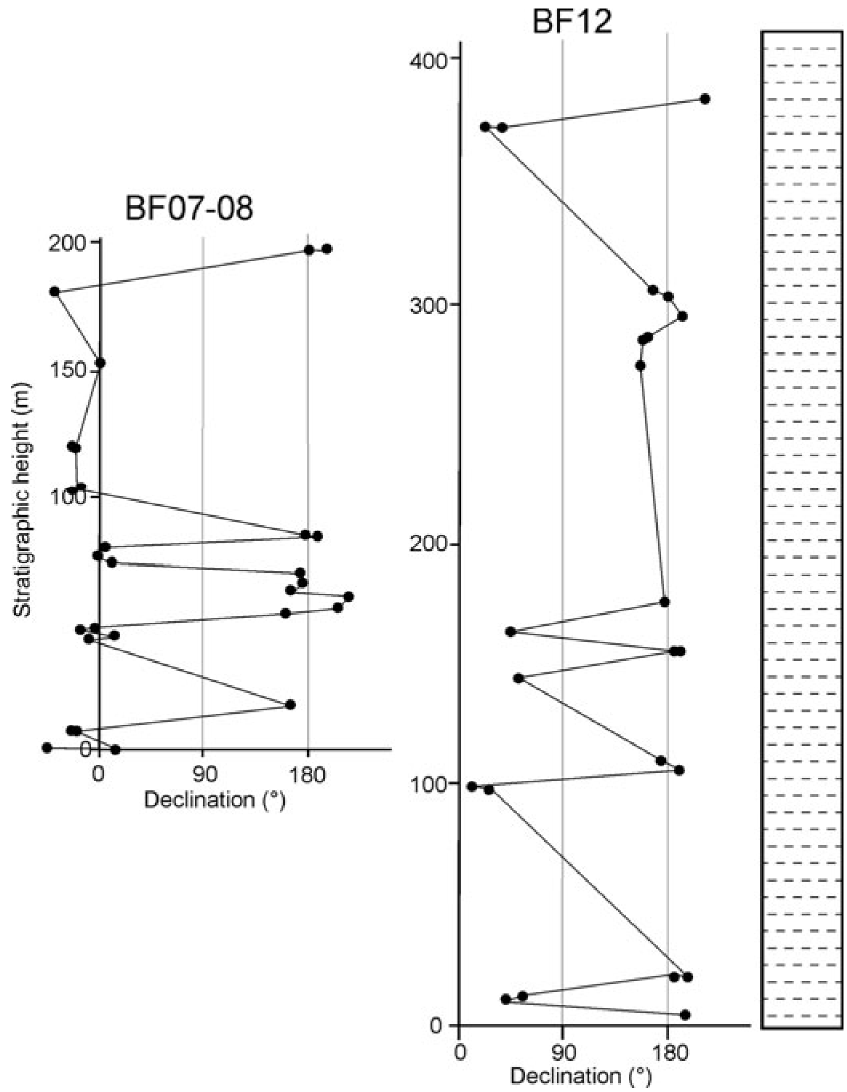

Figure 7. Magnetostratigraphy for sites BF07–08 and BF12 in the Brachina Formation. Because of low inclinations only the declination change with stratigraphic height is shown. The lithology of these two sections is red brown and minor olive green, thinly bedded siltstone (Plummer 1978; Preiss 1999).

also is diagenetic and concur with Schmidt *et al.* (2009, p. 35) that 'magnetisation therefore variably lags deposition, causing . . . magnetostratigraphic horizons to appear highly bedding-transgressive'. The usefulness of magnetostratigraphy for global correlations of Ediacaran strata is yet to be demonstrated.

5 DISCUSSION

5.1 Comparison of Brachina palaeomagnetic results with earlier results

Our Brachina Formation result (Table 1) and that of McWilliams & McElhinny (1980) are statistically significantly different. Because we give unit weight to specimens and McWilliams & McElhinny (1980) gave unit weight to sites, we have performed the comparison using results both for specimens and sites.

The 11 Brachina sites listed in Table 1 yield a mean site direction of $D = 179.7°$, $I = –20.9°$ ($k = 26.0$), whereas the mean direction given by McWilliams & McElhinny (1980) for eight sites is $D = 189°$, $I = –44°$ ($k = 13.4$). Using the relationships of McFadden & Lowes (1981, their eq. 25), the statistic to test whether these means have been drawn from the same population is $G = 7.32$, which is greater than the 0.05 significance point for the $F_{2,34} = 3.27$, indicating that for $p = 0.05$ the mean directions are significantly different.

Recalculating the mean results listed by McWilliams (1977, his table 2.8), the sample mean result for 24 samples is $D = 187.5°$, $I = –43.0°$ ($k = 5.754$). Using this result and our sample mean result (Table 1), the statistic to test whether these means have been drawn from the same population is $G = 11.6$, which is much greater than $F_{2,226} = 3.03$, again indicating that for $p = 0.05$ the mean directions are significantly different.

Comparing the mean direction of Karner (1974) from 44 samples, namely, $D = 205°$, $I = –5°$ ($k = 5.6$), with our sample mean result (Table 1) yields $G = 32.8$, which is very much greater than the 0.05 significance point for the $F_{2,226} = 3.04$, indicating that for $p = 0.05$ these mean directions also are significantly different.

The result for the Brachina Formation given in Table 3 supersedes previous results because the earlier studies employed 'bulk' cleaning and the results are significantly different from those presented herein.

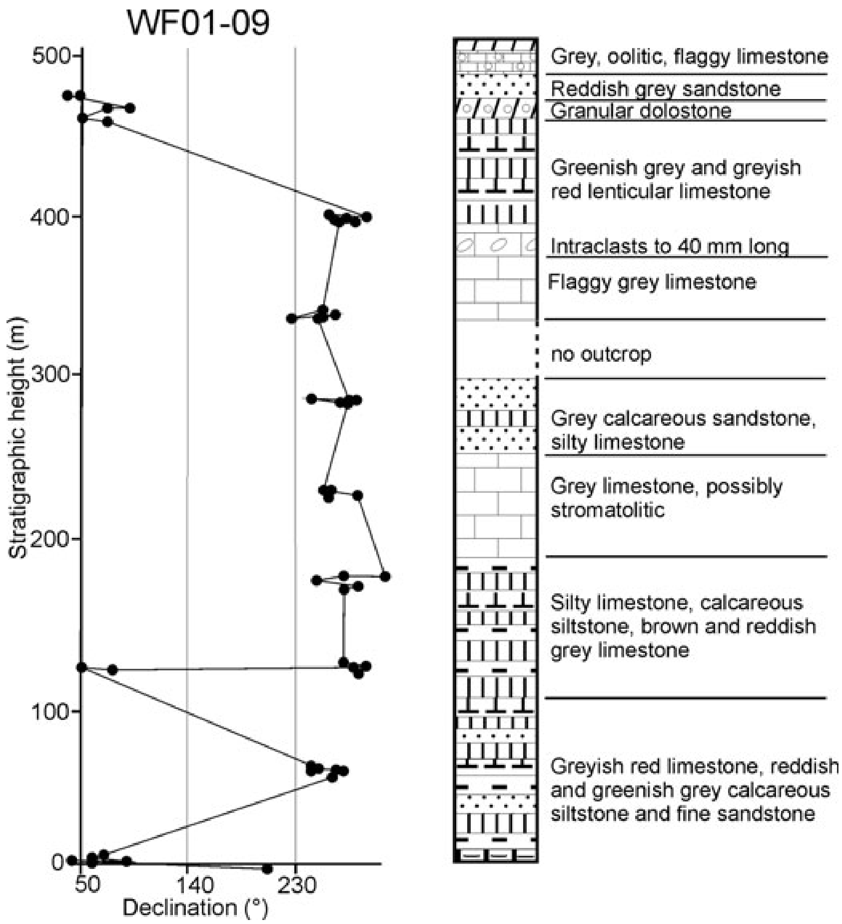

Figure 8. Magnetostratigraphy for sites WF01–09 in the Wonoka Formation. Changes in declination are plotted against stratigraphic height. Lithology after Forbes & Preiss (1987, fig. 86).

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/Group	Age (Ma)	Dec (°)	Inc (°)	α_{95} (°)	λ_p (°)	φ_p (°)	*dp* (°)	*dm* (°)	1	2	3	4	5	6	7	Q	Ref.
11 Black Hill Norite	487 ± 5	231.1	19.7	3.8	−37.5	34.4	3.0	6.0	√	√	√	√	√	×	√	6	a
10 Lower L. Frome Gp	~510	232.3	−0.5	10.1	−31.4	26.9	5.1	10.1	√	√	√	×	√	√	√	6	b
9 Kangaroo Is red beds	~515	224.5	−4.4	12.3	−33.8	15.1	6.2	12.3	√	√	√	×	√	√	√	6	b
8 Billy Creek Fm	~515	224.1	−1.2	14.4	−37.4	20.1	7.2	14.4	√	√	√	×	√	√	√	6	b
7 Hawker Group	530 − 515	233.4	−27.8	11.4	−21.3	14.9	6.8	12.5	√	√	√	×	√	√	√	6	b
6 Wonoka Fm	~560?	255.9	−23.7	6.4	−5.2	30.5	3.6	6.8	×	√	√	√	√	√	√	6	herein
5 Bunyeroo Fm	593 ± 32	236.6	−29.3	10.7	−18.1	16.3	6.5	11.8	×	√	√	√	√	√	×	5	c
4 Brachina Fm	609 ± 64	178.2	−22.6	4.4	−46.0	315.4	2.4	4.6	×	√	√	√	√	√	√	6	herein
3 Nuccaleena Fm		208.3	−34.9	3.4	−32.3	350.8	2.2	3.9	×	√	√	√	√	√	√	6	d
2 Elatina Fm	~635?	208.3	−12.9	4.2	−43.7	359.3	2.1	4.2	×	√	√	√	√	√	√	6	d
1 Yaltipena Fm		204.0	−16.4	11.0	−44.2	352.7	5.9	11.4	×	√	√	√	√	√	√	6	e

Notes: **1** to **11**: formations corresponding to poles in Fig. 9. Q, 1–7: Reliability criteria of Van der Voo (1990). (a) Schmidt *et al.* (1993); (b) Klootwijk (1980); (c) Schmidt & Williams (1996); (d) Schmidt *et al.* (2009); (e) Sohl *et al.* (1999). Ages of Cambrian units based on Gravestock (1995) and Gradstein *et al.* (2006). See Table 1 for explanations of other symbols.

5.2 Comparison of the Ediacaran APWPs for Australia and Laurentia

Palaeomagnetic results for late Cryogenian to post-Delamerian formations from the Adelaide Geosyncline have been filtered using the quality factor Q of Van der Voo (1990). The pole positions rating at five or more criteria out of a possible seven are listed in Table 3 and plotted in Fig. 9. The poles are statistically different and because they are stratigraphically constrained and each passes a McFadden (1990) fold test, they are therefore best visualized as an APWP. In fact, the poles form two APWP segments: one from the late Cryogenian Yaltipena Formation and Elatina Formation to the early Ediacaran to the Wonoka Formation; the second from the Early Cambrian Hawker Group to the post-Delamerian Black Hill Norite.

The systematic pole paths of both these segments lend confidence to their validity. The steady shift from the Yaltipena pole and

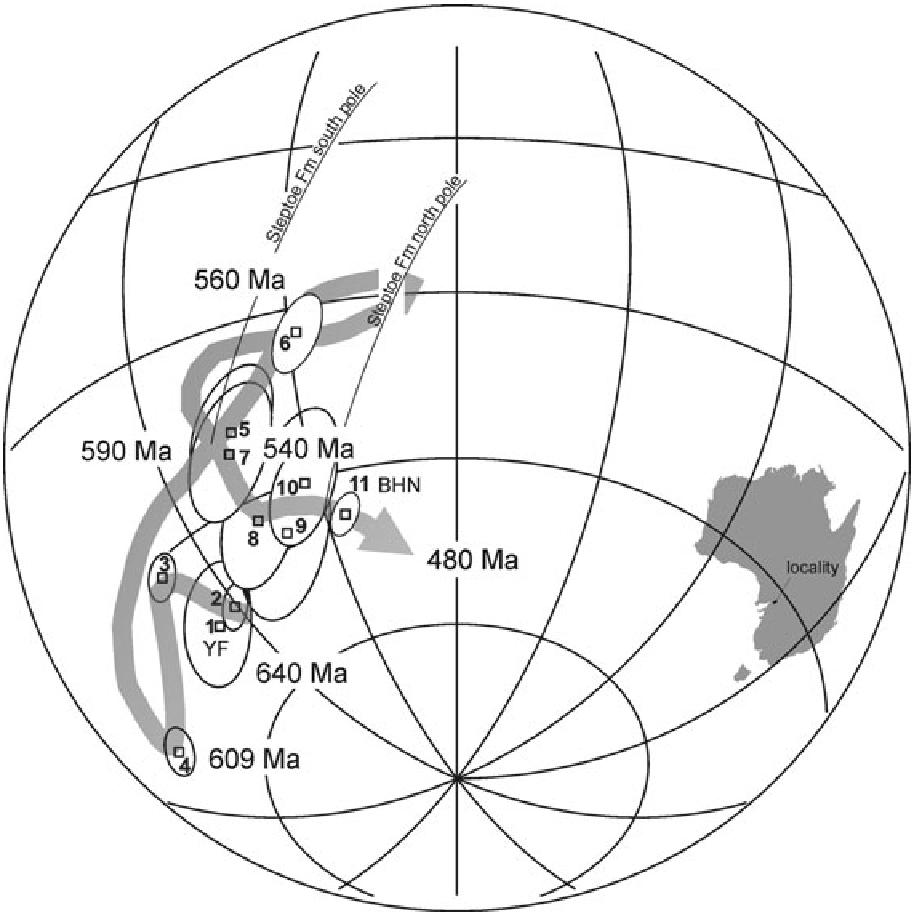

Figure 9. Apparent polar wander path for late Cryogenian, Ediacaran and Cambrian formations of the Adelaide Geosyncline. The numbers refer to the formations listed in stratigraphic order in Table 3 (1 oldest to 11 youngest). For reference to Table 3: YF, Yaltipena Formation; BHN, Black Hill Norite. Steptoe Fm from Pisarevsky *et al.* (2001a).

nearby Elatina pole, through the Nuccaleena pole to the Brachina pole, thence to the Bunyeroo pole and further away to the Wonoka pole, seems to reflect a continual change in both palaeolatitude and azimuthal orientation. The younger, Cambrian path shows a decrease of palaeolatitude after the Hawker Group, crossing the palaeoequator into the other hemisphere by post-Delamerian (Early Ordovician) times marked by the pole from the post-orogenic Black Hill Norite (487 ± 5 Ma; Schmidt *et al.* 1993). How the late Ediacaran path links in detail to the Cambrian path is, however, unclear. Attempts to determine high-quality pole positions for the uppermost Ediacaran formations (Bonney Sandstone and Rawnsley Quartzite; Fig. 1) have failed thus far (Embleton & Giddings 1974; McWilliams & McElhinny 1980). Fig. 9 also shows loci for north and south palaeopole alternatives for the inclination-only data from the Steptoe Formation of the Officer Basin (Pisarevsky *et al.* 2001a). When declinations are unavailable, such as for (azimuthally) unoriented drill core, alternative loci are indicated depending on the polarity chosen. For low-inclination data the ambiguity is marked and in the case shown in Fig. 9 it is not possible to determine which locus is correct.

It is instructive to compare the APWP for Australia from late Cryogenian to Ediacaran to Late Cambrian with poles for similarly aged units from Laurentia (McCausland *et al.* 2007). The APWP for Laurentia (Fig. 10) shows that landmass in high palaeolatitudes at 590–575 Ma, moving to low palaeolatitudes during the late Ediacaran and remaining in low palaeolatitudes throughout the Cambrian. Although these high-palaeolatitude poles have been interpreted to derive from magnetic overprints (Pisarevsky *et al.* 2001b; Hodych *et al.* 2004), they are dissimilar to any younger poles. There seems little doubt that by the late Ediacaran Laurentia had reached low palaeolatitudes and the signature of the later Ediacaran in Laurentia is one of shallowing magnetic inclinations and decreasing palaeolatitudes.

Overlaying the Ediacaran APWP for Australia on the Laurentian APWP permits some generalizations. Fig. 11 shows an arrangement whereby the ∼610 Ma Brachina Formation pole is brought into proximity to the 615 Ma segment of the Laurentian APWP defined by the Long Range Dyke pole (essentially confirmed by McCausland *et al.* 2009b), while the Australian Ediacaran APWP is aligned with the Laurentian path younging from 615 Ma. The Euler pole used is at latitude $\lambda_e = 0.4°$, longitude $\varphi_e = 312.3°$ and angle $\omega_e = 117.7°$. It should be recognized that the 'reconstruction' shown in the inset of Fig. 11 would only have existed fleetingly, because Australia and Laurentia were drifting with respect to each other.

The reason for bringing these APWPs together was to visually assess whether the paths reflect any TPW, which would be common to both paths. The paths plotted in Fig. 11 do not appear to show any coherent polar motion. Whereas the Brachina and Long Range Dykes poles are in close proximity by design, the Wonoka pole plots close to the 590 Ma Grenville B pole. However, the Wonoka Formation is thought to be <575 Ma and probably near 560 Ma.

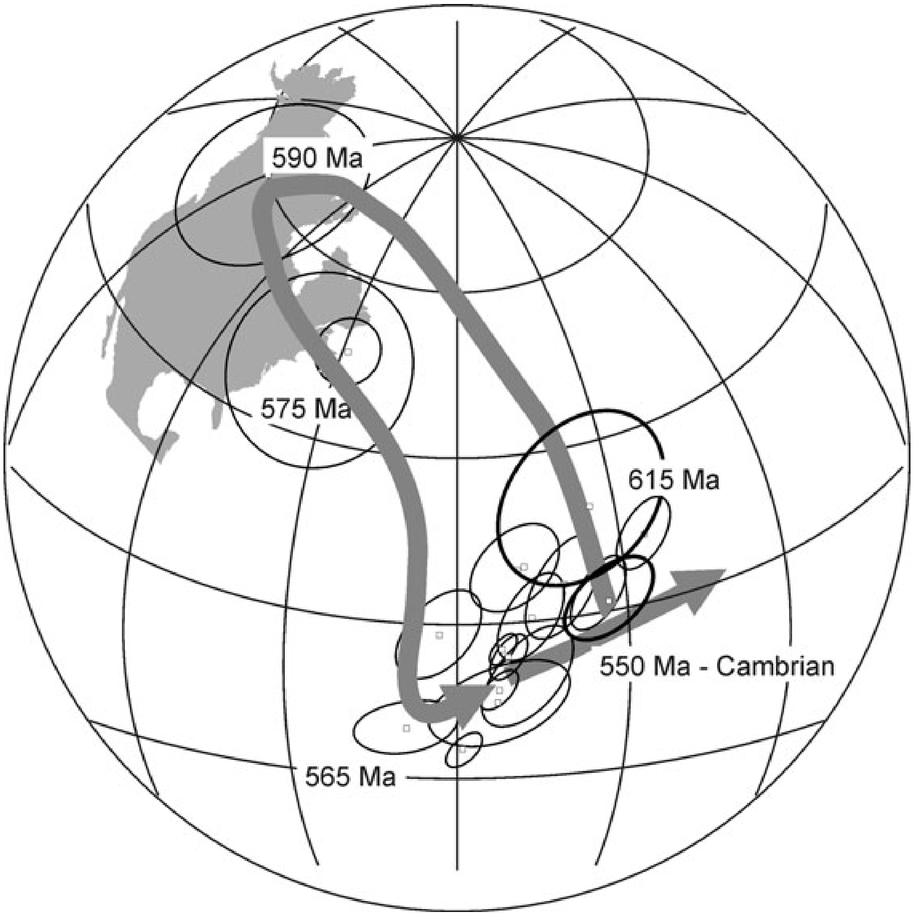

Figure 10. Apparent polar wander path for the Ediacaran to Cambrian of Laurentia (after McCausland *et al.* 2007). The heavy ovals (615 Ma) are for the Long Range Dykes (McCausland *et al.* 2009b), the 590 Ma pole is for the Grenville B Dykes (Murthy 1971; Buchan *et al.* 2004), the two poles near 575 Ma are for the Callander Complex (Simons & Chiasson 1991) and the Catoctin Basalts (Meert *et al.* 1994), and the pole near 565 Ma is for the Sept-Îles Complex (A pole; Tanczyk *et al.* 1987).

To place the Wonoka pole closer to the 564 Ma Sept-Îles pole for Laurentia would bring Australia and Laurentia into close proximity (notwithstanding the indeterminacy of longitude), but this would do little to weaken the conclusion that the Australian Ediacaran does not exhibit the large TPW that the Laurentian APWP is thought to show (Kirschvink *et al.* 2005; McCausland *et al.* 2007).

6 CONCLUSIONS

The late Cryogenian–Ediacaran–Cambrian APWP for Australia has been developed through many individual studies of formations in the Adelaide Geosyncline over the past three decades. The APWP places Australia in low palaeolatitudes throughout the entire interval, close to 150 Myr from 635 to 490 Ma. Almost all palaeomagnetic poles for these rocks are significantly different from each other, suggesting Australia underwent continual drift. The directional difference between the Elatina and Nuccaleena formations is mainly in inclination, whereas for most other contiguous stratigraphic units (e.g. Nuccaleena/Brachina, Bunyeroo/Wonoka) the differences are mainly in declination with minor inclination differences, indicating Australia was rotating about a nearby Euler pole in low latitudes throughout most of the Ediacaran. Conceivably Australia could remain in low latitudes during a TPW event, with the pole of rotation for the whole lithosphere being nearby; however, this would not preclude Australia from undergoing a large amount of polar motion if such an event did occur.

During the Cambrian, Australia recorded a slow change in inclination and drifted across the palaeoequator. Interpretation of magnetostratigraphic studies through the Ediacaran are fraught with difficulties and correlations are highly non-unique, if not entirely contradictory, suggesting that much denser sampling is required before the reason for this can be determined.

The large and seemingly rapid polar shifts at 615–590 and 575–565 Ma in the Laurentian APWP have not been captured by the primary/early magnetizations of the late Adelaidean strata. No major stratigraphic break where signs of large TPW might have been missed is evident in the Ediacaran succession of the Adelaide Geosyncline, and the hiatus in deposition at the base of the Wilpena Group is too old and of too brief a duration to be of relevance here. Because TPW should be recorded globally we therefore conclude that no large TPW occurred during the Ediacaran Period.

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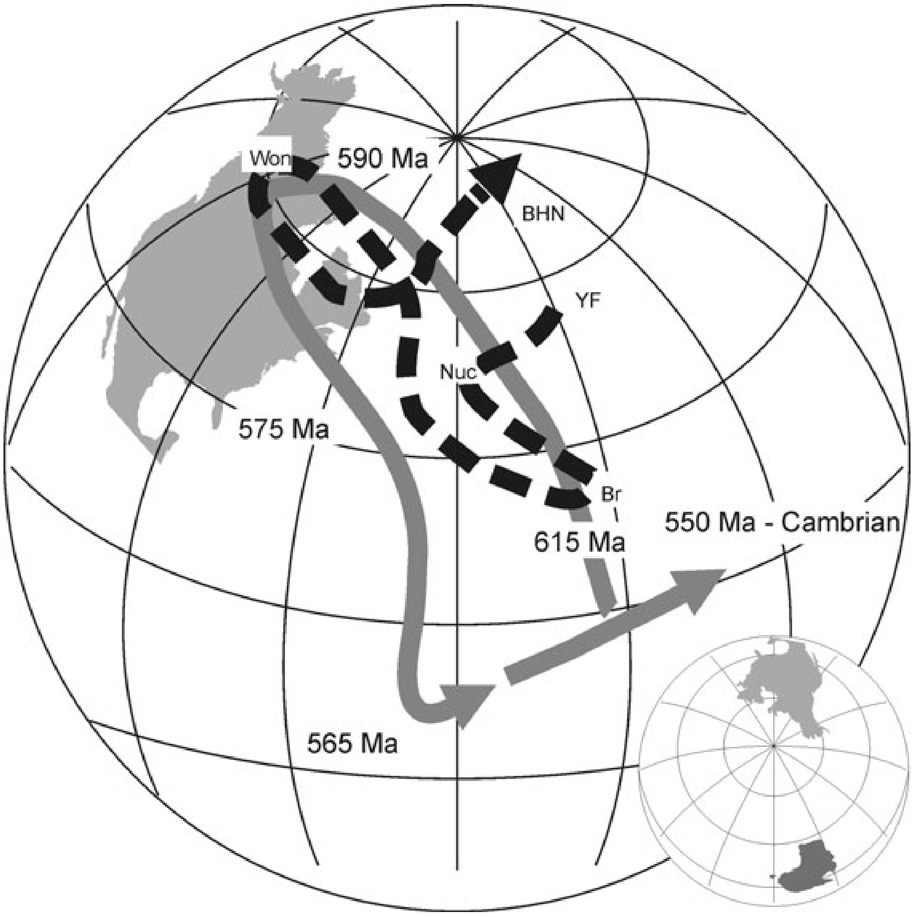

Figure 11. Approximate co-location of Ediacaran APWPs for Laurentia (continuous) and Australia (dashed). Inset shows the palaeogeographic reconstruction implied by overlaying the two Ediacaran APWPs. Ages refer to the Laurentian path. Abbreviations are for the Australian poles: YF, Yaltipena Formation; Br, Brachina Formation; Won, Wonoka Formation; BHN, Black Hill Norite (see Table 3). The Euler pole used to bring the ~610 Ma Brachina pole close to the 615 Ma Long Range Dykes pole was at latitude $\lambda_e = 0.4°$, longitude $\varphi_e = 312.3°$ and angle $\omega_e = 117.7°$.

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REFERENCES

Allen, P.A. & Etienne, J.L., 2008. Sedimentary challenge to Snowball Earth, *Nature Geosci.,* **1,** 817–825.

Buchan, K.L., Ernst, R.E. & Kumarapeli, P.S., 2004. Paleomagnetism of the Grenville diabase dyke swarm and implications for the midVendian paleolatitude of Laurentia, *EOS, Trans. Am. geophys. Un.,* **85**(17), Abstract GP24A-02, JA166.

Butler, R.F., 1992. *Paleomagnetism: Magnetic Domains to Geologic Terranes,* Blackwell, Oxford, 319 pp.

Calver, C.R. & Lindsay, J.F., 1998. Ediacarian sequence and isotope stratigraphy of the Officer Basin, South Australia, *Aust. J. Earth Sci.,* **45,** 513–532.

Collinson, D.W., 1983. *Methods in Rock Magnetism and Palaeomagnetism,* Chapman and Hall, London, 503 pp.

Compston, W., Williams, I.S., Jenkins, R.J.F., Gostin, V.A. & Haines, P.W., 1987. Zircon age evidence for the Late Precambrian Acraman ejecta blanket, *Aust. J. Earth Sci.,* **34,** 435–445.

Condon, D., Zhu, M., Bowring, S., Wang, W., Yang, A. & Jin, Y., 2005. U–Pb ages from the Neoproterozoic Doushantuo Formation, China, *Science,* **308,** 95–98.

Davidson, A., Hamilton, M.A., Heaman, L.M., Ernst, R.E. & Buchan, K.L., 2009. Grenville diabase dyke swarm: extent, age and comparative geochemistry, *EOS, Trans. Am. geophys. Un.,* **90**(22), Joint Assembly Supplement, Abstract GA13B-01.

Drexel, J.F. & Preiss, W.V. (eds), 1995. *The Geology of South Australia, Vol. 2*: *The Phanerozoic*, Geol. Surv. S. Aust. Bull., **54**, PIRSA Minerals and Energy Resources Division, Adelaide, 347 pp.

Embleton, B.J.J. & Giddings, J.W.G., 1974. Late Precambrian and Lower Palaeozoic palaeomagnetic results from South Australia and Western Australia, *Earth planet. Sci. Lett.,* **22,** 355–365.

Embleton, B.J.J. & Williams, G.E., 1986. Low palaeolatitude of deposition for late Precambrian periglacial varvites in South Australia: implications for palaeoclimatology, *Earth planet. Sci. Lett.,* **79,** 419–430.

Evans, D.A.D. & Kirschvink, J.L., 1999. Multiple episodes of rapid true polar wander in Neoproterozoic–Cambrian time? *Geol. Soc. Am. Abs. Prog.,* **31,** 318.

Fanning, C.M. & Link, P.K., 2008. Age constraints for the Sturtian glaciation: data from the Adelaide Geosyncline, South Australia and Pocatello Formation, Idaho, USA, *Geol. Soc. Aust. Abs.,* **91,** 57–62.

Fisher, R., 1953. Dispersion on a sphere, *Proc. R. Soc. Lond.,* **A217,** 295–305.

Foden, J., Barovich, K., Jane, M. & O'Halloran, G., 2001. Sr–isotopic evidence for Late Neoproterozoic rifting in the Adelaide Geosyncline at 586 Ma: implications for a Cu ore forming fluid flux, *Precambrian Res.,* **106,** 291–308.

Foden, J., Elburg, M.A., Dougherty-Page, J. & Burtt, A., 2006. The timing and duration of the Delamerian Orogeny: correlation with the Ross Orogen and implications for Gondwana assembly, *J. Geol.,* **114,** 189–210.

Forbes, B.G. & Preiss, W.V., 1987. Stratigraphy of the Wilpena Group, in *The Adelaide Geosyncline, Late Proterozoic Stratigraphy, Sedimentation, Palaeontology and Tectonics,* pp. 211–248, ed Preiss, W.V., Geol. Surv. S. Aust. Bull., **53**, PIRSA Minerals and Energy Resources Division, Adelaide.

Gehling, J.G., 2007. Fleshing out the Ediacaran period, in *The Rise and Fall of the Ediacaran Biota,* pp. 425–428, eds Vickers-Rich, P. & Komarower, P., Geol. Soc. Lond. Spec. Publ., **286**.

Giddings, J.A. & Wallace, M.W., 2009. Sedimentology and C–isotope geochemistry of the 'Sturtian' cap carbonate, South Australia, *Sediment. Geol.,* **216,** 1–14.

Giddings, J.A., Wallace, M.W., Haines, P.W. & Mornane, K., 2010. Submarine origin for the Neoproterozoic Wonoka canyons, South Australia, *Sediment. Geol.,* **223,** 35–50.

Gradstein, F.M., Ogg, J.G. & Smith, A.G., 2006. *A Geologic Time Scale,* Cambridge University Press, Cambridge, 589 pp.

Gravestock, D.I., 1995. Early and middle Palaeozoic, in *The Geology of South Australia*, *Vol. 2: The Phanerozoic,* pp. 3–91, eds Drexel, J.F. & Preiss, W.V., Geol. Surv. S. Aust. Bull., **54**, PIRSA Minerals and Energy Resources Division, Adelaide.

Grey, K. & Calver, C.R., 2007. Correlating the Ediacaran of Australia, in *The Rise and Fall of the Ediacaran Biota,* pp. 115–135, eds Vickers-Rich, P. & Komarower, P., Geol. Soc. Lond. Spec. Publ., **286**.

Haines, P.W., 1988. Storm-dominated mixed carbonate/siliciclastic shelf sequence displaying cycles of hummocky cross-stratification, late Proterozoic Wonoka Formation, South Australia, *Sediment. Geol.,* **58,** 237–254.

Haines, P.W., 1990. A late Proterozoic storm-dominated carbonate shelf sequence: the Wonoka Formation in the central and southern Flinders Ranges, South Australia, in *The Evolution of a Late Precambrian Rift Complex: The Adelaide Geosyncline,* pp. 177–198, eds Jago, J.B. & Moore, P.S., Geol. Soc. Aust. Spec. Publ., **16**.

Haines, P.W., Turner, S.P., Kelley, S.P., Wartho, J.-A. & Sherlock, S.C. 2004. ^{40}Ar–^{39}Ar dating of detrital muscovite in provenance investigations: a case study from the Adelaide Rift Complex, South Australia, *Earth planet. Sci. Lett.,* **227,** 297–311.

Hodych, J.P., Cox, R.A. & Kostler, J., 2004. An equatorial Laurentia at 550 Ma confirmed by Grenville inherited zircons dated by LAM ICP-MS in the Skinner Cove volcanics of western Newfoundland: implications for inertial interchange true polar wander, *Precambrian Res.,* **129,** 93–113.

Hoffmann, K.-H., Condon, D. J., Bowring, S.A. & Crowley, J.L. 2004. U–Pb zircon date from the Neoproterozoic Ghaub Formation, Namibia: constraints on Marinoan glaciation, *Geology,* **32,** 817–820.

Ireland, T.R., Flöttmann, T., Fanning, C.M., Gibson, G.M. & Preiss, W.V., 1998. Development of the early Paleozoic Pacific margin of Gondwana from detrital-zircon ages across the Delamerian orogen, *Geology,* **26,** 243–246.

Jenkins, R.J.F., 1992. Functional and ecological aspects of Ediacaran assemblages, in *Origin and Early Evolution of the Metazoa,* pp. 131–176, eds Lipps, J.H. & Signor, P.W., Plenum Press, New York.

Karner, G.D., 1974. Palaeomagnetism of the Brachina Formation at Hallett Cove, South Australia, *BSc thesis*. Flinders University, Adelaide, South Australia, 62 pp.

Kendall, B., Creaser, R.A. & Selby, D., 2006. Re–Os geochronology of postglacial black shales in Australia: constraints on the timing of "Sturtian" glaciation, *Geology,* **34,** 729–732.

Kennedy, M.J., 1996. Stratigraphy, sedimentology, and isotopic geochemistry of Australian Neoproterozoic postglacial cap dolostones: deglaciation, δ^{13}C excursions, and carbonate precipitation, *J. Sediment. Res.,* **66,** 1050–1064.

Kent, J.T., Briden, J.C. & Mardia, K.V., 1983. Linear and planar structure in ordered multivariate data as applied to progressive demagnetization of palaeomagnetic remanence, *Geophys. J. R. astr. Soc.,* **75,** 593–621.

Kirschvink, J.L., *et al*. 2005. Ediacaran rapid true polar wander: constraints on a possible driving mechanism from the paleomagnetism and geochronology of the Sept-Îles Intrusive Suite, Quebec, Canada, *EOS, Trans. Am. geophys. Un.,* **86**(18), Suppl., Abstract GP21A-05.

Klootwijk, C.T., 1980. Early Palaeozoic palaeomagnetism in Australia, *Tectonophysics,* **64,** 249–332.

Knoll, A.H., Walter, M.R., Narbonne, G.M. & Christie-Blick, N., 2004. A new period for the geologic time scale, *Science,* **305,** 621–622.

Knoll, A.H., Walter, M.R., Narbonne, G.M. & Christie-Blick, N., 2006. The Ediacaran period: a new addition to the geologic time scale, *Lethaia,* **39,** 13–30.

Mahan, K.H., Wernicke, B.P. & Jercinovic, M.J., 2010. Th–U–total Pb geochronology of authigenic monazite in the Adelaide rift complex, South Australia, and implications for the age of the type Sturtian and Marinoan glacial deposits, *Earth planet. Sci. Lett.,* **289,** 76–86.

Maloof, A.C., Halverson, G.P, Kirschvink, J.L., Schrag, D.P., Weiss, B.P. & Hoffman, P.F., 2006. Combined paleomagnetic, isotopic, and stratigraphic evidence for true polar wander from the Neoproterozoic Akademikerbreen Group, *Geol. Soc. Am. Bull.,* **118,** 1099–1124.

Martin, M.W., Grazhdankin, D.V., Bowring, S.A., Evans, D.A.D., Fedonkin, M.A. & Kirschvink, J.L., 2000. Age of Neoproterozoic bilatarian body and trace fossils, White Sea, Russia: implications for metazoan evolution, *Science,* **288,** 841–845.

McCausland, P.J., Van der Voo, R. & Hall, C.M., 2007. Circum-Iapetus paleogeography of the Precambrian–Cambrian transition with a new palaeomagnetic constraint from Laurentia, *Precambrian Res.,* **156,** 125–152.

McCausland, P.J., Hankard, F., Van der Voo, R. & Hall, C.M., 2009a. A test of high-latitude Laurentia: paleomagnetism and ^{40}Ar–^{39}Ar geochronology of the 584 Ma Baie des Moutons syenite, Quebec, *EOS, Trans. Am. geophys. Un.,* **90**(22), Joint Assembly Supplement, Abstract GA13B-03.

McCausland, P.J., Smirnov, A., Evans, D.A., Izard, C. & Raub, T.D., 2009b. Low-latitude Laurentia at 615 Ma: paleomagnetism of the Long Range dykes and coeval Lighthouse Cove Formation, Northern Newfoundland and SE Labrador, *EOS, Trans. Am. geophys. Un.,* **90**(22), Joint Assembly Supplement, Abstract GA13B-04.

McElhinny, M.W., 1964. Statistical significance of the fold test in palaeomagnetism, *Geophys. J. R. astr. Soc.,* **8,** 338–340.

McFadden, P.L., 1990. A new fold test for palaeomagnetic studies, *Geophys. J. Int.*, **103,** 163–169.

McFadden, P.L. & Lowes, F.J., 1981. The discrimination of mean directions drawn from Fisher distributions, *Geophys. J. R. astr. Soc.,* **67,** 19–33.

McFadden, P.L. & McElhinny, M.W., 1990. Classification of the reversal test in palaeomagnetism, *Geophys. J. Int.*, **103,** 725–729.

McWilliams, M.O., 1977. Late Precambrian palaeomagnetism of Australia and Africa, *PhD thesis*. Australian National University, Canberra, Australia, 162 pp.

McWilliams, M.O. & McElhinny, M.W., 1980. Late Precambrian paleomagnetism of Australia: the Adelaide geosyncline, *J. Geol.,* **88,** 1–26.

Meert, J.G., Van Der Voo, R. & Payne, T.W., 1994. Paleomagnetism of the Catoctin volcanic province: a new Vendian Cambrian apparent polar wander path for North America, *J. geophys. Res.,* **99,** 4625–4641.

Murthy, G.S., 1971. The paleomagnetism of diabase dykes from the Grenville Province, *Can. J. Earth Sci.,* **8,** 802–812.

Narbonne, G.M., 2005. The Ediacara biota: Neoproterozoic origin of animals and their ecosystems, *Ann. Rev. Earth planet Sci.,* **33,** 421–442.

Pisarevsky, S.A., Li, Z.X., Grey, K. & Stevens, M.K., 2001a. A palaeomagnetic study of the Empress 1A corehole in the Officer Basin: no evidence for high-latitude position for Australia in the Neoproterozoic, *Precambrian Res*., **110,** 93–108.

Pisarevsky, S.A., Kommissarova, R.A. & Khramov, A.N., 2001b. Reply to comments by J. Meert & R. Van der Voo on "New palaeomagnetic results from the Vendian red sediments of Cisbaialka and the problem of Siberia and Laurentia in the Vendian", *Geophys. J. Int.*, **146,** 871–873.

Plummer, P.S., 1978. Stratigraphy of the lower Wilpena Group (late Precambrian), Flinders Ranges, South Australia, *Trans. R. Soc. S. Aust.,* **102,** 25–38.

Preiss, W.V. (ed), 1987. The Adelaide Geosyncline. Late Proterozoic Stratigraphy, Sedimentation, Palaeontology and Tectonics, *Geol. Surv. S. Aust. Bull.,* **53**, 438 pp.

Preiss, W.V., 1993. Neoproterozoic, in *The Geology of South Australia, Vol. 1: The Precambrian,* pp. 171–203, eds Drexel, J.F., Preiss, W.V. & Parker, A.J., Geol. Surv. S. Aust. Bull., **54**, PIRSA Minerals and Energy Resources Division, Adelaide.

Preiss, W.V., 1999. *Parachilna, South Australia, Sheet SH54–13 1:250 000 Geological Series Explanatory Notes,* 2nd edn, Primary Industries and Resources South Australia, Adelaide, 52 pp.

Preiss, W.V., 2000. The Adelaide Geosyncline of South Australia and its significance in Neoproterozoic continental reconstruction, *Precambrian Res.,* **100,** 21–63.

Preiss, W., 2005. Global stratotype for the Ediacaran system and period: the Golden Spike has been placed in South Australia, *MESA J.,* **37,** 20–25.

Preiss, W.V., Dyson, I.A., Reid, P.W. & Cowley, W.M., 1998. Revision of lithostratigraphic classification of the Umberatana Group, *MESA J.,* **9,** 36–42.

Preiss, W.V., Gostin, V.A., McKirdy, D.M., Ashley, P.M., Williams, G.E. & Schmidt, P.W., 2009. The glacial succession of Sturtian age in South Australia: the Yudnamutana subgroup, in *Neoproterozoic Ice Ages,* Geol. Soc. Lond. Mem. (in press).

Raub, T.D. & Evans, D.A, 2004. Climate catastrophe, true polar wander, and inclination shallowing in the Ediacaran Period, *EOS, Trans. Am. geophys. Un.,* **85,** Suppl., U33A-0036.

Raub, T.D., Kirschvink, J.L., Higgins, M.D., Evans, D.A., Peek, S. & Raub, T.M., 2009. Paleomagnetic restudy of the late Ediacaran Sept Îles Mafic Suite, *EOS, Trans. Am. geophys. Un.,* **90**(22), Joint Assembly Supplement, Abs. GA13B-05.

Schmidt, P.W. & Williams, G.E., 1995. The Neoproterozoic climatic paradox: equatorial palaeolatitude for Marinoan glaciation near sea level in South Australia, *Earth planet. Sci. Lett.,* **134,** 107–124.

Schmidt, P.W. & Williams, G. E., 1996. Palaeomagnetism of the ejecta-bearing Bunyeroo Formation, late Neoproterozoic, Adelaide fold belt, and the age of the Acraman impact, *Earth planet. Sci. Lett.,* **144,** 347–357.

Schmidt, P.W., Williams, G.E. & Embleton, B.J.J., 1991. Low palaeolatitude of Late Proterozoic glaciation: early timing of remanence in haematite of the Elatina Formation, South Australia, *Earth planet. Sci. Lett.,* **105,** 355–367.

Schmidt, P.W., Clark, D.A. & Rajagopolan, S., 1993. A historical perspective of the early Palaeozoic APWP of Gondwana: new results from the early Ordovician Black Hill Norite, South Australia, *Explor. Geophys.,* **24,** 257–262.

Schmidt, P.W., Williams, G.E. & McWilliams, M.O., 2009. Palaeomagnetism and magnetic anisotropy of late Neoproterozoic strata, South Australia: implications for the palaeolatitude of late Cryogenian glaciation, cap carbonate and the Ediacaran System, *Precambrian Res.,* **174,** 35–52.

Simons, D.T.A. & Chiasson, A.D., 1991. Paleomagnetism of the Challander complex and the Cambrian apparent polar wander path for North America, *Can. J. Earth Sci.,* **28,** 355–363.

Sohl, L.E., Christie-Blick, N. & Kent, D.V., 1999. Paleomagnetic polarity reversals in Marinoan (ca. 600 Ma) glacial deposits of Australia: implications for the duration of low-latitude glaciation in Neoproterozoic time, *Geol. Soc. Am. Bull.,* **111,** 1120–1139.

Tanczyk, E.I., Lapointe, P., Morris, W.A. & Schmidt, P.W., 1987. A paleomagnetic study of the layered mafic intrusion at Sept-Îles, Québec, *Can. J. Earth Sci.,* **24,** 1431–1438.

Tauxe, L. & Kent D.V., 2004. A simplified statistical model for the geomagnetic field and the detection of shallow bias in palaeomagnetic inclinations: was the ancient magnetic field dipolar? in *Timescales of the Palaeomagnetic Field,* pp. 101–115, eds, Channell, J.E.T., Kent, D.V., Lowrie, W. & Meert, J.G., Geophys. Monograph Vol. 145, Am. geophys. Union, Washington DC.

Van der Voo, R., 1990. The reliability of paleomagnetic data, *Tectonophysics,* **184,** 1–9.

von der Borch, C.C., Grady, A.E., Eickhoff, K.H., DiBona, P. & Christie-Blick, N., 1989. Late Proterozoic Patsy Springs canyon, Adelaide Geosyncline: submarine or subaerial origin? *Sedimentology,* **36,** 777–792.

Walter, M.R., Veevers, J.J., Calver, C.R., Gorjan, P. & Hill, A.C., 2000. Dating the 800–544 Ma Neoproterozoic interval by isotopes of strontium, carbon, and sulfur in seawater, and some interpretative models, *Precambrian Res.,* **100,** 371–433.

Williams, G.E., 1979. Sedimentology, stable-isotope geochemistry and palaeoenvironment of dolostones capping late Precambrian glacial sequences in Australia, *J. geol. Soc. Aust.,* **26,** 377–386.

Williams, G.E. & Gostin, V.A., 2000. Mantle plume uplift in the sedimentary record: origin of kilometre-deep canyons within late Neoproterozoic successions, South Australia, *J. geol. Soc. Lond.,* **157,** 759–768.

Williams, G.E. & Gostin, V.A., 2005. Acraman–Bunyeroo impact event (Ediacaran), South Australia, and environmental consequences: twenty-five years on. *Aust. J. Earth Sci.,* **52,** 607–620.

Williams, G.E., Gostin, V.A., McKirdy, D.M. & Preiss, W.V., 2008. The Elatina glaciation, late Cryogenian (Marinoan Epoch), South Australia: sedimentary facies and palaeoenvironments, *Precambrian Res.,* **163,** 307–331.

Williams, G.E, Gostin, V.A., McKirdy, D.M., Preiss, W.V. & Schmidt, P.W., 2009. The Elatina glaciation (late Cryogenian), South Australia, in *Neoproterozoic Ice Ages,* Geol. Soc. Lond. Mem, (in press).

Zhang, S., Jiang, G. & Han, Y., 2008. The age of the Nantuo Formation and Nantuo glaciation in South China, *Terra Nova,* **20,** 289–294.

Zhou, C., Tucker, R., Xiao, S., Peng, Z., Yuan, X. & Chen, Z. 2004. New constraints on the ages of Neoproterozoic glaciations in South China, *Geology,* **32,** 437–440.

APPENDIX A: SAMPLING SITES

Brachina Formation

Sites BF01–03. Coastal cliffs at Hallett Cove, at 35°04′30″S, 138°29′43″E (Noarlunga 1:50 000 Topographic Map). Red sandstone/siltstone. Strike 190° (magnetic), dip 85°W.

Sites BF04–08. Railway cutting at Pichi Richi Pass, at 32°24′26″S, 137°58′18″E (Port Augusta 1:50 000 Topographic Map). Red siltstone. Strike 165° (magnetic), dip 30°W.

Sites BF07–08. Creek section near Warren Gorge, at 32°10′55″S, 138°00′28″E (Willochra 1:50 000 Topographic Map). Red siltstone. Strikes variable 168–176° (magnetic), dips variable 60–75°E.

Sites BF09–11. Terka quarry, at 32°41′44″S, 138°06′55″E (Wilmington 1:50 000 Topographic Map). Red siltstone. Strike 175° (magnetic), dip 35°W.

Site BF12. Creek section across Hancocks Lookout Road, at 32°41′05″S, 138°03′18″E (Wilmington 1:50 000 Topographic Map). Red siltstone. Strikes variable 30–40° (magnetic), dips variable 25–32°W.

Sites BF13–14. Road cutting on Main North Road 4 km west of Wilmington, at 32°24′26″S, 137°58′18″E (Port Augusta 1:50 000 Topographic Map). Red siltstone. Strike 165° (magnetic), dip 30°W.

Wonoka Formation

Sites WF01–09. Creek section, Brachina Gorge, at 31°20′04″S, 138°35′02″E (Oraparinna 1:50 000 Topographic Map). Well-bedded purple siltstone/mudstone. Strike 008° (magnetic), dip 31°W.

Sites WF10–12. Creek section along Heyson Trail, at 31°35′23″S, 138°32′01″E (Wilpena 1:50 000 Topographic Map). Well-bedded purple siltstone/mudstone. Strike 140° (magnetic), dip 55°NE.