Palaeomagnetic constraints on the Proterozoic tectonic evolution of Australia

MICHAEL T. D. WINGATE & DAVID A. D. EVANS

Tectonics Special Research Centre, Department of Geology and Geophysics,
The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia
(e-mail: mwingate@tsrc.uwa.edu.au)

Abstract: Recent plate tectonic models advocate assembly of Proterozoic Australia by tectonic processes that involved large-scale horizontal motions, whereas previous models suggested that the continent evolved as an essentially intact block of lithosphere. Geological and geochemical observations alone are insufficient to test whether the major cratonic blocks of Australia were together or widely separated during the Proterozoic; only palaeomagnetism can provide quantitative constraints on relative plate motions during the Precambrian. Despite deficiencies in the palaeomagnetic record for Proterozoic Australia, groups of overlapping palaeopoles for 1.7–1.8 and 1.5–1.6 Ga permit the North and West Australian cratonic assemblages to have occupied their present relative positions since at least *c.* 1.7 Ga, and to have been joined to the South Australian cratonic assemblage since at least *c.* 1.5 Ga. Nonetheless, additional geological, geochronological and palaeomagnetic data are required to test whether large oceans closed between any of the continental blocks.

It is generally accepted that processes similar to those of modern plate tectonics operated during the Proterozoic, if not earlier (Burke *et al.* 1976; Hoffman 1988; Windley 1995; Hamilton 1998; Collerson & Kamber 1999). The Proterozoic geology of Australia, however, has only relatively recently been interpreted in a plate tectonic context (e.g. Myers 1990; Tyler & Thorne 1990; Myers *et al.* 1996; Tyler *et al.* 1998; Krapez & Martin 1999). Plate tectonic models advocate growth of Australia by amalgamation of continental fragments, and invoke processes such as subduction, arc magmatism, terrane accretion and continent–continent collision, that occur at modern plate margins and involve large horizontal displacements.

The traditional view in Australia has been that the continent evolved as an essentially intact block of crust, by processes of mainly intracratonic rifting and vertical tectonics, although possibly with creation and destruction of small intercratonic ocean basins (e.g. Harrington *et al.* 1973; Rutland 1973; Etheridge *et al.* 1987, Wyborn 1988). The 'single-continent' model is based mainly on: (1) the prevalence of low-*P* high-*T* metamorphism; (2) the absence of rock types diagnostic of subduction, such as relicts of oceanic crust, paired metamorphic belts and calc-alkaline magmatism (e.g. Etheridge *et al.* 1987; Wyborn 1988; Mortimer *et al.* 1988*a*; Collins & Shaw 1995); (3) the observation that a single apparent polar wander path (APWP) can be constructed through all palaeopoles for Precambrian Australia, even though they are derived from different tectonic units (e.g. McElhinny & Embleton 1976; Veevers & McElhinny 1976; Idnurm & Giddings 1988; Plumb 1993; Idnurm *et al.* 1995); and (4) crustal thicknesses and seismic signatures more compatible with reworking of pre-existing crust than with terrane accretion (Drummond 1988).

Within Proterozoic orogenic belts, distinguishing between plate margin interaction and intraplate models on the basis of geological criteria can be problematic. Despite abundant evidence for compressional deformation, and for the prior truncation and subsequent juxtaposition of terranes of contrasting age, structure and metamorphic characteristics, the geology yields no information on how widely separated the terranes might have been prior to their inferred amalgamation. Neither do geochemical studies yield this information, although they can provide qualitative constraints on tectonic environments (e.g. Krapez & Martin 1999; Sheppard *et al.* 1999*a*) and have shown that subduction may have operated since 3.8 Ga (Collerson & Kamber 1999). The presence of ophiolites constitutes direct evidence for closure of an ocean basin, but does not indicate its original size, and few ophiolites have been recognized in Proterozoic orogenic belts (Moores 1986; Helmstaedt & Scott 1992; Windley 1995).

Only palaeomagnetism can reveal the past relative positions and motions of crustal fragments in Australia during these ancient times. Many new palaeomagnetic and isotopic age data have been generated in the last decade. This paper will provide a brief summary of current geological and palaeomagnetic information for Proterozoic Australia, focus on apparent agreements and conflicts between the two data sets, and attempt to reassess models for the continent's evolution.

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Tectonic summary

Recent geological syntheses portray the assembly of Australia as a protracted and complex series of events (e.g. Myers *et al.* 1996; Tyler *et al.* 1998). Precambrian rocks of Australia comprise three main regions, referred to here as the North, West and South Australian cratonic assemblages, each of which contains blocks of Archaean and/or Palaeoproterozoic crust, is bounded by Palaeoproterozoic–Mesoproterozoic mobile belts, and is partly overlain by younger sedimentary basins (Fig. 1). These three regions were interpreted by Myers *et al.* (1996) to have formed independently in the Palaeoproterozoic, prior to their final amalgamation along Late Mesoproterozoic (1.3–1.0 Ga) orogenic belts (Figs. 2 & 3). Several geological and palaeomagnetic observations, however, favour coherence of these regions since at least the Late Palaeoproterozoic, as discussed below. The following simplified overview of the Proterozoic tectonic evolution of each cratonic assemblage focuses mainly on observations and interpretations that are suggestive of tectonic environments.

West Australian cratonic assemblage (WAC)

The WAC (Fig. 1a) contains three geologically distinct terranes inferred to have assembled by *c.* 1.8 Ga. The Gascoyne Complex is thought to represent a Late Archaean–Palaeoproterozoic microcontinent joined to the northern margin of the Archaean Yilgarn Craton along the 2.0–1.96 Ga Glenburgh Orogen (Sheppard & Occhipinti 2000). Sheppard *et al.* (1999*b*) interpreted the temporal and spatial distribution of granitoids to indicate north-dipping subduction and subsequent collision. Myers (1989) suggested that thrust sheets of deformed and metamorphosed mafic and ultramafic plutonic and volcanic rocks (the Trillbar Complex and Narracoota Volcanics; Fig. 1a), transported southwards onto the Yilgarn Craton, represent obducted parts of a volcanic arc.

Structural and magmatic observations were interpreted to indicate that an ocean basin was consumed by N–S oblique convergence and south-dipping subduction between the Archaean Yilgarn and Pilbara Cratons during the 1.83–1.78 Ma Capricorn Orogeny (Tyler & Thorne 1990; Tyler 1999; Hall *et al.* 2001). High-*P* kyanite-bearing mineral assemblages in the Capricorn Orogen are consistent with subduction and continental collision (Baker *et al.* 1987; Tyler & Thorne 1990; Fitzsimons, pers. comm.). Subsequent deformation included westward extrusion of material caught between the Pilbara and Yilgarn Cratons (Tyler & Thorne 1990) and regional extension after *c.* 1.62 Ga (Nelson 1998) to accommodate sediments of the Bangemall Basin (Fig. 1a).

North Australian cratonic assemblage (NAC)

Synchronous deformation, metamorphism and magmatism occurred during the 1.89–1.87 Ga Barramundi Orogeny across much of the NAC (Fig. 1b), including the Pine Creek, Tennant Creek, northern Arunta and Mount Isa Blocks, and possibly the Georgetown Block (Etheridge *et al.* 1987; Page 1988). Etheridge *et al.* (1987) argued that the Barramundi orogeny was intracontinental, based on the predominance of low-*P* metamorphism and the absence of features diagnostic of modern intercontinental orogeny. They proposed a model of mafic underplating and continental extension driven by small-scale mantle convection, followed by low-*P*/high-*T* compression driven by crust–mantle delamination and A-subduction. Wyborn (1988) argued that geochemical signatures of 1.88–1.84 Ga felsic igneous rocks across most of Australia are consistent with such a model.

The Kimberley Block is thought to have accreted to the NAC along the Halls Creek Orogen at *c.* 1.85–1.82 Ga (Bodorkos *et al.* 1999). Layered mafic–ultramafic bodies and associated mafic to felsic sheets of the Tickalara Complex (Fig. 1b) have geochemical signatures consistent with either an oceanic island-arc-/back-arc basin or an ensialic marginal basin setting (Sheppard *et al.* 1999*a*). On the eastern edge of the NAC, volcanics and sediments were deposited on Archaean– Palaeoproterozoic continental crust in a passive margin setting (Sheppard *et al.* 1999*a*). Sheppard *et al.* (1999*a*) argued that their observations are more consistent with processes similar to those of modern plate margin interactions than with previous ensialic models (Etheridge *et al.* 1987; Page & Hancock 1988).

The Strangways Orogeny includes both early (1.78–1.77 Ga) and late (1.745–1.73–Ga) events in the northern Arunta Inlier (Collins & Shaw 1995), and was inferred by Myers *et al.* (1996) to reflect oblique convergence and accretion of magmatic arcs along the southern margin of the NAC. Between *c.* 1.8 and 1.6 Ga, sedimentation and volcanism occurred across the NAC in a series of interconnected basins (Fig. 1b), remnants of which are best preserved in the McArthur Basin, and the Mount Isa and Georgetown Inliers (Plumb *et al.* 1990). Giles *et al.* (2001) suggested that these basins formed during back-arc continental extension above a long-lived, north-dipping subduction zone along the southern margin of the NAC. The 1.68–1.66 Ga Argilke event may reflect accretion of a strip of continental crust to the same margin. On geochemical grounds, Zhao & Cooper (1992) argued for subduction and consumption of

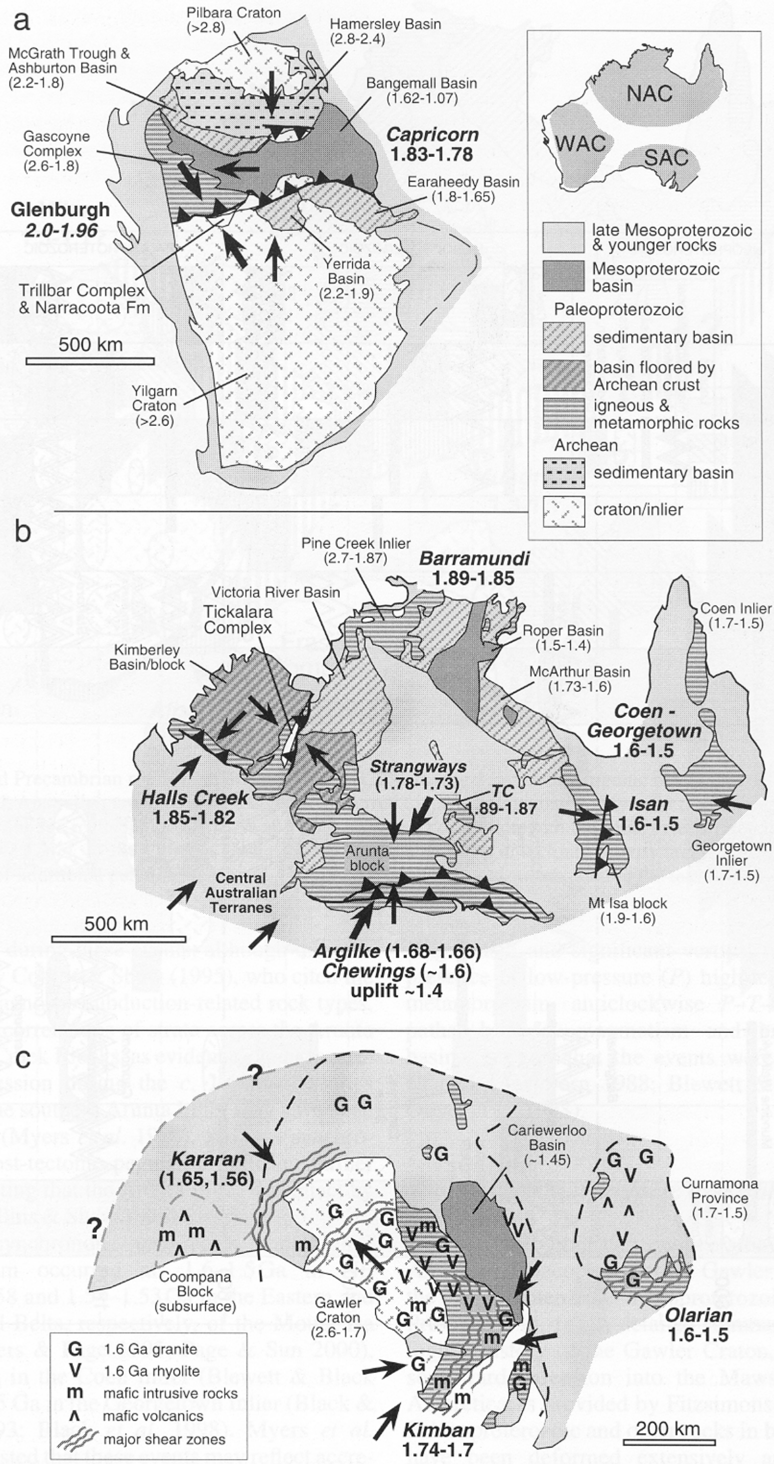

Fig. 1. (**a–c**) Simplified geology of the West, North and South Australian cratonic assemblages (WAC, NAC and SAC respectively). Orogens (italics) and associated times of tectonic activity are indicated (ages in Ga). TC, Tennant Creek Block.

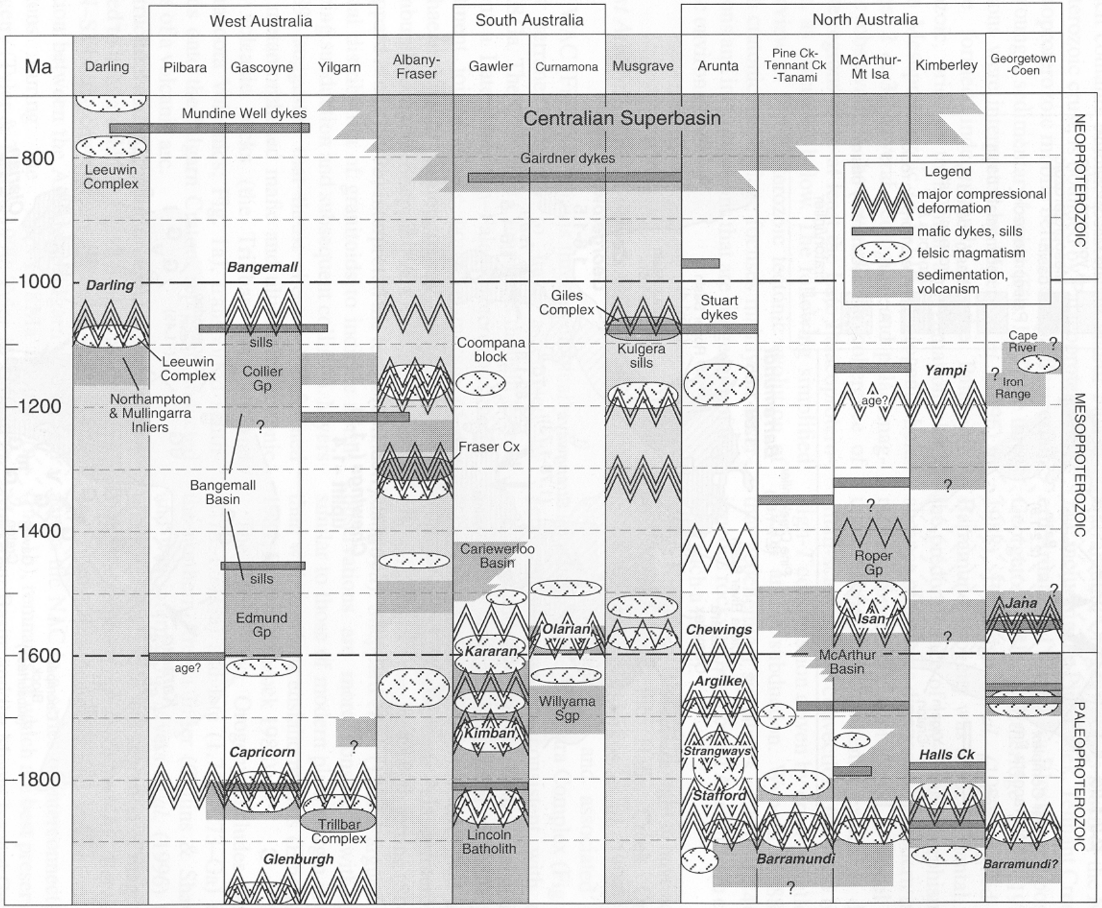

Fig. 2. Schematic time–space diagram showing major 1.8–0.7 Ga deformation, basin formation and magmatic events in the different crustal blocks of mainland Australia and in 1.3–1.1 Ga orogenic belts. The names of tectonothermal events are in italics. Compiled from literature sources cited in the text.

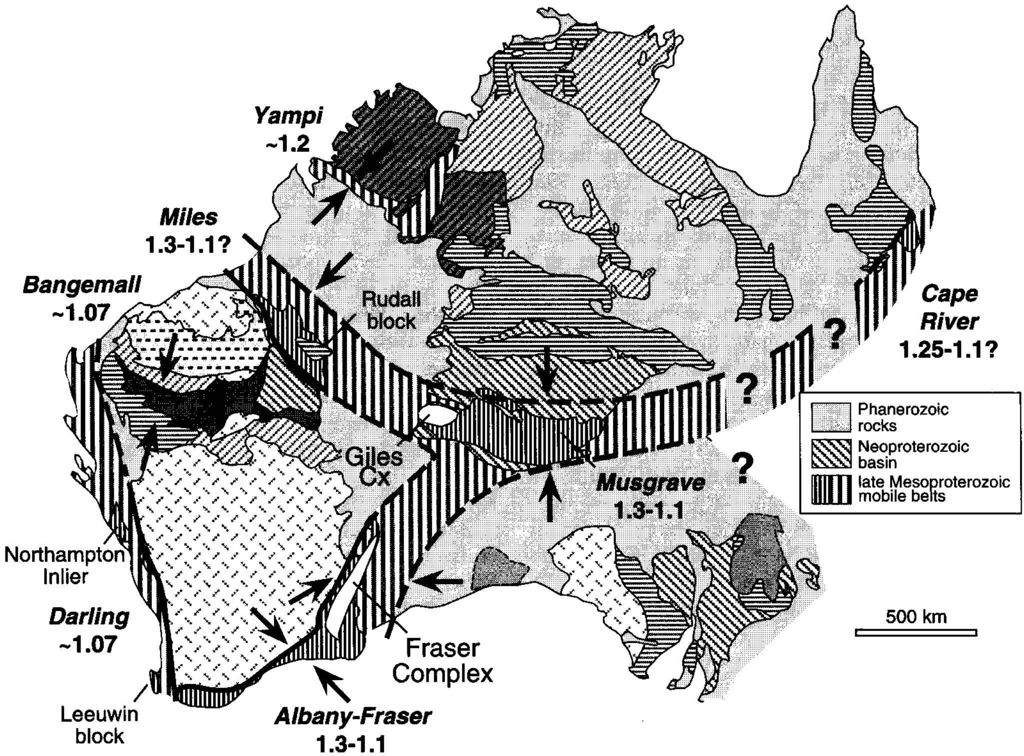

Fig. 3. Exposed Precambrian rocks of mainland Australia, illustrating 1.3–1.1 Ga orogenic belts along which the North, West, and South Australian cratonic assemblages are inferred to have amalgamated (Myers *et al.* 1996). Also shown are possible Grenville-age rocks in NE Australia and their proposed connection with the Musgrave Orogen in central Australia (Blewett *et al.* 1998). Orogens (in italics) and associated times of tectonic activity are indicated (ages in Ga). See Figure 1 for additional parts of the legend. Compiled from literature sources cited in the text.

oceanic crust during these events, although this was questioned by Collins & Shaw (1995), who cited the scarcity of diagnostic subduction-related rock types, and apparent correlations of strata across the Arunta and Tennant Creek Blocks, as evidence against accretion. Compression during the *c.* 1.6 Ga Chewings Orogeny in the southern Arunta Inlier may have been intracratonic (Myers *et al.* 1996), and was synchronous with post-tectonic pegmatite intrusion farther north, suggesting that the Arunta Inlier was intact by that time (Collins & Shaw 1995).

Broadly synchronous orogenesis and high-*T* metamorphism occurred at: 1.6–1.5 Ga in NE Australia; 1.58 and 1.54–1.53 Ga in the Eastern and Western Fold Belts, respectively, of the Mount Isa Inlier (Conners & Page 1995; Page & Sun 2000), 1.59–1.55 Ga in the Coen Inlier (Blewett & Black 1998); *c.* 1.55 Ga in the Georgetown Inlier (Black & Withnall 1993; Black *et al.* 1998). Myers *et al.* (1996) suggested that these events may reflect accretion of the Georgetown and Coen Blocks to the eastern margin of the NAC. However, the absence of ophiolites, paired metamorphic belts, calc-alkaline magmatism and significant vertical uplift, and the presence of low-pressure (*P*) high-temperature (*T*) metamorphism, anticlockwise *P*–*T*–time (*P*–*T*–*t*) paths, bimodal magmatism and broad shallow basins, suggest that the events were intraplate in character (Wyborn 1988; Blewett & Black 1998; Oliver *et al.* 1998).

South Australian cratonic assemblage (SAC)

The SAC contains two main cratonic blocks, the Archaean–Palaeoproterozoic Gawler Craton and the Palaeoproterozoic–Mesoproterozoic Curnamona Province (Fig. 1c). A detailed summary of the geological history of the Gawler Craton, including its southward extension into the Mawson Block of Antarctica, is provided by Fitzsimons (2002). Most Palaeoproterozoic and older rocks in both provinces have been deformed extensively and metamorphosed to amphibolite or granulite facies.

Voluminous felsic and mafic granitoids and minor mafic dykes of the Lincoln Batholith were emplaced at the SE margin of the Gawler Craton at *c.* 1.85 Ga, coincident with the final stages of deposition of Hutchison Group sediments onto Archaean Sleaford Complex basement (Mortimer *et al.* 1988*a*; Hoek & Schaefer 1998). Limited compressional deformation at this time may have accommodated successive pluton emplacement (Hoek & Schaefer 1998; Vassallo & Wilson 2002). Mortimer *et al.* (1988*a*) argued that the Lincoln Granitoids are not compatible compositionally with subduction processes and advocated a model, similar to that proposed by Etheridge *et al.* (1987), of magma generation by remelting of underplated mafic material in an intracratonic setting. The Lincoln Batholith was juxtaposed against the Hutchison Group along the Kalinjala Shear Zone, a major structure active during the 1.74–1.70 Ga Kimban Orogeny, which included regional deformation and metamorphism of Hutchison Group sedimentary rocks and their underlying Archaean basement, and emplacement of extensive granitoids of the 1.74–1.70 Ga Moody Suite (Daly *et al.* 1998; Hoek & Schaefer 1998; Vassallo & Wilson 2002). Myers *et al.* (1996) suggested that the Curnamona Province was amalgamated to the Gawler Craton during the Kimban Orogeny.

In the NW Gawler Craton, dip-slip structures formed during the 1.65 and 1.57–1.54 Ga Kararan Orogeny have been interpreted in terms of a 1.65 Ga collision between the Gawler Craton and a 'proto-Yilgarn' Craton (Daly *et al.* 1998), and may also have involved accretion of the Coompana Block (known in the subsurface only). Giles *et al.* (2001) and Fitzsimons (2002) suggested that a belt of 1.65–1.55 Ga synorogenic granite plutons (the Ifould Complex; Daly *et al.* 1998) SE of the Karari Fault Zone could represent a magmatic arc predating collision at *c.* 1.56 Ga. Mafic and ultramafic bodies associated with these mobile belts have been taken to imply crustal thinning (Daly *et al.* 1998), but have not been interpreted in terms of specific tectonic processes. The central Gawler Craton contains extensive outcrops of the 1.6–1.55 Ga subaerial felsic and minor mafic Gawler Range Volcanics and comagmatic Hiltaba Suite Granites, thought to have been generated by extensive mafic underplating and melting of Archaean and Palaeoproterozoic crust (Flint 1993; Daly *et al.* 1998).

The oldest rocks recognized in the Curnamona Province (Fig. 1c) are metasedimentary and bimodal meta-igneous rocks of the Willyama Supergroup that were deposited at *c.* 1.69 Ga (Page & Laing 1992). Inherited zircon ages of 1.78–2.7 Ga suggest the presence of Archaean and/or Early Palaeoproterozoic basement (Page & Laing 1992; Robertson *et al.* 1998). These rocks were subsequently deformed and metamorphosed to amphibolite and granulite facies during the *c.* 1.6 Ga Olarian Orogeny (Page & Laing 1992). The Curnamona Province also contains abundant late synorogenic to post-orogenic granitoid and bimodal volcanic rocks that are similar in age to, and possibly correlative with, the 1.6–1.55 Ga Gawler Range Volcanics and Hiltaba Suite Granitoids of the Gawler Craton (Daly *et al.* 1998; Robertson *et al.* 1998).

Mesoproterozoic amalgamation (?)

Both the Albany–Fraser and Musgrave Mobile Belts (Fig. 3) preserve a record of two major tectonothermal events: collision at *c.* 1.3 Ga, followed by intracratonic reactivation of sutures at 1.2 Ga (Clarke *et al.* 1995; Nelson *et al.* 1995; White *et al.* 1999; Clark *et al.* 2000). These observations imply that the Albany–Fraser Orogen is continuous with the Musgrave Orogen, as suggested by Myers *et al.* (1996). They also suggest that the NAC and WAC could have been combined prior to collision with the South Australian–Antarctic Craton, and that the Miles Orogeny, along the eastern edge of the combined Yilgarn–Pilbara Block (Fig. 3), was intracratonic.

Limited geochemical data from the Albany–Fraser and Musgrave Belts are equivocal, but suggest that *c.*1.3 Ga felsic orthogneisses are collision related, whereas *c.* 1.2 Ga granitoids have a more intraplate signature (Nelson *et al.* 1995; Sheraton & Sun 1995). Based on the absence of Late Mesoproterozoic plutons in the SE Yilgarn Craton, Clark *et al.* (2000) suggested that initial collision at 1.3 Ga involved subduction of oceanic crust beneath the South Australian–Antarctic Craton. Within the eastern Albany–Fraser Orogen, the Fraser Complex (Fig. 3) consists of imbricated slices of a layered mafic intrusion (Myers 1985) that was emplaced, metamorphosed to granulite grade, then uplifted and thrust onto the SE Yilgarn Craton margin within *c.* 30 Ma at 1.3 Ga (Fletcher *et al.* 1991). Geochemical data were interpreted by Condie & Myers (1999) to indicate that the Fraser Complex represents remnants of oceanic arcs accreted before or during collision. The presence of Archaean and/or Palaeoproterozoic crustal components within the Albany–Fraser and Musgrave Belts (e.g. Nelson *et al.* 1995; Camacho & Fanning 1995; Clark *et al.* 2000) implies that these orogens may be floored, at least in part, by continental crust. Extensive swarms of mafic dykes were emplaced subparallel to the margins of the Yilgarn Craton at *c.* 1.2 Ga (Evans 1999; Wingate *et al.* 2000; Wingate unpublished data).

Evidence for Late Mesoproterozoic activity between the NAC and WAC is provided by a U–Pb zircon age of 1310 Ma (Nelson 1996), and Rb–Sr ages of 1.3 and 1.1 Ga (Chin & De Laeter 1981), for foliated granite in the Palaeoproterozoic Rudall Block (Fig. 3). Inherited zircons ranging in age from 1.3 to 1.0 Ga in the Cape River Province and Anakie Inlier suggest the existence of a Grenville-age belt in northeastern Australia that may extend westward, beneath younger cover, to connect with the Albany–Fraser–Musgrave Orogen (Blewett *et al.* 1998; Hutton *et al.* 1998; Ferguson *et al.* 2001).

A late phase of deformation at *c.* 1060 Ma in the Musgrave Block (Sun *et al.* 1996; White *et al.* 1999) has been recognized (but not dated) in the Albany–Fraser Belt (Clark *et al.* 2000), and is synchronous with 1060–1090 Ma deformation and magmatism in the Darling Mobile Belt and the Bangemall Basin (Bruguier *et al.*, 1999; Wingate *et al.* 2002). Fitzsimons (2001) suggested that the Mesoproterozoic blocks in the Darling Mobile Belt (Northampton and Leeuwin Blocks; Fig. 3) were accreted to the western Australian margin some time after they were deformed and metamorphosed further to the south (present coordinates), but before 'stitching' of the Northampton Block (Fig. 3) to the western Australian margin at 755 Ma by the Mundine Well Dykes (Fig. 4a; Wingate & Giddings 2000).

Neoproterozoic events

Proterozoic Australia had essentially stabilized by 1.0 Ga, and sedimentation in the continent-wide Centralian Superbasin commenced at 850–830 Ma (Walter *et al.* 1995). The Gairdner Dykes (Fig. 4a) reflect NE–SW extension during initial rifting in eastern and central Australia at 825 Ma (Wingate *et al.* 1998). The Mundine Well Dykes (Fig. 4a) are parallel to the continental margin and their emplacement may have preceded separation of an unknown continental fragment (possibly Kalahari) from the western Australian margin (Wingate & Giddings 2000; Powell & Pisarevsky 2002). Although Australia remained essentially intact during breakup events along its eastern margin at some time after *c.* 780 Ma (Powell *et al.* 1994; Preiss 2000), several intracratonic events occurred in the latest Neoproterozoic (Fig. 4b). The *c.* 550 Ma Petermann Ranges Orogeny involved reactivation of the Miles–Musgrave Orogen, with both north- and south-directed thrusting and considerable exhumation in the Musgrave Block (Maboko *et al.* 1992; Preiss & Krieg 1992; Camacho & Fanning 1995; Scrimgeour & Close 1999), as well as SW-directed thrusting at the eastern edge of the Pilbara Craton and in the King Leopold Orogen (Tyler *et al.* 1998). It has been suggested that an anticlockwise rotation of the NAC with respect to the rest of the continent occurred at this time (Powell *et al.* 1994).

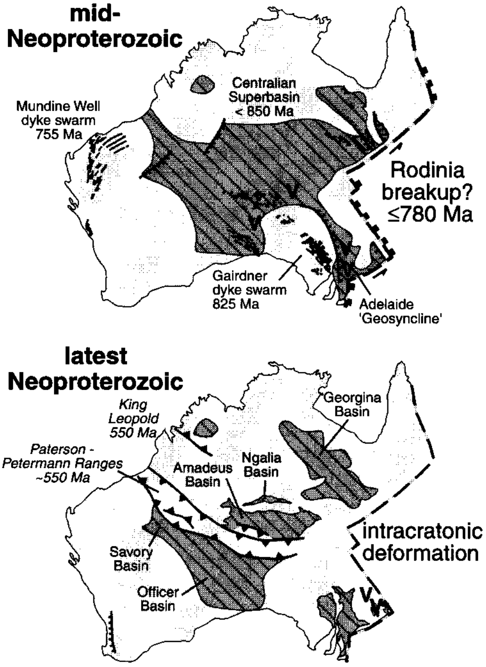

Fig. 4. (**a**) Sedimentation in the Centralian Superbasin started at *c.* 850 Ma (Walter *et al.* 1995). Rift-related magmatism preceding breakup along the eastern Australian margin commenced at *c.* 830 Ma, with emplacement of the Gairdner Dyke Swarm and associated volcanic rocks (Wingate *et al.* 1998). (**b**) Mainly intracratonic deformation occurred along latest Neoproterozoic belts, exhuming the Musgrave and Arunta Blocks, and disrupting the Centralian Superbasin.

Palaeomagnetism

Palaeomagnetism is the only method for quantitatively determining the relative positions of continental fragments during Precambrian time. Palaeomagnetic directions yield information about the latitude and orientation of a sampling locality relative to the palaeomagnetic pole at the time the magnetization was acquired. The positions of palaeopoles relative to Australia between 1.8 and 0.7 Ga (Fig. 5) show that the Australian continent underwent many changes in latitude and orientation relative to the pole during the Proterozoic.

The APWP is constructed by joining palaeopoles, backwards through time, by the shortest possible segments. Although this is the simplest approach, the result is not a unique solution. Lack of a continuous record of field reversals back to the Proterozoic leads to ambiguity in choosing a pole versus its antipole and, because of large age gaps between adjacent poles, it is inevitable that some important features of the path are overlooked. Another

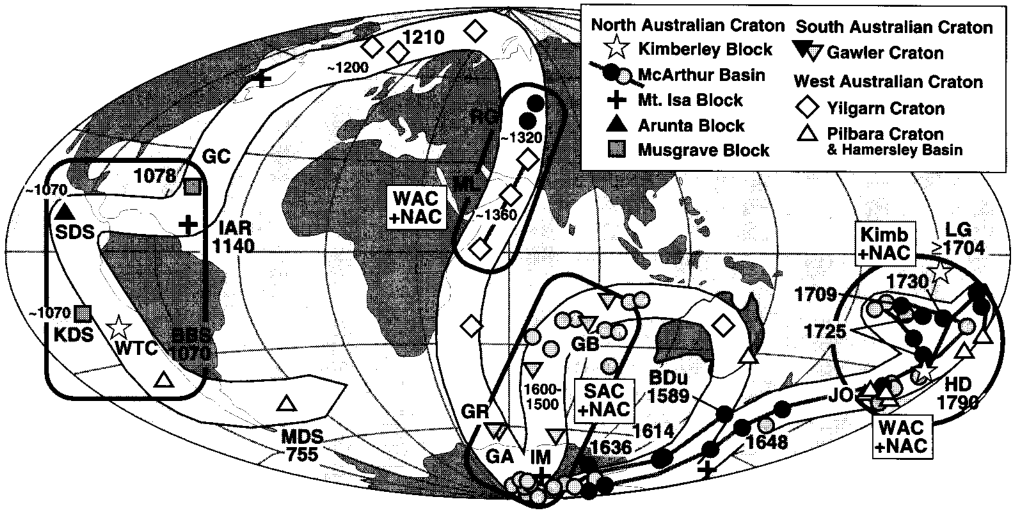

Fig. 5. Apparent polar wander path (APWP) for Australia between 1.8 and 0.7 Ga. Grey symbols for the McArthur Basin and Gawler Craton indicate overprint palaeopoles. Times at which poles from different cratonic blocks overlap are circled. Ages are in Ma (more reliable results are in larger font). Updated from Idnurm & Giddings (1988) and Idnurm *et al.* (1995), with data from Idnurm (2000), Li (2000*a*, *b*), Pisarevsky & Harris (2001), Wingate & Giddings (2000) and Wingate *et al.* (2002). NAC, WAC, SAC; North, West and South Australian cratonic assemblages, respectively; Kimb, Kimberley Block. For Palaeopole abbreviations refer to poles discussed in the text.

critically important uncertainty is the lack of well-dated palaeopoles. Many are dated imprecisely and/or their magnetizations cannot be demonstrated to be primary (see examples below). Nevertheless, all palaeopoles from a single crustal block will help to define the APWP for that block (provided the rocks have not been rotated by later deformation events); those reflecting secondary overprints will lie on a younger segment than primary poles for the same rocks. Most intracratonic deformation, including formation or destruction of small (≤1000 km) ocean basins, will not be detectable within typical uncertainties (A_{95}) of 5–15° in palaeopole determination. With these constraints in mind, the data can be explored in three ways.

Firstly, matching of APWP from two or more tectonic blocks over an interval of time enables, in principle, a unique reconstruction of their relative positions. Although many studies have been conducted in the last decade, the data are still insufficient to construct adequate APWP for the different blocks. The only well-defined path is that for the 1.73–1.59 Ga McArthur Basin (Fig. 5; Idnurm *et al.* 1995; Idnurm 2000). As a second example, preliminary poles reported by Idnurm & Giddings (1988) for the Morawa Lavas and enclosing sedimentary rocks appear to yield a consistently directed APWP vector for the Yilgarn Craton at *c.* 1.36 Ga (ML on Fig. 5).

Secondly, if the constituent terranes of Australia assembled during the Proterozoic via large horizontal motions, such as those that characterize Phanerozoic plate tectonic regimes, then it is unlikely that the palaeopoles from all the different blocks would fall on a single APWP. In particular, if large oceans closed between the NAC, WAC and SAC at 1.3 Ga (or earlier), the APWP should be dissimilar prior to that time, and should converge to produce a common path for times after the blocks were joined. As noted in previous palaeomagnetic analyses (e.g. Idnurm & Giddings 1988; Plumb 1993), it is possible to construct a single APWP for all Proterozoic poles, even though they are derived from different tectonic blocks (Fig. 5). All recent results also plot on the APWP defined by Idnurm & Giddings (1988). This is consistent with the different regions of Australia having evolved in essentially their present relative positions since at least 1.8 Ga, although, owing to the inadequacies in the APWP described above, significant relative movements between the crustal blocks cannot be ruled out (Plumb 1993).

Thirdly, if two or more blocks are in their correct relative positions for a particular time, the palaeopoles of that age from the different blocks should overlap. Note that when matching individual (or, in this case, average) pole positions, rather than APWP, longitude is unconstrained, hence E–W separation between blocks cannot be discerned. There are four segments of the APWP where data from different blocks overlap (Fig. 5).

Segment 1:1.8–1.7 Ga

Palaeopoles from the McArthur Basin at *c.* 1.73–1.7 Ga (Idnurm *et al.* 1995; Idnurm 2000) are similar to those (LG and HD on Fig. 5) for the 1.79–1.7 Ga Elgee Formatton (McNaughton *et al.* 1999; Li 2000*a*) and the 1.79 Ga Hart Dolerite (McElhinny & Evans 1976) of the Kimberley Block, consistent with geological evidence for accretion of the Kimberley Block to the NAC by 1.82 Ga (Bodorkos *et al.* 1999; Sheppard *et al.* 1999*a*). Structural and palaeomagnetic studies indicate that a Pilbara syn-folding overprint pole (JO on Fig. 5; Schmidt & Embleton 1985) was acquired during the 1.83–1.79 Ga Capricorn Orogeny (Li 2000*a*). Proximity of this pole, and similar poles from Pilbara iron-ore deposits (Porath & Chamalaun 1968; Li *et al.* 1993; Schmidt & Clark 1994), to the McArthur Basin and Kimberley Poles implies that the NAC and WAC were in their present relative positions since at least 1.7 Ga (Li 2000*a*).

Segment 2: 1.6–1.5 Ga

Numerous 1.59–1.5 Ga overprint poles from the McArthur Basin (Idnurm *et al.* 1995; Idnurm 2000) and a 1.55–1.5 Ga post-metamorphic cooling pole (IM on Fig. 5) from Mount Isa (Tanaka & Idnurm 1994) overlap with poorly dated overprint poles from South Australian iron-ore deposits (Chamalaun & Porath 1968) and mafic dykes (GA and GB on Fig. 5; Giddings & Embleton 1976). Collectively, the data suggest that the NAC and SAC were joined by at least 1.5 Ga, although current age constraints are poor. Although the Tournefort Dykes (Parker *et al.* 1987), from which the GA and GB palaeopoles (Fig. 5) were obtained, intruded the 1.85 Ga Lincoln Batholith at *c.* 1.81 Ga (Schaefer 1998), they were metamorphosed during the Kimban Orogeny at *c.* 1.72 Ga (Bendall 1994) and have yielded Rb–Sr ages of 1.6–1.55 Ga (Mortimer *et al.* 1988*b*). Together with the lack of field tests to verify the stability of the GA and GB dyke magnetizations, these observations suggest that the magnetizations could be overprints, possibly with ages approximated by the Rb–Sr results.

Poles for the 1592±2 Ma Gawler Range Volcanics (GR on Fig. 5; Chamalaun & Dempsey 1978) and the 1589±3 Ma upper Balbirini Dolomite of the McArthur Basin (BDu on Fig. 5; Idnurm 2000) are *c.* 60° apart (Fig. 5), although the rocks are identical in age (Fanning *et al.* 1988; Page *et al.* 2000). If both poles are primary, this is evidence that the NAC and SAC were not in their present relative positions at 1.59 Ga. It is possible, however, that either pole might be significantly younger than the rocks themselves. It was argued by Schmidt & Clark (1992), for example, that the GR magnetization is a younger overprint, because palaeomagnetic directions they obtained from steeply dipping lower parts of the unit are similar to those obtained previously from the flat-lying upper flows; the combined data set would therefore suggest a negative fold test. Both successions, however, are essentially the same age and the upper flows were erupted at 950–1000°C (Creaser & White 1991), hence it is possible that the entire unit did not cool through its magnetic blocking temperatures until after the younger eruptions, or that the lower flows were reheated and overprinted by overlying rocks. In both cases the magnetization should have been acquired during cooling of the upper flows shortly after 1592 Ma. We thus favour a primary age for the GR pole, although the Gawler Range Volcanics should be investigated further by conducting additional field and laboratory stability tests on samples from the upper succession. Combined data from the upper and lower Balbirini Dolomite indicate a pre-folding age for the magnetization (Idnurm *et al.* 1995; Idnurm 2000), and we tentatively regard the BDu pole as primary.

Segment 3: 1.36–1.32 Ga

Preliminary results for the Morawa Lavas (ML on Fig. 5), and underlying and overlying sedimentary rocks, yield an APWP vector for the Yilgarn Craton at *c.* 1.36 Ga (Idnurm & Giddings 1988). Intrusion of dolerite at *c.* 1320 Ma (preliminary SHRIMP U–Pb baddeleyite age; Claoué-Long, pers. comm.) was likely responsible for overprints in the Roper Group (RG on Fig. 5) sedimentary rocks (Plumb 1993; Idnurm *et al.* 1995). These results are consistent with a connection between the NAC and WAC prior to 1.3 Ga.

Segment 4: 1.07 Ga

Late Mesoproterozoic palaeopoles (Fig. 5) have been obtained from the Giles Complex (GC on Fig. 5) the Stuart Dykes (SDS on Fig. 5), and the Kulgera Sills (KDS on Fig. 5) in central Australia (Facer 1971; Idnurm & Giddings 1988; Camacho *et al.* 1991). Although the Giles Complex is well dated at 1078 Ma (Glikson *et al.* 1996), the palaeopole [GC on Fig. 5; Facer 1971; recalculated by Tanaka & Idnurm (1994)] was not obtained using modern techniques and is of low reliability. The Stuart and Kulgera Intrusions yielded Sm–Nd isochron ages of 1076±33 and 1090±32 Ma, respectively (Zhao & McCulloch 1993). Reliability of the preliminary SDS palaeopole (Idnurm & Giddings 1988) is difficult to assess because no analytical details have been published. Reliable constraints on palaeohorizontal are not available for the Giles, Kulgera or Stuart Intrusions (no tectonic corrections were applied), and all three suites are located in crustal blocks that were deformed and probably re-oriented during the latest Neoproterozoic (Petermann Ranges) and/or Carboniferous (Alice Springs) tectonothermal events (Tanaka & Idnurm 1994; Wingate *et al.* 2002). The Giles Complex may also have been deformed during the later stages of the Musgrave Orogeny (White *et al.* 1999). A new palaeopole (BBS on Fig. 5), from dolerite sills in the Bangemall Basin, does not agree with the previous *c.* 1070 Ma results, but is significantly more reliable (Wingate *et al.* 2002). The BBS pole is inferred to be primary, is dated precisely at 1070±6 Ma and structural control is well defined in adjacent sedimentary rocks. Discrepancies between the BBS pole and *c.* 1070 Ma poles from central Australia could be due to inadequate tectonic corrections for the central Australian poles, unrecognized overprints (GC and SDS on Fig. 5), and/or differences in age.

Palaeomagnetic data for the latest Mesoproterozoic are thus inadequate to demonstrate that Australia had amalgamated by this time, although this interpretation is supported by the crude grouping of the *c.* 1070 Ma poles (Fig. 5). A palaeopole (WTC on Fig. 5) for the dolomite cap of the Walsh Tillite of the Kimberley Block was proposed to indicate a Sturtian (*c.* 750–700 Ma) age for that unit (Li 2000*b*), despite other evidence indicating a correlation with the Marinoan (c. 600 Ma) glacial interval (Grey & Corkeron 1998). Compelling arguments can be made toward either interpretation and a provocative alternative is proposed here: could similarity between the WTC pole and other Australian poles for 1070 Ma indicate a Late Mesoproterozoic age for some of the glaciogenic rocks in the Kimberley Block?

Discussion

The timing of the Capricorn, Late Barramundi and Halls Creek tectonothermal events was broadly similar at *c.* 1.8 Ga (Fig. 2). Other similarities across the NAC include widely developed low-*P*/high-*T* metamorphic conditions and extensive magmatism with intraplate geochemical signatures (e.g. Etheridge *et al.* 1987; Wyborn 1988; Mortimer *et al.* 1988*a*). Basin evolution across the NAC between *c.* 1.8 and 1.6 Ga (Scott *et al.* 2000) was contemporaneous with deformation in central Australia and the Gawler Craton. The 1.74–1.7 Ga Kimban Orogeny in the Gawler Craton was contemporaneous with the Late Strangways orogenic event in the Arunta Inlier, although rocks older than *c.* 1.6 Ga have not been observed (or preserved) in the intervening Musgrave Block (White *et al.* 1999).

Several geological observations suggest amalgamation of the North, West and South Australian cratonic assemblages prior to 1.3 Ga. Orogenic events at 1.3 and 1.2 Ga in the Albany–Fraser and Musgrave Belts suggest a combined West and North Australian block by 1.3 Ga, although there was continued activity between them, in the Miles Belt (Fig. 3), between 1.3 and 1.1 Ga. Striking similarities in the ages (*c.* 1.8–1.55 Ga) of basin formation, magmatism, mineralization, deformation and styles of alteration among the eastern Gawler Craton, Curnamona Province and the Georgetown and eastern Mount Isa Inliers have prompted several researchers to suggest that these blocks formed part of a regionally extensive Late Palaeoproterozoic–Early Mesoproterozoic mobile belt, referred to as the Diamantina Orogen (Page & Laing 1992; Connors & Page 1995; Laing 1996; Black *et al.* 1998; Robertson *et al.* 1998). This hypothesis implies that the NAC and at least the Curnamona Province of the SAC were joined since at least 1.7 Ga. Note, however, that a Late Mesoproterozoic collisional orogen (Fig. 3) extending between the Musgrave and Cape River Blocks, as suggested by Blewett *et al.* (1998), would preclude the existence of a Late Palaeoproterozoic orogen linking Mount Isa and the Curnamona Province with these blocks in their present relative positions.

Based on a detailed tectonostratigraphic comparison, Giles & Betts (2000) proposed that an anticlockwise rotation of 55° and a slight eastward translation of the SAC relative to the NAC would better align what may have been continuous and linear Palaeoproterozoic–Mesoproterozoic tectonic elements. In their reconstruction, for example, mobile belts of the Arunta and Gawler–Curnamona Blocks would have formed a continuous accretionary margin between 1.88 and 1.67 Ga. Giles & Betts (2000) invoked a cycle of extension and breakup between the SAC and NAC at *c.* 1.45 Ga, with subsequent reamalgamation between 1.3 to 1.1 Ga to yield the present configuration of the cratons. It is intriguing that this reconstruction achieves independent support from palaeomagnetic data to first order. Accepting that both the GR and BDu poles (Fig. 5) represent their respective cratons at *c.* 1.59 Ga (see discussion above), rotation of the SAC craton and the GR pole according to this model (Fig. 6) better aligns the GR and BDu poles along the aggregate APWP from the McArthur Basin (Idnurm 2000). Alignment is still not exact, however, suggesting that the GR and/or BDu poles may not be primary, or that modification of the Giles & Betts (2000) model may be required.

Although it is likely that collisional orogeny did occur by interactions between the Australian crustal blocks and also that intraplate processes can occur within a plate tectonic context, there is no compel-

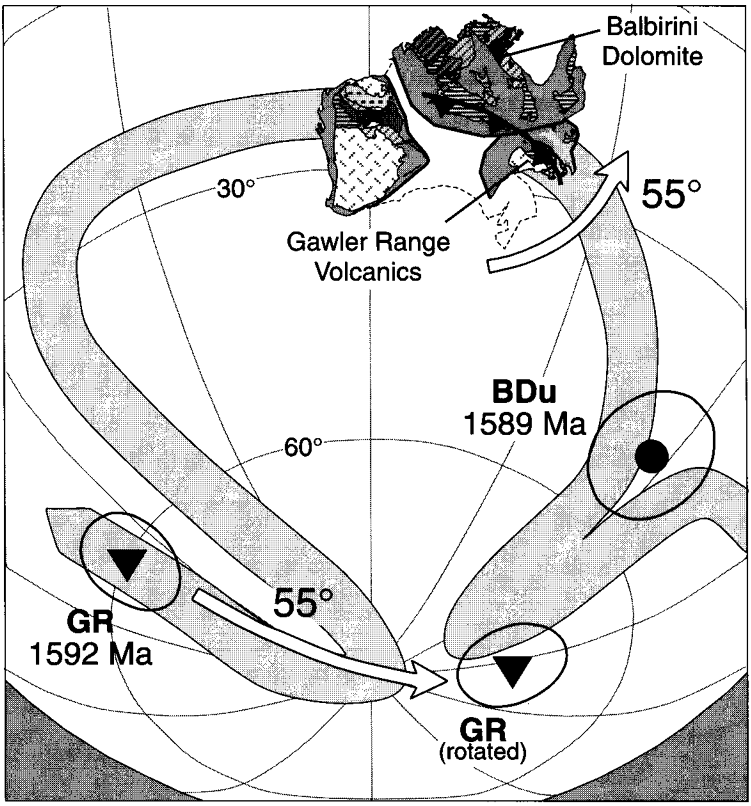

Fig. 6. Restoration of the Gawler Range Volcanics pole (GR) according to the tectonic model of Giles & Betts (2000). Thus restored, the GR pole falls on the apparent polar wander path from the McArthur Basin (Idnurm 2000), but fails to overlap precisely with the pole from the coeval upper Balbirini Dolomite (BDu; Idnurm 2000). See text for discussion.

ling evidence for large ocean basins having closed between any of the Australian blocks since at least 1.8 Ga. Geological and geochemical observations alone are insufficient to test whether the major cratonic blocks of Australia were together or were widely separated during the Proterozoic – conclusive evidence for large horizontal motions of crustal fragments in Australia during the Proterozoic must come from palaeomagnetism. Although the palaeomagnetic record is far from complete, groups of overlapping palaeopoles permit the NAC, WAC and SAC to have occupied their present relative positions since at least 1.5 Ga, and possibly the NAC and WAC to have been assembled prior to *c*. 1.7 Ga. These conclusions are consistent with the idea that the constituent blocks of Australia were not widely separated since at least 1.8 Ga, which is supported by several pre-1.3 Ga geological correlations, as discussed above.

Despite the recent addition of many high-quality results, the palaeomagnetic database is inadequate to rule out large horizontal motions between the Australian crustal blocks since 1.8 Ga. Ideally, APWP need to be defined for each block. Current studies, however, should focus on obtaining well-dated palaeopoles of precisely the same age from different blocks at several key points in time, from which minimum (i.e. latitudinal) separations can be determined. Reliable palaeomagnetic information will enhance, and provide key tests of, the applicability of plate tectonic interpretations in understanding Australian Proterozoic geology. If models involving large horizontal motions of the Australian fragments during the Proterozoic are correct, support is likely to be found eventually from palaeomagnetism. Until then, however, the single-continent model – perhaps incorporating minor jostlings among its constituent cratons (e.g. Giles & Betts 2000) – should not be discarded.

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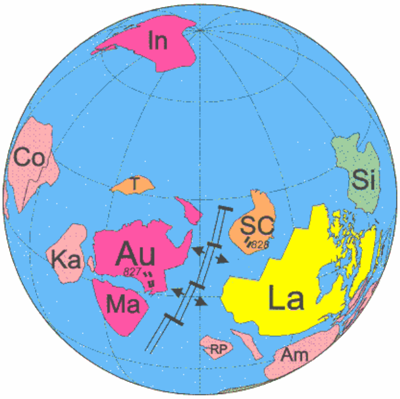
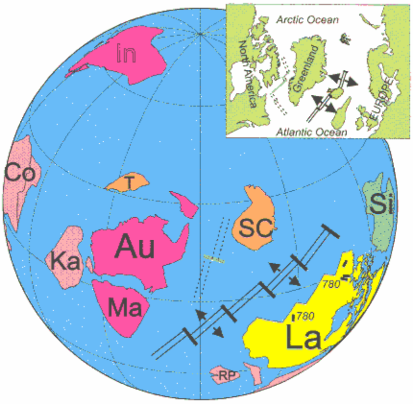


780 - 770 Ma



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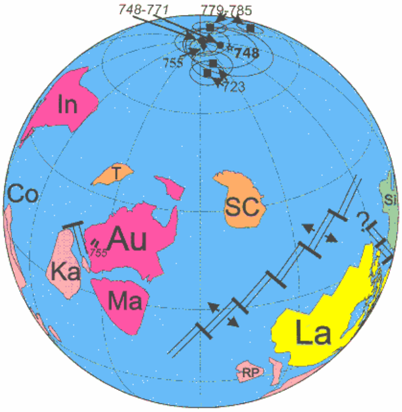

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