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Precambrian and Early Palaeozoic palaeomagnetism in Australia

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The apparent polar wander path for Australia between 750 and 400 million years (Ma) shows rapid polar motion averaging 1°/Ma. The data are derived from stratigraphic sequences, mainly in northern, central and southern Australia, that have good age control. This contrasts with other Gondwanic continents where age control is relatively poor. On the Smith–Hallam reconstruction of Gondwanaland, data from all these continents are consistent with the Australian path and suggest Gondwanaland was a unit at least as far back as 750 Ma ago. The common pole path is consistent with the widespread occurrences of Late Precambrian glacial deposits in Australia and Africa, suggesting their timing and location are related to rapid polar migration. The apparent unity of Gondwanaland through the Pan-African Orogeny at 550 ± 100 Ma provides strong support for the view that these orogenic belts were of ensialic origin.

Extensive Precambrian palaeomagnetic data are consistent with a common apparent polar wander path for Australia back to at least 2500 Ma ago. The average polar wander rate of 0.3°/Ma is similar to that derived for other continents. The consistency of the data irrespective of craton or the presence of some younger intervening orogenic belts provides some support to the view that these belts were also of ensialic origin.

1. Introduction

The problem of whether or not the concepts of plate tectonic theory and its geological consequences can be applied to Precambrian times is now the subject of much debate. There is a general feeling among those who study Precambrian geology that the nature of geological activity has changed during geological time (Sutton & Watson 1974). The major structures have altered although as at the present time they always appear to have formed parts of a global tectonic arrangement. Palaeomagnetic measurements from Precambrian rocks of North America (Irving & Park 1972) and Africa (Piper, Briden & Lomax 1973) have tended to support the view that many of the older orogenic belts occurred by internal deformation and not through plate tectonic processes such as plate convergence. At the present stage the data are too few to make unequivocal statements that plate tectonics did not operate during the early history of the Earth. However, as more data accumulate the remarkable consistency of Precambrian palaeomagnetic results from different parts of the globe is only emphasized further. In this paper we summarize palaeomagnetic data from the Precambrian and Early Palaeozoic of Australia that relate to this problem.

There are two parameters necessary to provide complete palaeomagnetic information from a single study for use in plotting apparent polar wander paths and making deductions concerning the past motions of continents. Besides the position of the palaeomagnetic pole it is necessary to assign an absolute age to the palaeomagnetic data. In the Phanerozoic this is most often provided by palaentological controls, but in the Precambrian it becomes necessary to rely on isotopic information. The two parts to each piece of palaeomagnetic information are of equal

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importance. A well determined palaeomagnetic pole position is of little value if the age to be assigned to it is unknown or known only within broad limits. Indeed it is easy to show that the difficulties with Precambrian palaeomagnetism arise not so much from the acquisition of the palaeomagnetic data but with the determination of isotopic ages of sufficient accuracy.

Table 1. Classification system for palaeomagnetic poles: the total classification is given by the sum $P+A$

		age classification			
palaeomagnetic classification	P	Early Palaeozoic	Late Precambrian (1000–600 Ma)	Precambrian (> 1000 Ma)	A
minimum criteria of McElhinny (1973) (8 samples + stability test)	1	age known within 2 geological periods	± 200 Ma	± 500 Ma	1
minimum of 4 sites, $A_{95} < 25°$	2	age known within 1 geological period	± 100 Ma	± 200 Ma	2
minimum of 4 sites, 15 samples, $A_{95} < 15°$	3	age known to subdivision of a geological period	± 50 Ma	± 100 Ma	3

Palaeomagnetic measurements from different parts of the world covering different time spans suggest that apparent polar wander paths have rates typically about 0.3°/Ma (McElhinny 1973). In the early Precambrian it is often difficult to determine isotopic ages to better than ± 100 Ma. This means that the proper location of poles along an apparent polar wander path may not be known to better than ± 30° irrespective of the polar errors assigned by the palaeomagnetic data. When considering palaeomagnetic results therefore it is necessary to consider the combined effects of the polar errors and accuracy of age. The technique used here is to assign a maximum score of three points to each of the two pieces of information according to the scheme outlined in table 1. The palaeomagnetic constraints remain unchanged with age but a three tier system is used depending upon the age range when assigning points for isotopic ages. The scheme is a simpler and rather more lenient version of one proposed by Stewart & Irving (1974). It has been tailored to the data being considered at the present time. In the future it will obviously be appropriate to use more stringent criteria.

The points allocated to each pole position are added to give a maximum of 6 points. These are the best determined points and are referred to as key poles. According to the total points allocated to each determination pole positions are given three classifications as follows:

key poles	6 points,
subsidiary poles	4 or 5 points,
supporting poles	2 or 3 points.

In the discussion that follows we shall consider the data in two groups, first those points younger than 1000 Ma and later all Precambrian data.

2. Australian data younger than 1000 Ma

Figure 1 shows the various sampling localities for rocks younger than 1000 Ma and older than about 400 Ma (Siluro–Devonian) from the main part of the Australian continent. We exclude data from the Tasman Orogenic Zone for which a separate geological history has already been argued (McElhinny & Embleton 1974). Pole positions and age information are

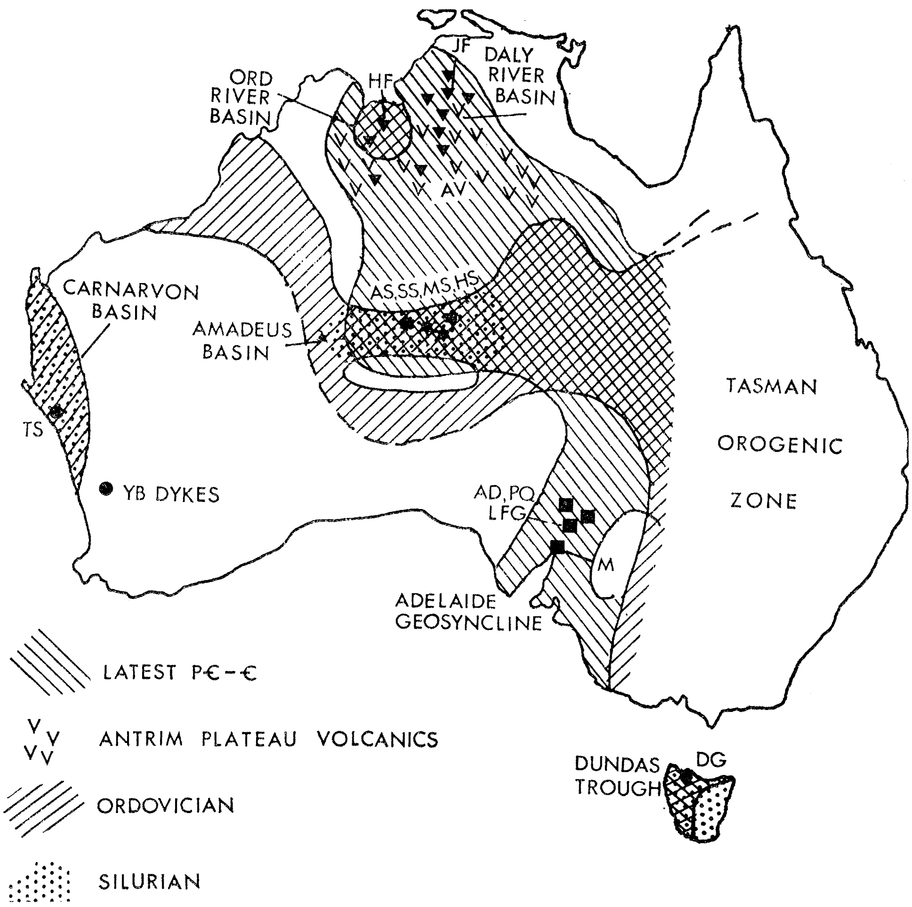

FIGURE 1. The distribution of Late Precambrian to Silurian sediments on the Australian platform (outside the Tasman Orogenic Zone). Sampling localities for palaeomagnetic investigations are indicated.

TABLE 2. LATE PRECAMBRIAN (< 1000 Ma) AND EARLY PALAEOZOIC PALAEOMAGNETIC POLES FOR AUSTRALIA

(The rotated pole position is that with Australia rotated to the Smith & Hallam (1970) reconstruction of Gondwanaland and with Africa remaining fixed in its present day coordinates. The classification $P+A$ is according to table 1.)

			position		
rock unit	symbol ($P+A$)	age	pole	rotated pole	reference
YB dykes	YB (1+3)	750 ± 30 Ma	20° S, 282° E	26° S, 296° E	Giddings (1975)
Marinoan glacial sediments	M	*ca.* 700 Ma	(palaeolatitude 80°)		Briden (1967 *a*)
Pound quartzite	PQ (2+2)	latest Pr. Є	60° S, 6° E	5° S, 6° E	Embleton & Giddings (1974)
Antrim Plateau Volcanics	AV (2+2)	Pr/Єl	9° S, 340° E	26° N, 319° E	McElhinny & Luck (1970)
Arumbera Sandstone	AS (2+2)	Pr/Єl	8° N, 325° E	24° N, 294° E	Embleton (1972 *a*)
Aroona Dam sediments	AD (2+3)	Єl	36° S, 33° E	21° N, 20° E	Embleton & Giddings (1974)
Hugh River Shale	HS (1+3)	Єl-m	11° N, 37° E	68° N, 33° E	Embleton (1972 *a*)
Hudson Formation	HF (3+3)	Єl	18° N, 19° E	72° N, 338° E	Luck (1970)
Lake Frome Group	LFG (3+3)	Єm-u (Ol)	14° S, 24° E	43° N, 8° E	Embleton & Giddings (1974) Briden (1967 *b*)
Dundas Group	DG (1+3)	Єu	23° S, 13° E	31° N, 358° E	Giddings & Embleton (1974)
Jinduckin Formation	JF (3+3)	Ol	13° S, 25° E	44° N, 10° E	Luck (1970, 1972)
Stairway Sandstone	SS (2+3)	Om	2° S, 50° E	51° N, 49° E	Embleton (1972 *b*)
Tumblagooda Sandstone	TS (3+2)	O	30° S, 31° E	27° N, 18° E	Embleton & Giddings (1974)
Mereenie Sandstone	MS (2+2)	S?-D	41° S, 40° E	16° N, 25° E	Embleton (1972 *b*)

listed in table 2 together with their classifications according to the scheme of table 1. The apparent polar wander path deduced from these data is illustrated in figure 2.

A striking feature of the Early Palaeozoic data is the large shift of the pole during the Cambrian. This is observed both in Northern Australia and the Amadeus Basin (Embleton 1972*a*; McElhinny & Embleton 1974). Near the Cambro/Ordovician boundary there is a clustering of poles from five parts of Australia strongly suggesting the unity of the main part of the Australian continent for the past 500 Ma. There is only limited information available prior to the Precambrian/Cambrian boundary (represented by poles for the Antrim Plateau Volcanics of

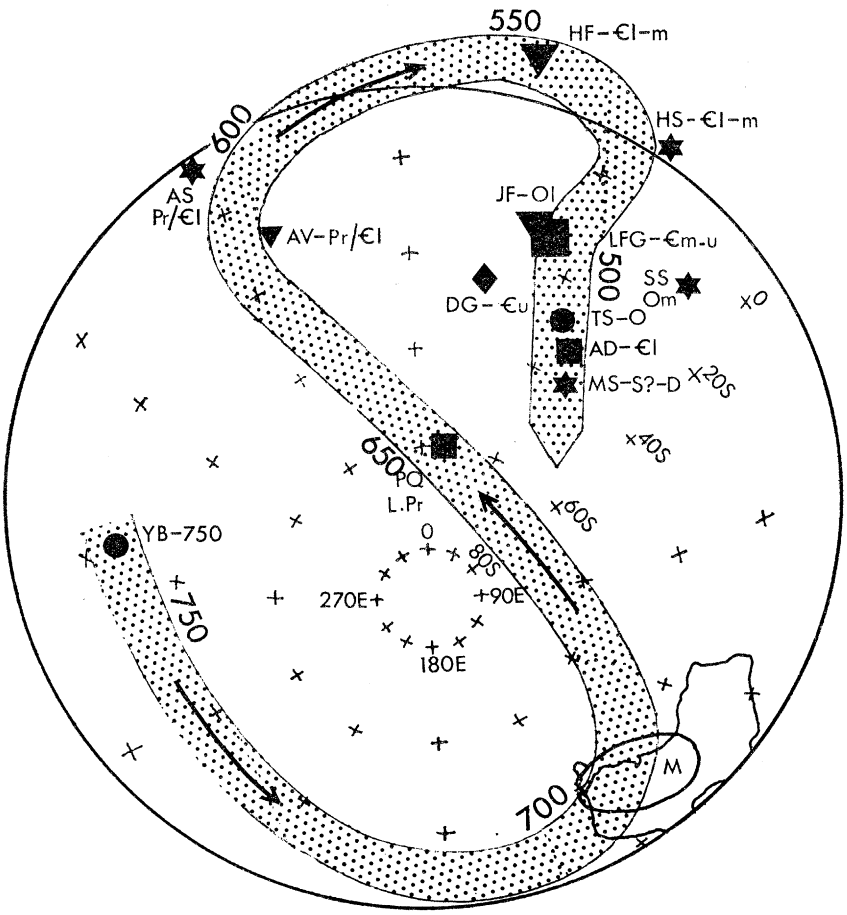

Figure 2. Apparent polar wander path for the main Australian platform for the period 750–400 Ma ago. The symbols correspond to the sampling localities in figure 1 and table 2. The symbols are plotted in three sizes depending on the total classification ($P+A$) of table 1. Large symbols, 6 points; intermediate, 4 or 5 points; small, 2 or 3 points. M is the locus of possible pole positions from borecore inclinations.

Northern Australia and the Arumbera Sandstone of the Amadeus Basin) and younger than 1000 Ma. Deposition of the Arumbera Sandstone was initiated during the final stages of the Petermann Ranges Orogeny, which affected the southern margin of the Amadeus Basin, and continued when orogenic activity ceased (Wells, Forman, Ranford & Cook 1970). Daily, Jago & Milnes (1973) regard the principal phase of this orogeny as post-Ediacaran. The Ediacaran fauna is preserved in the upper member of the Pound Quartzite. The palaeomagnetic pole for the Pound Quartzite was however derived from the pre-Ediacaran lower member and therefore clearly pre-dates the Arumbera Sandstone. The Pound Quartzite pole lies 50° away from the poles for the Arumbera Sandstone and Antrim Volcanics and extends the pole path back into the Late Precambrian.

Throughout Australia sedimentary sequences generally record the presence of two distinct tillite horizons (see Dunn, Thompson & Rankama 1971) indicating continental glaciation in the Late Precambrian. Latitude control on the youngest of these glacial horizons, the Marinoan glaciation, is provided by inclination data reported from two borecores in South Australia (Briden & Ward 1966, Briden 1967*a*). Early Marinoan sediments gave shallow inclinations of 41° and 36° in the two borecores (palaeolatitudes of 24° and 20° respectively) while the Marinoan glacial beds in one borecore gave a mean inclination of 85° (equivalent palaeolatitude 80°). The Marinoan glacials are overlain by the Wilpena Group of which the Pound Quartzite is the youngest member. These borecore inclinations are consistent with the extension of the pole path back from the Pound Quartzite to the YB dykes† of Western Australia (750 Ma) as shown in figure 2. Steep inclinations from the Marinoan glacials indicate the pole must lie within 10° of the sampling locality (the locus of possible pole positions is shown by the oval in figure 2), hence the pole was situated close to Southern Australia at the time of the Marinoan glaciation (about 700 Ma ago).

Between 750 and 400 Ma ago the apparent polar wander path of figure 2 suggests polar movement of 360° with respect to Australia, an average rate of at least 1°/Ma. This is considerably greater than the rates of about 0.3° per million year observed during the Phanerozoic (McElhinny 1973).

3. A comparison with Gondwanaland

It is interesting now to compare the pole path derived for Australia between 750 and 400 Ma ago with results from the rest of Gondwanaland. To do this we have rotated all the data for Australia (table 1) and other parts of Gondwanaland (table 3) for this time interval to conform with the Smith & Hallam (1970) reconstruction. Palaeomagnetic evidence from the southern continents strongly suggests this to be correct (McElhinny & Embleton 1974; Embleton & McElhinny 1975). The resulting plot is shown in figure 3.

Although the pole path for Australia can be determined sequentially from stratigraphic relations, this is not so for any of the other continents. Therefore the approach made is to demonstrate that the data from the other continents are still consistent with the Australian path after reconstruction. Examination of figure 3 shows that this is indeed the case. In plotting the data for the Salt Range (McElhinny 1970; Wensink 1972) we have rotated the two pole positions according to the hypothesis of Crawford (1974). This supposes that the Salt Range has been rotated through 75° in a counter-clockwise direction about a nearby Euler pole. The consistency of the Gondwanaland data extends back to about 750 Ma when there is excellent agreement between the well-dated 750 Ma YB dykes pole from Australia and the 745 Ma Malani Rhyolite pole from India. Prior to 750 Ma ago the data are exclusively from Africa. At 1150 Ma (Lake View dolerite, Australia) there appears to be no relation between poles from Africa and Australia.

The overall agreement between Gondwanic palaeomagnetic data between 750 and 400 Ma has two important consequences. The first is that this time interval includes the period of the

† Giddings (1975) has subdivided the various dyke swarms of the Yilgarn Block into six periods of intrusion based on groupings of palaeomagnetic directions and Rb–Sr data. The groups of dykes have been arbitrarily labelled YA to YF and range in age from 2500 to 750 Ma (see §4.2).

TABLE 3. PALAEOMAGNETIC POLE POSITIONS FROM THE GONDWANIC CONTINENTS OTHER THAN AUSTRALIA FOR THE PERIOD 1000–400 Ma

(The rotated pole positions are those for each continent rotated to the Smith & Hallam (1970) reconstruction and with Africa remaining fixed in its present-day coordinates. African data compiled from Piper (1972), Piper *et al.* (1973) and McElhinny *et al.* (1974), Arabian data from Burek (1969). Other points are given in McElhinny *et al.* (1974). The classification $P+A$ is according to table 1.)

rock unit	symbol $(P+A)$	age	pole position	rotated pole
AFRICA				
Kigonero Flags	KE (1+1)	> 890 Ma	12° N, 273° E	—
Kleinkaras dykes	KK (1+1)	*ca.* 878 Ma	20° N, 294° E	—
Gagwe Lavas	G (3+2)	813 Ma	29° N, 113° E	—
Bukoban intrusives	BI (2+2)	806 Ma	11° N, 101° E	—
Malagarasi Sandstone	MS (1+1)	1200–800 Ma	7° N, 112° E	—
Manyovu Redbeds	MB (1+2)	< 813 Ma	24° N, 118° E	—
Mbozi Complex	MC (3+2)	743 Ma	72° N, 68° E	—
Lower Buanji Series	LB (3+0)	< 1350 Ma	87° N, 263° E	—
Pre-Nama dykes	ND (2+2)	653 ± 70 Ma	85° N, 228° E	—
Plateau Series, Zambia A	PZA (2+0)	< 1000 Ma	71° N, 173° E	—
Plateau Series, Zambia B	PZB (2+0)	< 1000 Ma	60° N, 25° E	—
Ouarzazate Volcanics	OV (2+1)	Pr/Ꞓ	30° N, 237° E	—
Sijarira Group	SG (2+1)	Pr/Ꞓ	2° N, 352° E	—
Ntonya Ring Structure	N (3+3)	630 ± 24 Ma	28° N, 345° E	—
Klipheuvel Formation	K (2+1)	Pr/Ꞓ	16° N, 316° E	—
Amouslek Tuffs	AT (2+1)	Ꞓl	41° N, 250° E	—
Sabaloka Ring Structure	SR (3+0)	> 540 Ma	83° N, 339° E	—
Fish River Series	FR (1+1)	Pr/Ꞓ	55° N, 137° E	—
Moroccan Lavas	MRL (1+2)	Ꞓm	53° N, 34° E	—
Table Mountain Series	TM (1+1)	O	50° N, 349° E	—
Hook Intrusives	HI (1+2)	500 ± 17 Ma	14° N, 336° E	—
Plateau Series, Zambia C	PZC (2+1)	Lr. Pal	10° N, 172° E	—
Plateau Series, Zambia D	PZD (1+1)	Lr. Pal	22° N, 19° E	—
ARABIA				
Jordanian Redbeds	JRD (3+1)	Ꞓ (-O)	37° N, 323° E	41° N, 321° E
ANTARCTICA				
Charnockites	C (3+3)	Ꞓu-Ol	2° N, 208° E	49° N, 14° E
Sør Rondale Intrusives	SRI (2+3)	Ol-m (485 ± 25 Ma)	28° N, 190° E	18° N, 15° E
INDIA				
Malani rhyolites	MR (3+3)	745 ± 10 Ma	78° N, 45° E	40° S, 282° E
Bhander Sandstone	BH (3+1) >	Pr/Ꞓ	49° N, 213° E	15° S, 335° E
Upper Rewa Sandstone	UR (1+1)	Pr/Ꞓ	35° N, 222° E	11° S, 350° E
Upper Bhander Sandstone	UB (3+1)	Pr/Ꞓ	32° N, 199° E	4° N, 339° E
Purple Sandstone	PS (2+3)	Ꞓl	28° N, 346° E†	71° N, 357° E
Salt Pseudomorph Beds	SP (2+3)	Ꞓm	30° N, 354° E†	66° N, 13° E
SOUTH AMERICA				
Purmamarca Village	PV (1+2)	Ꞓ	61° N, 293° E	36° N, 295° E
South Tilcara	ST (1+2)	Ꞓ	52° N, 27° E	82° N, 329° E
North Tilcara	NT (1+2)	Ꞓ	49° N, 23° E	80° N, 350° E
Purmamarca	P (1+2)	Ꞓ	5° N, 39° E	45° N, 80° E
Abra de Cajas	AC (1+2)	Ꞓ	2° N, 28° E	41° N, 66° E
Salta and Jujuy	SJ (1+1)	Ꞓ-O	12° N, 329° E	22° N, 358° E
Salta	S (1+2)	O	31° N, 13° E	63° N, 25° E
Sediments, Bolivia	SB (1+2)	O	4° N, 302° E	1° S, 342° E
Urucum Formation	UF (1+1)	O-S	17° N, 347° E	37° N, 10° E

† Pole position rotated according to hypothesis of Crawford (1974) involving 75° rotation of the Salt Range about at pole at 33° N, 74° E.

so-called Pan-African belts whose ages cluster around 550 ± 100 Ma (Clifford 1968). This provides strong evidence against a plate convergence model for these belts (Hurley 1972; Burke & Dewey 1972). It does not completely exclude such models but restricts them to rather special cases involving the opening and closing of intercratonic oceans generally in an east–west rather than north–south direction. General support is therefore provided for an

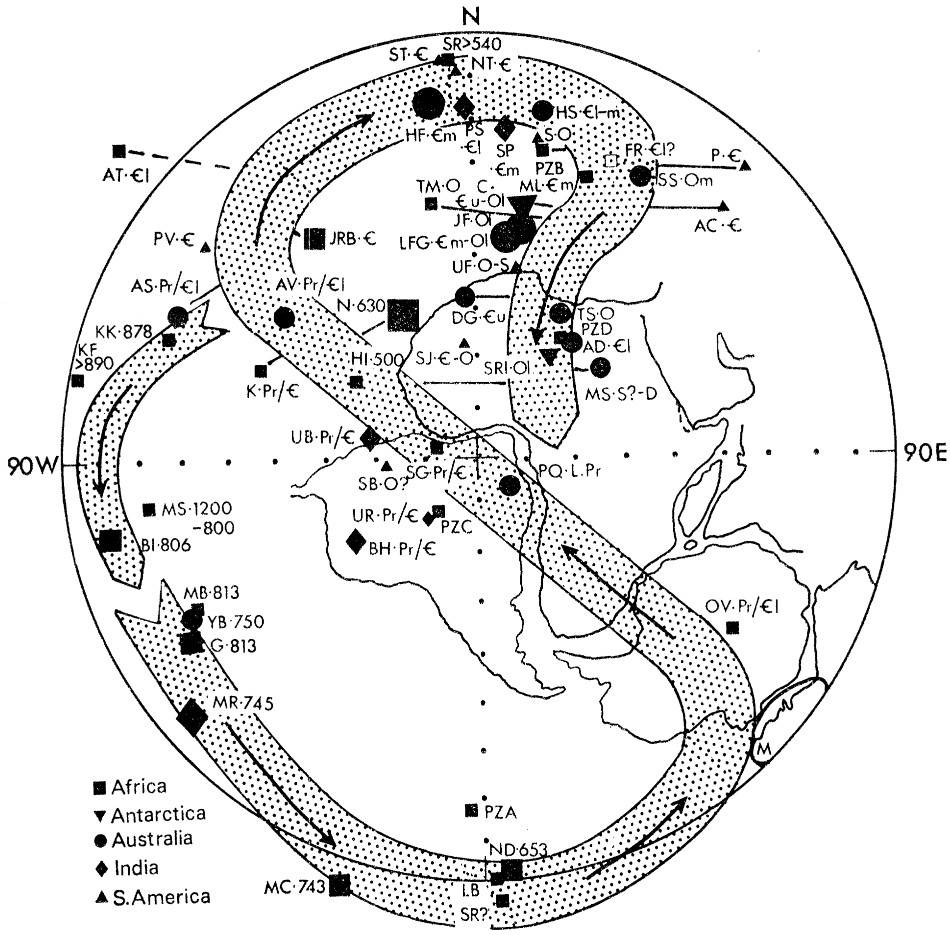

Figure 3. Pole positions for the Gondwanic continents from 1000 to 400 Ma plotted on the Smith & Hallam (1970) reconstruction and compared with the Australian path of figure 2. Data of tables 2 and 3 plotted in different size symbols as explained in figure 2. Present coordinates of Africa are used for the reconstruction.

ensialic origin of these belts (Clifford 1968, 1970; Shackleton 1969, 1973). The joint pole path for Gondwanaland predicts that the pole swept across the supercontinent from Australia to northwest Africa between about 700 Ma ago and the Precambrian/Cambrian boundary (about 600 Ma ago). A consequence of this prediction is that there should be extensive occurrences of Late Precambrian glacial deposits during this time interval across Gondwanaland. This has been discussed previously by McElhinny, Giddings & Embleton (1974) but in this paper we have modified the overall pole path to take account also of the Australian Marinoan glaciation.

In figure 4 the occurrences of Late Precambrian glacial deposits in Gondwanaland are compared with the combined pole path derived in figure 3. As predicted by the pole sequence these deposits get younger from east to west. Although the age of the Marinoan glaciation in

Australia is based upon Rb-Sr dating of shales, interpretation of these ages in terms of age of deposition is a matter of conjecture. However there appears to be good evidence to suggest the age of this glaciation is around 700 Ma (Dunn *et al.* 1971). In southwest Africa glacial horizons occur in the upper part of the Damara and Nama Systems. Immediately underlying the Nama System are the Blaubeker Formation glacials and the Bushmannsklippe tillite. These are

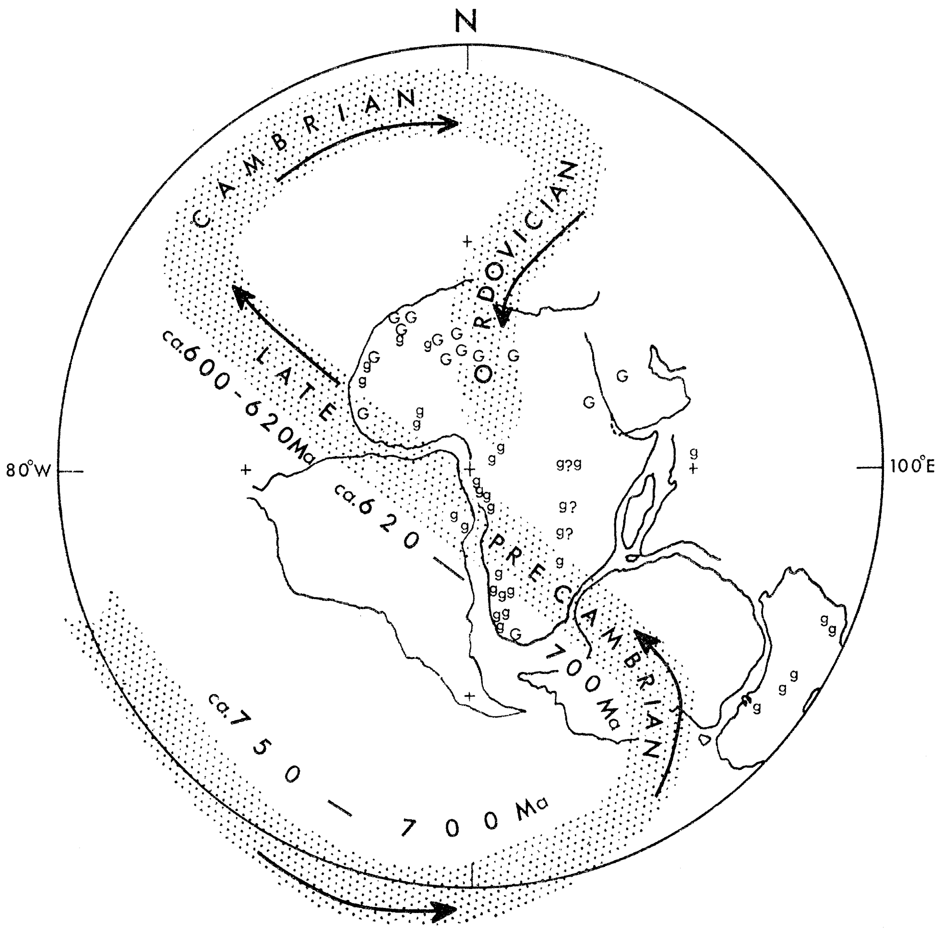

Figure 4. The pole path of figure 3 from 750 to 400 Ma ago compared with the distribution of Late Precambrian (g) glacial deposits and Late Ordovician (G) glacial deposits.

correlated with the Numees Formation glacial deposits. The Blaubeker–Bushmannsklippe–Numees glacials are probably in the time scale 700–650 Ma. In northwest Africa the Saharan 'Eocambrian' tillite has been dated at 650–620 Ma (Biju-Duval & Gariel 1969) and the Oti tillite of Ghana has a minimum age of 620 Ma (Trompette 1972). This succession strongly suggests that the centres of glaciation migrated westwards between 700 and 600 Ma ago following the path of the pole as it swept from east to west across Gondwanaland.

During the Cambrian the broad trends of climatic change are perceptible in North Africa. Eocambrian glacial deposits give way to thick successions of Lower Cambrian warm water deposits (King 1961). Cambrian rocks are frequently brightly coloured and include redbeds suggestive of a warm climate, but they give way to more drab Ordovician sequences culminating in the great, Late Ordovician, Saharan glaciation (Beuf, Biju-Duval, Stevaux & Kulbicki 1966). These climatic trends are compatible with the pole path of figures 3 and 4.

From near polar conditions in northwest Africa the broad loop taken by the pole during the Cambrian placed North Africa in low latitudes with a return to intermediate, and finally polar, latitudes during the Ordovician. The general agreement of the palaeoclimatic evidence with the pole path provides strong independent support for its validity.

FIGURE 5. Simplified structural map of Australia showing the main features of the Precambrian. Basement ages are given in units of Ga and palaeomagnetic sampling localities are indicated. N, Nullaginian sediments (2.3–1.8 Ga); C, Carpentarian sediments (1.8–1.4 Ga); A, Adelaidean sediments (1.4–0.6 Ga); P, Phanerozoic sediments (< 0.6 Ga).

4. Precambrian of Australia

(a) Geology

The Precambrian geology and geochronology of Australia is summarized in the simplified map of figure 5. Age information has been summarized previously by Compston & Arriens (1968), Arriens (1971) and De Laeter & Blockley (1972). The largest Precambrian nucleus is the Yilgarn Craton of Western Australia with basement ages ranging from 3100 to 2700 Ma. To the north it is separated from the Pilbara Craton (basement ages 3100–2900 Ma) by the younger Opthalmian mobile belt whose age is about 1700 Ma. To the south and southeast the Yilgarn Craton is bounded by the Albany–Fraser mobile belt with ages lying between 1300 and 1000 Ma. This pattern of ancient Precambrian cratons separated and surrounded by younger mobile belts is closely analogous to that reported from Africa (Clifford 1970; Glikson & Lambert 1973). Arriens (1971) has suggested that the contrasting geochronology of the Pilbara and Yilgarn Cratons indicates they must have been widely separated from one another during much of the Archaean. It is not clear as yet however whether the southerly younger Albany–Fraser belt represents a suture between colliding continents (Glikson & Lambert 1973).

The basement ages from the other Precambrian cratons are much younger than observed in the Yilgarn and Pilbara Cratons and generally do not exceed 1800 Ma. They are separated from one another by later Phanerozoic cover so that the relation between them is not clear. However Davidson (1973) believed that in the Musgrave mobile belt of central Australia there is an example of Proterozoic plate tectonics in which a proto-Musgrave Craton and a subducting Arunta Craton collided along a convergent plate boundary. Suturing occurred along a belt now marked by the Giles complex mafic–ultramafic sequence and major thrust faults. This event probably occurred around 1400 Ma ago or later. An alternative view, however, is that this tectonic event was a result of intracontinental mobility (Duff & Langworthy 1974). The Mt Isa mobile belt and the Adelaide Geosyncline were probably marginal to a Proterozoic Australian continent since the eastern part of the present continent is largely devoid of Precambrian rocks and occupied by the Palaeozoic Tasman Orogenic Zone.

Proterozoic sedimentary basins occupy parts of the Precambrian platform and they have been subdivided into three divisions according to the proposal of Dunn, Plumb & Roberts (1966). Nulliginian sediments of age between 2300 and 1800 Ma are mainly represented in the Hammersley Basin overlying the Pilbara Craton of Western Australia. Carpentarian sediments (1800–1400 Ma) occupy wide regions of northern Australia while Adelaidean sediments (1400–600 Ma) occur mainly in the southern and northwest parts of the continent. The Kimberley Basin of northwest Australia (Carpentarian and Adelaidean in age) is bordered to the south by the King Leopold mobile belt and to the east by the Halls Creek mobile belt with ages in the range 1900–1700 Ma.

(*b*) *Palaeomagnetic results*

Table 4 summarizes the Precambrian palaeomagnetic data for Australia. The poles are classified according to the scheme of table 1 and sampling localities are indicated in figure 5. In some instances the age constraints are rather poor but this is offset by the fact that the sequence of poles is known also from cross-cutting relations (Giddings 1975). Studies of the numerous dyke swarms of the Yilgarn Craton have shown that of the six ages so far identified (YA to YF), the relative ages must conform with the observation that YA is older than YC which in turn is older than YB (YA > YC > YB), and YD is older than YC (YD > YC). Unfortunately the age assigned to the YA group of dykes is equivocal from Rb-Sr data and they could be either about 2500 Ma or about 1700 Ma in age. Both these ages are consistent with the relative and absolute ages determined for the other dyke suites.

Until recently most Precambrian palaeomagnetic data from Australia had been derived from various iron ore bodies of Western Australia (Porath & Chamalaun 1968) and South Australia (Chamalaun & Porath 1968). Consequently attempts to draw apparent polar wander paths have been purely speculative (Facer 1974). The haematite ore bodies occur in both Archaean and Proterozoic banded iron formations (Trendall 1973). In the Mt Goldsworthy region (Pilbara Craton) the lode ores are considered to be a post-tectonic hypogene enrichment of the banded iron formation by hydrothermal-metamorphic reconcentration of the iron. Two poles (MG1 and MG3) were obtained from the lode ore. Porath & Chamalaun (1968) suggested that the samples giving pole MG3, which come from the outer zones of the lode ore, may represent the early stages of ore forming process, envisaged as progressing inwards from the outer zones. The crust ore (MG2) is considered to be of supergene origin and to post-date the lode ores. The age sequence of poles from Mt Goldsworthy is therefore MG3 > MG1 > MG2. The banded iron formations have a minimum age of 3050 ± 180 Ma determined from granites of the Pilbara Craton (De Laeter & Blockley 1972). A conglomerate

Table 4. Precambrian palaeomagnetic poles for Australia

(The classification $P+A$ is according to table 1. Cross-cutting relations suggest YA > YC > YB and YD > YC in age.)

rock unit	symbol ($P+A$)	age Ma	pole position	reference
dykes, group YE	YE (1+2)	2500 ± 200	28° N, 180° E	Giddings (1975)
Ravensthorpe dykes	RD (2+3)	2500 ± 100	38° N, 316° E	Giddings (1975)
Widgiemooltha dykes	WD (3+3)	2420 ± 30	9° N, 337° E	Evans (1968)
dykes, group YA	YA (2+1)	*ca.* 2500 or *ca.* 1700	22° N, 314° E	Giddings (1975)
Mt Goldsworthy lode ore	MG3 (3+1)	3000–2000	31° N, 330° E	Porath & Chamalaun (1968)
Mt Goldworthy lode ore	MG1 (3+0)	< MG3	20° N, 84° E	Porath & Chamalaun (1968)
Mt Goldsworthy crust ore	MG2 (2+0)	< MG1	22° N, 259° E	Porath & Chamalaun (1968)
Koolyanobbing-Dowd's Hill	KD (3+1)	2750–2200	43° N, 356° E	Porath & Chamalaun (1968)
Koolyanobbing-'A' deposit	KA (1+0)	—	26° N, 92° E	Porath & Chamalaun (1968)
Mt Tom Price	TP (3+2)	*ca.* 1800	22° N, 57° E	Porath & Chamalaun (1968)
Mt Newman	MN (3+2)	*ca.* 1800	17° N, 66° E	Porath & Chamalaun (1968)
Hart dolerite	HD (2+3)	1800 ± 25	29° N, 46° E	McElhinny & Evans (1975)
Edith River Volcanics	ERV (2+3)	1760	6° N, 346° E	Irving & Green (1958)
dykes, group YF	YF (3+2)	*ca.* 1700	25° N, 102° E	Giddings (1975)
dykes, group YD	YD (3+2)	*ca.* 1700	24° N, 226° E	Giddings (1975)
dykes, group IA	IA (1+2)	< 1750	12° N, 300° E	Duff & Embleton (1975)
dykes, group YC	YC (3+2)	< 1500	80° N, 3° E	Giddings (1975)
dykes, group GB	GB (3+3)	1700 ± 100	23° N, 266° E	Giddings & Embleton (1975)
dykes, group GA	GA (3+2)	1500 ± 200	61° N, 231° E	Giddings & Embleton (1975)
Iron Monarch, pos. group	IMp (3+2)	1800–1500	15° N, 272° E	Chamalaun & Porath (1968)
Iron Monarch, neg. group	IMn (3+2)	1800–1500	64° N, 267° E	Chamalaun & Porath (1968)
Iron Prince	IP (3+2)	1800–1500	39° N, 247° E	Chamalaun & Porath (1968)
Lunch Creek Lopolith	LC (3+3)	1498 ± 70	63° N, 21° E	Duff & Embleton (1975)
Morowa Lavas	ML (2+2)	1390 ± 140	43° N, 22° E	Giddings (1975)
Giles Complex	GC (1+2)	1250–1140	68° N, 343° E	Facer (1971)
Lake View dolerite	IB (2+3)	1149 ± 12	58° N, 282° E	Duff & Embleton (1975)
dykes, group YB	YB (1+3)	750 ± 30	20° N, 102° E	Giddings (1975)
Pound Quartzite	PQ (2+2)	latest Pr.	60° N, 186° E	Embleton & Giddings (1974)

belonging to the Mt Bruce Supergroup contains cobbles of lode ore. The source lode ore was therefore in existence prior to 1950 Ma, the estimated minimum age of the Mt Bruce Supergroup (Compston & Arriens 1968). This suggests that the oldest of the lode ore poles (MG3) is constrained within the rather broad limits of 3000–2000 Ma ago.

The ore bodies of the Koolyanobbing Hills in the Yilgarn Craton comprise a number of irregular lenses. In the Dowd's Hill deposit, two generations of haematite ore are recognized, the younger being in the form of veins of specular haematite resulting from hydrothermal activity in the region. The veins cut older massive geothite ore which gave similar directions of magnetization. Porath & Chamalaun (1968) therefore related the magnetization to the hydrothermal activity whose age is most likely within the time span 2750–2200 Ma, a period of widespread granite emplacement and basic intrusion (Compston & Arriens 1968; Arriens 1971). In table 4 a pole has also been calculated from a group of samples from the 'A' deposit at Koolyanobbing (Porath & Chamalaun 1968). There is no age information associated with this pole.

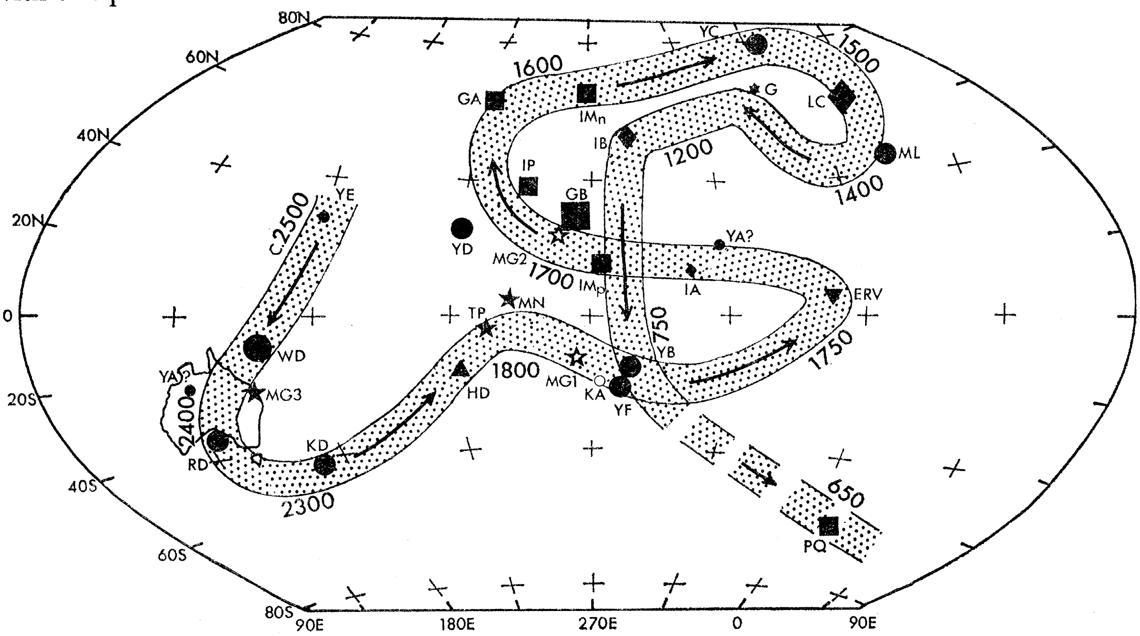

FIGURE 6. Precambrian apparent polar wander path for Australia. The symbols correspond to the sampling localities of figure 5. Data of table 4 plotted in different size symbols as explained in figure 2. Approximate ages in Ma are indicated for various sections of the path.

Banded iron formation in the Hamersley Basin belong to the Hamersley Group of the Mt Bruce Supergroup. The Hamersley Group lies between 2200 and 2000 Ma (Compston & Arriens 1968). The ore bodies are located in favourable structures, such as synclinal troughs, generated by folding of the Opthalmian Orogeny of age about 1800 Ma. Two ore bodies one at Mt Tom Price and the other at Mt Newman were sampled by Porath & Chamalaun. In South Australia, Chamalaun & Porath (1968) studied the ore bodies of the Middleback Ranges at Iron Monarch and Iron Prince. The age of the basement is 1780 ± 120 Ma (Compston & Arriens 1968) and a minimum age of the Middleback Group is given by an age of 1535 ± 20 Ma determined for the Corunna Conglomerate (Compston, Crawford & Bofinger 1966). The conglomerate contains pebbles of haematite ore (Miles 1955) as well as cobbles of banded iron formation. The ore bodies thus lie between 1800 and 1500 Ma.

(*c*) *Apparent polar wander path*

Our overall interpretation of the Precambrian palaeomagnetic data for Australia is given in figure 6. Without violating any of the age constraints it is possible to join the poles in sequence to form a single apparent polar wander path. The path is defined irrespective of the region from which the results are derived. The data can be imagined to be restricted to a swathe of width 10°–15° and in figure 6 approximate ages corresponding to various points along the path are indicated. The rate of polar movement is not uniform, although this may be due to scarcity of data at particular time intervals. The average rate of polar wander is 0.3°/Ma, although between 1800 and 1200 Ma the average rate is much higher at 0.7°/Ma. This time interval covers the Carpentarian of Australia (1800–1400 Ma) and extensive deposits of this age occur

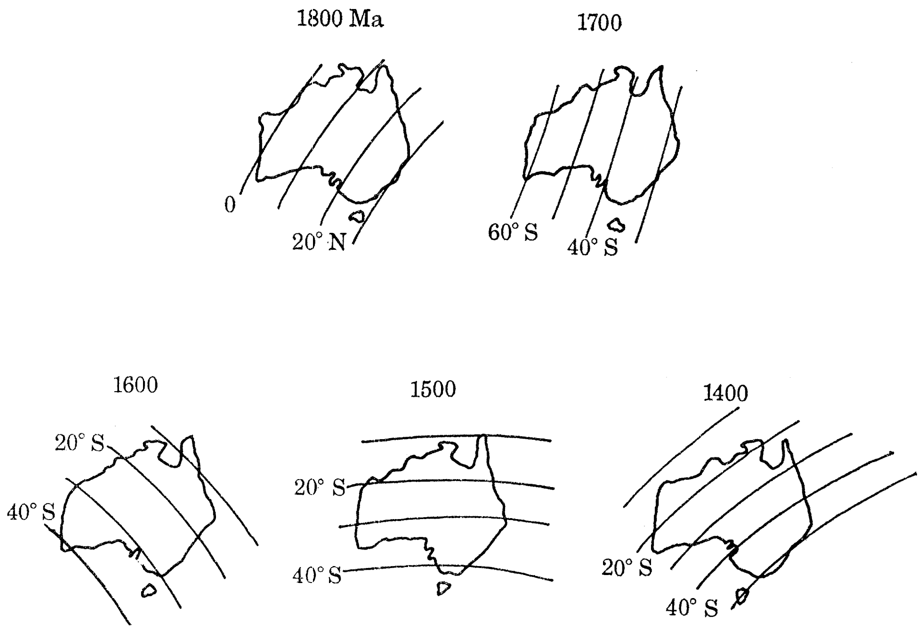

FIGURE 7. Palaeolatitudes of Australia at 100 Ma intervals through the Carpentarian from the pole path of figure 6.

in northern Australia (figure 5). The path however is largely derived from measurements in southern Australia in the Yilgarn and Gawler Cratons. By using the apparent polar wander path of figure 6 the palaeolatitudes of Australia can be drawn at 100 Ma intervals through the Carpentarian as shown in figure 7. This shows that the palaeolatitudes of the northern part of Australia were consistently low throughout this time in spite of the fact that the pole path exhibits a number of loops and bends. This is in excellent agreement with the palaeoclimate evidence derived from Carpentarian sequences of northern Australia. According to Brown, Campbell & Crook (1968) the widespread accumulation at this time of carbonates, including stromatolite reefs, suggests that a tropical climate then prevailed over northern Australia.

The data for ages greater than 1800 Ma are derived exclusively from the Yilgarn Craton. Therefore it is not possible to draw any conclusions regarding the origin of the older mobile belts whose ages are about 1800 Ma (Opthalmian, King Leopold, Halls Creek). The data from rocks younger than 1800 Ma support the view that the Precambrian platform has remained a structural unit since that time. Therefore the data strongly support the view that

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

the younger mobile belts (Albany–Fraser, Musgrave) of about 1300 Ma age are of ensialic origin and were not the result of plate convergence. However, because the data are only constrained to broad swathes that define the apparent polar wander path, it needs to be stressed that certain special plate tectonic situations are not excluded. These involve the opening and closing of small (possibly 1000–1500 km) intercratonic oceans. These special cases will only be excluded after detailed investigations of the palaeomagnetism of rocks situated on either side of one of these belts. Our conclusions from Australian Precambrian palaeomagnetic data are in broad agreement with those derived from African Precambrian data by Piper *et al.* (1973).

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