Exploration Geophysics (1993) **24**, 257–262

An Historical Perspective of the Early Palaeozoic APWP of Gondwana: New Results from the Early Ordovician Black Hill Norite, South Australia

P.W. Schmidt
CSIRO Division of Exploration
and Mining
PO Box 136
North Ryde, NSW 2113

D.A. Clark
CSIRO Division of Exploration
and Mining
PO Box 136
North Ryde, NSW 2113

Shanti Rajagopalan
Department of Geology and Geophysics
University of Adelaide
Adelaide, SA 5001

Abstract

While paleomagnetic pole paths and the palaeo-distribution of the continents is reasonably well understood for the past 200 Ma, there is an urgent need for more reliable Palaeozoic palaeomagnetic poles, especially from the Gondwana continents. The distribution of continents and the disposition and convergence of their margins is an important consideration in conceptual models of terrane accretion. Some continental distributions suggest only small oceans between Laurentia and Gondwana throughout the Palaeozoic, while others suggest a wide oceanic separation existed in the Devonian-Carboniferous. Current thoughts on the Gondwana Palaeozoic pole path may be grouped into, the autochthonous school, the allochthonous school and the Kanimblan overprinting push. The pole position from the Black Hill Norite, South Australia, suggests that some Australian Cambrian pole positions which plot nearby may be Early Ordovician overprints.

Key words: Black Hill Norite, APWP, Palaeozoic, Delamarian, Gondwana

Introduction

A cursory comparison of Australian Palaeozoic apparent polar wander paths (APWP) since the first compilation by Irving and Green (1958) suggests that there has been a great deal of progress. However, the Palaeozoic APWP for Gondwana is still known only rudimentarily. In a Gondwana reconstruction the Cambrian part of the APWP is somewhere near north Africa, the Permian part is close to Australia and there is controversy concerning how the path gets from one to the other. Some workers prefer a simple path crossing Africa from the northwest to the southeast, discarding pole positions from the possibly allochthonous Tasman Fold Belt of eastern Australia. The implications of the different models are of major global palaeogeographic and tectonic significance. Some models suggest only small oceans between Laurentia and Gondwana throughout the Palaeozoic, while others suggest a wide oceanic separation existed in the Devonian-Carboniferous. There is an urgent need for reliable Palaeozoic palaeomagnetic poles from the Gondwana continents.

The Pole Paths

Figure 1 shows how the path has evolved with time, plotted in African co-ordinates using the rotation parameters of Lawver and Scotese (1987) with the modifications proposed by Veevers *et al.* (1991) for the Australia/Antarctica fit. Figure 1a is drawn after Irving and Green (1958), re-cast in the Gondwana framework. This work is remarkable in that it was based on natural remanent magnetisations (NRM), that is, data without palaeomagnetic cleaning. The path shown in figure 1b was proposed by McElhinny *et al.* (1968) and while it was based entirely on African data it showed the same general trend as the 1958 path. This confirmed the longevity of Gondwana, at least for the Palaeozoic. The next development (Fig. 1c) was the allochthonous model of Embleton *et al.* (1974) and McElhinny and Embleton (1974) in which the then recent data from middle Palaeozoic rocks of the Tasman Fold Belt were seen as evidence for a displaced terrane. A disjunction was recognised between the early Palaeozoic poles of cratonic Australia and the mid-Palaeozoic poles from the Tasman Fold Belt. It is worth remembering that this model pre-dated the wide acceptance of allochthonous terranes, especially from the Mesozoic/Cainozoic Cordillera of North America. Next Schmidt and Morris (1977) pointed out that by using the anti-poles of the early Palaeozoic poles, a continuous path could be constructed utilising all the data without a disjunction (Fig. 1d). This model advocated the opposite geomagnetic polarity for the early Palaeozoic compared to that conventionally used. Another continuous path model proposed which retained the original polarity convention was that of Morel and Irving (1978) (Fig. 1e). In essence, this model recognised the possibility (probability?) that there are gaps in the record and disjunctions are inevitable.

Klootwijk (1980) put forward a pole path which did not directly address the polarity problem, or the origin of the Tasman Fold Belt, but added considerable detail to the early Palaeozoic (Fig. 1f). A period of pronounced overprinting was recognised during the Cambro-Ordovician Delamerian Orogeny of South Australia yielding magnetisation directions not previously reported for the Australian Palaeozoic. Based on new data from the Tasman Fold Belt, Goleby (1980) produced a path with a loop similar to that of Morel and Irving's path, adding support for an autochthonous Tasman Fold Belt (Fig. 1g). The reality of this loop has been confirmed by Klootwijk (1988) and Klootwijk and Giddings (1988), although these workers maintain that it is the record of Kanimblan (mid-Carboniferous) overprinting throughout the southern Tasman Fold Belt (Fig. 1h).

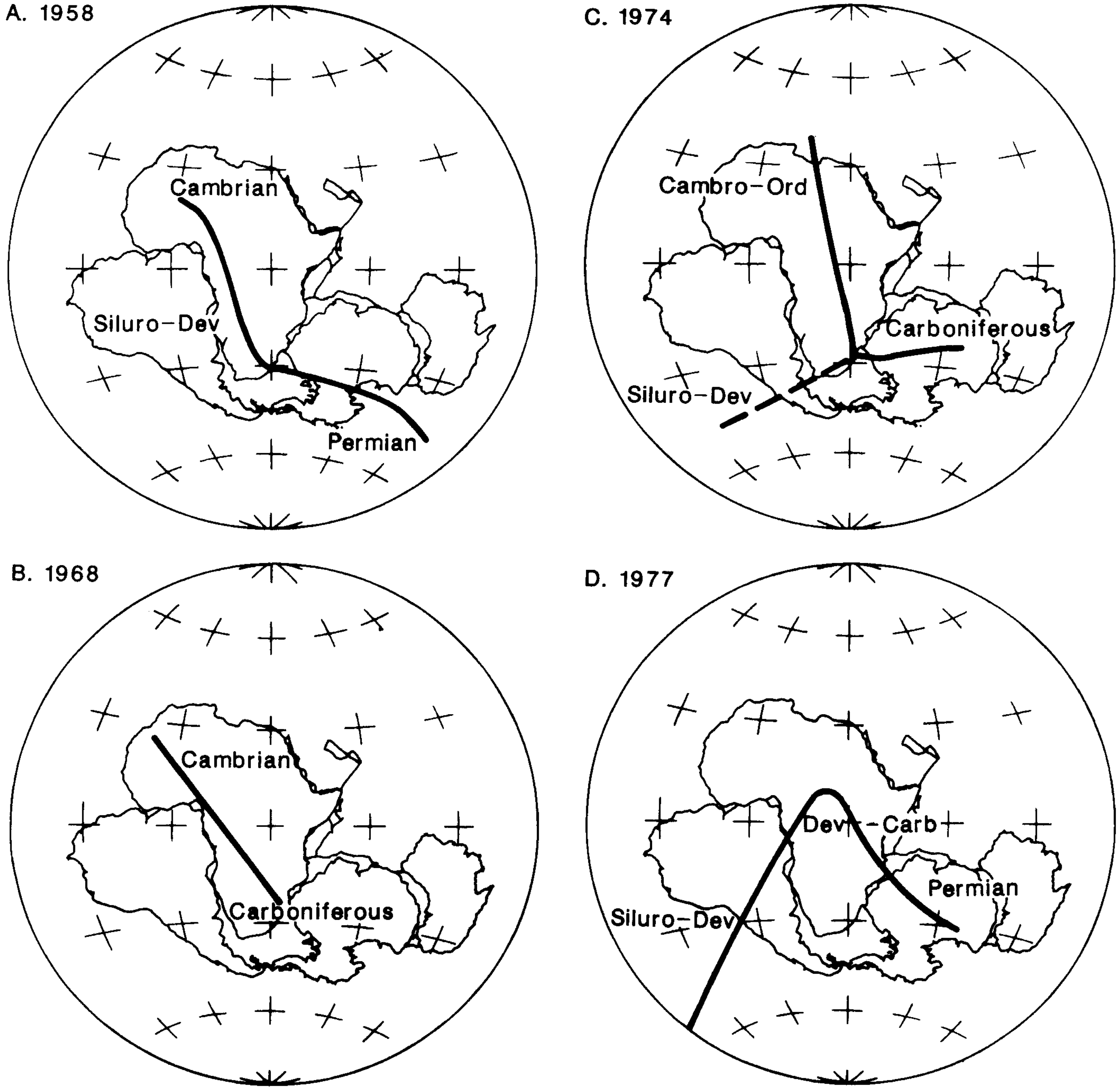
Since 1988 there have been further 'refinements' to the Gondwana Palaeozoic APWP. Based on geological considerations and the appearance of some new Silurian and Devonian data from Australia and Africa, Schmidt *et al.* (1990) supported the autochthonous model but added the caveat that there was a long segment of the APWP in the Ordovician-

Silurian time that is not represented by any reliable data. This segment is dotted in figure 1i.

Bachtadse and Briden (1991) argue for a conservative pole path, similar to the 1958 path, dismissing as suspect, or remagnetised, all poles from the Tasman Fold Belt rock units older than Carboniferous (at least in the context of Gondwana, Fig. 1j). Finally, in a synthesis of global data, Van der Voo (1992) proposed a "filtered" path (Fig. 1k) which nevertheless recognises the autochthonous Tasman Fold Belt but differs from the previous paths in detail, particularly the segment over which the path is interpolated.

At this stage there does seem to be a majority consensus on general features of the Gondwana Palaeozoic APWP, although fine details and their timing are not agreed on. To summarise the present position it is fair to say that there are three schools, in order of numerical dominance:

(1) the autochthonous school (CSIRO, UWA and North American workers) who accept that the Tasman Fold Belt formed basically in-situ and that the mid-Palaeozoic path for Gondwana extends southwestward to a position off Chile, although there are no reliable data points for the earlier south trending segment;
(2) the allochthonous school, represented by European workers;
(3) the AGSO school that believes that many of the pole positions that define the mid-Palaeozoic loop are actually related to Carboniferous Kanimblan overprinting and the real mid-Palaeozoic path is well to the north (in an African reference frame).

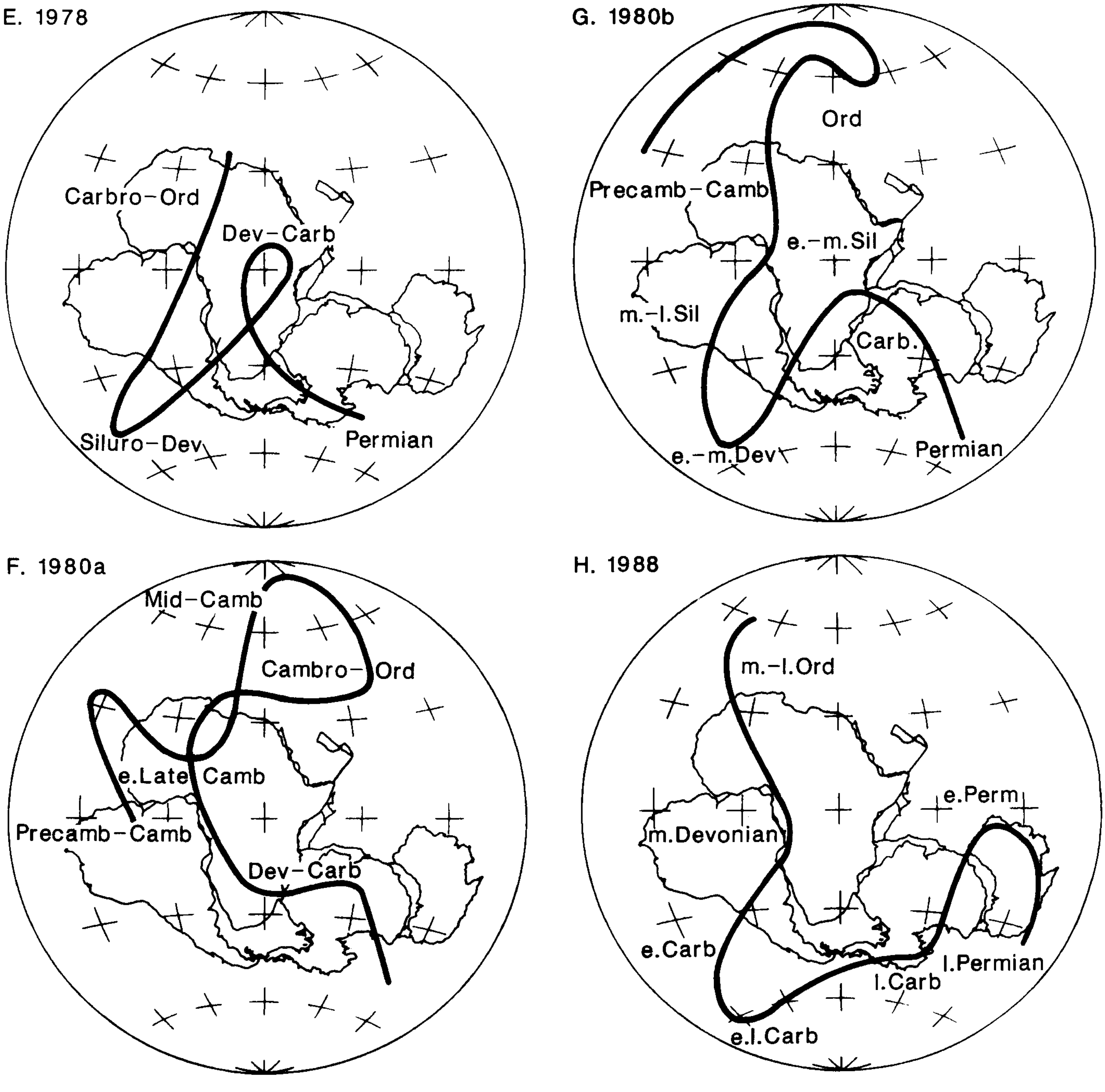


At the present time the differences between the above models precludes definitive continental reconstruction for early Palaeozoic times. It is extraordinarily difficult to acquire reliable palaeomagnetic data from early Palaeozoic rocks from Gondwana for a variety of reasons. These include remagnetisation associated with tectonic processes, the presence of an ancient regolith with attendant problems from weathering, lightning and poor outcrop. Thus the following preliminary account is unusual in that we report results from an early Palaeozoic intrusion that has not been overprinted in the least since the time of formation.

The Black Hill Norite

Mafic intrusions that occur in the Adelaide Geosyncline date from various stages of the Delamerian Orogeny with some being pre- to syn-tectonic and others being post-tectonic. We have collected samples across the range of tectonic settings and preliminary rock magnetic results correlate well with their respective tectonic histories. The Black Hill Norite is a post-tectonic gabbroic body with a well constrained age at 487±5 Ma, i.e. Early Ordovician. A summary of magnetic properties is reported in Table 1. The rock has a high average magnetic susceptibility of 0.049 SI (3911 μG/Oe), a strong remanent magnetisation with Dec = 221.2°, Inc = 7.6° and an intensity of 4.9 Am^{-1} (4941 μG) and a Koenigsberger ratio (Q) of 2.1, giving rise to a pronounced low aeromagnetic anomaly (see Rajagopalan *et al.*, this volume).

Hysteresis measurements and Curie temperatures show that magnetite is the only significant magnetic carrier present in the Black Hill Norite. Thermal demagnetisation was carried out after cooling to liquid nitrogen temperature (-197°C) and



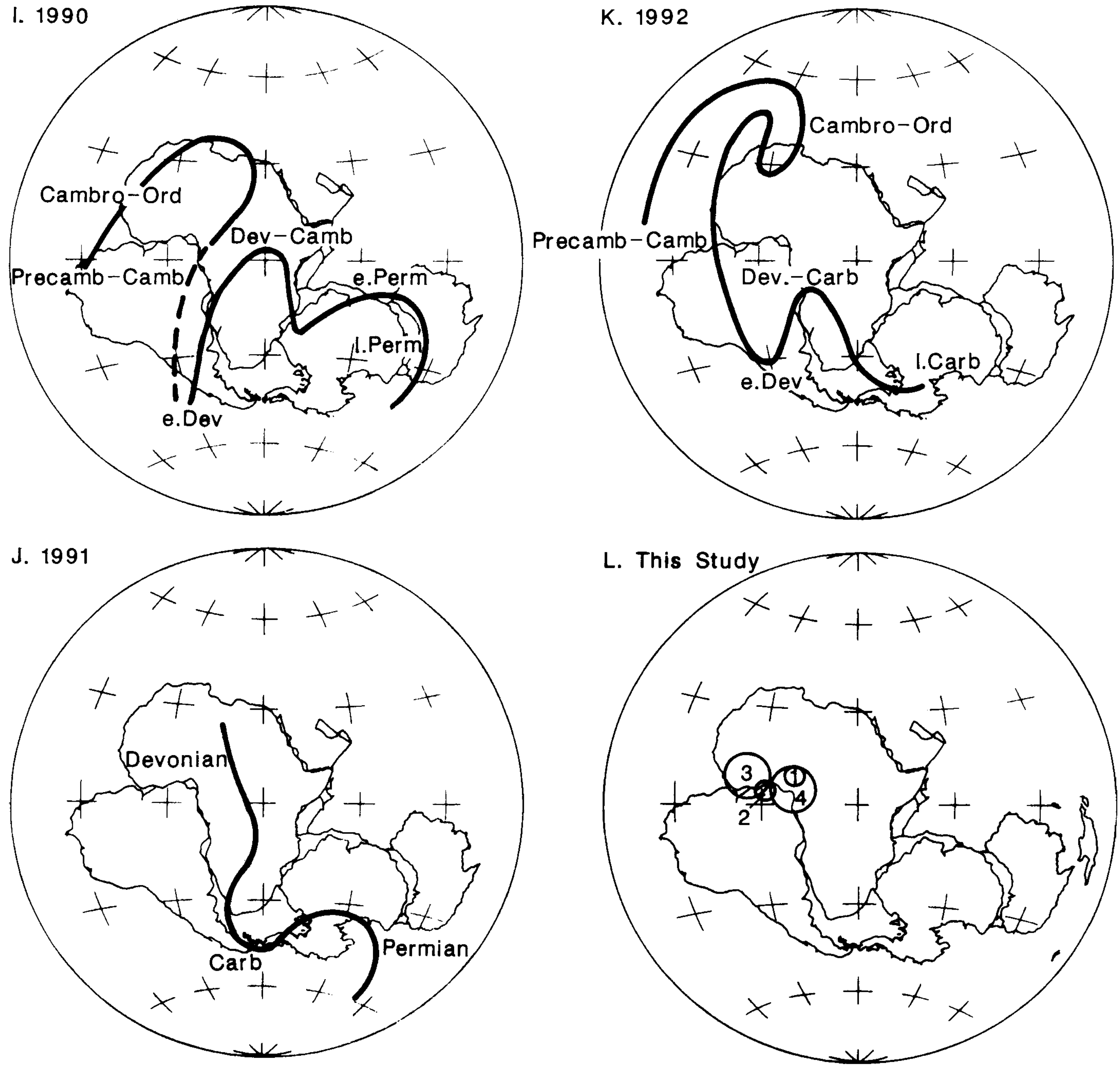


FIGURE 1
Palaeozoic APWP models proposed for Australia and Gondwana using the reconstruction of Lawver and Scotese (1987), as modified by Veevers *et al.* (1991) for the Australia/Antarctica fit; (a) Irving and Green (1958) based on Australian data, (b) McElhinny *et al.* (1968) based on African data, (c) the allochthonous model of the Tasman Fold Belt given by Embleton *et al.*, (1974) and McElhinny and Embleton (1974), (d) the autochthonous model given by Schmidt and Morris (1977) after invoking the polarity option for Cambrian and Ordovician poles (which plot on the obscured hemisphere for this projection), (e) the "Y" path of Morel and Irving (1978) introducing the Siluro-Devonian loop and implying an autochthonous Tasman Fold Belt, (f) after Klootwijk (1980) showing the Delamarian overprint poles of Cambro-Ordovician age, (g) after Goleby (1980) showing similarities with the loop path, (h) after Klootwijk and Giddings (1988) and Klootwijk (1988) re-calibrating the age of the loop, (i) Schmidt *et al.* (1990) using only reliable data and emphasising the missing link (Ordovician-Silurian segment dotted), (j) Bachtadse and Briden's (1991) conservative solution, and (k) Van der Voo (1992) synthesising reliable data from all Gondwana continents. (l) Pole position from the different remanence components identified: high temperature (1); intermediate temperature (2); high AF coercivity (3); intermediate AF coercivity (4).

TABLE 1
Raw Remanences and Susceptibilities

	N	Dec (°)	Inc (°)	Int (Am^{-1})	k (SI)	k (cgs)	Q
Site 1	6	218.7	5.9	6.565	0.050	3976	2.7
2	6	219.8	7.8	6.856	0.041	3262	3.5
3	5	221.7	7.8	3.236	0.051	4035	1.3
4	6	229.2	10.7	3.153	0.055	4369	1.2
Mean	4	221.2	7.6	4.941	0.049	3911	2.1

Dec — declination, Inc — inclination, Int — Intensity, k — susceptibility and Q — koenigsberger ratio (assuming a magnetic field of 48 Am^{-1}, ≈60000 nT) rewarming in field-free space to test for remanence carried by multidomain magnetite. This procedure changed the intensity of remanence minimally indicating that the remanence is carried by fine magnetically stable single domain magnetite. Significant decay of intensity was observed only above 530°C on thermal demagnetisation (Figs. 2a, 2b) and above 60 mT on AF demagnetisation (Figs. 2c, 2d) which provides further evidence for a very stable remanent magnetisation. The median destructive field (MDF) was about 100 mT.

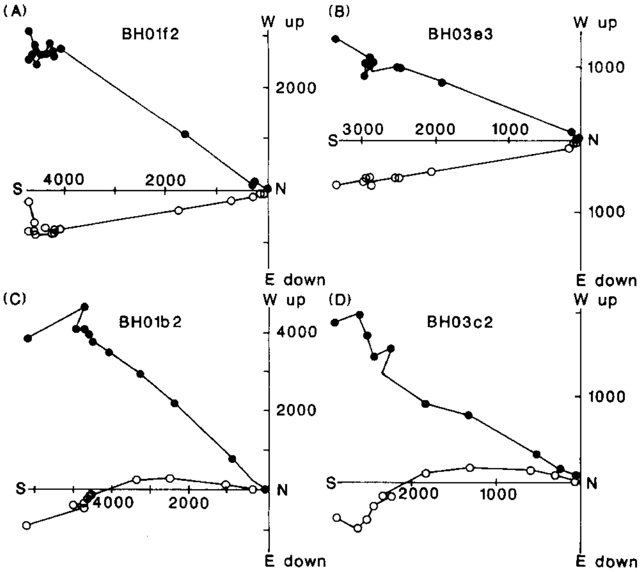


FIGURE 2

Orthogonal projections of thermal demagnetisation at steps of 170°C, 220°C, 270°C, 320°C, 370°C, 420°C, 470°C, 505°C, 530°C, 540°C, 552°C, 554°C, 564°C, 575°C, 618°C and 636°C (a and b) and of alternating field (AF) demagnetisation at 5 mT, 10 mT, 60 mT, 80 mT, 100 mT, 125 mT, 150 mT, 175 mT, 200 mT and 225 mT (c and d). Substantial intensity decay occurred only above 530°C or above 48 kAm^{-1} (600 Oe). Intensity units are mAm^{-1} (x10^{-6} emu/cc= μG).

After demagnetisation the remanent magnetisations were analysed using principal component analysis (PCA). An interesting feature displayed by these samples is a slight but systematic difference of remanent magnetisation direction depending on the demagnetisation procedure used. The mean direction of magnetisation for magnetite grains demagnetised at intermediate temperatures, at around 470°C, is significantly different from that demagnetised at high temperatures, i.e those grains with unblocking temperatures (T_{ub}) above 550°C. While this is not unusual in itself, the high T_{ub} direction is distinctly different from that associated with high remanent coercivity (H_{cr}) of around 150 mT. This is displayed in Table 2 and figures 2 and 3. It is also noteworthy that the high T_{ub} direction is similar to the directions associated with lower H_{cr} of around 80 mT (Table 2, Fig. 3). That is, magnetite grains that have the highest T_{ub} do not have the highest H_{cr} and grains which have the highest H_{cr} actually have intermediate T_{ub}. This suggests that there are two distinct populations of fine grained magnetite present with distinctly different morphologies. This may be a common phenomena but it is unusual in that the directions carried by the two populations are systematically different. It is conceivable that this may be a record of secular variation of the geomagnetic field during the initial cooling of the Black Hill Norite, although we would expect such directional variation to be best differentiated by T_{ub}, and not necessarily H_{cr}.

TABLE 2
Cleaned Remanences and Pole Positions

	N	Dec (°)	Inc (°)	*k*	α_{95} (°)	Lat (°N)	Long (°E)	A_{95} (5°)
1 High temp	22	231.1	19.7	67.5	3.8	-37.5	34.4	3.2
2 Int temp	22	222.5	8.9	123	2.8	-40.4	21.7	2.6
3 High AF	10	223.9	-5.5	47.8	7.1	-34.4	16.4	6.6
4 Int AF	10	227.2	23.0	47.0	7.1	-41.6	33.4	6.8

Dec — declination, Inc — inclination, Int — Intensity, *k* — precision parameter, α_{95} — half-angle of cone of confidence on directions, Lat — latitude, Long — longitude, A_{95} — half angle of cone of confidence on pole positions.

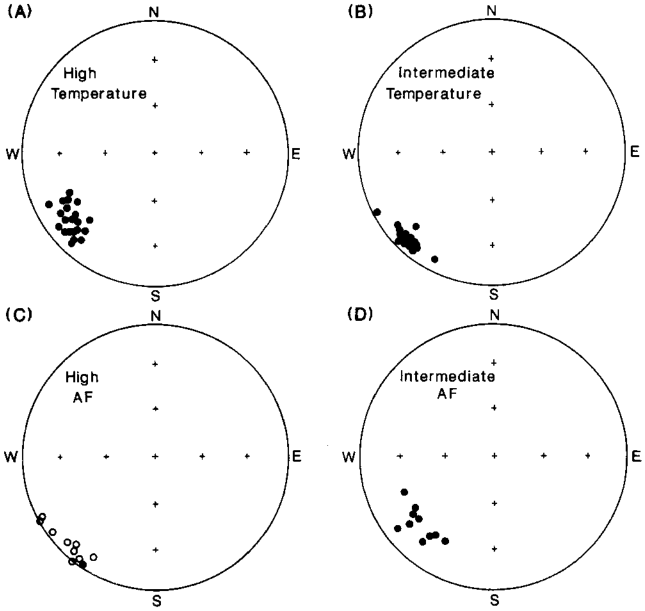


FIGURE 3

Equal area stereographic projections of a) high temperature components above (550°C), b) intermediate temperature components (≈470°C), c) high AF (≈150 mT) and d) intermediate AF (≈80 mT). The closed symbols refer to downward directions while the open symbols refer to upward directions.

The Black Hill Norite has a well-defined magnetic fabric, which comprises a subvertical WNW-striking foliation and a lineation that plunges steeply to the SSW. This fabric probably reflects magmatic flow during emplacement. This low-field susceptibility anisotropy is about 15% and predominantly arises from the preferred dimensional orientation of large multidomain magnetite grains. The anisotropy of anhysteretic remanence (acquired in a peak alternating field of 100 mT) reflects preferred orientation of fine pseudosingle domain magnetite grains and is somewhat more pronounced (~21%). The slightly different remanence directions recorded by different coercivity fractions may be a result of differing degrees of magnetic anisotropy for high and intermediate coercivity populations, causing small, but variable, deflections of remanence carried by each subpopulation. This aspect of the magnetisation of the Black Hill Norite is being investigated further by measuring the T_{ub} and H_{cr} spectra of anisotropies of thermoremanent and anhysteretic remanent magnetisations (ATM and AAM) respectively and will be reported elsewhere.

Clearly the remanent magnetisation of the Black Hill Norite is extremely stable. While such extreme stability is rare, it has been reported from other post-tectonic mafic intrusions where it has been found to arise from very fine grained magnetite exsolved in pyroxene and plagioclase. The gabbroic rocks at Black Hill "intruded at relatively low pressures after the end of regional metamorphism and have not experienced any metamorphism subsequently . . . " (Turner and Stüwe, 1992). In addition, radiometric ages of 486 Ma from K-Ar, 487±5 Ma from Rb-Sr (Milne *et al.,* 1977) and 489±10 Ma from Nd-Sm (Turner, 1991) are in excellent agreement indicating that none of the isotopic systems has been disturbed since intrusion. Thus the combined evidence from petrology, dating and rock magnetic properties suggests that remagnetisation of these rocks is extremely unlikely. The mean direction of the high and low temperature components are Dec= 231.1°, Inc= 19.7° (α_{95}= 3.8°) and Dec= 222.5°, Inc= 8.9° (α_{95}= 2.80) respectively (Table 2, Figs. 3a,b). The direction of the high and intermediate coercivity AF components are Dec= 223.9°, Inc= -5.5° (α_{95}= 7.1°) and Dec= 227.2°, Inc= 23.0° (α_{95}= 7.1°) respectively (Table 2, Figs. 3c,3d). The corresponding palaeomagnetic pole positions are 37.5°S, 34.4°E (A_{95}= 3.2°), 40.4°S, 21.7°E (A_{95}= 2.6°), 34.4°S, 16.4°E (A_{95}= 6.6°), 41.6°S and 33.4°E (A_{95}= 6.8°) which are plotted in figure 1l.

Conclusions

More reliable pole positions of Late Ordovician and Early Silurian age are required to discriminate between the various models for Palaeozoic APWP of Gondwana. Results from the Black Hill Norite suggest that the Early Ordovician pole position, immediately following the Delamerian Orogeny, was near the African Bight rather than northeast of Africa. This raises the spectre that some Australian Cambrian pole positions which plot nearby may have been overprinted during the Delamerian Orogeny.

References

Bachtadse, V. and Briden, J.C., (1991), 'Palaeomagnetism of Devonian ring complexes from the Bayuda Desert, Sudan — new constraints on the apparent polar wander path for Gondwanaland'. *Geophys. J. Int.,* **104**, 635-646.

Embleton, B.J.J., McElhinny, M.W., Crawford, A.R., and Luck, G.R., (1974), 'Palaeomagnetism and the tectonic evolution of the Tasman Orogenic Zone'. *J. Geol. Soc. Aust.,* **21**, 187-194.

Goleby, B.R., (1980), 'Early Palaeozoic paleomagnetism in South East Australia'. *J. Geomag. Geoelectr.,* **32**, 11-21.

Irving, E. and Green, R., (1958), 'Polar movement relative to Australia'. *Geophys. J. R. Astr. Soc.,* **1**, 64-72.

Klootwijk, C.T., (1980), 'Early Palaeozoic palaeomagnetism in Australia'. *Tectonophysics,* **64**, 249-332.

Klootwijk, C.T., (1988), 'Palaeomagnetism, pp 25-30, *in*, Finlayson, D.M., (Ed.), Eromanga-Brisbane Geoscience Transect: Position Papers presented in February 1998. *BMR Rec.,* **1988/10**.

Klootwijk, C. and Giddings, J., (1988), 'An alternative APWP for the middle to late Palaeozoic of Australia — implications for terrane movements in the Tasman Fold Belt'. *Geol. Soc. Aust. Abstracts,* **21**, 219-220.

Lawver, L.A. and Scotese, C.R., (1987), 'A revised reconstruction of Gondwanaland'. pp 17-23, *in*, McKenzie, G.D., (Ed.), Gondwana Six: Structure, Tectonics and Geophysics. *AGU Monograph,* **40**.

McElhinny, M.W., Briden, J.C., Jones, D.L. and Brock, A., (1968), 'Geological and geophysical implications of paleomagnetic results from Africa'. *Rev. Geophys.,* **6**, 201-238.

McElhinny, M.W. and Embleton, B.J.J., (1974), 'Australian paleomagnetism and the Phanerozoic plate tectonics of Eastern Gondwanaland'. *Tectonophysics,* **22**, 1-29.

Milnes, A.R., Compston, W. and Daily, B,, (1977), 'Pre- to syn-tectonic emplacement of early Palaeozoic granites in southeastern South Australia', *J. Geol. Soc. Aust.,* **24**, 87-106.

Morel, P. and Irving, E., (1978), 'Tentative palaeocontinental maps for the Early Phanerozoic and Proterozoic'. *J. Geol.,* **86**, 535-561.

Schmidt, P.W. and Morris, W.A., (1977). 'An alternative view of Gondwana Palaeozoic apparent polar wander path'. *Can. J. Earth Sci.,* **14**, 2674-2678.

Schmidt, P.W., Powell, C.McA., Li, Z.X. and Thrupp, G.A., (1990), 'Reliability of Palaeozoic palaeomagnetic poles and APWP of Gondwanaland'. *Tectonophysics,* **184**, 87-100.

Turner, S.P., (1991), 'Late-orogenic, mantle-derived, bimodal magmatism in the southern Adelaide foldbelt, South Australia'. *PhD Thesis (unpubl), University of Adelaide,* pp196.

Turner, S.P. and Stüwe, K., (1992), 'Low-pressure corona textures between olivine and plagioclase in unmetamorphosed gabbros from Black Hill, South Australia'. *Mineralogical Magazine,* **56**, 503-509.

Van der Voo, R., (1992). 'Paleomagnetism of the Atlantic, Tethys and Iapetus Oceans'. *Cambridge University Press, Cambridge,* pp411.

Veevers, J.J., Powell, C.McA. and Roots, S.R., (1991), 'Review of seafloor spreading around Australia. I. Synthesis of the patterns of spreading'. *Aust. J. Earth Sci.,* **38**, 373-389.