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Australian Palaeozoic palaeomagnetism and tectonics—II. A revised apparent polar wander path and palaeogeography

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Abstract—New palaeomagnetic data from mid- to Late Palaeozoic rocks in Australia have enabled us to revise the Palaeozoic apparent polar wander path (APWP). This modified Australian APWP is supported by data from other parts of Gondwanaland. The palaeomagnetic poles indicate that during the Early and mid-Palaeozoic, Australia underwent rapid rotation: first clockwise during the mid-Ordovician to the Early Silurian, then counterclockwise from the mid-Silurian until the end of the Devonian, while it remained at low to equatorial latitudes. This was succeeded by a rapid southward movement during mid-Carboniferous times. The implications of the palaeomagnetic data for the tectonic relationship between the Lachlan Fold Belt (LFB) and cratonic Australia are consistent with the tectonic evidence that the LFB has been in place since the mid-Devonian.

INTRODUCTION

IN THE past two decades, work on the Palaeozoic apparent polar wander path (APWP) of Australia has shed light on the tectonic evolution of Australia (and thus Gondwanaland), but also has created a degree of contention. Three fundamentally different models of the Australian Palaeozoic APWP have emerged: (1) the allochthonous model (Fig. 1a) (Embleton *et al.* 1974, McElhinny & Embleton 1974) suggests that the Lachlan Fold Belt (LFB, see Fig. 2) of southeastern Australia was an exotic terrane before the Late Palaeozoic, and has been favoured by many workers (Perroud *et al.* 1984, Livermore *et al.* 1985); (2) the autochthonous model (Fig. 1b) (Schmidt & Morris 1977) invokes the alternative polarity for the pre-mid-Palaeozoic poles and suggests a single APWP for both cratonic Australia and the LFB. This model assumes an Early to Middle Devonian age for the Mereenie Sandstone pole (MS), originally assigned a Silurian–Devonian age (Embleton 1972); (3) a third model, first proposed by Morel & Irving (1978), and later revised by Goleby (1980) (see Fig 1c) and Schmidt *et al.* (1986, 1987), combines aspects of models (1) and (2) in that it is autochthonous but retains the original polarity assigned for the pre-mid-Palaeozoic poles. Model (3) interposes the mid-Palaeozoic poles of the LFB between the Early Palaeozoic poles and the Late Palaeozoic poles of cratonic Australia to generate a single APWP. Recently, this third model has gained support by Hargraves *et al.* (1987) and has been used by Van der Voo (1988). A crucial aspect of this model is that it requires exceptionally rapid movement of Gondwanaland during the mid-Palaeozoic.

The range of models is mainly due to the lack of reliable palaeomagnetic poles from cratonic Australia, especially poles of mid-Palaeozoic age. For a long time the only 'Siluro-Devonian' pole from cratonic Australia was that from the Mereenie Sandstone (MS) in the Amadeus Basin (Fig. 2) (Embleton 1972). Although two fold limbs were sampled to provide a potential fold test (Graham 1949) on the relative age of the magnetization, the samples of one limb were found to be remagnetized and the MS pole was derived from one section only. The quality of many of the early poles from the LFB has also been questioned because of the lack of evidence for either the palaeohorizontal, or the magnetization age, or both (Schmidt & Embleton 1987, Powell *et al.* 1990). In this paper, we first discuss briefly the reliability of the recently acquired palaeomagnetic data from both cratonic Australia and the LFB, which satisfy at least the 'B^-' criteria as listed in Table 1 (modified after Briden & Duff 1981). By combining these data with selected existing data from other Gondwana continents, we then revise the APWP of Australia (and thus Gondwanaland) and discuss its tectonic significance.

RECENTLY AVAILABLE MID-PALAEOZOIC DATA FROM AUSTRALIA

Several reliable mid-Palaeozoic palaeomagnetic poles have been obtained from both cratonic Australia and the

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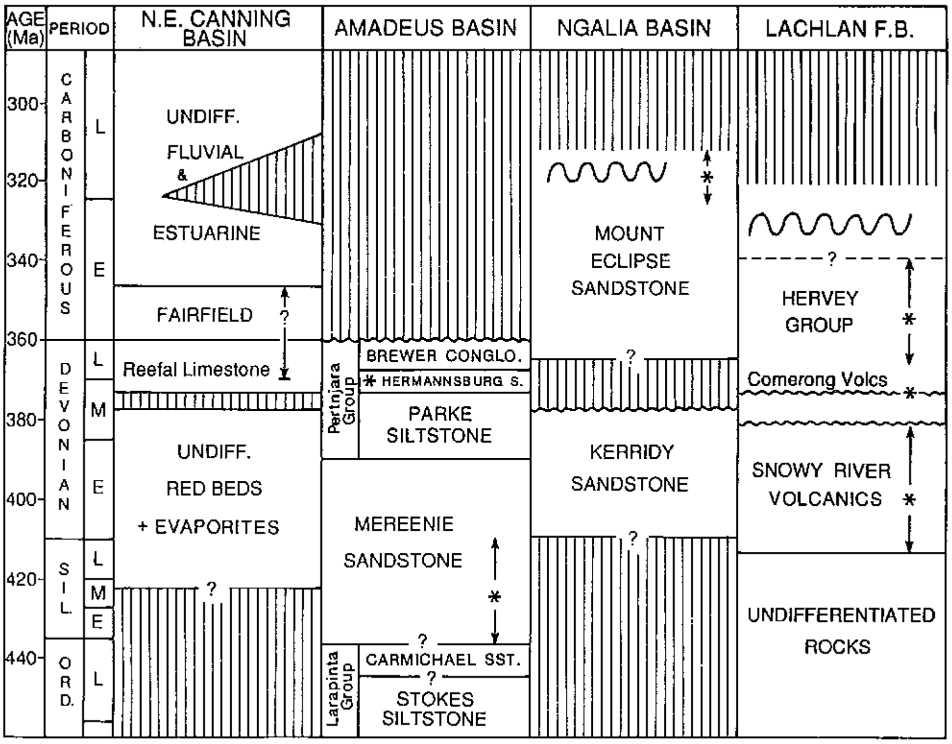

Fig. 3. Stratigraphic position of the rock formations from Australia, from which reliable palaeomagnetic poles have been revealed during recent studies (formations with a star). Positions of the stars indicate the inferred ages for the characteristic magnetic remanences, and the arrows the possible ranges of their ages. The poles involved are: CB (Canning Basin Limestone), HS (Hermannsburg Sandstone), EL (Mt Eclipse Sandstone), SRV (Snowy River Volcanics), CV (Comerong Volcanics) and HG (Hervey Group).

margin of western Gondwanaland. Exceptions are poles DM and N2 from Africa and pole AF from South America (pole AF is near SW Australia in Fig. 5). Also, the positions of the two Silurian poles (poles AIR and ME) differ significantly. The Devonian–earliest Carboniferous poles are all from Australia. The Permo-Carboniferous poles group around eastern Gondwanaland (Antarctica, India and Australia). The distribution of these poles is generally in good accord with their relative ages.

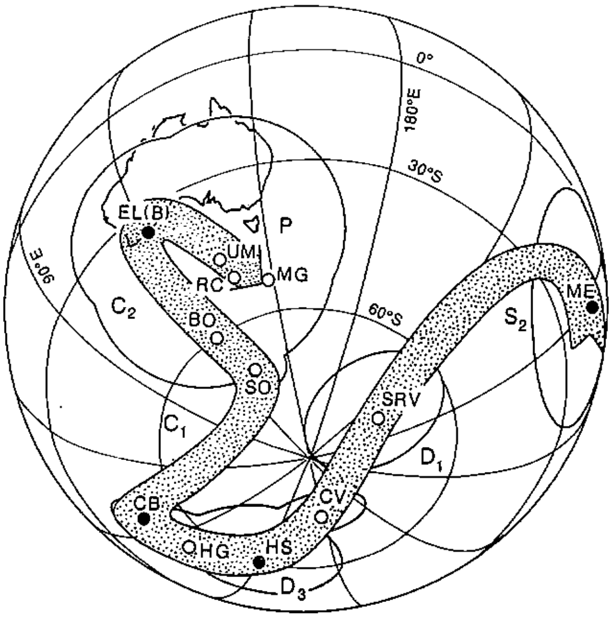

Fig. 4. Revised mid- to Late Palaeozoic apparent polar wander path of Australia. Solid circles are B and B⁻ class poles from cratonic Australia, and open circles are the A to B⁻ class poles from southeastern Australia (Table 2). Orthographic projection.

The Palaeozoic APWP of Gondwanaland is constructed from the above trend (Fig. 5). The three discrepant poles (N2, DM and AF) have been omitted from this APWP. Pole N3, an overprint pole dated after the Pan-African Orogeny in southwest Africa (Kröner *et al.* 1980), falls in the middle of the Cambrian poles. Pole N2, pre-dates the Pan-African Orogeny, and could therefore be of latest Precambrian age. The same may be true for pole DM, although this pole does not clearly pre-date the Pan-African Orogeny. The anomalous position of the AF pole seems to be due to its uncertain age. Of the two K–Ar ages (416 ± 10 Ma and 294 ± 15 Ma) of the oldest pillow lavas in this formation, the younger age was rejected because of suspected argon loss (Vilas & Valencio 1978). As shown in Fig. 5, however, the AF pole falls close to the Late Carboniferous part of the Gondwanaland APWP, an age consistent with the younger K–Ar age, and suggests the pole could be the result of a Late Carboniferous overprint.

The other pole which is discordant on this APWP is the overprint pole of Klootwijk (1980) (pole KL2 in Fig. 5), originally assigned a Cambrian–Ordovician age, but from the close location of its anti-pole position with that of the Silurian ME pole, we believe it could also be a Silurian pole. This interpretation reduces the overall APWP length appreciably.

As an alternative to the above proposed APWP, if we use the original polarity of the KL2 pole given by

Klootwijk (1980), then the ME pole has to be inverted to its opposite polarity to minimize the distance between them (poles KL2 and ME shown as open circles in Fig. 5). However, this interpretation makes it difficult to connect the AIR pole to the Early Silurian part of the APWP.

Yet another alternative is to involve the polarity option for all the Cambrian–Ordovician poles as Schmidt & Morris (1977) did, but keep the ME and KL2 poles as they are in the proposed APWP in Fig. 5. In addition to having difficulty in connecting with the AIR pole in its correct position on the APWP, this alternative

Table 2. Selected Palaeozoic palaeomagnetic poles from Gondwanaland

Rock formation	Mnemonic	Age (Ma)	Plat (°N)	Plong (°E)	α_{95} (°) (DP, DM)	Q	Ref.*
Southeast Australia:							
Upper Marine Latites	UM	P_2	−46	136	15	B^-	1
Rocky Creek Conglomerate	RC	C_2	−52	138	17	B^-	2
Main Glacial Stage	MG	C_2	−53	148	11	B	2
Buchan Cave Limestone Overprint	BO	mid-C?	−64.7	127.9	4.0 4.5	B	3
Snowy River Volcanics Overprint	SO	mid-C?	−68.7	132.5	5.0 5.7	B	3
Hervey Group	HG	D_3–C_1	−54.4	24.1	8.4 16.2	B	4
Comerong Volcanics	CV	D_2–D_3	−76.9	330.7	7.2	B	5
Snowy River Volcanics	SRV	D_1	−74.3	222.7	10.9 14.5	A	3
Cratonic Australia:							
Mount Eclipse Sandstone	EL(B)	~320	−33.8	121.2	19.2 19.7	B	6
Canning Basin Limestone	CB	D_3	−49.1	38.0	7.8	B	7
Hermannsburg Sandstone	HS	D_2–D_3	−61.0	0.9	15.6	B^-	8
Mereenie Sandstone	ME	S–D_1	−15.7	242.6	23.7	B^-	8
Tumblagooda Sandstone	TS	O	−26.7	33.7	2 3	B	9
Є–O Overprint	KL2	Є–O	27.0	72.0	7.3	B^-	10
Lake Frome Group	LFG	Є$_2$	−31.4	26.9	5.1 10.1	B^-	10
Billy Creek Fm, Wirrealpa Limestone and Aroona Creek Limestone	BWA	midЄ	−37.4	20.1	7.2 14.4	B^-	10
Cambrian rocks in the Kangaroo Island	KI	Є$_1$	−33.8	15.1	6.2 12.3	B^-	10
Hawker Group	HKG	Є$_1$	−26.7	2.3	8.1 14.3	B^-	10
Todd River Dolomite, Allua Fm and Eninta Sandstone	MI	Є$_1$	−43.2	339.9	7.7 4.5	B^-	11
Africa:							
Permian rock formations	MC2	P	−31.6	61.7	12.1	B	12
Upper Seri d'Abadla	SD	P_1?	−29	60	5	B	13
K3 redbeds	K2	P_1	−27.0	89.0	15.5	B^-	14
K3 redbeds	K1	C_2?	−45.5	40.0	8.0	B^-	14
Dywka glacial varves	DV	C_1?	−26.5	26.5	10.5	B^-	14
Lower Carboniferous rocks	MC1	C_1	−4.8	55.5	6.1	B^-	12
Gneiguira supergroup	GN	C_1?	−35.2	43.6	3.0 5.6	B	15
Silurian ring complexes	AIR	~435	−43.4	8.6	6.2	A	16
Graafwater Formation	GW	O_1	28.0	14.0	8.8	B	17
Nama Group, overprint	N3	<Є	−2	344	19 23	B^-	18
Nama Group	N2	Є	5	271	9 16	B^-	18
Mulden Group	DM	Є$_1$	13	270	16	B^-	19
South America:							
La Colina Formation	LCA	P	−81	327	4.0	B	20
Paganzo Group (middle)	PG	266 ± 7	−78	249	3	A	21
La Colina Formation	LCB	295 ± 5	−49	343	5	B	22
Alcaparrosa Formation	AF	416 ± 19	−56.2	32.8	16.4	B	23
Suri Formation	SF	O_1	−8.5	5.9	5.9	B^-	24
India:							
Speckled Sandstone	SS	P_1	13.0	137.5	5.1 9.5	B^-	25
Salt Pseudomorph Beds	SP	Є$_2$	−22.1	31.7	6.8 11.3	B^-	26†
Upper Bhander sandstones	UB	Є	−48.5	33.5	3.0 5.5	B	27
Eastern Antarctica:							
Lamprophyre Dykes from Taylor Valley	LD	~470	−9.3	26.7	5.5 10.9	B^-	28
Intrusive Rocks from the Sør Rondane Mountains	IR	~480	−28	10	5 6	B^-	29†
Charnockitic rocks from Mirnyy Station	CR	~502	−1.5	28.5	8 16	B^-	30

* References: (1) Irving & Parry 1963; (2) Irving 1966; (3) Schmidt *et al.* 1987; (4) Li *et al.* 1988; (5) Schmidt *et al.* 1986; (6) Li *et al.* 1989; (7) Hurley & Van der Voo 1987; (8) Li 1988 and Li *et al.* in press; (9) Schmidt & Embleton in press; (10) Klootwijk 1980; (11) Kirschvink 1978; (12) Martin *et al.* 1978; (13) Morel *et al.* 1981; (14) McElhinny & Opdyke 1968; (15) Kent *et al.* 1984; (16) Hargraves *et al.* 1987; (17) Bachtadse *et al.* 1987; (18) Kröner *et al.* 1980; (19) McWilliams & Kröner 1981; (20) Thompson 1972; (21) Valencio *et al.* 1977; (22) Sinito *et al.* 1979; (23) Vilas & Valencia 1978; (24) Valencio *et al.* 1980; (25) Wensink 1975; (26) Wensink 1972; (27) Klootwijk 1973; (28) Manzoni & Nanni 1977; (29) Zijderveld 1968; (30) McQueen *et al.* 1972.

Plat, Plong = latitude and longitude of the palaeopole; α_{95} = half-angle of the cone of 95% confidence (Fisher 1953) around the pole; DP, DM = the semi-axes of the elliptical error around the pole at a probability of 95%, DP in the colatitude direction and DM perpendicular to it; Q = quality classification according to Table 1. Age mnemonics: Є = Cambrian; O = Ordovician; S = Silurian; D = Devonian C = Carboniferous; P = Permian. † indicates pole recalculated from the original data.

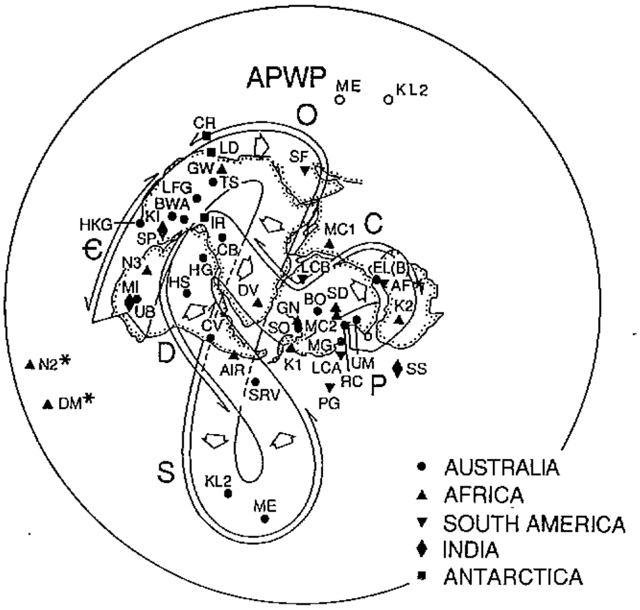

Fig. 5. Proposed Palaeozoic apparent polar wander path of Gondwanaland. The poles shown are the poles listed in Table 2. *Poles were not used for calibrating the APWP because of their anomalous positions. The Gondwanaland construction is adopted from Lawver & Scotese (1987). Lambert equal-area projection. € = Cambrian, O = Ordovician, S = Silurian, D = Devonian, C = Carboniferous and P = Permian.

APWP conflicts with the pattern of the migration path of palaeoglaciation centres suggested by Caputo & Crowell (1985). We thus prefer our interpretation shown in Fig. 5, but recognize that more work is required on the Ordovician to Early Devonian part of the APWP.

The revised APWP belong to the autochthonous class of models. It is similar to Morel & Irving's (1978) 'Y' path and other revised paths (e.g. Goleby 1980, Schmidt *et al.* 1986). The most notable feature of this APWP is that it implies a rapid relative polar movement of Gondwanaland during the mid-Ordovician and the Silurian (over 150–180° in about 60 Ma). This is consistent with a similarly rapid polar movement of western Gondwanaland suggested by Caputo & Crowell (1985) from glaciation data.

PALAEOGEOGRAPHY OF AUSTRALIA DURING THE ORDOVICIAN-CARBONIFEROUS INTERVAL

Figure 6 shows the palaeolatitudes and palaeogeography of Australia during the Ordovician–Carboniferous interval. The palaeolatitudes for the Early to mid-Ordovician time are given by the averaged palaeomagnetic poles of that age from the whole of Gondwanaland (see Table 2 and Fig. 5). Palaeolatitudes for mid-Silurian to mid-Carboniferous times are given using the Australian palaeomagnetic data only.

The palaeogeographic maps highlight the large clockwise rotation of Australia relative to the Earth's rotation axis during the Ordovician and Silurian. For example, the Alice Springs region (⊗ in Fig. 6) rotated more than 135° clockwise while remaining within 10° of the palaeo-equator. Concurrent with this interval of rapid (2–2.5° per Ma) clockwise rotation of Gondwanaland was the formation of a marginal sea and island arc in the Tasman orogenic zone. This palaeogeography was terminated at the end of the Ordovician by the Benambran deformation (Powell 1983).

The palaeomagnetic data are insufficient to test whether the Benambran deformation corresponds precisely with the end of the large Ordovician to Early Silurian clockwise rotation of Australia. However, we note that the succeeding continental extensional phase, a mid-Silurian to mid-Devonian dextral transtensional regime (Powell 1983, 1984), corresponds to an interval of counterclockwise rotation of Australia (Figs. 6b–d), during which Australia recovered about two-thirds of the previous clockwise rotation. The Alice Springs region would have rotated about 80° counterclockwise during this interval at a rate around 2° per Ma, again remaining close to the palaeo-equator.

According to the revised APWP, this counterclockwise rotation continued until the end of the Devonian (Figs. 4 and 6e) when a new phase of apparent polar wander began. At the beginning of the Carboniferous, Australia was in tropical latitudes, with the palaeo-equator situated in northern Queensland (Fig. 6e). By the mid-Carboniferous (Namurian, ~320 Ma ago) the south pole was near southwestern Australia, and the entire Australian region lay poleward of 60°S (Fig. 6f). There was no apparent azimuthal rotation during this interval of rapid poleward flight (~1.5° per Ma), the end of which coincided with the most extensive Palaeozoic compressive deformation of Australia: the Kanimblan deformation (Fig. 6f) (Powell 1984).

Thereafter, Australia remained at polar latitudes for at least 25 Ma, and it has been argued (Powell & Veevers 1987) that large areas were covered by ice sheets. Melting of the ice sheets in the Westphalian–Stephanian (300–290 Ma) is interpreted to have formed the extensive glacigene deposits at the base of the Gondwana basins (Veevers & Powell 1987).

SUMMARY

The recently available mid-Palaeozoic palaeomagnetic data from Australia have enabled us to revise the apparent polar wander path (APWP) of Australia and to test the tectonic relationships between some of the suspect terranes in eastern and cratonic Australia. The palaeomagnetic poles from the Lachlan Fold Belt (LFB) agree well with poles from cratonic Australia since the mid- to Late Devonian, with an Early Devonian pole from the LFB being easily accommodated in a revised APWP for cratonic Australia. Therefore, we suggest that the LFB could have been joined to the craton since the Early Devonian. Reliable pre-Devonian palaeomagnetic poles from the LFB are needed to constrain the tectonic relationships of older terranes of the LFB and cratonic Australia in the Early Palaeozoic.

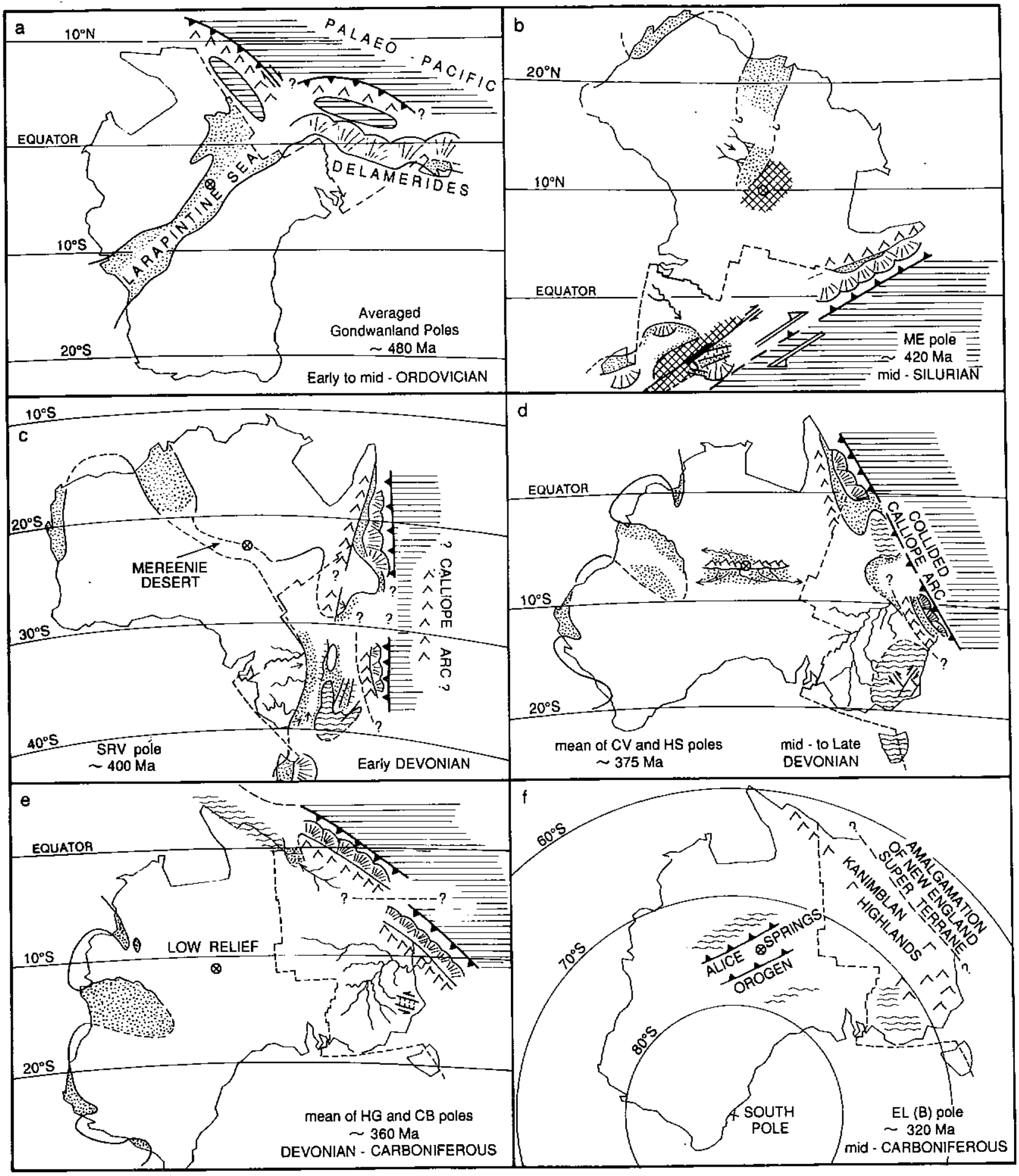

Fig. 6. Palaeogeography of Australia during the Ordovician to Carboniferous period. The Tasman Line and palaeogeographic elements are based on diagrams in Powell (1984), with updates from more recent work by Owen & Powell (Central Australia) and Powell (western LFB). Symbols: close stipple — shallow marine, ^ — volcanic chain, close-ruled — deep marine (? oceanic floor), short wavy line — folded areas, # — uplifted areas. Deep-sea fans and continental drainage indicated where known. For discussion of palaeogeographic basis see Powell (1984). Palaeomagnetic poles used for the palaeolatitudes are indicated in each diagram.

The revised APWP suggests that during the Early to mid-Palaeozic, Australia occupied low-equatorial palaeolatitudes and underwent rapid azimuthal rotations. During the Carboniferous, Australia moved rapidly to the south polar region. The rapid azimuthal rotations, and the succeeding latitudinal motion could have contributed to the regional tectonic events.

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