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A NEW PALAEOMAGNETIC INVESTIGATION OF MESOZOIC IGNEOUS ROCKS IN AUSTRALIA

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ABSTRACT

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Palaeomagnetic results have been obtained from four Australian igneous rock formations ranging in age from Early Jurassic to Early Cretaceous. These new sampling localities cover a much larger area than previously represented by Australian data. It is demonstrated that the pole positions yielded by the Kangaroo Island basalt (viz. 39° S 183° E, $A_{95} = 11°$) dated at 170 m.y. and the Early Jurassic western Victoria basalts (viz. 47° S 186° E, $A_{95} = 4°$) agree with results from other continents in the context of Gondwanaland. The pole position for the Bendigo dykes (47° S 135° E, $A_{95} = 39°$) confirm the 'anomalous' results previously obtained from southeastern Australia. The fourth pole position, obtained from the Bunbury basalt of Western Australia (dated at around 90 m.y.) is in good agreement with other Cretaceous data for Australia, implying that pole positions for the Jurrassic and Cretaceous periods should now be considered separately.

INTRODUCTION

Several Australian Mesozoic rock bodies received palaeomagnetic attention over a decade ago (Almond et al., 1956; Irving, 1956 and 1963; Boesen et al., 1961; Robertson and Hastie, 1962; Robertson, 1963; and Stott, 1963), however no further investigations have been reported since. These rock types embrace sedimentary and igneous units which lie within the southern portion of the Tasman orogenic zone representing a small part of the Australian continent. They yield results which have long been documented as anomalous (Irving and Robertson, 1969; Creer et al., 1969; and McElhinny and Embleton, 1974). The mean pole position calculated from those investigations not only gives anomalously high palaeolatitudes (Embleton, 1973) but is also significantly different from poles of similar age from the other continents which constitute Gondwanaland. The major inconsistency exists between the results reported by Irving (1963; first studied in 1956) for the Tasmanian dolerites and the results of Bull et al., (1962) for the Ferrar dolerites from Antarctica. Although those dolerites have been shown to be similar in age (McDougall, 1963) and closely related chemically (Compston et al., 1968), their respective pole positions remain quite distinct after rotation of Australia and Antarctica to their pre-drift positions as predicted by geometrical and geological constraints (Sproll and Dietz, 1969; and Smith and Hallam, 1970).

Griffith (1971) has suggested relative motion of Tasmania prior to the intrusion of the Tasmanian dolerites as an explanation. On the other hand Francheteau (1970) considers the results of the Ferrar dolerites to be at fault. These explanations are unsatisfactory. Firstly, results from serveral Mesozoic rock formations from mainland Australia are in good agreement with the results from Tasmania (Irving et al., 1963) and consequently any motion relative to Antarctica at that time would presumably also have involved this portion of the mainland. Results from leg 27 of the Deep Sea Drilling Project (DSDP) do not clarify the Mesozoic problem. Mesozoic basalts from bore-cores off the northwest shelf yield a pole locus consistent with the south-eastern Australian data whereas bore-core material drilled off the Perth shelf yields a pole locus consistent with the Ferrar dolerite pole of Antarctica (McElhinny, 1974; McElhinny and Embleton, 1974). A clockwise rotation of the Australian Mesozoic pole position of 25° about a pole of rotation at 131°E 39°N is required to reconcile the data. This appears to be highly improbable solution from geological considerations. Secondly, there appears to be no reason to doubt the reasons obtained from the Ferrar dolerites since they are internally consistent and also show good agreement with results from Africa, Arabia, India and South America (McElhinny and Embleton, 1974). In an attempt to solve this problem and further delineate the apparently anomalous region, a palaeomagnetic investigation has been extended to Mesozoic igneous bodies elsewhere in Australia.

SAMPLING LOCALITIES

Figure 1 shows the sampling localities for the igneous bodies described below.

Kangaroo Island

On Kangaroo Island a basalt flow of about 15 m thickness is exposed near Kingscote in quarries and coastal cliffs, while 10 km to the west the basalt occurs as breakaways on flat-topped hills around Wisanger (Daily et al., 1974). A further outcrop is poorly exposed 34 km east of Kingscote near Penneshaw. McDougall and Wellman (in preparation) obtained the following dates from three samples of the basalt, 165 ± 4, 163 ± 4 and 175 ± 4 m.y., using the K/Ar technique. The age of the basalt is therefore Middle Jurassic which is the same age as the Tasmanian dolerite. A total of 31 samples were collected from three sites. The first, and best exposed of these, was the Old

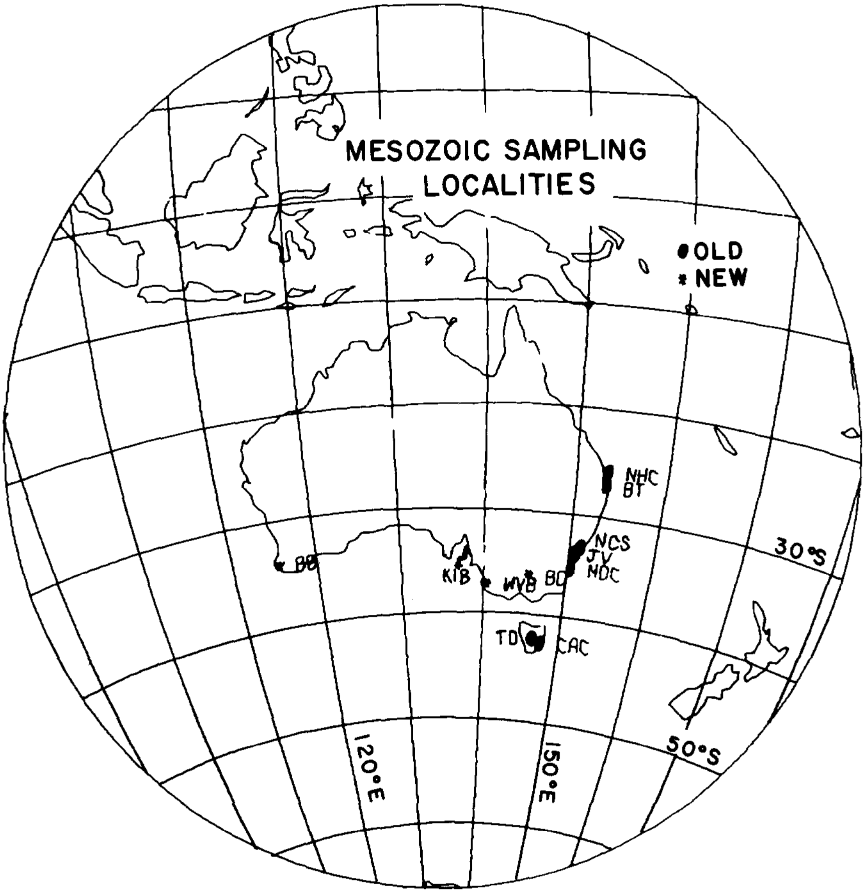

Fig. 1. Sampling localities in Australia. KIB = Kangaroo Island basalt; WVB = Western Victoria basalt; BD = Bendigo dykes; BB = Bunbury basalt (this paper). NCS = Narrabeen chocolate shale; BT = Brisbane tuff; JV = Jurassic volcanics; TD = Tasmanian dolerite; CAC = Cygnet alkaline complex; MDC = Mt. Dromedary complex (McElhinny and Embleton, 1974).

Government quarry at Kingscote and the other two were hillside outcrops near Wisanger and Penneshaw.

Western Victoria

Another Jurassic basalt is to be found north of Casterton in western Victoria where it is well exposed in quarries, river banks, and hillsides (Spencer-Jones, 1956). There is no definite field evidence for the existence of more than one flow although a number of plugs are present. McDougall and Wellman (in preparation) assign an age of Early Jurassic or older to the basalt but they suggest additional age measurements are required. Six sites have been sampled from which a total of 49 samples were analyzed. The sites include two quarries, a riverside outcrop and three small hillside excavations.

Bendigo, Victoria

A number of lamprophyre dykes intrude the country rocks near Bendigo, Victoria (Edwards, 1938a). The dykes are generally less than 1 m in width. They have been exposed in road cuttings through the Harcourt Granite on the Calder Highway about 17 km south of Bendigo, in an erosion gully at Kangaroo Flat, north of Bendigo and in new mine workings of the Lone Star Exploration Co. at Maldon, 20 km to the southwest of Bendigo. Dykes have also been intersected in old disused mine shafts in Bendigo which were inaccessible at the time of collection. Two samples from mullock heaps have given ages of 146 ± 4 and 155 ± 4 m.y. (McDougall and Wellman, in preparation). The dykes are therefore slightly younger than the Kangaroo Island basalt and western Victoria basalt. 24 samples of the dykes and three samples of the contact in the Harcourt Granite were collected.

Western Australia

In the southwest province of Western Australia an extensive basalt sheet outcrops in numerous localities (Edwards, 1936 and 1938b). Although only one flow (maximum thickness of up to 100 m) is exposed in any one site, the basalt occurs over a large area (2000 sq. km); it is uncertain if there is more than one flow present. Ages of 90 ± 3, 88 ± 4, 101 ± 5 and 89 ± 4 m.y. are given by McDougall and Wellman (in preparation) and they conclude that the Bunbury Basalt is at least 90 m.y. old (Late Cretaceous). From the least weathered outcrops the five sites chosen were Rocky Point at Bunbury, a quarry 1 km east of Gelorup, Black Point on the south coast 30 km West of Pemberton, the junction of Red Gully and Blackwood River near the Brockman Highway and a small road cutting on the Vasse Highway about 6 km south of the Donnelly River. A total of 57 samples were collected from those five sites.

TECHNIQUES AND RESULTS

In all cases block samples were collected and oriented with both a sun-compass/clinometer (Embleton and Edwards, 1973) and a magnetic compass. Four or more specimens were prepared and measured on a 'complete results' spinner magnetometer (Molyneux, 1971) and each specimen has been treated by step-wise demagnetization with the use of an A.F. demagnetizer (McElhinny, 1966). The statistics of Fisher (1953) have been used to analyze the measured directions of magnetization and a system similar to that described by McElhinny et al. (1974), for eliminating intermediate and anomalous directions has also been employed. This was necessary because samples from some formations (especially the Kangaroo Island basalt) exhibit large deviations from the mean direction of magnetization. There appears, however, to be no systematic correlation of the intensity of these transitional or intermediate directions as found by Wilson et al. (1972) when analyzing data from Icelandic lava flows. It is worthwhile noting that whereas McElhinny et al. (1974) rejected *poles* that lay greater than 40° from their mean pole position, the process here is applied to the *directions* that lay greater than 40° from their mean direction. Because the mean direction of magnetization has high inclinations (>60°) for all formations, this is a more conservative approach possibly resulting in the rejection of less data. At high palaeolatitudes, the virtual geomagnetic poles (V.G.P.) corresponding to the palaeomagnetic directions always have a higher dispersion than do the directions themselves. The directions which have been rejected on this basis are designated with a cross in the stereographic projection diagrams (Fig. 2). The mean pole positions calculated from these directions by giving unit weight firstly to samples and secondly to sites are given for each formation in Tables I and II. Usually there is little, if any difference between the pole positions calculated by assigning unit weight to sites or samples. The half angle of the cone of confidence (A_{95}), however, is sometimes greater for the case where the unit weight is given to sites. Sample mean directions from different sites are given different symbols in the figures.

Kangaroo Island basalt

Most sample mean directions change considerably (up to 80°) before becoming stable (usually above 20 mT peak field) during A.F. demagnetization. This is reflected in the demagnetization curve and coercivity spectrum which show that a large secondary component is removed before the 20 mT peak field is reached. The secondary magnetizations of the Wisanger and Penneshaw sites have a wider coercive force spectrum than that of the quarry site, probably reflecting the different states of weathering of the samples collected. A number of directions from the Wisanger and Penneshaw sites remained oblique to the principal axis of magnetization. They have been omitted from the final calculations on the premise that they are anomalous directions as previously described. The possibility that these directions actually arise from inadvertant sampling of slumped blocks must be considered especially since Daily et al. (1974) specifically note the presence of such blocks in the Wisanger area (brought to the author's attention after making the collection). Since no magnetic reversals were measured, the oblique directions do not appear to be transitional although this does not rule out the possibility that they represent intermediate directions (Lawley, 1970; Barbetti and McElhinny, 1972; and McElhinny et al., 1974). The pole position calculated from the remaining twenty samples is given in Table I and plotted in Fig. 3. The sample mean direction from the Penneshaw site (K1), which

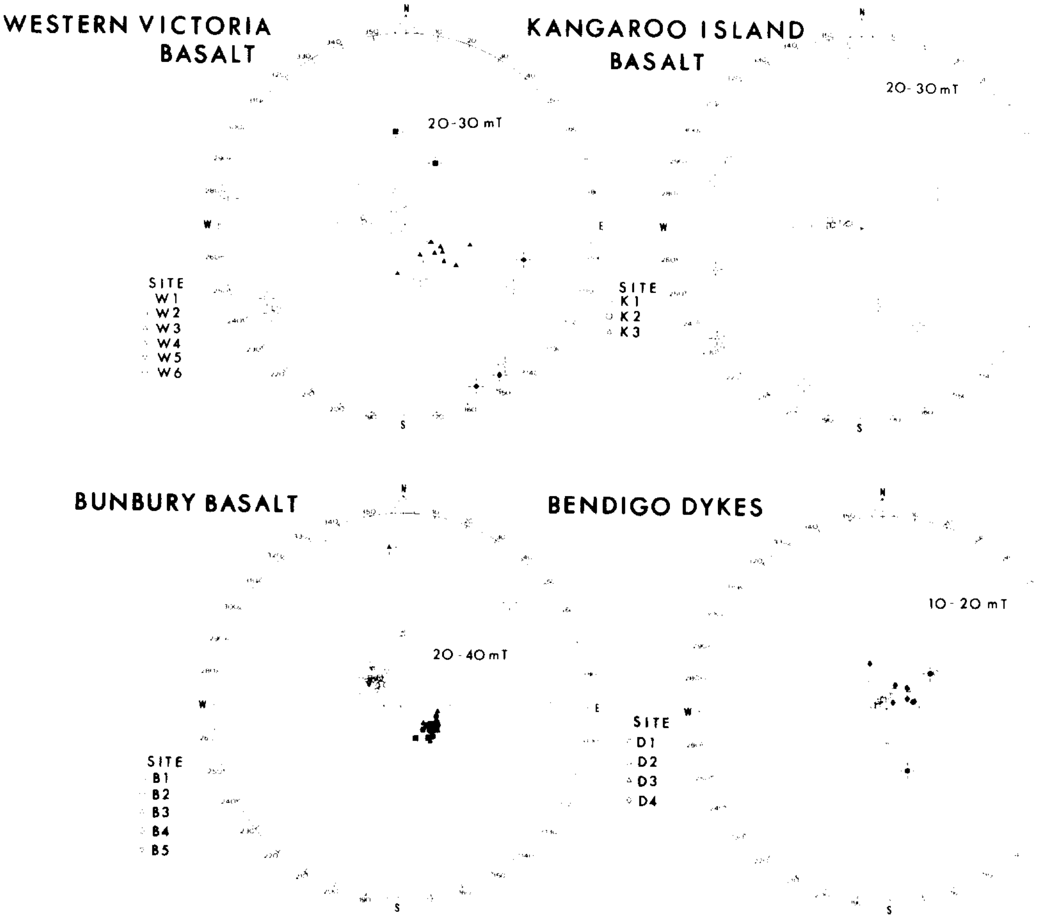

Fig. 2. Cleaned magnetic directions. Symbols marked with a cross have been rejected (see text).

has not been eliminated, is included with the site mean direction calculated for the Wisanger site (K2) in Table I.

Western Victoria basalt

The 'cleaned' directions of all samples were shown in Fig. 2. The majority of specimens reveal a stable (original) direction above 20 mT, after the removal of a large secondary component (shown by their demagnetication curve and coercivity spectrum. Five sites (W1, W2, W4, W5 and W6) contain normal directions while one site is reversed (W3). The specimens with reversed polarities initially increase in intensity during demagnetization while specimens with normal polarities decrease in intensity indicating the secondary components removed are not randomly distributed. They are directed closely to the present field axis.

TABLE I

Lower to middle jurassic pole positions

Site	Mean direction				Pole position		
	D *	*I*	*N*	*R*	Lat. (°S)	Long. (°)	A_{95} (°)
Kangaroo Island basalt (170 m.y.)							
K1 — Old Government quarry (35°36'S, 137°30'E)	272.7	−72.7	10	9.74	32	173	12
K2 — Wisanger (35°36'S, 137°30'E)	298.7	−60.9	10	9.35	45	196	17
Mean pole position — sites	2		2	1.96	39	183	—
— samples			20	18.13	39	183	11
Western Victoria basalt (?Early Jurassic)							
W1 — Moree quarry (37°20'S, 141°30'E)	291.3	−74.3	12	11.16	46	184	18
W2 — Chetwynd (37°02'S, 141°24'E)	306.4	−60.2	3	2.99	49	208	13
W3 — Government quarry (37°20'S, 141°20'E)	132.9	62.5	9	8.79	55	204	12
W4 — Dergholm (37°20'S, 141°20'E)	304.4	−70.2	2	1.95	49	181	—
W5 — Red Cap (37°24'S, 141°20'E)	206.8	−77.7	8	7.78	17	151	17
W6 — Wando Vale (37°30'S, 141°30'E)	333.2	−79.9	2	1.99	54	156	—
Mean pole position — sites			6	5.64	47	178	18
— samples			36	31.05	45	179	10

* *D*, *I* are declination and inclination of the magnetic directions, *N* is the number of directions and *R* the length of their resultant unit vectors. A_{95} is the circle of 95% confidence determined from V.G.P.s which have been calculated from the directions.

The presence of reversal indicates that the time interval covered by sampling is considerable (10^3—10^4 year, McElhinny, 1971) and strongly suggests that there is more than one flow represented. Transitional or intermediate directions are again omitted from final calculations. One such direction possessed an abnormally high N.R.M. intensity and could have resulted from a lightning strike. The pole position is plotted in Fig. 3.

Bendigo dykes

Stable components of remanent magnetication have been isolated from all samples. One of the dykes (D4) contains reversed polarities and the other three (D1, D2 and D3) are normally magnetized. The presence of at least two polarity intervals again indicates that a long period of time has been

TABLE II

Upper Jurassic to upper cretaceous pole positions

Site	Mean direction				Pole position		
	D	*I*	*N*	*R*	Lat. (°S)	Long. (°E)	A_{95} (°)
Bendigo dykes (150 m.y.)							
D1 — Kangaroo Flat (37°S, 144°20′E)	38.2	−60.4	3	2.96	69	125	18
D2 — Road cutting (37°00′S, 144°20′E)	226.8	−84.9	8	7.94	48	155	7
D3 — Road cutting (37°00′S, 144°20′E)	65.3	−77.8	6	5.51	42	116	39
D4 — Maldon (37°00′S, 144°20′E)	42.2	76.2	7	6.87	17	162	16
Mean pole positions — sites			4	3.54	47	135	39
— samples			26	20.02	42	144	14
Bunbury basalt (90 m.y.)							
B1 — Rocky Point (33°20′S, 115°36′E)	120.8	66.6	16	15.98	44	167	2
B2 — Gelorup (33°25′S, 115°40′E)	225.0	−70.4 *	9	8.89	58	153	11
B3 — Red Gully (34°10′S, 115°30′E)	221.7	−64.6 *	9	8.67	56	170	15
B4 — Vasse highway (34°20′S, 115°40′E)	285.2	−74.9	5	4.95	37	150	15
B5 — Black point	308.4	−66.5	15	14.95	50	168	4
Mean pole positions — sites			5	4.93	49	161	10
— samples			54	51.67	50	163	4

* These sites have mixed polarities.

sampled. Although the granite contact samples were weakly magnetized (< mAm^{-1}) their directions agree with the directions measured in the dykes indicating their magnetic stability since the time of intrusion. The stable 'cleaned' directions are shown in Fig. 2. Only three (oblique) directions have been rejected as indicated. The site and sample mean pole position are given in Table II.

Bunbury basalt

A high degree of stability was exhibited by the cleaned directions of magnetization of samples from the Bunbury basalt. The demagnetization intensity curves show a large change in intensity up to 20 mT. This was accompanied by a small change in magnetic direction (usually <10°). The secondary component is directed closely to the earth's present field axis. The 'cleaned' directions plot as two closely antiparallel groups.

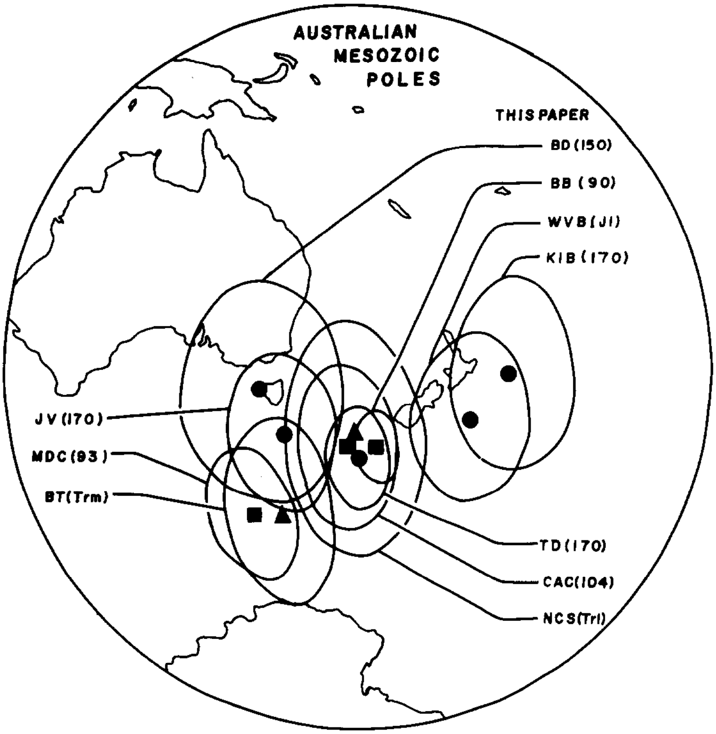

Fig. 3. Mesozoic TR, ▲, J, ● and K, ■ poles and 95% cones of confidence, for Australia. Notice the two poles (this paper) that lie northeast of the main assemblage. Abbreviations as in Fig. 1.

Of the five sites sampled, two sites contain mixed polarities, one site reversed and two sites have normal polarities. Although one of the sites (B2) having mixed polarities is very well exposed (the quarry near Gelorup), there is no evidence that more than one flow is present. It appears that a single flow has recorded both normal and reversed polarities. Indeed, both polarities have been found coexisting within one sample, suggesting that perhaps some self-reversal mechanism was operating. Attempts to distinguish between specimens with opposite polarities by other techniques have failed. If different titanomagnetite phases were present a difference in Curie temperature should be discernible between the normal and reversed samples. No such difference was detected by experiments carried out with a thermomagnetic balance. Several Curie points in both normally and reversely magnetized basalt samples were measured revealing a common Curie temperature between 180 and 200°C. Polished-section examinations reveal similarly sized titanomagnetite crystals of skeletal habit in both groups. Incipient exsolution lamallae are also common to both groups. The magnetic remanence did not spontaneously reverse after heating above the blocking temperature (close to the Curie temperature) and allowing them to cool in a known field direction (as does the Haruna dacite; Nagata et al., 1952). This test does not preclude the possibility of self-reversal since whatever is established under laboratory conditions may not be legitimately extrapolated to natural conditions. Misorientation of samples is ruled out as an explanation of the within-site reversal. The within-sample reversal has been checked by redrilling and careful slicing.

DISCUSSION

From these new results it is now apparent there is inconsistency *within* the Australian Mesozoic data. However, two pole positions (that of the Kangaroo Island basalt and Western Victoria basalt) show good agreement with poles derived from the other Gondwana continents. It would therefore appear they could be more representative of Australia as a whole (assuming the validity of the geological and geometrical reconstructions) than the pole positions further to the west (as shown in Fig. 4). This also implies that the Jurassic and Cretaceous poles for Australia are quite distinct since the pole for the Bunbury basalt closely agrees with that of the Mt. Dromedary complex (Robertson, 1963) and the Cygnet alkaline complex (Robertson and Hastie, 1962). The Cretaceous and Jurassic pole positions for Australia previously formed one group. (see Fig. 3).

The age of the Bendigo dykes (about 150 m.y.) might conceivably be young enough to explain its apparent agreement with the Cretaceous data. On the other hand, the coincidence of this pole positions with pole positions from other eastern Jurassic rocks (McElhinny and Embleton, 1974) may be taken to suggest that the anomaly has been duplicated. Further work is required to fix more precisely the Jurassic/Cretaceous apparent polar shift suggested for Australia.

There now appears little to suggest the Cretaceous data from southeastern Australia should be treated as anomalous, since the pole position obtained from the Bunbury basalt (southwestern Australia) agrees with the Mt. Dromedary complex and Cygnet alkaline complex palaeomagnetic data. Gondwanaland had begun to disintergrate at this time as evidenced by the Cretaceous poles for both India and South America which begin to diverge from the African data during the Late Jurassic and Cretaceous (McElhinny and Embleton, 1974). No Cretaceous pole position for Eastern Antarctica is available to independently check this conclusion — sea-floor spreading data infer that Australian and Antarctica formed a single unit at that time, prior to their Early Tertiary separation (Le Pichon and Heirtzler, 1968).

The anomalous Jurassic palaeomagnetic directions from southeastern Australia remain unexplained. It is, however, noteworthy that while a variation of the conglomerate test (Graham, 1949) proved positive for the Tasmanian dolerite (Irving, 1963), the majority of specimens have not been treated by demagnetization techniques and small but systematic components in the present field direction may be present. In fact the samples that have been de-

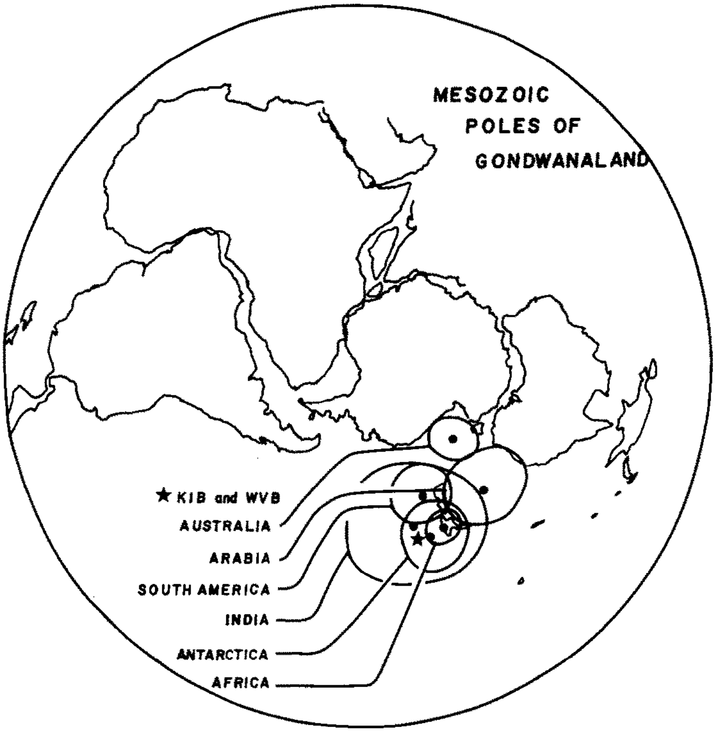

Fig. 4. Mesozoic pole positions and 95% cones of conficence for the southern continents (including Arabia/Turkey and India). The two pole groups shown for Australia consist of that given by McElhinny (1973) and the mean pole position of the Western Victoria and Kangaroo Island basalts. All other poles for the southern continents are those used by McElhinny (1973). Linear polar projection.

magnetized (Stott, 1963) from the Red Hill Dyke yield a pole position which does agree with the Ferrar dolerite pole from Antarctica. As noted by Irving (1963), these cleaned directions do not vary significantly from the N.R.M. directions and do not therefore contain considerable amounts of secondary magnetization in the present field direction. The coincidence of the Red Hill V.G.P. and the pole positions for the Kangaroo Island basalt and the western Victoria basalt with the Mesozoic pole position for the rest of Gondwanaland, does however suggest that the application of more recent palaeomagnetic techniques to the Tasmanian dolerite might prove fruitful. Therefore, at the suggestion of Dr. Irving, a new investigation of the Tasmanian dolerate using both A.F. and thermal demagnetization techniques is being undertaken. Further palaeomagnetic works also includes the Garawilla Volcanics (Bean, 1974) from N.S.W., with the intention of extending the investigation in the southeastern region, to a sequence of igneous rocks that may cover more than one polarity interval.

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