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The non-uniqueness of the Australian Mesozoic palaeomagnetic pole position

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Summary. Palaeomagnetic results for the Jurassic obtained from the Tasmanian dolerites, the Gingenbullen dolerite, the Prospect dolerite, the Gibraltar syenite (all previously examined over a decade ago) and the Garrawilla volcanics, the Nombi extrusives and the Glenrowan intrusives (representing a new study) are presented. It appears that for some rock formations early experimental techniques failed to remove completely secondary components. Evidence suggests that a particularly harsh period of weathering (probably during the Late Cretaceous/Early Tertiary) may be partly responsible for secondary components. Rotational remanent magnetization (RRM) has also been detected and eliminated during alternating field (AF) demagnetization procedures. The results from the Tasmanian doleraites are in close agreement with the previously published results, while those from the other reinvestigations are seen to be markedly different from the early results. In the light of these and other recent data, a new interpretation of the Australian Mesozoic palaeomagnetic pole position is given. The mean Triassic (52° S, 153° E), Jurassic (47° S, 176° E) and Cretaceous (53° S, 152° E) pole positions are now considered as separate. On the basis of the palaeomagnetic data, a spread in age for the Tasmanian dolerite is suggested and the age of the breakup of eastern Gondwanaland is constrained between 100 and 160 My ago. The Australian Jurassic pole position is compared to the Late Triassic–Middle Jurassic palaeomagnetic poles from other southern lands and India in their pre-drift configuration as dictated by geomorphological reconstructions. It is shown that these poles form a tight group around their mean pole position at 63° S, 71° E ($A_{95} = 3°$) with respect to present day Africa.

1 Introduction

Initial palaeomagnetic results from Mesozoic rocks of Australia proved to be internally consistent (Boesen, Irving & Robertson 1961, Robertson & Hastie 1962; Robertson 1963; Irving 1963 and Irving *et al.* 1963). The palaeomagnetic pole position derived by combining these early results if 46° S, 145° E ($A_{95} = 8°$) (McElhinny & Embleton 1974). However, Irving & Robertson 1969; Creer, Embleton & Valencio 1969 and McElhinny & Embleton 1974 have recorded the Australian Mesozoic pole position anomalous when compared with

Mesozoic pole positions from other continents of Gondwanaland. In addition, McElhinny & Embleton (1974) noted that without exception the early studies were made on rock units outcropping in Southeastern Australia and, in particular, in the southern part of the Tasman Orogenic Zone (a Palaeozoic mobile region). This instigated a study of Mesozoic rocks which are far removed from this anomalous area to further test the consistency of the Australian data. Schmidt (1976) reports results from these rock bodies which are compatible with data from other southern continents. These results, examined in the framework of the early results, raise questions of the tectonic stability of Southeastern Australia since the time of formation of the rock units. However, geological evidence for such disturbances is lacking. On the contrary, strata in Mesozoic sedimentary basins in Southeastern Australia are essentially horizontal, showing no large scale tectonism since deposition.

These conflicting conclusions have led to the resampling of the Tasmanian dolerite, the Gingenbullen dolerite and the Gibraltar syenite while an entirely new study has been made on the Garrawilla volcanics (including the Nombi-extrusives and Glenrowan intrusives). Although the Garrawilla volcanics outcrop in Southeastern Australia, they are approximately 300 km inland which is much further inland than the other rock bodies studied in Southeastern Australia.

The subsequent results of these studies suggest that anomalous data should be verified (or otherwise) with improved techniques now available. To this end further magnetic cleaning of samples of the Prospect dolerite (originally collected by Boesen *et al.* 1963) has been completed.

Most samples were cored in the field with a portable rock drill and orientations were performed with both a suncompass/clinometer and a magnetic compass. Altogether 150 samples were collected from Jurassic igneous rock types outcropping over 10° of latitude.

2 Garrawilla volcanics and Nombi extrusives (including Glenrowan intrusives)

A sequence of basic lavas which occur in Northeastern New South Wales have been described by Bean (1974). They belong to two different types of volcanism which Bean (1974) refers to as the Garrawilla volcanics and Nombi extrusives. The lavas are comprised of basalt, hawaiite, mugearite, trachyte and basinite and their present total thickness is 180 m. In addition to the flows, a number of dolerite bodies are intrusive, forming sills and dykes within the lava sequence and underlying Triassic sedimentary rocks.

An age of the Garrawilla volcanics has been determined by K–Ar analysis as 193 ± 10 My while a date of 181 ± 5 My was given by the Glenrowan intrusives (Dulhunty & McDougall 1966). The lavas are overlain at their margins by Jurassic sedimentary rocks and they in turn overly Triassic sediments. These relationships and the radiometric ages indicate a Late Triassic–Early Jurassic age.

All sampling sites are shown in Fig. 1. Three sections were sampled (Table 1) in the lava sequence, two of these including Nombi extrusives while the third was entirely comprised of Garrawilla volcanics. Usually, 3 cores were drilled from each flow and altogether 20 flows were sampled, 9 of these being from Section 1. As well as the flows, the Glenrowan intrusives were sampled at a site in a road cutting 2 km south of Mullaley.

2.1 TASMANIAN DOLERITE

The geology of Eastern Tasmania is dominated by thick dolerite sills intruding Triassic sediments (Carey 1958). The age of the Red Hill dyke (a part of the dolerite complex) has been shown by K–Ar dating to the Middle Jurassic (*ca.* 170 My – McDougall 1961). This is therefore similar in age to the Ferrar dolerite of Antarctica. The dolerites are also similar chemi-

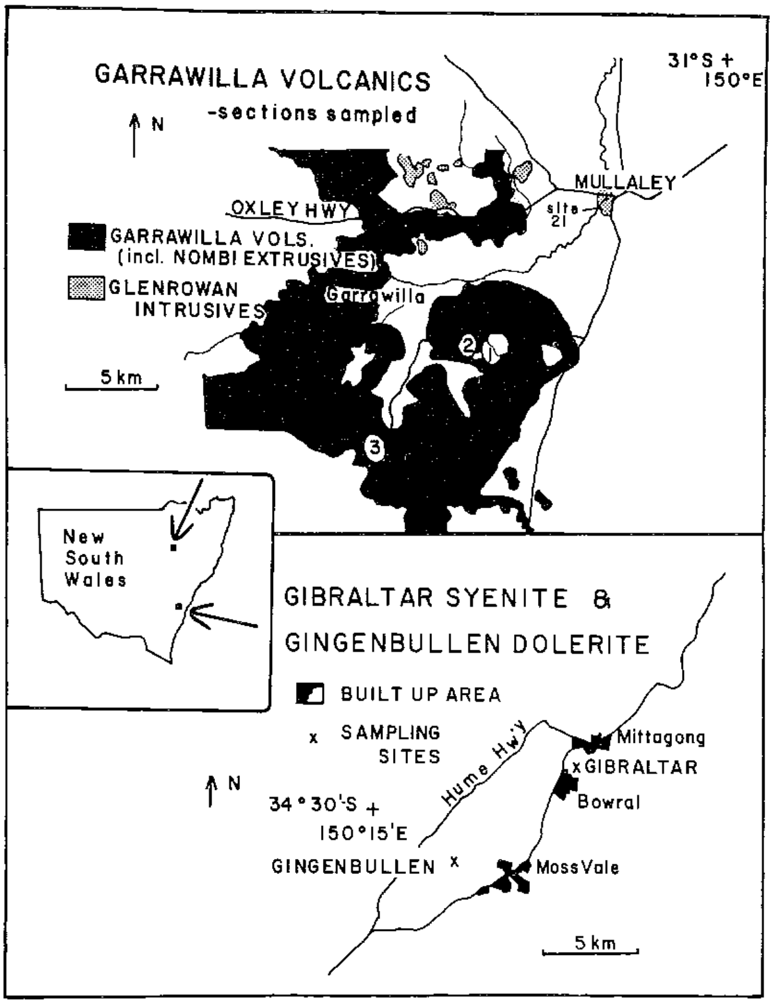

Figure 1. Sampling sections in the Garrawilla volcanics are denoted by the numerals 1, 2 and 3. Site 21 refers to the sampling site in the Glenrowan intrusives while sampling sites in both the Gibraltar syenite and the Gingenbullen dolerite are marked with a cross.

cally and almost certainly have been derived from a distinctive geochemical source (Compston, McDougall & Heier 1968). Fig. 2 shows the dolerite outcrop and distribution of the 33 sampling sites in Tasmania. A number of the sites sampled by Irving (1963) have been resampled, however, many new sites were sampled to achieve a more even distribution. In particular, whereas Irving collected 12 sites from the Mt Wellington sill near Hobart, 3 sites were taken for the present study (Table 2) so disproportionate weight would not be given to this body.

2.2 JURASSIC INTRUSIVES OF NEW SOUTH WALES

During this study samples from four igneous intrusions of similar age, namely 168–181 My, have been investigated (the Gingenbullen dolerite, the Gibraltar syenite, the Prospect dolerite and the Glenrowan intrusives). The geology of the first three of these bodies has been described elsewhere (Boesen *et al.* 1961) and shall not be repeated here. The geology of

Table 1. Garrawilla volcanics and Nombi extrusives (193 My)

Flow		Rock type	Pole position Lat (°S)	Pole position Long (°E)
Site	1-I	GW	45.4	170.0
	1-H	NB	32.9	177.6
	1-G	NB	31.4	176.4
	1-F	GW	38.6	180.7
	1-D	GW	47.0	182.1
	1-C	GW	33.4	199.2
	1-B	GW	65.7	133.9
	1-A	NB	53.8	192.3
Site	2-E	GW	37.2	190.7
	2-D	GW	46.4	172.8
	2-A	GW	73.2	181.9
Site	3-D	GW	69.8	159.4
	3-B	GW	43.0	183.5
	3-A	GW	13.5	144.0
	Mean		46.1	175.2
			(A_{95} =	10.0°)

Notes:

Results above were obtained from site mean directions for which $N = 2$ or 3 and $k > 30$ (except site 3-A for which $k = 13$). Oblique (see text) results have been omitted. Site numbers refer to Fig. 1.

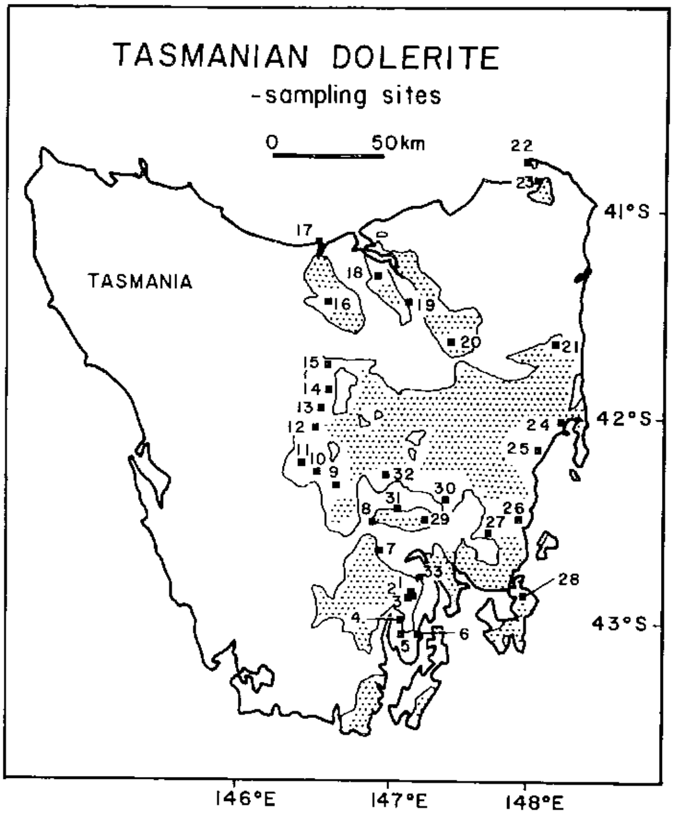

Figure 2. The stippled region shows the outcrop of dolerite while the numbered squares refer to sampling sites.

the Glenrowan intrusives is treated by Bean (1974) as referred to in Section 2. Recently a K–Ar date of 172 My has been reported for the Gingenbullen dolerite (McDougall & Wellman 1976) which agrees with the geological constraints placed on the age. Radiometric dates are now available from each of these bodies.

Table 2. Tasmanian dolerite (167 My)

Site	Pole position Lat (°S)	Long (°E)	Site	Pole position Lat (°S)	Long (°E)
1	55.7	148.3	19	52.6	164.8
2	47.2	176.5	20	63.0	168.6
3	63.8	162.2	22	41.5	193.6
4	49.1	196.5	23	51.9	164.4
5	52.0	147.3	24	39.3	138.5
6	56.7	178.5	25	48.9	107.8
7	30.2	183.9	26	49.3	173.3
8	33.5	184.1	27	44.1	170.8
9	22.3	109.4	28	53.3	174.4
10	42.9	133.4	29	51.1	174.6
11	47.3	125.9	30	45.4	144.7
12	55.6	124.4	31	40.5	125.6
13	52.5	148.5	32	40.8	173.5
14	45.7	75.2	33	53.3	165.7
15	49.5	142.0	34	41.9	187.8
16	59.5	94.9	Mean	52.0	156.3
17	68.7	209.2		(A_{95} = 6.6°)	
18	47.8	159.6			

Notes:

Results above were obtained from the site mean directions for which $N = 2$ and $k > 20$ (usually 100) except site 17 for which $k = 6$. Site 21 has been omitted because the magnetic directions were oblique (see text). Site numbers refer to Fig. 2. Site 34 from Stott (1963).

3 Techniques and results

Three or four specimens were sliced from each core except when fracturing prevented more than two being taken. The approximate dimensions of each specimen is 2.5 cm (diameter) x 2.2 cm (height). All measurements and computing of directions were performed on a complete results Digico spinner magnetometer (Molyneux 1971). The magnetometer has been improved by the addition of a set of three orthogonal sets of Helmholtz coils to cancel the magnetic field above the μ-metal shield on the spinner unit. This was necessary because during the measurement procedure a specimen is exposed to the Earth's field in such a way that the resultant VRM (viscous remanent magnetization) is non-zero and when the NRM (natural remanent magnetization) is demagnetized sufficiently this extraneous component becomes appreciable. In addition to the Earth's field, a large vertical magnetic field is produced as a result of the geometry of the shield in the region where the specimen is exposed. The coils rectify this problem. A two-axis tumbler AF (alternating field) demagnetizer and a thermal demagnetizer were used for demagnetization and elimination of secondary magnetic components. Both methods were used except for the Gingenbullen dolerite where only the coercivity spectrum was investigated. Usually about 20 per cent of each collection were selected to run as pilots and the remainder of each collection treated in an optimum field. This was determined on the basis of the pilot results and the stable end point method of McElhinny & Gough (1963). During AF demagnetization a procedure suggested by Brock & Iles (1974) for the detection of RRM (rotational remanent magnetization) was used. This proved necessary to isolate the primary remanent magnetization of some samples of the Garrawilla volcanics, Nombi extrusives and Prospect dolerite. The statistics of Fisher (1953) were used to analyse the results of all measurements.

3.1 GARRAWILLA VOLCANICS AND NOMBI EXTRUSIVES

VGP positions (see Fig. 5) derived from stable, non-random site mean directions have been combined to give a formation palaeomagnetic pole (Table 1). The lavas and the intrusion are all of normal magnetic polarity with no reversed directions being detected. Six sites were rejected because their directions were either internally random or oblique to the overall site mean direction and are therefore not considered close records of the axial field direction at the time of formation. Random directions were defined after Irving (1964) and oblique directions have been determined using a similar system to that described by McElhinny, Embleton & Wellman (1974).

A feature which became obvious during demagnetization was the viscous nature of the magnetic material in both the Garrawilla volcanics and the Nombi extrusives. Extreme care was therefore taken to ensure no spurious components were added between demagnetization and measurement. Although VRM effects were eliminated, some samples continued to give scattered directions. On closer inspection this scattering was seen to be due to a component of magnetization added during the actual demagnetization procedure. The component appeared to result from RRM as described by Wilson & Lomax (1972) or more specifically RRM 2 (Brock & Iles 1974). As found by these workers the RRM is directed along the inner axis of the tumbling mechanism and usually in the opposite sense to the angular velocity vector. This effect was cancelled by firstly *reversing the specimen* in the tumbler and secondly by *reversing the direction of rotation* of the tumbler, between otherwise equivalent demagnetization runs (Brock & Iles 1974). Both these methods gave identical results, and the mean direction of duplicate demagnetizations was accepted as being free from RRM contamination. That both the methods achieve the same result is testimony to the fact that the demagnetization is free of ARM (anhysteretic remanent magnetization). If this were not so, the methods should give different results for the extraneous component of magnetization. RRM and VRM had no discernible effects on the samples of the Glenrowan intrusives.

NRM and cleaned directions of both Garrawilla volcanics and Nombi extrusives are compared in Fig. 4(a), the rejected directions being marked with a cross. For consistency of interpretation and presentation, the results from the Glenrowan intrusives are included with the results from the other intrusive rocks of New South Wales (see Table 3). The site VGPs (using the flow as the unit of observation) for the Garrawilla volcanics and Nombi extrusives are given in Table 1 and plotted in Fig. 5. The mean of these poles is 46° S, 175° E ($A_{95} = 10°$, $N = 14$).

3.2 TASMANIAN DOLERITE

Eleven pilot samples were AF demagnetized in 15 successive steps from 5 mT to 200 mT and thermally demagnetized at 12 discrete temperatures between 200°C and about 600°C. After each step the sample mean directions and sample VGPs were statistically combined to judge the most effective cleaning step. K (the precision parameter) increased to a peak at 30 mT during AF demagnetization and 300°C during thermal demagnetization. These values were maintained over a plateau region before slowly decreasing as the intensities decreased to small percentages of their initial NRM values. The mean sample direction and mean VGP did not change significantly until high fields and temperatures were applied. The changes that did occur were shown to be due to the addition of systematic components during measuring (before the Helmholtz coils were added to the magnetometer – see Section 3.0).

Demagnetization curves, coercivity spectra and blocking temperature spectra are shown for 5 pilots in Fig. 3. All curves show very similar features, the most notable being the peak in their blocking temperature spectrums at about 580°C. The majority of the coercivities are

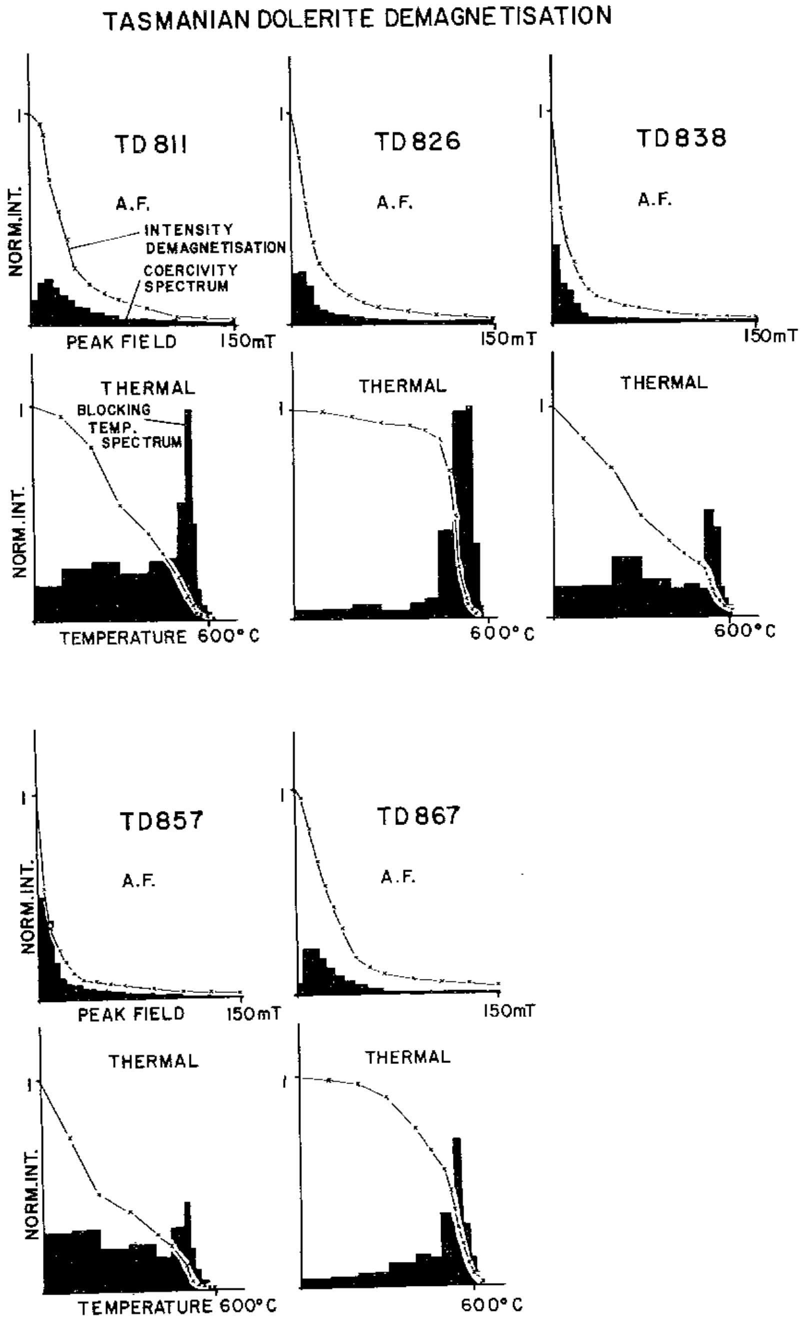

Figure 3. Intensity demagnetization curves, coercivity spectra and blocking temperature spectra for some pilot samples of Tasmanian dolerite. The spectra were calculated using the gradient of the demagnetization curves between successive steps. Notice the peak in the blocking temperature spectra at about 580°C.

below 40 mT, although an appreciable portion of the magnetic minerals possess coercivities of over 100 mT. These properties are consistent with those of titanomagnetite which was observed to be the most common opaque mineral present when examined by reflected light microscopy.

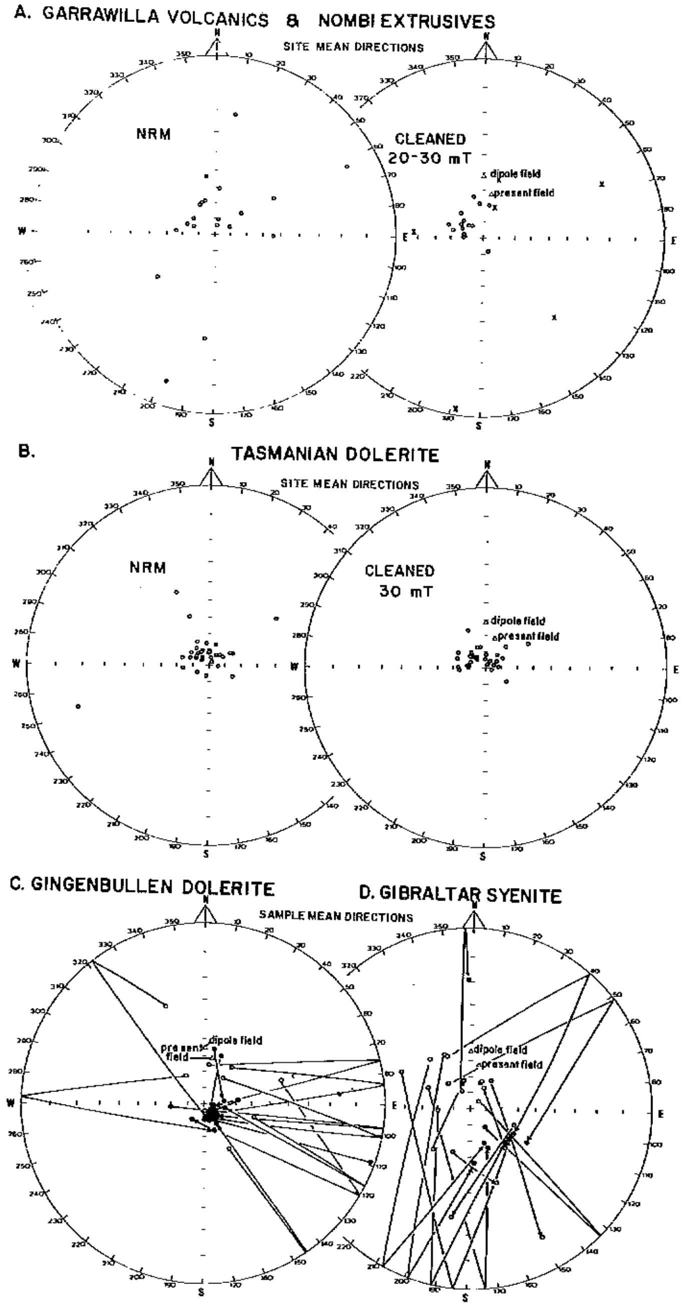

Figure 4. Equal angle stereoplots comparing NRM and cleaned directions of magnetization. The lines joining points in C and D do not necessarily represent the path the magnetic direction followed during demagnetization.

Fig. 4(b) shows both NRM and cleaned directions. One site mean direction remained oblique throughout the whole range of coercivity and blocking temperature spectra. The reason for this is unknown and it has been rejected for the purposes of calculating the formation mean directions and the formation pole position. At this point mention should be made of the distribution of the site mean directions and virtual geomagnetic poles (Fig. 5).

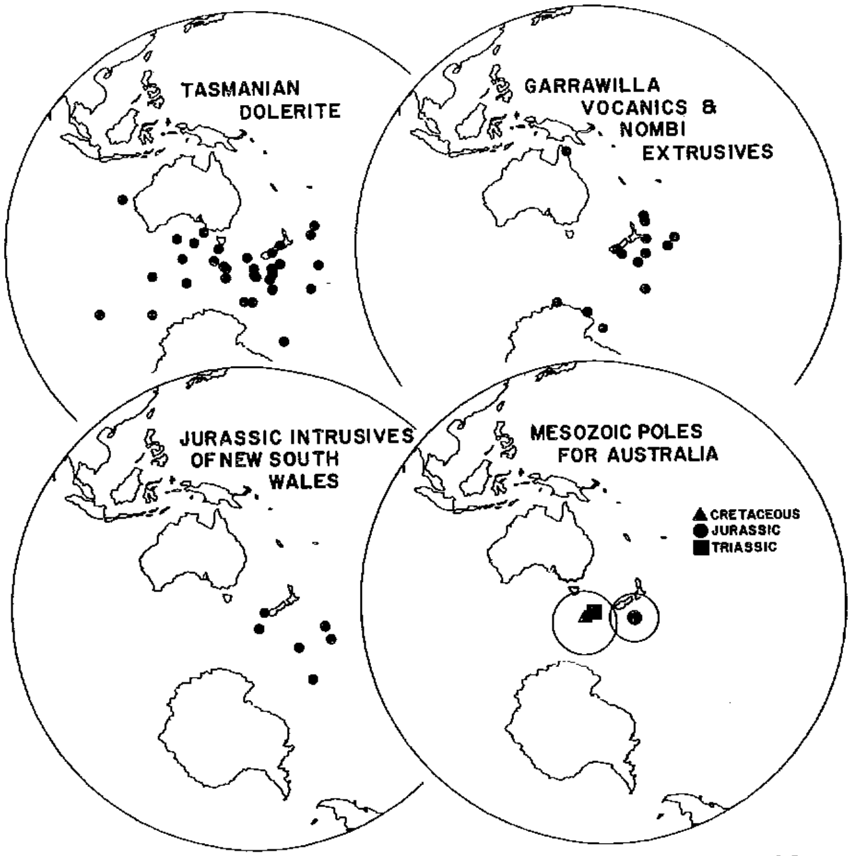

Figure 5. Linear polar projections showing pole positions for formations and groups of formations (see text for discussion).

Although there are over 30 sites, neither distribution appears to be circular and in fact they are non-Fisherian (using the statistical test described by Watson & Irving 1957). This is particularly evident in their azimuthal ranges which show concentrations of data in the east–west direction. On closer inspection, the data appear to fall into two main groups which are derived from two distinct geographical regions. The significance of this observation is elusive since a solution involving secular variation or tectonic movement between the two regions is not readily apparent. On the one hand, secular variation would be expected to have been averaged (considering the geological nature of the rocks sampled) and on the other, although block faulting and rifting were common during the Tertiary there has been no obvious relative motion of the scale required (Solomon 1962).

The pole position calculated from the cleaned site mean directions as given in Table 2, namely 52° S, 156° E (A_{95} =7°, N = 33) is not significantly different from the palaeomagnetic pole position determined by Irving (1963) at 51° S, 160° E from NRM data – the results of Stott (1963) are included here since these involved AF cleaning. Irving justified his use of NRM directions firstly with a field test (which was a variation on a conglomerate test) and secondly with results of a geophysical study of a dyke – which is closely related to the sills (Stott 1963). The magnetic survey involved AF cleaning and served to show that NRM directions did not differ significantly from cleaned directions. A baked contact test (Graham 1949) also, indicated a high degree of magnetic stability. The results reported here indicate that these tests were sufficient to justify such use of NRM data before magnetic cleaning became routine practice. However, it is probably desirable to use data derived from standard cleaning techniques and the pole position for the Tasmanian dolerite in Table 2 is used instead of the early result.

3.3 JURASSIC INTRUSIVES OF NEW SOUTH WALES

The following describes results from the Gingenbullen dolerite, Gibraltar syenite, the Prospect dolerite and the Glenrowan intrusives.

(a) *Gingenbullen dolerite*

All 14 samples collected were AF demagnetized and their directions of magnetization reached stable end points after 20–25 mT. Fig. 4(c) shows NRM directions, which are scattered (most having negative inclinations) and the cleaned primary directions, which are well grouped with steep positive inclinations. This indicates the geomagnetic field had reversed polarity when the dolerite cooled, but a subsequent normally polarized field has masked the reversed direction (probably through the action of VRM – viscous remanent magnetization, and/or CRM – chemical remanent magnetization).

The Gingenbullen dolerite is a thick (100 m) body and must therefore have taken considerable time to cool. The sampling locality has accordingly been divided into the margin and central region. The VGP positions given in Table 3 are 46° S, 165° E ($N = 8, A_{95} = 11°$) and 52° S, 164° E ($N = 6, A_{95} = 9°$) respectively. Both these poles are significantly different from the previously published pole position for the same formation (sampled at the same locality) by Boesen *et al.* (1961). Their pole is 20° west of the pole reported here. Inadequate elimination of secondary components during demagnetization is probably the reason for this because the eight samples used by Boesen *et al.* (1961) have been subjected to further AF cleaning at 20 and 25 mT with the result that directions similar to those reported here were measured.

Table 3. Jurassic intrusives of New South Wales (Jl–Jm)

Formation–site	Age (My)	N	R	Dec	Inc	Lat (°S)	Long (°E)
Prospect dolerite – 1 (33.7°S, 150.7°E)	168	5	4.914	297.4°	–70.5°	42.6°	194.6°
Prospect dolerite – 2 (33.7°S, 150.7°E)	168	4	3.956	317.9°	–70.9°	53.8°	188.6°
Gingenbullen dolerite –1 (34.5°S, 150.3°E)	172	8	7.918	141.6°	81.6°	46.4°	164.7°
Gingenbullen dolerite – 2 (34.5°S, 150.3°E)	172	6	5.974	156.1	79.4°	52.2°	163.5°
Gibraltar syenite – 1 (34.5°S, 150°4 E)	178	8	7.840	141.2°	63.3°	58.9°	207.6°
Glenrowan intrusives – 1 (31.1°S, 149.9°E)	181	4	3.998	304.8	–66.4	45.2	200.0°
Mean pole position		6	5.869			51.0°	186.1°
						(A_{95} =	10.9).

(b) *Gibraltar syenite*

These samples were initially subjected to AF demagnetization and one specimen from each samples was later heated to high temperatures and allowed to cool in zero field to attempt to thermally isolate the primary components. Fig. 4(d) shows results of the AF demagnetization with NRM directions scattered on the upper hemisphere and cleaned directions grouped on the lower hemisphere. Cleaning in peak fields of above 40 mT was necessary before the directions converged on the bottom hemisphere. The eight directions used to calculate the pole position have steep positive inclinations similar to the cleaned directions of Gingenbullen dolerite (the other end points shown are not necessarily stable and only indicate the general direction in which the magnetization vector moved during demagnetization). Because these eight samples were collected from the same small area of outcrop, the pole position at 59° S, 208° E (A_{95} = 12°) must be considered as a VGP. The mean sample direction is 141°, 63° (N = 8).

The direction previously reported (Boesen *et al.* 1961) was of normal polarity (27° – 86°), which is grossly at variance to the direction calculated here. The pole position is correspondingly different. This is almost certainly due to the unsatisfactory elimination of secondary components and the failure to recognize this aspect of the magnetization. While Boesen *et al.* (1961) state 'the effect (of demagnetization) in Gibraltar specimens is negligible up to 200 Oe (20 mT), higher fields of 40 mT and above will almost reverse directions in specimens which are not too weathered. Further demagnetization of samples collected by Boesen *et al.* (1961), failed to yield reversed directions.

Although the process responsible for the secondary magnetization appears to be associated with weathering, the directions are different from either present field or dipole field directions. Therefore, if weathering is the cause then it does not seem to be recent weathering, but rather Tertiary or perhaps Cretaceous weathering. Other possibilities include PTRM (partial thermo-remanent magnetization) resulting from the extrusion of basalts 30–54 My ago, although this does not account for the low intensities of magnetization found in some samples.

(c) *Prospect dolerite*

Of the ten samples originally collected by Boesen *et al.* (1961), one has been used for saturation magnetization experiments and is, therefore, of no use for further NRM demagnetization. Three pilot samples were selected from the nine remaining samples (which had been partially demagnetized) and demagnetized in increments from 15–100 mT. The procedure discussed in Section 3.1 revealed these samples to be susceptible to RRM. At 60 mT, the RRM developed was of a similar intensity to the remaining partial NRM, yet it could be successfully eliminated by this procedure. The other six samples which were treated in steps up to 50 mT, had usually stabilized in direction by 30 mT. These samples have been taken from three separate quarries and represent both fine grained and coarse grained varieties of the dolerite. Since the rock body is thought to be a laccolith these sites might legitimately be considered to have cooled at different instances of time. On this basis, the results were divided into two groups and a pole position calculated for each. These pole (VGP) positions are 43° S, 195° E (A_{95} = 20°, N = 5) and 54° S, 189° E (A_{95} = 16°, N = 4). The pole position previously published at 51° S, 151° E (Boesen *et al.* 1961) is again, significantly different. Inadequate cleaning techniques, complicated by the influence of RRM, is thought to be the agent responsible for this. There appeared to be no connection between weathering and secondary components as found to be the case in the Gingenbullen dolerite and Gibraltar syenite.

(d) *Glenrowan intrusives*

AF demagnetization of samples of the Glenrowan intrusives show the directions of magnetization above 20 mT peak field have reached stable end points and have been combined to yield the mean sample direction given in Table 3. The pole positions calculated from each sample direction were subsequently meaned to give a pole position at 45° S, 200° E.

The six pole positions derived from these igneous bodies, are each considered an independent estimate of the geomagnetic pole (VGP) at the time of cooling. Therefore, to give a more realistic pole position for the Early–Middle Jurassic they have been combined (Table 4) yielding the coordinates 51° S, 186° E ($A_{95} = 11°$, $N = 6$). This pole position supersedes pole 9.1 of McElhinny & Embleton (1974).

4 Discussion

In the introduction, mention was made of the inconsistency that has plagued interpretation of the Australian Mesozoic palaeomagnetic results for almost a decade. After reconstructing Australia to Gondwanaland, following the methods of Sproll & Dietz (1969) or Smith & Hallam (1970), the Australian pole positions previously formed a group which could be shown to be statistically distinct from the group formed by pole positions derived from the other continents. The fact that the Australian data were apparently internally consistent has

Table 4. Mesozoic poles of Australia

Formation	Age	(My)	Si (Sa)	Lat (°S)	Long (°E)	A_{95}
Bunbury basalt[1]	Kl	(100)	5 (54)	49°	161°	10°
Mt. Dromedary complex[2]	Kl	(93)	22 (55)	55°	139°	8°†
Cygnet alkaline complex[3]	Kl	(98)	15 (45)	53°	156°	11°†
Noosa Heads complex[2]	Ju	(140)	4 (24)	(38°	132°)	26°*†
Bendigo dykes[1]	Ju	(150)	4 (26)	(42°	144°)	39°*
Tasmanian dolerite[4]	Jm	(167)	33 (69)	52°	156°	7°
Kangeroo Is basalt[1]	Jm	(170)	2 (20)	39°	183°	—
Jurassic intrusives[4]	Jl–m	(168–181)	6 (35)	51°	186°	11°
Western Victoria basalt[1]	Jl	(191)	6 (36)	45°	179°	10°
Garrawilla volcanics[4]	Jl	(193)	14 (36)	46°	175°	10°
Brisbane tuff[2]	Tr_m		6 (12)	56°	144°	13°†
Narrabeen shale[5]	Tr_l		4 (32)	48°	160°	19°†
Mean Kl	$N = 3$ ($k = 113.9$)			53°	152°	12°
Mean Jl–Jm	$N = 5$ ($k = 75.1$)			47°	176°	9°
Mean Tr_l–Tr_m	$N = 2$ ($k = 82.3$)			52°	153°	—

References

[1] Schmidt (1976)
[2] Robertson (1963)
[3] Robertson & Hastie (1962)
[4] This paper
[5] Irving (1963)

Notes:

* These pole positions are rejected on the grounds $A_{95} > 20°$ and the pole is therefore placed in the B category. (Hicken *et al.* 1972).

† These values have been recalculated giving unit weight to site VGP positions.

previously been accepted as strong evidence for the reliability of the data. Recently, Schmidt (1976) suggested that the Australian Cretaceous pole positions ought to be considered separate from the other Mesozoic poles. Using the Jurassic and Cretaceous data given in Table 4, an *F*-ratio test (Watson & Irving 1957) gives a value of $F_{2,12} = 6.00$. This indicates the two groups are significantly different at the 95 per cent confidence level (the 5 per cent cut-off point is 3.88). These poles are shown in Fig. 5. A similar analysis of the Triassic and Jurassic pole positions is not possible because there are only two Triassic poles. Their positions, intermediate between Permian and Jurassic pole positions, however, suggests that they may be separate and that the Australian Mesozoic palaeomagnetic poles form three distinct groups, Lower Triassic, Upper Triassic to Middle Jurassic and Upper Jurassic to Lower Cretaceous. The apparent polar wander path is seen to shift 12° east between the Triassic and Jurassic, then return during the Upper Jurassic–Lower Cretaceous (Fig. 5). The absence of reliable data from Australia for these critical epochs prevents the timing of the return to be accurately estimated. However, the westward shift must have occurred between *ca.* 160 My and *ca.* 100 My ago. Two pole positions from rock bodies of this age are categorized as *B* poles, according to the criterion of Hicken *et al.* (1972), i.e. the half angle of their cones of confidence (A_{95}) exceeds 20°. These formations are the Noosa Heads complex (Robertson 1963) and the Bendigo dykes (Schmidt 1976) which are 140 and 150 My old respectively. It is interesting to note that while the magnetic directions measured in these bodies are scattered, their pole positions lie well to the west of the Jurassic assemblage and may reflect the movement of the pole during this time. This leads to speculation on the westerly position of the Tasmanian dolerite pole and the spread of VGP positions from the Jurassic mean pole position through to the Cretaceous mean pole position (Fig. 5). In addition, although the Red Hill dyke has been dated as Middle Jurassic (McDougall 1961) none of the actual sills have been dated. Bearing this in mind the westerly VGP positions determined from some of the dolerite sills may simply be the result of these sills being younger than the dyke. This is supported by the fact that the VGP determined from the Red Hill dyke (42° S, 188° E) is in close agreement with the mean Jurassic pole position (47° S, 176° E). Further radiometric dating of the dolerite is clearly required to test this, and perhaps resolve the timing of the disintegration of eastern Gondwanaland.

Table 5. Upper Triassic–middle Jurassic poles for Gondwanaland

					Rotated to Africa	
	N	A_{95} (°)	Lat (°S)	Long (°E)	Lat (°S)	Long (°E)
Africa	18	3.9	67.8	73.6	—	—
South America	4	8.3	78.0	257.9	58.3	65.3
India	2	—	20.0	127.6	64.3	68.9
Madagascar	1	—	74.2	97.1	62.6	69.8
Antarctica	5	8.7	55.0	215.1	63.2	77.9
Australia (new)	5	8.8	47.0	176.3	60.1	69.1
Australia (old)	7	7.6	50.0	147.9	41.2	67.5
Mean	6	3.2	—	—	62.7	70.5

Notes:

The pole positions have been taken from the following sources (identified by *Geophys. J. R. astr. Soc.* pole list numbers and other references): Africa (6/40–43, 8/59, 63, 67, 72, 10/77, 12/35, 36, 40, 93, 14/248, 249, 250, 288, 290, 693 and Daly & Pozzi 1976); South America (11/46, 12/102 and 14/241, 274); India (11/43, 45); Madagascar (14/269); Antarctica (2/26, 27, 6/36, 10/70 and 14/239); Australia-old (McElhinny & Embleton 1974) and Australia-new (Schmidt 1976 and this paper).

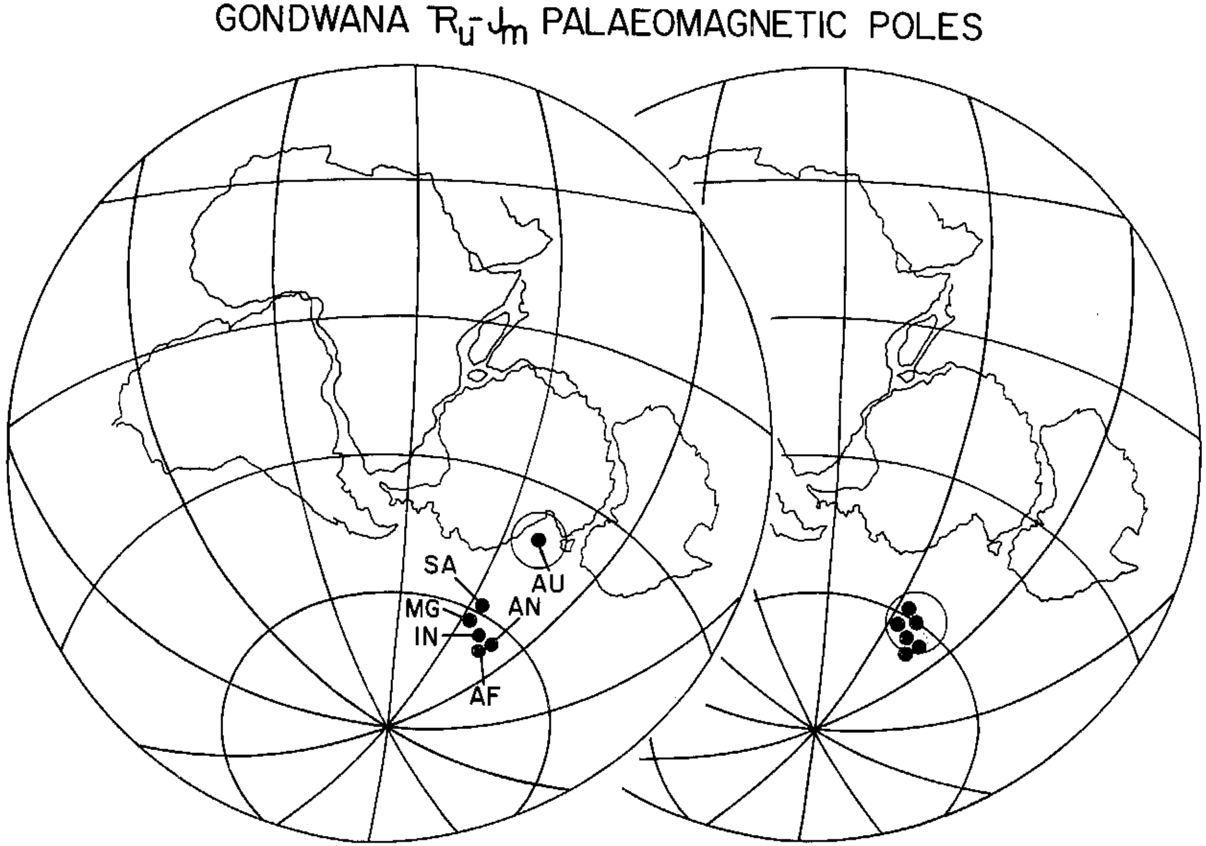

Figure 6. Linear polar projections of Gondwanaland (after the Smith–Hallam model) with Africa in its present-day coordinates. The Australian Mesozoic pole given by McElhinny & Embleton (1974) is compared to the Upper Triassic–Middle Jurassic Australian pole reported here (their cones of confidence (95 per cent) are also shown for comparison). The other pole positions are those given in Table 5, Africa (AF), South America (SA), India (IN), Madagascar (MG) and Antarctica (AN).

Interpreting the results presented here in the context of a unified southern landmass (Gondwanaland) it is possible to combine pole positions from each constituent continent to provide an overall pole position thought to represent the rotational pole immediately prior to fragmentation. Details of the data sources are given in Table 5. It is evident that all these poles closely agree after they have been rotated to their pre-drift positions. Fig. 6 shows how the new Jurassic pole reported here conforms with poles of equivalent age from the rest of Gondwanaland. The original Mesozoic pole for Australia is also shown for comparison. Clearly it is anomalous within the framework of Gondwanaland.

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