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Magnetic Overprinting in Southeastern Australia and the Thermal History of its Rifted Margin

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The magnetizations of many rock units in southeastern Australia have been severely overprinted. Interpretation of early work was hindered by this, and one of the aims of the current research is to ascertain the nature of the overprint mechanism, its geological significance, and its regional extent. Results from three igneous bodies from the Sydney Basin, which have been studied previously in a reconnaissance fashion, have provided a new insight into the reason for such widespread magnetic overprinting. The Hornsby Breccia (HB) and Milton Monzonite (MM) yield similar magnetic signatures, both containing discrete high- and low-temperature magnetizations with directions of dec = 72°, inc = +83° (α_{95} = 4°) and dec = 13°, inc = −76° (α_{95} = 2°), respectively, for HB, and dec = 60°, inc = +78° (α_{95} = 4°) and dec = 348°, inc = −79° (α_{95} = 6°) respectively for MM. The corresponding pole positions are 29°S, 166°E (A_{95} = 7°) and 59°S, 139°E (A_{95} = 4°) for HB, and 22°S, 171°E (A_{95} = 7°) and 55°S, 158°E (A_{95} = 11°) for MM. The paleomagnetic direction and pole from the third body studied, the Mogo Hill Basalt (MH), are dec = 241°, inc = 81° (α_{95} = 5°) and 41°S, 130°E (A_{95} = 9°). This pole position and the two low-temperature overprint pole positions from HB and MM are consistent with ages ranging from 100 m.y. to approximately 70 m.y. when compared to the Late Mesozoic apparent polar wander path. We relate the overprinting to uplift, erosion, and rapid supracrustal cooling of the southeastern margin of Australia associated with initial phases of marginal rift development prior to seafloor spreading in the Tasman Sea. The temperatures of rocks now exposed may have reached 200°C or higher, before the rapid cooling blocked and stabilized the overprint magnetizations.

INTRODUCTION

Paleomagnetic studies of igneous and sedimentary rocks from the Sydney Basin in southeastern Australia [*Schmidt,* 1976*a; Robertson,* 1979; *Embleton and McDonnell,* 1980] and southern and western Australia [*Schmidt,* 1976*b*] have provided the key to the elucidation of the apparent polar wander path (APWP) for Mesozoic time. Since the 1960's, researchers had commented repeatedly on the anomalous nature of the Mesozoic results from Australia [*Irving and Robertson,* 1969; *Creer et al.,* 1969; *McElhinny and Embleton,* 1974] and were unable to fit the data satisfactorily into a global analysis of the geomagnetic field in terms of supercontinent reconstruction. Paleomagnetic poles for rock units with ages from Late Paleozoic to Cretaceous formed a scattered group off southeastern Australia, and the distribution of the poles led to the firm belief that Australia had exhibited little or no latitudinal movement relative to the south pole.

Subsequent studies established that the early-mid-Jurassic poles plot further eastward: the earlier studies [e.g., *Boesen et al.,* 1961; *Irving,* 1963] had failed to remove stubborn overprint components of magnetization. After a reassessment of the paleomagnetism based on resampling specific rock units from within the Sydney Basin, data were added from the Garrawilla Volcanics, the Western Victorian Basalt, and the Kangaroo Island Basalt [*Schmidt,* 1976*b*].

A preliminary investigation of the chronologic history of the Sydney Basin igneous rock deposits led *Robertson* [1979] to confirm independently the eastward extension of the APWP. The time for which the pole was situated east of Australia is based on radiometric ages for the Jurassic intrusives of New South Wales (168–181 m.y.), the Kangaroo Island Basalt (170 m.y.), the Tasmanian Dolerites (170 m.y.), the Garrawilla Volcanics (193 m.y.), and the Western Victorian Basalt (190 m.y.).

The results described here for the Mogo Hill Basalt confirm *Robertson*'s [1979] preliminary result, but the new result for the Hornsby Breccia must be taken to supersede the preliminary work. The breccia has been found to contain a multicomponent magnetic remanence which was originally unresolved. Although *Robertson* [1964] clearly discussed the pronounced secondary magnetization of the Milton Monzonite, techniques had not been developed at that time to enable the evaluation of this secondary component as an ancient magnetization. Herein we recognize the antiquity of this secondary component and reproduce Robertson's primary component with greater precision.

REGIONAL GEOLOGY

The geology of the Sydney Basin is well documented [*Packham,* 1969; *Mayne et al.,* 1974; *Branagan et al.,* 1976]. The Permian and Triassic strata are mostly flat lying, having suffered little tectonism since deposition. The sediments range from the coal-bearing sequences of Late Permian age into conglomerates, quartz sandstones, red and green shales, and claystones of the Early Triassic sequences. Numerous intrusions and volcanics occur throughout the basin, some of which have been radiometrically dated. From K-Ar determinations, bodies such as the Milton Monzonite (245 m.y,), the Currambene Dolerite (234 m.y.), and the Gerringong Volcanics (252 m.y.) are thought to be Late Permian in age (J. R. Richards, cited by *Joplin* [1968, p. 284], and *Facer and Carr* [1979]), possibly associated with the initiation of the basin development. Intrusions in the Mittagong area and near Prospect have been dated as lying between 195 m.y. and 168 m.y., around the Triassic/Jurassic boundary [*Evernden and Richards,* 1962; *McDougall and Wellman,* 1976]. Further igneous activity of mainly extrusive character occurred during the Tertiary [*Wellman and McDougall,* 1974; *Facer and Carr,* 1979].

Numerous diatreme bodies [*Adamson,* 1969; *Hamilton et al.,* 1970; *Crawford,* 1973] have been found in the central part of the basin, but no radiometric ages are available from these. However, their maximum age is given by palynological studies as Early Jurassic (R. J. Helby, cited by *Branagan et al.* [1976, p. 40]). The diatremes consist dominantly of breccia, although massive basalt and inclusions of a variety of rock types

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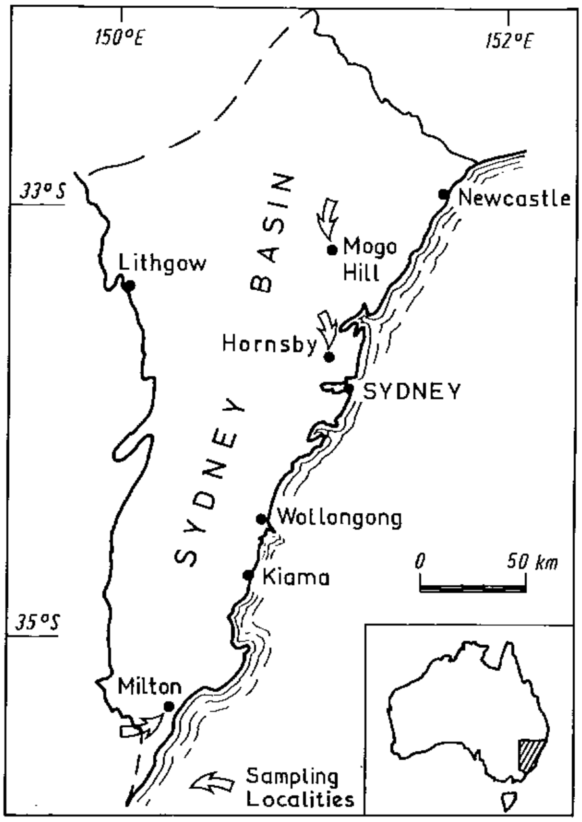

Fig. 1. Sketch map of Sydney Basin showing sampling localities.

are common. The results from two of these diatremes and another intrusion are given below.

SAMPLING AND TECHNIQUES

The areas sampled are shown in Figure 1. A portable field drill was used to collect oriented cores from each of the bodies sampled, and the cores were oriented using both a sun compass and a magnetic compass. Approximately six samples (cores) were collected from each site, and the samples were sliced into several specimens with approximate dimensions of 22-mm height × 25-mm diameter.

DIGICO complete result magnetometers [*Molyneux,* 1971] were used to measure the remanent magnetization of specimens and to compute the *Fisher* [1953] statistics and pole positions. Stepwise demagnetization was carried out using Schonstedt alternating field (af) and thermal demagnetizers (models GSD-1 and TSD-1, respectively). A low-field, 217-Hz excitation frequency transformer bridge, capable of heating and cooling specimens while monitoring susceptibility, was used for Curie temperature estimates. Orthogonal projections [*Zijderveld,* 1967] have been employed throughout to facilitate the recognition of discrete magnetic components, while vector subtraction [*Roy and Park,* 1974] has been utilized to estimate the directions of components removed by stepwise cleaning procedures.

RESULTS

Hornsby Breccia

The breccia is well exposed as a funnel-shaped structure in a quarry at Hornsby, approximately 25 km northwest of Sydney (Figure 1). It is formed as a double-neck about $\frac{1}{2}$ km across and 3 km long. Layering of the breccia is well displayed in the form of symmetrical 40°–50° dips in the wall section and horizontal beds in the central section. Thirteen sites were sampled from a selection of these layers outcropping on a bench across the eastern face of the quarry. The layering has been interpreted as a flow structure formed during intrusion and is considered to be primary [*Wilshire,* 1961]. A general model for the formation of maar-diatreme volcanoes has been discussed by *Lorenz* [1975].

The most striking feature of the paleomagnetic results is the multicomponent nature of the magnetization, which is only revealed by thermal demagnetization. This is displayed in Figure 2 by the use of orthogonal plots. Representative thermal demagnetization trends (Figures 2*a*, 2*b*) show that one magnetic component is demagnetized below 400°C while a second is demagnetized above 400°C. That is, the components are thermally discrete [*Irving and Opdyke,* 1965]. However, it appears from af demagnetization (Figures 2*c*, 2*d*) that only one component is demagnetized up to 100 mT. Other samples showed different af characteristics indicating distributed and indistinct stability spectra, i.e., overlapped instability. For this reason the results from af cleaning are not considered to indicate reliably that a primary magnetization has been isolated, although directionally, the magnetization is unquestionably stable.

Previous work on the breccia was based largely on af results, and although thermal demagnetization to 700°C was also reported, the high-temperature component was not detected [*Robertson,* 1979]. The directions reported earlier (dec = 029°, inc = −62° after 40-mT af treatment, and dec = 043°,

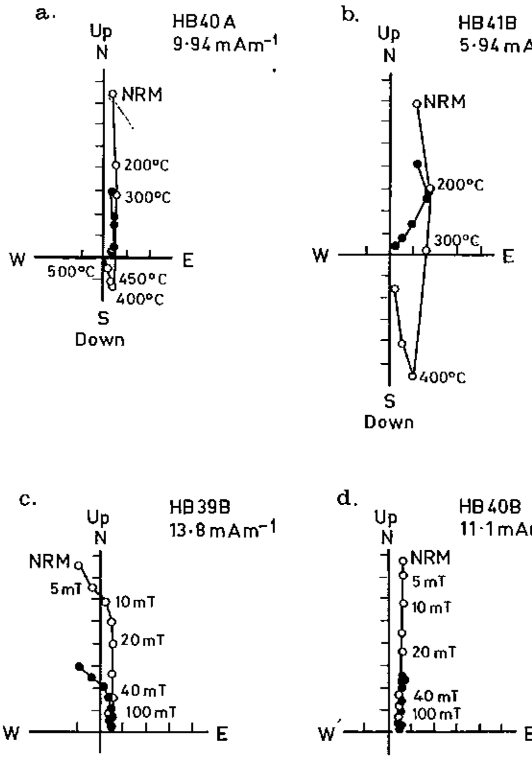

Fig. 2. Orthogonal projections of magnetization vectors from the Hornsby Breccia, following the method outlined by *Zijderveld* [1967]. Solid (open) symbols refer to the horizontal (vertical) plane; *a* and *b* are from thermal demagnetization, while *c* and *d* are from af demagnetization. NRM intensity is given under the specimen reference number.

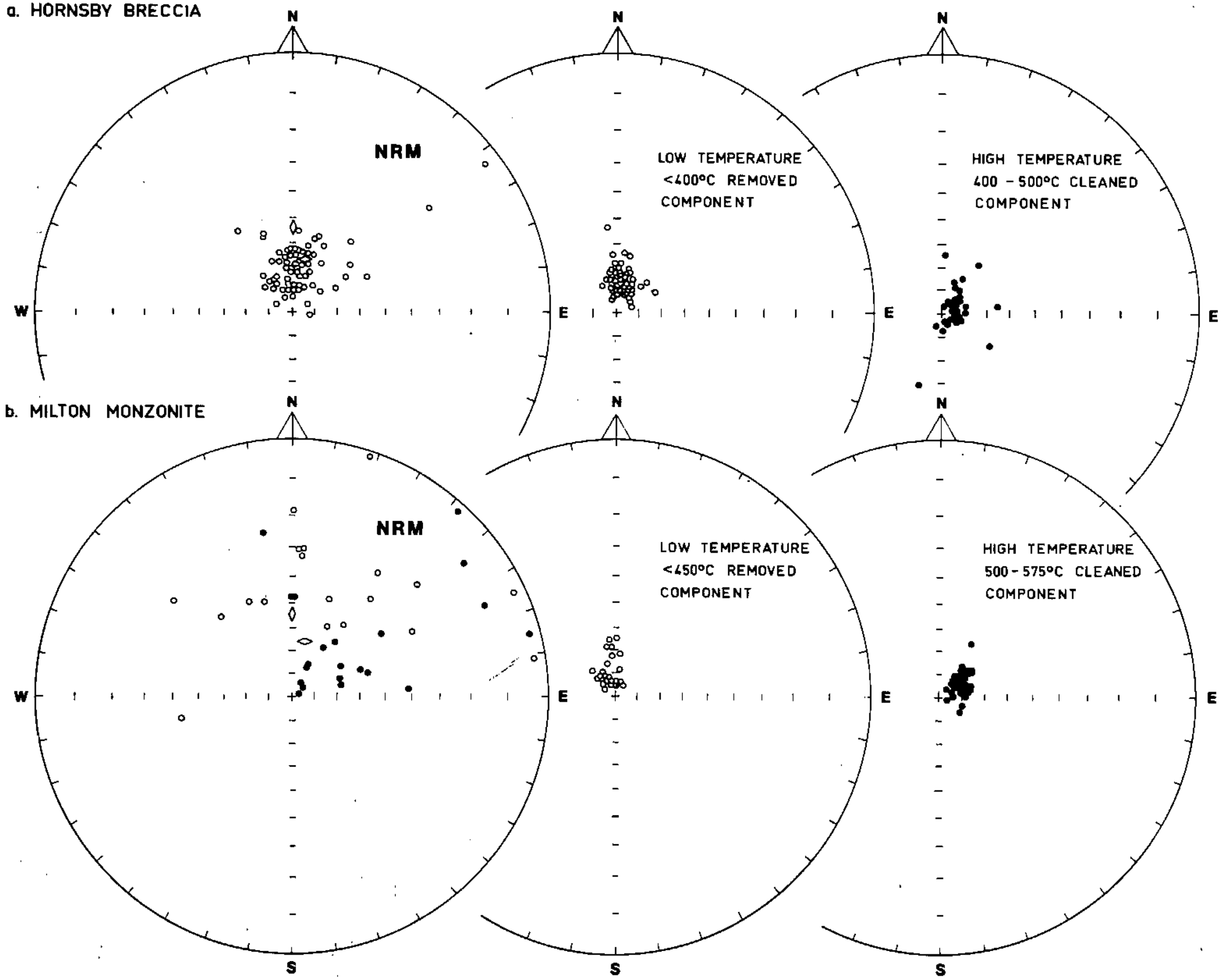

Fig. 3. Equal-angle stereoplots of directions of magnetizations for (*a*) the Hornsby Breccia and (*b*) the Milton Monzonite. The solid (open) symbols refer to the lower (upper) hemisphere. The vertical and horizontal diamonds represent the dipole and present field directions, respectively.

TABLE 1. Hornsby Breccia (33°43′S, 151°05′E): Directions of Magnetization and Pole Positions

	NRM					Removed (200°–400°C)					Cleaned (400°–500°C)				
Site	N	Dec, deg	Inc, deg	R	α_{95}, deg	N	Dec, deg	Inc, deg	R	α_{95}, deg	N	Dec, deg	Inc, deg	R	α_{95}, deg
1	6	047	−43	5.53	21.4	6	016	−81	5.99	3.3	6	094	83	5.99	2.2
2	5	055	−69	4.91	11.5	5	023	−75	4.96	7.5	4	129	80	3.94	12.9
3	5	006	−63	4.99	3.9	5	002	−68	4.99	3.8	···	···	···	···	···
4	6	334	−71	5.86	11.3	6	015	−72	5.97	4.9	5	083	84	4.73	20.5
5	6	000	−68	5.89	9.8	6	016	−75	5.99	3.4	4	077	81	3.94	13.3
6	5	007	−65	4.96	7.1	5	015	−73	4.92	6.3	5	055	82	4.97	6.7
7	6	106	−69	5.99	2.8	6	041	−80	5.97	4.9	···	···	···	···	···
8	5	005	−70	4.97	6.0	5	004	−78	4.99	4.6	···	···	···	···	···
9	3	354	−63	2.96	18.1	3	000	−73	3.00	4.0	···	···	···	···	···
10	9	353	−66	8.17	17.4	9	035	−75	8.96	3.8	···	···	···	···	···
11	7	339	−78	6.92	6.9	7	007	−77	6.99	2.2	···	···	···	···	···
12	5	001	−77	4.96	7.3	5	002	−79	4.98	5.5	4	028	82	3.89	18.0
13	3	352	−76	2.96	17.0	3	008	−75	3.00	5.2	3	040	81	3.00	5.6
Mean	13	009.1	−69.2	12.71	6.5	13	013.0	−75.5	12.96	2.3	7	072.0	83.0	6.98	3.8

Mean VGP	N	Latitude, °S	Longitude, °E	R	A_{95}, deg
200°–400°C	13	59.1	139.4	12.88	4.2
400°–500°C	7	28.7	165.8	6.92	7.0

Symbols and abbreviations: N, number of unit vectors; dec, declination; inc, inclination; R, resultant of N unit vectors; α_{95}° and A_{95}, half-angle of cone of confidence at 95% probability level of directions and poles, respectively; VGP, virtual geomagnetic pole.

inc = −60° after 400°C) are composites of the low- and high-temperature components and therefore cannot be meaningfully included with those here. Indeed, five sites studied here did not yield consistent high-temperature (>400°C) directions. The remaining eight sites, however, yield a mean high-temperature site direction of dec = 072°, inc = +83° with an α_{95} of 3.8°. The low-temperature component was found to be ubiquitous, and from the 13 sites the mean site direction for this component is dec = 013°, inc = −76° with an α_{95} of 2.3°. High- and low-temperature sample directions are plotted in Figure 3*a*. Natural remanent magnetization (NRM) intensities were generally in the range 10 to 50 mA m^{-1}.

Samples from site 7 consisted entirely of basaltic inclusions. These were collected to investigate the degree of partitioning of the high- and low-temperature components between the matrix and inclusion fractions, which would provide constraints for a model of the origin of the magnetization in the breccia. Unlike the thermal demagnetization behavior of the breccia, the results for the inclusions by themselves showed no significant changes in direction as high temperatures were approached. Any high-temperature components present should have been resolved after heating to 400°C. As none were apparent, it is concluded that the basalt inclusions carry a single magnetic component (Table 1), and that the high-temperature component is carried by the matrix only. Since *k-T* curve analysis reveals that the magnetic carriers in the basalt inclusions have unblocking temperatures of over 450°C and thus are at least potentially capable of carrying a higher-temperature component than they do, this would seem to favor a chemical origin (possibly acquired during diagenesis) for the high-temperature component because it is difficult to envisage a thermal mechanism which would magnetize the matrix but not affect the basaltic inclusions. Some smaller (up to a few millimeters in diameter) basaltic fragments were physically separated, and after examination of the *k-T* curves and a comparison with curves for the breccia, they were found to carry a minor fraction of the magnetization of the breccia as a whole. Thus the majority of the low-temperature component and all of the high-temperature component is carried by the fine grained matrix. The high-temperature component appears to be of low-temperature chemical origin, which has resulted in the observed high unblocking temperatures. The postulated low temperature of formation of the breccia pipes [*Hamilton et al.,* 1970] further supports this view. We therefore suggest that the high-temperature component is actually a chemical remanent magnetization (CRM) developed in the matrix, during, or soon after formation of the pipe.

The ubiquity of the low-temperature component in samples of both breccia (containing both matrix and inclusions) and basaltic inclusions suggests that this magnetization is a viscous partial thermo-remanent magnetization (VPTRM; *Chamalaun* [1964]) or possibly a thermo-CRM imparted during a thermal event sometime after intrusion. Sites 3 and 7 to 11 appear to have been completely remagnetized by these effects. The conclusions are further corroborated by the results from the other intrusions discussed below.

Milton Monzonite

Approximately 175 km south-southwest of Sydney, a monzonite body is intruded into the mid-Permian Upper Marine Series (Figure 1). Samples have been collected from four sites in a quarry and two sites in a stream bed 5 and 3 km west of Milton, respectively. The results of both thermal and af demagnetization of representative samples are displayed as orthogonal plots in Figure 4. The multicomponent nature of the remanence of these samples is clear from both cleaning methods, although better defined by thermal (Figure 4*a*, 4*b*) than by af demagnetization (Figure 4*c*, 4*d*), implying that while the thermal stability spectra of the components are discrete, the coercivity stability spectra are overlapped. This is particularly evident in sample MM06D2 (Figure 4*d*). To ensure maximum resolution of the components, all vector differences have therefore been calculated only from results of thermal demagnetization (Table 2).

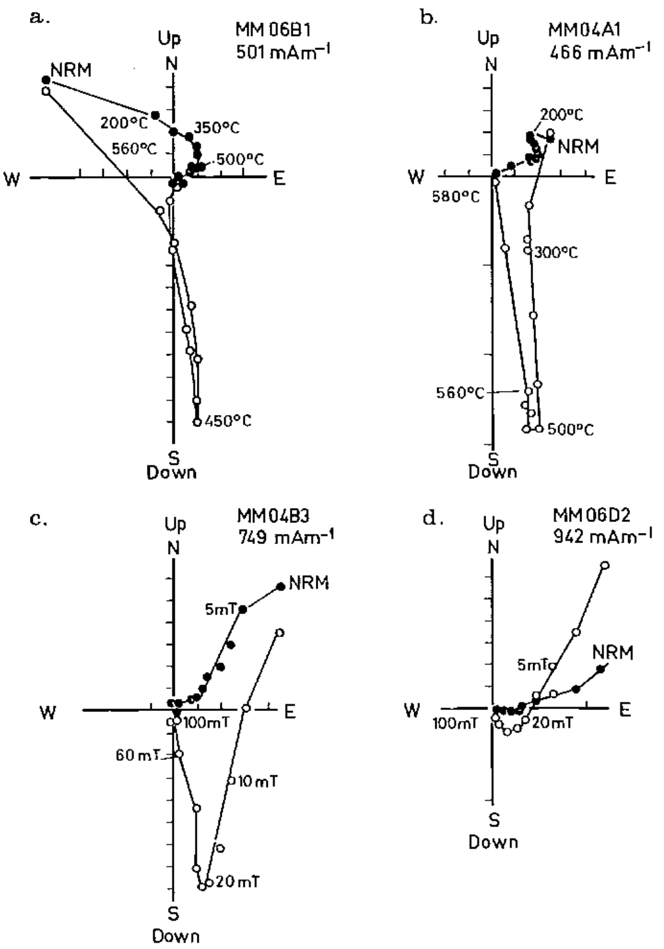

Fig. 4. Orthogonal projections of magnetization vectors from the Milton Monzonite. Explanation as for Figure 2.

NRM intensities encountered were usually 500–700 mA m^{-1}, although highly variable reflecting the hybrid character of the NRM's. The directions of the NRM's are scattered (Figure 3*b*). After examination of vector differences of the thermal demagnetization data, consistent low-temperature (200°–450°C) directions of magnetization were found in sites 3 to 6. They yield a mean site direction of dec = 348°, inc = −79° with an α_{95} of 5.9° (Table 2). Stable endpoints above 500°C were determined from samples of all sites, yielding a mean site direction for the high-temperature component of dec = 059°, inc = +78° with an α_{95} of 3.6° (Table 2). Although more precise, this result agrees with the earlier study of *Robertson* [1964] which gave a mean site direction of dec = 085°, inc = +81° with an α_{95} of 15°. The improved definition of this direction is significant, since the corresponding pole appears anomalous with respect to the previously published APWP's for the upper Paleozoic to Mesozoic. The magnetic directions of both high- and low-temperature components of individual samples are plotted in Figure 3*b*.

Low-field susceptibility versus temperature (*k*-*T*) plots for the monzonite reveal a single magnetic mineral phase with a Curie temperature (T_c) of 575°C (Figure 5*a*). Also, the *k*-*T* curves are reversible, showing that this mineral phase is not altered during heating. The form of the thermomagnetic curve indicates the presence of multidomain magnetite. A single mineral phase is carrying two remanences, so it seems that the low-temperature component is probably of thermal, rather than chemical nature.

The grain size distribution of the magnetites would provide a spectrum of blocking temperatures which accounts for the widely varying thermal stabilities observed (from about 200° to 570°C). Although the two magnetizations present are distinct, the blocking temperature spectrum is continuous [*Irving and Opdyke*, 1965] which is strong evidence for a thermal origin for the low-temperature component.

A viscous PTRM origin is therefore suggested for this low-temperature component, and the high-temperature component is assumed to be a TRM dating from the time of initial cooling.

Mogo Hill

Eight sites were sampled from a quarry at Mogo Hill, about 75 km north of Sydney. The rock type exposed in this diatreme is predominantly basaltic. Orthogonal diagrams (Figure 6) show the behavior of representative samples to both af (Figure 6*a*, 6*b*) and thermal (Figure 6*c*, 6*d*) demagnetization. NRM intensities were generally in the range 1000–4000 mA m^{-1}; af demagnetization reveals the low coercivity of the bulk of the remanence in these rocks; e.g., Figure 6*b* displays detailed af demagnetization for specimen MH03C3. It is evident that a very soft magnetization, with an intensity in excess of 1000 mA m^{-1}, is demagnetized below 5 mT. However, no

TABLE 2. Milton Monzonite (35°19′S, 150°25′E): Directions of Magnetization and Pole Positions

	NRM					Removed (200°–450°C)					Cleaned (500°–575°C)				
Site	*N*	Dec, deg	Inc, deg	*R*	α_{95}, deg	*N*	Dec, deg	Inc, deg	*R*	α_{95}, deg	*N*	Dec, deg	Inc, deg	*R*	α_{95}, deg
1	5	061	65	4.96	8.0	...	...	...	...	...	5	055	75	4.95	8.2
2	5	054	77	4.89	13.0	...	...	...	...	...	5	096	83	4.98	4.7
3	8	057	−21	6.07	33.9	8	332	−83	7.98	3.0	8	070	80	8.00	1.1
4	10	030	30	8.11	24.8	7	354	−72	6.93	6.3	10	055	76	9.96	3.0
5	5	000	−48	4.42	31.5	5	344	−82	4.98	5.6	5	051	75	4.99	3.9
6	6	358	−41	5.67	17.7	6	350	−79	5.97	4.9	6	048	79	5.98	4.3
Mean	6	029.9	10.1	3.54	64.5	4	347.6	−79.0	3.99	5.9	6	059.9	78.3	5.98	3.6

Mean VGP	*N*	Latitude, °S	Longitude, °E	*R*	A_{95}, deg
200°–450°C	4	55.2	158.2	3.96	10.6
500°–575°C	6	22.1	170.9	5.95	7.0

Symbols and abbreviation as for Table 1.

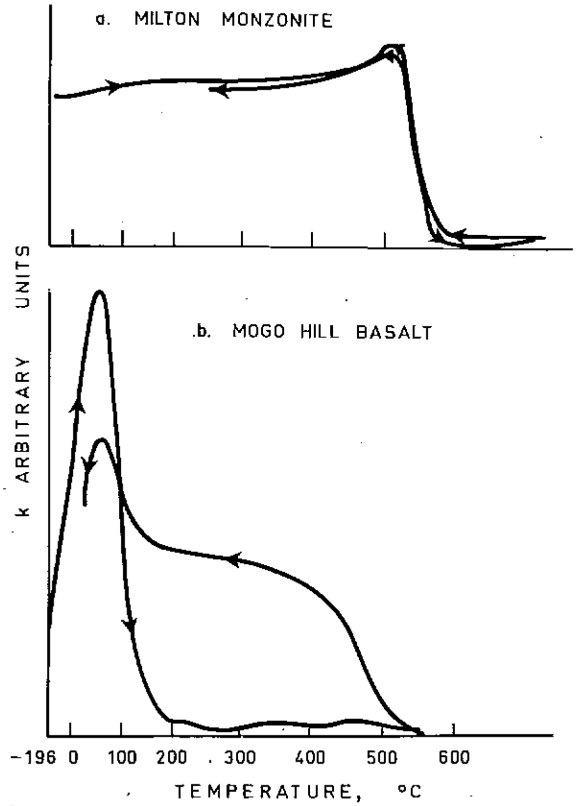

Fig. 5. Low-field susceptibility versus temperature (k-T) curves for (*a*) the Milton Monzonite and (*b*) the Mogo Hill Basalt. The thermocouple used (Pt-Rh) is nonlinear at low temperatures; hence the scale from liquid nitrogen temperatures (−196°C) to room temperature is compressed.

consistency in direction between different samples was found for these soft magnetizations, and no geological significance has been associated with them. These randomly directed, low-coercivity components of high intensity give rise to scattered NRM directions (Figure 7). Under thermal demagnetization (Figures 6*c*, 6*d*) the specimens are effectively demagnetized by 300°C. Above this temperature these specimens are extremely sensitive to stray (although not necessarily strong) laboratory fields, as the intensity is diminished and small spurious magnetizations become dominant. Figure 5*b* gives a typical k-T curve for this rock type. The characteristic Hopkinson peak and tail are compatible with, although not diagnostic of, the presence of titanium-rich magnetite with a Curie point of about 200°C [*Radhakrishnamurty et al.,* 1979]. The curves are reversible below 250°C indicating that the rapid fall in susceptibility is not related to a chemical change during heating. Fine grained superparamagnetic particles also reveal a rapid drop in susceptibility with temperature [*Radhakrishnamurty et al.,* 1979], although from probe work (S. Y. Wass, personal communication, 1980) the iron ore appears to be 64% ulvospinel, thus favoring our initial interpretation that the magnetite is rich in titanium. Because of the low unblocking temperatures associated with titaniferous magnetite and the problem regarding remagnetization in the laboratory, thermal demagnetization was not generally applied.

After partial demagnetization in the range of 5–20 mT, the magnetization directions of all samples group well. Twelve specimens studied by *Robertson* [1979] yielded similar directions and have been included here as one site. Table 3 gives the mean site direction as dec = 241°, inc = +81° with an α_{95} of 4.7°. Directions from individual samples are plotted in Figure 7.

DISCUSSION

The similarity of the paleomagnetic signature of the Hornsby Breccia and the Milton Monzonite is clear from a comparison of Figures 3*a* and 3*b* or Tables 1 and 2. The fact that both bodies have recorded the same low-temperature event, however, is less surprising than the fact that their high-temperature directions are also similar, since their ages of formation are thought to be very different. As mentioned above, the age of the breccia pipes in the Sydney Basin are post-Triassic, while the age of the Milton Monzonite from radiometric studies appears to be Late Permian (~245 m.y.). Indeed the anomalous magnetic directions from the Milton Monzonite have been previously commented on [*Robertson,* 1964], since they were at variance with results from the Gerringong Volcanics and other Permian volcanics from north of Sydney. Reasons postulated by Robertson to account for this difference included (1) a 15° tectonic tilt to the west-southwest, (2) the presence of secondary components, (3) insufficient averaging of secular variation, and (4) the direction representing a field direction not previously recorded. With regard to this last postulate, the large error (>20°) associated with the corresponding pole position may have weakened this argument, although the pole position has been duplicated in the present study with greater precision, so the anomaly persists. Each of the other arguments may be satisfactorily countered. As recognized by

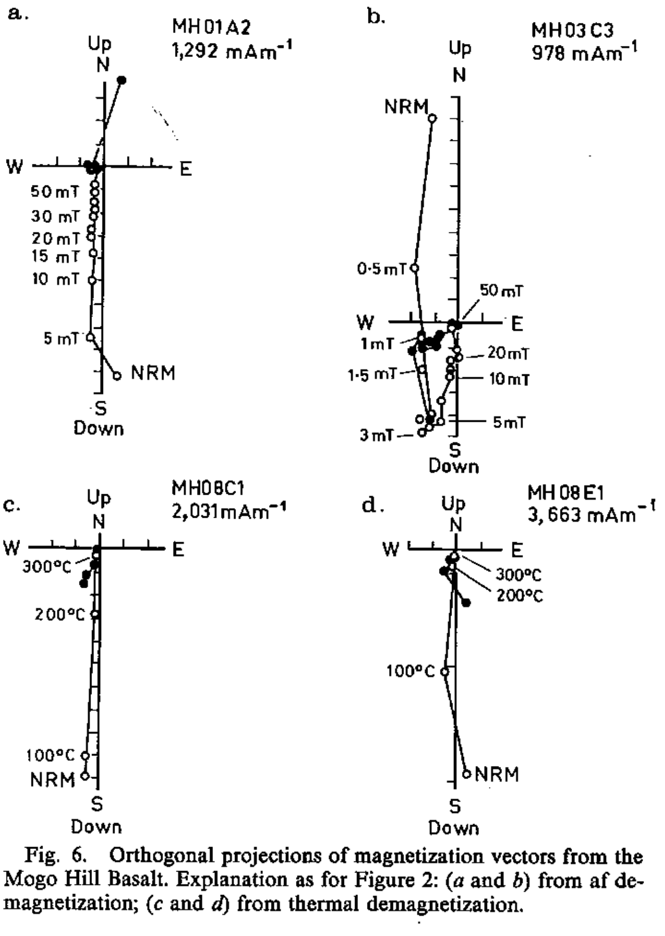

Fig. 6. Orthogonal projections of magnetization vectors from the Mogo Hill Basalt. Explanation as for Figure 2: (*a* and *b*) from af demagnetization; (*c* and *d*) from thermal demagnetization.

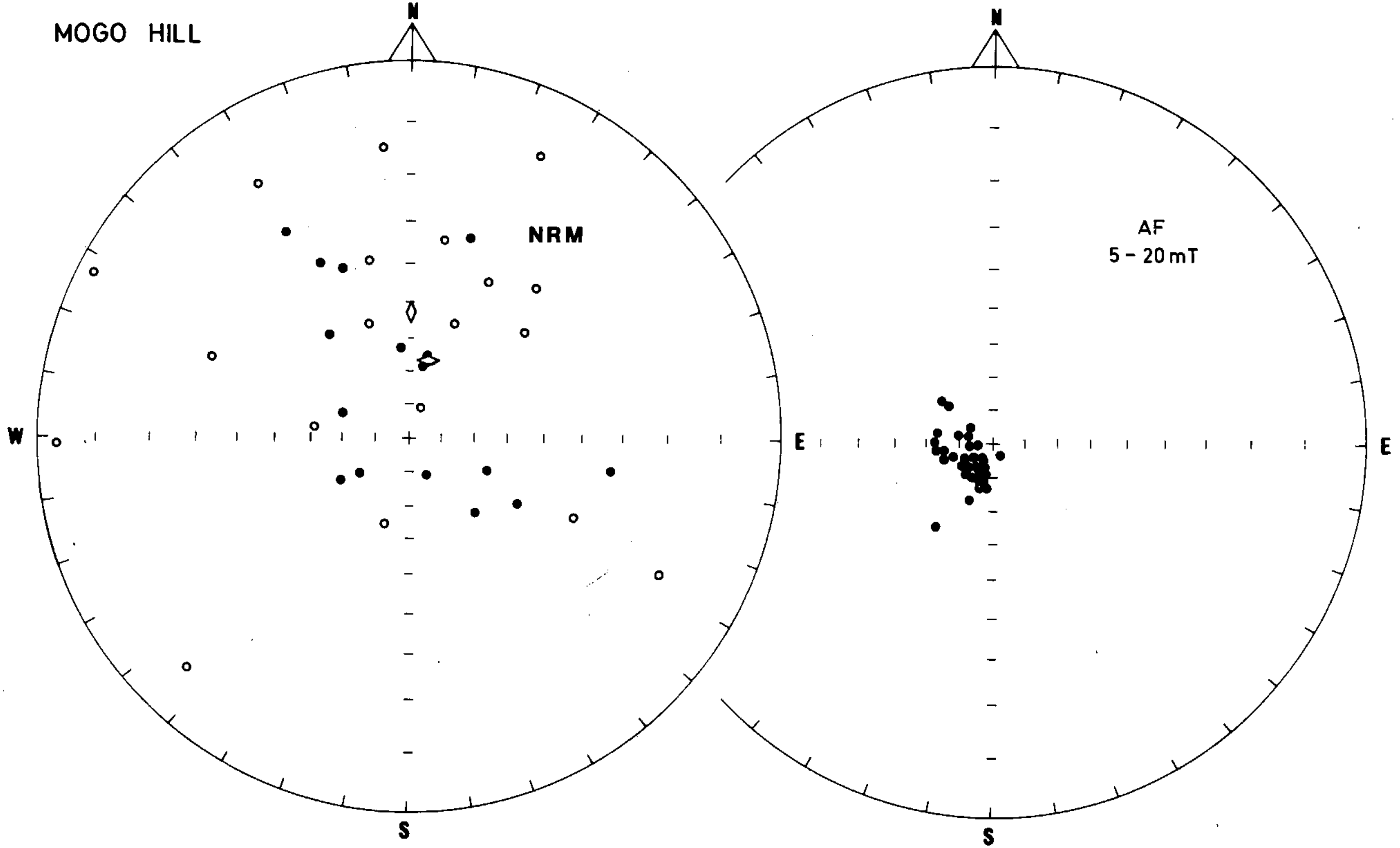

Fig. 7. Equal-angle stereoplots of directions of magnetizations for the Mogo Hill Basalt. Explanation as for Figure 3.

TABLE 3. Mogo Hill (33°10′S, 151°04′E): Directions of Magnetization and Pole Positions

	NRM					Cleaned				
Site	N	Dec, deg	Inc, deg	R	α_{95}, deg	F, mT	Dec, deg	Inc, deg	R	α_{95} deg
1	5	024	61	4.17	38.9	20	248	82	4.96	7.2
2	4	308	−16	3.41	45.3	7.5–15	263	77	3.98	7.3
3	3	111	−58	···	>90	5	238	78	2.99	7.4
4	5	016	−07	2.82	82.1	10	221	79	4.98	5.4
5	3	005	−64	2.89	29.7	15	297	72	2.98	11.9
6	3	338	−08	···	>90	15	218	84	2.99	5.5
7	4	088	54	2.93	68.2	10	190	79	3.99	6.0
8	5	253	61	3.54	57.2	10	215	76	4.95	8.7
R*	12	···	···	···	···	10	249	84	11.73	6.8
Mean	8, 9†	359.6	0.1	2.94	85.3		241.0	80.7	8.93	4.7

Mean VGP	N	Latitude, °S	Longitude, °E	R	A_{95}, deg
5–20 mT	9	40.6	130.2	8.78	8.6

Symbols and abbreviations as for Table 1, except F, which is the cleaning field or range applied to yield directions quoted.

*This site is from a previous study by *Robertson* [1979].

†N is 8 for NRM and 9 for cleaned directions.

Robertson, the sediments of the Upper Marine Series, into which the monzonite is intruded, are essentially flat lying and show no evidence of the tilting suggested. It is also difficult to sustain the argument that secondary components may be the cause, since the present work reveals a very tight cluster of stable directions (although the mean direction is not significantly different from the earlier result). That secular variation has not been averaged out is always a major consideration, however, given the dimensions of this particular body (outcropping over approximately 50 km^2) and the broad thermal stability spectrum of its magnetic minerals, it would seem that most, if not all, secular variation should be averaged out.

Thus we accept the pole position determined from the high-temperature directions of the Milton Monzonite as a true palaeomagnetic pole, representative of the average south pole position when the body was formed. Although this pole position falls near the 160-m.y. to 130-m.y. apparent polar wander path segment shown in Figure 8, at this stage we can only assume this to be coincidental and attribute the pole to otherwise unobserved Permian polar movement.

The essential difference between the APWP proposed here (Figure 8) and those paths previously defined is the loop passing through the Coral Sea between 170 m.y. and 100 m.y. ago. While some of the data points falling on this loop have been published for some time, individually they have apparently not justified serious consideration. For example, *Milton et al.* [1972] gave a pole position from Gosses Bluff (130 m.y.) at 25°S, 170°E. Since no errors were quoted, it was not easy to determine the significance of this 'divergent' pole, particularly with the only other pole nearby being that of the Milton Monzonite, albeit 245 m.y. old. However, both these pole positions have been confirmed by recent studies with high precision and cannot therefore be excluded from any analysis. The established Gosses Bluff pole position is now 13°S, 164°E, $\alpha_{95} = 4°$ (H. C. Halls, unpublished data, 1980), which is very similar to that given by *Milton et al.* [1972]. The pole position from the high-temperature directions of the Hornsby Breccia is also similar (Table 1, Figure 8), and since the age of the breccia is known to be a maximum of Early Jurassic, this pole position must fall on the post-Triassic APWP. Likewise for the Erskine Park pole position of *Robertson* [1979]. In addition, the reversed magnetizations from the Bendigo dykes [*Schmidt,* 1976*a*] yield a virtual geomagnetic pole (VGP) close to the Gosses Bluff pole (Figure 8). Although some of the Bendigo dykes possessed normal directions, they are generally more scattered than the reversed directions, suggesting that the normal magnetizations are composite and the underlying reversed magnetizations have not been resolved. For these reasons we postulate the APWP loop shown in Figure 8 to account for these otherwise unexplained data.

Regarding the thermal history, the evidence from the Hornsby Breccia to account for the low-temperature components is that either a viscous PTRM or a thermo-CRM has been imparted to the body sometime after intrusion, while that from the Milton Monzonite favors a viscous PTRM. Comparing the pole positions calculated from these directions (Tables 1 and 2) with those of known ages from other igneous rocks from western and eastern Australia, the time that these magnetizations become blocked appears to be 90–100 m.y. ago (Figure 8). This estimate is based on K-Ar dating and paleomagnetic data for the Mt. Dromedary Complex [*Evernden and Richards,* 1962; *Robertson,* 1963; *Schmidt,* 1976*c*], the Cygnet Alkaline Complex [*Evernden and Richards,* 1962; *Robertson and Hastie,* 1962], and the Bunbury Basalt [*McDougall and Wellman,* 1976; *Schmidt,* 1976*a*]. Paleomagnetic studies of the Triassic Patonga Claystone [*Embleton and McDonnell,* 1980] have also isolated an overprint magnetization. The corresponding pole position (lat. 57°S, long. 143°E, $\alpha_{95} = 3.6°$) is plotted in Figure 8 and is seen to date from about the same period as the overprints of the Hornsby Breccia and Milton Monzonite. The concurrence of these magnetic overprints strongly suggests a single causative event. The age of the pole position from the Mogo Hill Basalt, displaced approximately 20° to the northwest, appears to be 60 m.y. to 70 m.y. when compared to a recent analysis of late Mesozoic pole positions from India and Australia [*Klootwijk and Peirce,* 1979, Figure 3*b*]. Because the Australian record is devoid of pole positions of this age, appropriate transformations based on seafloor spreading data are used to allow direct comparison with the Indian pole positions. We should point out that this age is correlated with the magnetization age and not necessarily the age of formation of the Mogo Hill Basalt body unless it was intruded subsequently to the thermal event in this area. Because of the low unblocking temperature and low Curie point temperature observed, we cannot confidently relate the magnetization to that of initial TRM. A later low-temperature reheating episode could conceivably have reset the magnetization, since there is no significant high-temperature component. The overprint magnetizations of the Hornsby Breccia, Milton Monzonite, and Patonga Claystone (widely separated units in the basin) appear to indicate rapid lowering of the ambient crustal temperature, either by lowering the regional geothermal gradient or by rapid erosion, or both. This sudden fall in temperature is required to account for the blocking of low-temperature magnetic components. A corollary is that the Sydney Basin has not experienced a similar thermal event since.

The magnetic overprinting which affected such a large tract of the Sydney Basin can be broadly correlated with events which led up to the initiation of seafloor spreading in the Tasman Sea. From seafloor spreading anomalies, it has been suggested that the Lord Howe Rise–New Zealand block separated from Australia about 82 m.y. ago [*Hayes and Ringis,* 1973; *Weissel and Hayes,* 1977].

Falvey [1974] has proposed a general model for the formation of Atlantic-type rift margins. With specific reference to southeastern Australia he claims that the absence, or near absence, of a rift valley sequence indicates rapid development of the continental margin, i.e. in a period of time considerably less than 50 m.y. The two-stage model describes thermal expansion of the upper mantle and lower lithosphere which leads to surface uplift and erosion followed by thermal metamorphism in the deep crust. The second stage leads to regional subsidence and block collapse in the rift zone.

Initiation of seafloor spreading requires the emplacement of new lithosphere between the opposing rift margins composed of old lithosphere. As the new accreting plate boundary migrates from the rift margin, the old lithosphere undergoes thermal contraction and further subsides to levels lower than previously, due to the diminished crustal thickness.

In evaluating the magnetic results, only geological processes that affect supracrustal regimes should be considered. Ambient crustal temperatures may be raised through burial under a thick sedimentary pile and/or through the presence of an increased heat flux due to the upward migration of a heat source. The second condition is likely to pertain, according to *Falvey*'s [1974] model, in the active rift environment but, as will be shown, may not be the dominant heating mechanism which affected the supracrustal regime. Since rocks near the surface are not strongly affected by an increased geothermal gradient, moderate burial is implied to explain the magnetic overprinting discussed above. Uplift and erosion followed by fairly rapid cooling is then required to block the overprints at 90–100 m.y. ago.

Morley et al. [1980] have shown that fission tracks in apatites yield ages from Paleozoic granites in southeastern Australia which decrease from about 360 m.y. at a distance of 100 km inland to about 80 m.y. along the coast. They attribute the youngest ages to processes active at the time of initiation of seafloor spreading in the Tasman Sea. Therefore close temporal relationships of the magnetic overprints can be clearly established. Let us examine briefly the available evidence regarding the actual ambient crustal temperatures at that time.

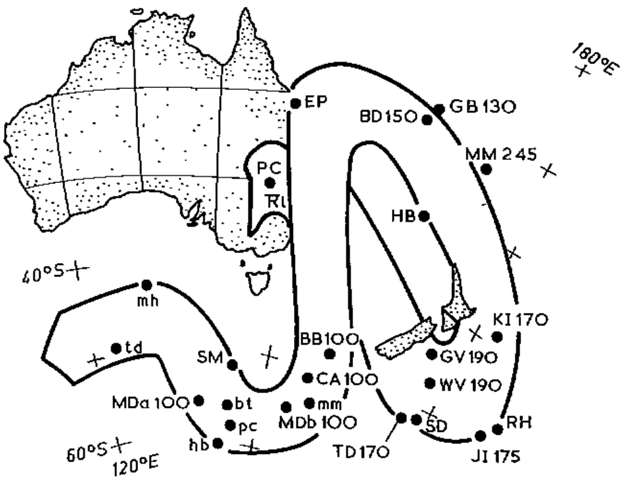

Fig. 8. Mesozoic APWP for Australia. Poles identified by uppercase letters are derived from directions thought to be primary: BB, Bunbury Basalt; BD, Bendigo Dykes; KI, Kangaroo Basalt; WV, Western Victorian Basalt [*Schmidt,* 1976*a*]; CA, Cygnet Alkaline Complex [*Robertson and Hastie,* 1962]; MDa, Mount Dromedary [*Robertson,* 1963]; MDb, Mount Dromedary [*Schmidt,* 1976*c*]; SM, St. Marys Breccia; EP, Erskine Park sill [*Robertson,* 1979]; GB, Gosses Bluff (H. C. Halls, unpublished data, 1980); GV, Garrawilla Volcanics; JI, Jurassic Intrusives [*Schmidt,* 1976*b*]; SD, Sydney Dykes (including Barrenjoey Dyke, Collaroy Dyke, Minchinbury Dyke [*Robertson,* 1979], and Luddenham Dyke [*Manwaring,* 1963]; RH, Ruby Hill (W. A. Robertson, cited by *Lovering* [1964]); TD, Tasmanian Dolerite [*Schmidt and McDougall,* 1977]; PC, Patonga Claystone [*Embleton and McDonnell,* 1980]; MM, Milton Monzonite; HB, Hornsby Breccia (this paper). Poles identified by lowercase letters are derived from magnetizations we interpret as overprints, or magnetization of unknown origin: bt, Brisbane Tuff [*Robertson,* 1963]; pc Patonga Claystone [*Embleton and McDonnell,* 1980]; td, Tasmanian Dolerites [*Schmidt and McDougall,* 1977]; mm, Milton Monzonite; hb, Hornsby Breccia; and mh, Mogo Hill (this paper).

The minimum temperature attained in the presently outcropping coastal sequences can be confidently estimated from the fission track studies on apatites. As *Morley et al.* [1980] point out, the track retention temperature for apatite is well constrained and has been estimated at 100° ± 20°C [*Gleadow and Brooks* 1979; *Naeser and Faul,* 1969]. A further constraint is suggested from the study by *Raam* [1968] on the Permian Broughton Sandstone from the Kiama district. He described the presence of an authigenic mineral assemblage characteristic of the laumontite zone of the zeolite facies. He agreed, however, that 'the low grade burial' metamorphism, induced by increasing temperatures in response to increasing load pressures, alone could not have produced the observed mineral assemblages, since the maximum depth of burial calculated from the preserved geology is less than 1000 m and might have been only about 750 m. Nevertheless, he recognized, from a comparison of similar authigenic mineral assemblages in other terrains, that temperatures approaching 200°C are generally required to promote that degree of metamorphism.

Dunlop and Buchan [1977] have proposed a theoretical model which relates magnetic unblocking temperatures observed in the laboratory to reheating times that pertain in geological situations. The study describes the thermal activation of pure magnetite and pure hematite. The thermomagnetic experiments carried out on the Milton Monzonite (described here) and Patonga Claystone samples [*Embleton and McDonnell,* 1980] suggest that they contain single magnetic carriers, viz., magnetite and hematite, respectively. The maximum overprint unblocking temperature in the Milton Monzonite is estimated at around 500°C and in the Patonga Claystone at around 600°C. For reheating times of the order of 10 m.y., they suggest ambient crustal temperatures of about 350°C and 450°C, respectively. The experimental results of *Pullaiah et al.* [1975] indicate that the theoretical curves yield an underestimate of the laboratory scale, short-term, unblocking temperatures. The corollary to the conclusions of *Dunlop and Buchan* [1977] is that the observed unblocking temperatures will yield anomalously high ambient temperatures at which the magnetic overprints were acquired. The magnetite and hematite temperature solutions should be regarded therefore as maximum estimates. Although the theoretical curves are not particularly sensitive to reheating times in a geological context, the large difference between the observed unblocking temperatures indicates that the rocks were exposed to elevated temperature regimes for a considerable period of time.

We feel confident in proposing that the rocks present at the surface throughout much of the coastal area of the Sydney Basin were elevated to temperatures of at least 100°C to 200°C at some time prior to 80 m.y. A substantial degree of burial is essential to provide the ambient crustal temperatures suitable for promoting each of (1) fission track annealing in apatites, (2) the observed regional metamorphic facies in the sediments, and (3) the magnetic overprint with unblocking temperatures as observed in magnetite and hematite.

Further support for the existence of high ambient temperatures is provided from measurements of vitrinite reflectance in coals [*Shibaoka and Bennett,* 1977]. Reflectance values in excess of 1% indicate paleo-temperatures in excess of 150°C (M. Middleton, personal communication, 1979). The increased heat flux which promoted the establishment of an anomalous thermal regime is a feature of the rift environment during the evolution of Atlantic-type continental margins. However, an extreme palaeogeothermal gradient of around 50°C/km requires a minimum of nearly 2 km of overburden to have been removed. Uplift and erosion of a considerable sedimentary pile is indicated: this process is described in *Falvey*'s [1974] paper. Doming in the early stages of rift development would promote the removal of overburden; however, on that model it is unlikely that such high rates of heat flow would be present at supracrustal levels so early in the evolution of the rift environment. It is likely that erosion processes have removed more than 2 km of overburden from at least part of the coastal region of the Sydney Basin.

The Permo-Triassic sediments preserved in the central and southern parts of the Sydney Basin are essentially flat lying, the regional dips of <5° probably being the result of Tertiary warping. At least in the southern coastal region around Kiama, *Raam* [1968] noted that the diagenetic reconstruction of the sediments is of regional extent. *Morley et al.* [1980] have further demonstrated that the fission track ages in apatites increase dramatically inland. Vitrinite reflectance measurements in coal deposits generally decrease inland and also northwards from the axis of maximum coal rank in the Wollongong region [*Shibaoka et al.,* 1973]. Clearly, there is a regional variation in the amount of overburden removed and/or in the ambient crustal temperatures reached by the presently exposed rock sequences. The timing of the removal of the overburden may also vary regionally. The overprint magnetizations obtained from samples of the Hornsby Breccia and Patonga Claystone, which outcrops north of Sydney, yield pole positions that lie on a younger section of the currently defined APWP than the overprint pole obtained from the Milton Monzonite. This observation is consistent with progressive wedge-shaped rifting from south to north modeled for the eastern margin of the Australian continent.

Magnetic overprinting, induced in an active rift environment, is also the most likely explanation of results obtained by *Briden* [1965] from studies of some Paleozoic rocks from Tasmania and South Australia. Indeed, he suggested that the remanence was a viscous PTRM and that it was probably acquired during a period of elevated rock temperatures. The issue in Tasmania is further complicated by the subsequent development of a rift margin when Australia and Antarctica separated at around 53 m.y. [*Weissel and Hayes,* 1972].

The results reported here have a clear significance in relation to the acquisition of magnetic overprint signatures that are induced by geological processes active during the development of Atlantic-type continental margins. Paleomagnetic work from the margins of Africa [*Briden et al.,* 1973] and Britain [*Storetvedt and Carmichael,* 1979] has revealed similar magnetic overprints which suggest the widespread occurrence of this phenomenon. Fission track studies along the southern coast of Australia [*Gleadow and Lovering,* 1978] and in Greenland [*Gleadow,* 1978] identified similarly reset apatite ages: they also correlate with rifting and the formation of continental margins.

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