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Linearity spectrum analysis of multi-component magnetizations and its application to some igneous rocks from south-eastern Australia

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Summary. A method that enables the objective resolution of almost parallel multi-component magnetizations is described and demonstrated. A feature distinguishing this method from others is its simultaneous analysis of demagnetization data from a group of specimens, rather than the analysis of data from one specimen at a time. The only prerequisite is that the specimens are derived from a homogeneous source. Thus for a formation carrying a simple single component magnetization, all specimens from the formation may be simultaneously reduced. For a more complicated two component magnetization it is shown that only specimens from a particular site can be considered homogeneous, and for a complex three component system each *sample* often requires undivided attention. Thus the workload is proportionally increased to achieve analyses of comparable reliability from data of variable quality.

New pole positions from Mesozoic intrusions of the Sydney Basin, NSW are: from the Marsden Park Breccia pipe 48°S, 127°E ($A_{95} = 6°$); the St Marys Breccia pipe 46°S, 150°E ($A_{95} = 8°$); the Prospect Dolerite 60°S, 142°E ($A_{95} = 13°$) and 53°S, 180°E ($A_{95} = 6°$); and from the Dundas Breccia pipe 58°S, 162°E ($A_{95} = 36°$) and 31°S, 195°E ($A_{95} = 16°$). The last two formations possess multi-component magnetizations. These pole positions are consistent with previous results from south-eastern Australia.

Introduction

The Sydney Basin is a structural unit in south-eastern NSW, which has suffered little deformation since its formation in the late Palaeozoic-Mesozoic. Literally hundreds of intrusions pervade the sediments, which are predominantly quartz sandstones, siltstones and claystones. Palaeomagnetic investigations of the Sydney Basin were among the first in Australia (Boesen, Irving & Robertson 1961; Manwaring 1963; Irving 1963) although the basin has failed to attract further attention until the last few years (Schmidt 1976; Robertson 1979; Schmidt & Embleton 1981). These later investigations show that many of the rock units throughout the basin carry partial magnetic overprints. It is perhaps the basin's seemingly pristine condition, that has made the widespread nature of the magnetic overprinting all the more intriguing. An episode of burial and uplift appears unavoidable in order to explain satisfactorily the presence of this overprinting. It is conceivable that such an episode is an integral part of basin evolution, although in this instance the age of the overprinting and the coeval onset of the opening of the Tasman Sea strongly suggests a causal relationship. The present investigation is concerned with the resolution and dating of magnetic overprints, and the dating of the times of formation of various intrusives within the Sydney Basin.

Perhaps the most familiar techniques presently used to examine complex magnetizations are orthogonal graphs (Zijderveld 1967), vector subtraction (Roy & Park 1974), circles of remagnetization (Khramov 1958; Halls 1976, 1978; McFadden 1977), difference vector circles (Hoffman & Day 1978), and more recently principal component analysis (PCA) as presented by Kirschvink (1980). The use of earlier methods, such as the stable end-point and the optimum demagnetization step, has diminished, since they are inadequate for defining the directions of magnetizations which are removed during 'cleaning' of a multi-component remanence. Nevertheless there is still scope for improved data analysis. The method described below, although developed for a specific reason, can be adapted to cover a wide range of circumstances. Examples include studies of one, two and three magnetic component systems.

Multi-component resolution using the linearity spectrum

The analytical procedures utilized here evolved from the requirement of resolving magnetizations which have similar directions. Inevitably as greater regard is given to overprint magnetizations, which are characteristically soft, the question arises, when is the direction of the removed component different from that of the underlying (harder) component?

Perhaps the most encompassing technique developed so far for dealing with multi-component magnetizations is that described by Kirschvink (1980), who has adapted PCA to the palaeomagnetic arena. PCA involves the least-squares fitting of lines and planes to vector end-points in three-space and utilizes more data than other methods, resulting in less data being rejected or simply ignored. The problem remaining is how to define the interval on which the least-squares fitting is to be performed. The search routine suggested by Kirschvink to define the interval has two drawbacks. First, the routine is dependent upon a pre-defined rejection level which may introduce a bias. For instance, consider N vectors composed of NRM plus $N-1$ demagnetization steps. Beginning with the interval bound by the $(N+1)$th and the $(N-1)$th data points (i.e. the origin and the end-point of the $(N-1)$th vector), the interval is tested against the pre-set level and either accepted or rejected. The interval is then either expanded or shifted towards the NRM step (depending on whether the initial interval was accepted or rejected) and the test repeated. This iterative procedure converges on the largest segment that passes the test, which is then fitted with a least-squares line. However, a covert bias may be present if the rejection criterion is set too coarse. This is depicted in Fig. 1 where several points, off the linear segment, are included in the PCA (a′ and b′). Obviously such a bias is systematic and should be avoided. The method described below circumvents this problem by seeking segments with *maximum* linearity levels, thus ensuring only points on the linear segment are included (Fig. 1, segments a and b). More recently Kirschvink (private communication) has modified his method to overcome this problem.

A second improvement in the search routine may be achieved by expanding the interval under scrutiny, alternately towards the NRM step and then back towards the origin, then towards the NRM step again, and so on. This modification conceivably yields longer segments (thus utilizing more data) in some instances. Furthermore, it ought to be possible to associate a parameter with each data point, which reflects the behaviour of neighbouring points, thereby enabling data points to be weighted.

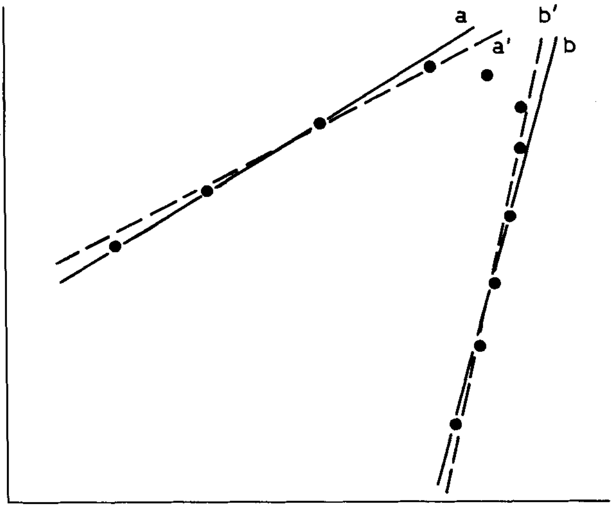

Figure 1. The primed lines (a' and b') are biased as a result of a too coarse rejection level. The best fit lines (a and b) are achieved by maximizing the linearity.

A technique incorporating these ideas and improvements is given below, in which the sole assumption is that the data set is derived from samples, or sub-samples (specimens), of a homogeneous group. Since the technique was originally developed to approach an objective procedure for resolving between magnetizations with similar directions, it was imperative to consider the data set *in toto*, unlike other methods which tend to examine data from one specimen at a time (leaving the worker responsible for interrelating specimens). A parameter, the collinearity (or simply linearity), was therefore prescribed to enable specimens to be compared.

The linearity of a segment may be defined in a variety of ways. The simplest method is to use the ratio of the distance between the bounding data points, to the sum of the distances between the intervening points. Although quick in terms of computation time, the linearity defined in this way will fail if data density is high enough such that the difference between the intervening points approaches the noise level of the system (i.e. measurement plus demagnetization noise). Although these instances are not common, it is possible to use an alternative definition of linearity if the need arises. It is apparent that the cosine of the maximum angular deviation (MAD – Kirschvink 1980) of a segment, has a range from 0 to 1 since $0° < \mathrm{MAD} < 90°$, similar to the distance ratio parameter (the MAD angle is derived from the eigenvalue ratios of the matrix of sums of squares and products). However, because the cosine function is not sensitive to differences between small angles, if the MAD is to be used it is considered that the sine should be more discriminating. To give the parameter the correct range $1 - \sin$ (MAD) has been used. In the examples given below, although distance ratio parameter is generally used, for the Prospect Dolerite a comparison of the two parameters shows that for the present data either parameter will suffice. A value of unity implies perfect linearity.

Linearity also reflects the behaviour of neighbouring data points in the following fashion. Beginning with a data point and its two nearest neighbours, a linearity level may be calculated, and the window moved to successive points repeating the calculation (the minimum number of points required to define a linearity level is three). A somewhat more complicated procedure, using the alternating search routine described above, is to maximize the linearity associated with any point by expanding the segment about the point until the linearity level no longer increases. Again these two slightly different techniques are demonstrated on the Prospect Dolerite. Thus for all data points of a particular specimen, a maximum linearity level may be calculated, and from all kindred specimens a *mean* maximum linearity level may be calculated for each demagnetization step. By taking the mean level, the method discriminates between random and systematic departures from linearity, excluding the latter which commonly occur when more than one component is being removed simultaneously (e.g. points on the curved segment of Fig. 1).

The end result is a spectrum of linearities for each sample, site or formation, depending upon the complexity of magnetization and which level is defined as representing the group. That is, for simple behaviour the group might be defined as all specimens from the formation, for more complicated behaviour the group might be defined at the site level, and so on until all members of the group behave in a homogeneous fashion.

Having defined the linearity spectrum for the group of specimens under analysis, the next step is to determine plateaux in the spectrum. In terms of the demagnetization behaviour, such plateaux generally reflect intervals where only one magnetic component is being removed. Likewise, troughs in the linearity spectrum reflect intervals where more than one component is being removed. Fig. 2 represents the different types of spectra often encountered. The overall character of a group is accordingly established. Equipped with this information it is possible to approach the data set in an objective fashion in order to define the direction of the distinct magnetic components being removed around the linearity peaks of the spectra.

If a maximum within a plateau is found to occur at a particular demagnetization step, say the Ith step, the maximum linearity level for all specimen data sets (comprising the group data) should be expected to be relatively large. Specimens are unique and their individual linearity peaks may not coincide with the mean maximum level for the group, however by expanding the interval about the Ith demagnetization step and *maximizing* the associated linearity, the segment thus defined will most probably contain both data points coinciding with the plateau peak of the group and the specimen peak (if they are different at all). In this manner, for each peak in the group linearity spectrum, a linear segment may be defined for each specimen.

Subsequent application of PCA to each segment fits a least-squares line yielding the best estimate of the direction of the magnetization removed over each segment. Thus, directions from each specimen which correspond to a particular group linearity peak may be combined statistically (Fisher 1953; Bingham 1974), yielding an overall mean direction for the group, corresponding to the linearity peak being considered.

The linearity level operates as a stability index designed for multi-component magnetizations, as opposed to many previously proposed indices which tended to be preoccupied

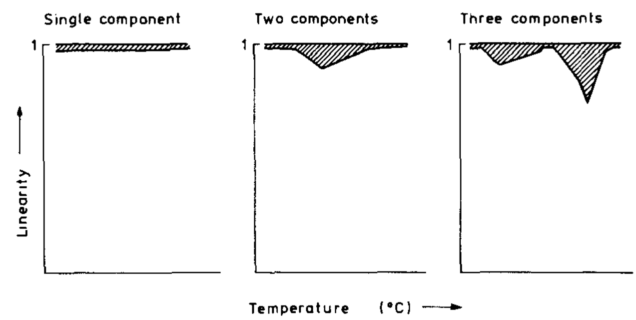

Figure 2. Linearity spectra from groups of specimens possessing a single component, two components and three components. Plateau regions usually reflect the demagnetization of one component only.

with defining optimum demagnetization treatment or isolating the most stable magnetic component in a rock (see Giddings & McElhinny 1976 for discussion). Finally, although the method outlined above concerns least-squares lines, a parallel procedure can be adapted for least-squares planes when appropriate.

Examples using LSA

The following examples have been drawn from studies of some igneous rock deposits in the Sydney Basin, NSW. Previous palaeomagnetic investigations near the coast of south-east Australia have established that a major period of magnetic overprinting has occurred in that area (Schmidt 1976; Schmidt & Embleton 1981). This period dates from about 90 Myr ago, and is correlated with precursor events which led to rifting in the primordial Tasman Sea. These results represent a continuing investigation of the processes involved in magnetic overprinting, with a special emphasis on the responses of different rock formations to a single thermal event.

The investigations are presented in order of increasing complication to allow the reader to gain some insight into the usefulness of LSA under varying degrees of complexity. Firstly two occurrences of single component magnetization are described. It might seem somewhat redundant or sophisticated to examine such data using LSA when a more simplistic approach would suffice, but the third study gives the lie to this notion. What appears to be basically a single component of magnetization is shown in the third study to be two, almost parallel but undoubtedly different, components of magnetization. Lastly, a three component magnetization system is presented. Although LSA plays a major role in each of these investigations, the analysis has not been conducted to the exclusion of all else. The importance of orthogonal diagrams (Zijderveld 1967) is emphasized, particularly with the study of the more complex three component magnetization system. Nevertheless, LSA affords a versatile analytical tool to aid in studies of multicomponent magnetizations.

While collecting samples, a magnetic and a sun-compass were used for orienting either blocks or drill-cores. Complete result flux-gate magnetometers (Molyneaux 1971) were used to measure magnetic remanence vectors, while Schonstedt demagnetizers (thermal and alternating field-AF) were used for the progressive demagnetization of specimens. A Tektronix 4050 series graphics system was programmed for all data analysis.

MARSDEN PARK BRECCIA PIPE

The volcanic neck at Marsden Park, 50 km west of Sydney, consists of volcanic breccia and basalt, outcropping over an area of approximately 4 ha (Crawford 1973). Three sites were collected from breccia and six sites from basalt. Each site consisted of four independently oriented blocks or cores. The NRM intensities of the breccia were typically 20–50 mA m^{-1}, while those of the basalt varied from 200 to 1000 mA m^{-1}. Orthogonal projections of thermal demagnetization of a breccia specimen (MPO2A) and three specimens of basalt (Fig. 3) show that there are no great differences in their behaviour. The basalt samples tended to reveal a very low temperature ($< 250°$C) component close to the present geomagnetic field direction. Notwithstanding this, it is apparent that a single magnetic component which is demagnetized by 500°C, is present in each specimen. At least one specimen from each site was subjected to AF demagnetization yielding similar directions.

Fig. 4 is a composite plot of the linearity spectrum for all specimens. The salient feature is a convergence of the spectra towards unity at 400°C, which indicates that the 'average' specimen possesses a single component of magnetization which is best resolved by demagnetization around 400°C. Thus for this formation, all specimens have been simultaneously

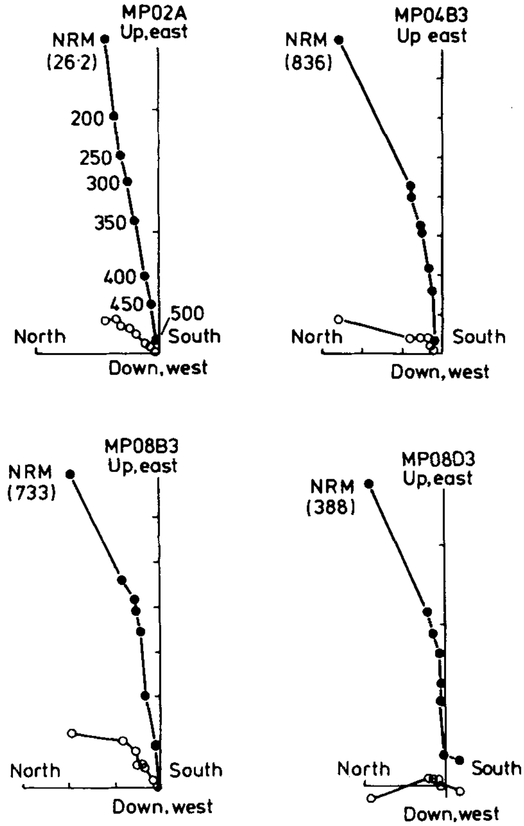

Figure 3. Orthogonal demagnetization plots from specimens of Marsden Park Breccia. Closed circles, vertical plane; open circles, horizontal plane.

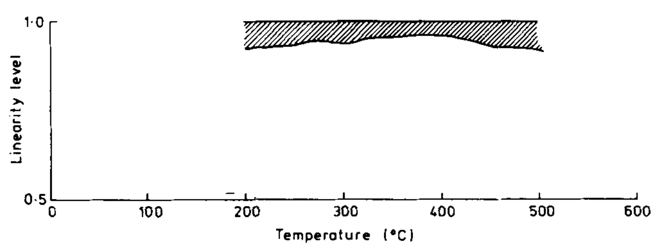

Figure 4. Linearity spectra envelope of demagnetization data from specimens of Marsden Park Breccia. The persistent high linearity level reflects the demagnetization of a single magnetic component.

included in the group, since their behaviour is uniform. The LSA indicates that the best overall palaeomagnetic direction from the Marsden Park Breccia may be estimated by meaning those directions found after applying PCA to segments from each specimen, such segments being defined by maximizing the linearity of their individual demagnetization points about the 400°C step. For these 36 specimens this gives a Dec. = 42.3°, Inc. = −78.0° and an α_{95} = 1.9°.

Table 1. Summary of palaeomagnetic results from the Marsden Park Breccia pipe (33.7°S, 150.8°E).

			Direction				Pole	
Site	T(°C)	N	Dec.(°)	Inc.(°)	R	α_{95}(°)	Lat.(°S)	Long.(°E)
1	300	4	21.6	−77.5	3.993	4.5	55.2	135.6
2	350	4	42.8	−75.4	3.998	2.1	50.7	121.1
3	350	4	28.5	−72.7	3.999	1.2	59.0	121.4
4	450	4	34.8	−75.0	3.995	3.6	54.3	123.3
5	350	4	30.9	−78.0	3.990	5.4	52.2	131.7
6	400	4	62.9	−84.0	3.990	5.2	38.4	137.3
7	400	4	62.9	−77.8	3.990	5.3	41.3	122.8
8	450	4	61.4	−74.3	3.981	7.3	42.8	114.9
9	350	4	72.4	−83.0	3.989	5.6	36.8	134.3
Mean		9	43.6	−78.0	8.965	3.4	48.1	127.2 (A_{95} = 6.2°)

Symbols and abbreviations: T, temperature of linearity peak; N, number of unit vectors; Dec., declination; Inc., inclination; R, resultant of N unit vectors; α_{95} and A_{95}, half-angles of cones of confidence at 95 per cent probability level of directions and poles (calculated independently of directions) respectively (Fisher 1953); Lat., latitude; Long., longitude.

To determine to what extent the above result might alter if the group level was changed, LSA was applied to individual sites. For each sites the linearity peaked between 300 and 450°C, yielding a mean site direction of Dec. = 43.6°, Inc. = −78.0° and an α_{95} = 3.4° (Table 1). This more conservative estimate is not significantly different except for the slightly larger error.

ST MARYS BRECCIA PIPE

This volcanic neck is several kilometres south of that at Marsden Park, outcropping over an area of about 12 ha (Crawford 1973). Six samples were taken from each of four sites at different bench levels in a quarry. The rock type sampled is entirely of breccia. Similarly to the NRM intensities of the breccia from Marsden Park, the NRM intensities of St Marys Breccia generally range from 20 to 50 mA m^{-1}. After examining the orthogonal plots of the thermal demagnetization data from these breccia samples, two samples show distinctive behaviour (SM02C2 and samples in Fig. 5). The directions defined by the (approximately) straight line segments revealed by the orthogonal plot of data from specimen SM02C2 are reminiscent of the two dominant magnetic components from many of the specimens of the Hornsby Breccia (Schmidt & Embleton 1981). The significance of this is discussed later, for the present it is sufficient to point out that not all samples from the St Marys Breccia have responded to thermal demagnetization in the same way.

The linearity spectra yield a peak mean linearity level at 300°C. Furthermore there is a second peak at 525°C, raising the possibility that the St Marys Breccia has two magnetizations. However a closer inspection of the linearity spectra reveals that these two peaks really result from the dominating influence of one of the two component specimens (Fig. 6). If this specimen, which shows two strong peaks, was ignored, the peak mean linearity level would be 400°C.

Thus for the purposes of defining the linearity peak, specimen SM02C2 has been eliminated on the grounds that the assumption of a homogeneous group has been violated. Segments were subsequently expanded around 400°C for all specimens (including SM02C2), with linearity values often greater than 0.999. For these segments a mean direction of Dec. = 359.8°, Inc. = −83.0°, α_{95} = 2.2° was calculated.

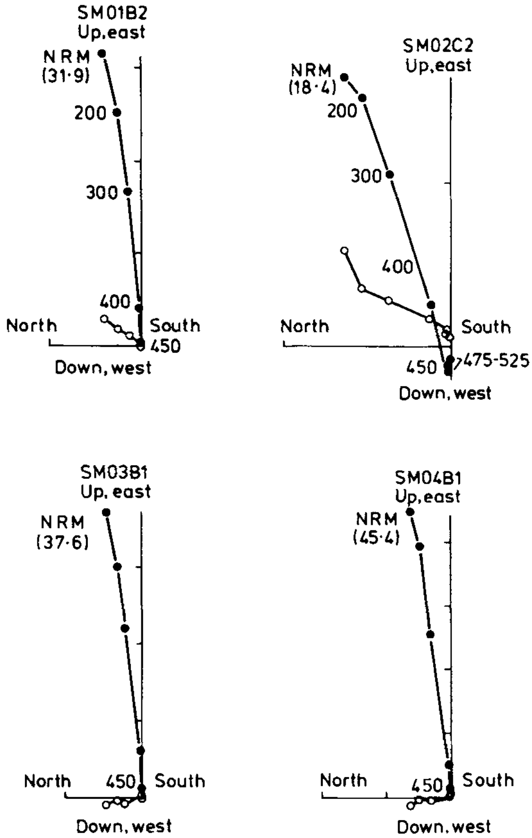

Figure 5. Orthogonal demagnetization plots from specimens of the St Marys Breccia.

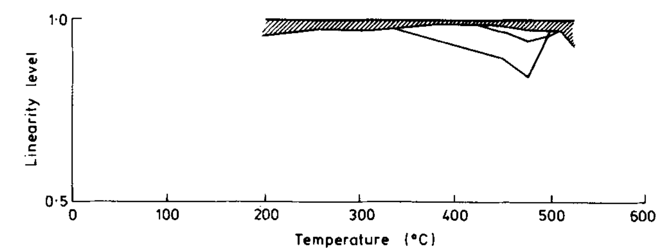

Figure 6. Linearity spectra envelope from specimens of St Marys Breccia. The spectra from two specimens are plotted alone, those possessing two components as opposed to a single component for the remainder.

As for the data from the Marsden Park Breccia, LSA was applied to individual sites, with all sites yielding a peak mean linearity level at 400°C. The mean site direction from this more conservative analysis is Dec. = 2.3°, Inc. = −83.9° and an α_{95} = 3.9° (Table 2), which is less than 1° of arc from the direction analysed using all specimens as the group. Notwithstanding the two component samples from site 2, the similarity with the result from the Marsden Park Breccia is striking. Robertson (1979) has also studied the St Marys Breccia and

Table 2. Summary of palaeomagnetic results from the St Marys Breccia pipe (33.8°S, 150.8°E) (symbols and abbreviations as for Table 1).

			Direction				Pole	
Site	T(°C)	N	Dec.(°)	Inc.(°)	R	α_{95}(°)	Lat.(°S)	Long.(°E)
1	400	6	40.6	−86.9	5.978	4.4	38.4	145.7
2	400	6	13.2	−80.9	5.975	4.7	50.9	144.5
3	400	6	345.5	−82.7	5.980	4.2	47.6	156.1
4	400	6	348.3	−83.6	5.995	2.1	46.1	154.5
Mean		4	2.3	−83.9	3.995	3.9	45.9	150.1(A_{95} = 7.6°)

arrived at a similar direction (Dec. = 14°, Inc. = −81°) using the optimum demagnetization step technique. Therefore it might be opined that the foregoing technique is overly complicated or unnecessary, however the following application exonerates such indulgence.

PROSPECT DOLERITE

An early investigation of the Prospect Dolerite was among the first to show that rocks could be dated by palaeomagnetism (Boesen *et al.* 1961). Although thought to be Tertiary on petrological grounds, the Prospect Dolerite was shown from its palaeomagnetism to be Mesozoic. At that time it was not possible to estimate magnetic ages more precisely. The age was later substantiated from radiometric dating which yielded an age of 168 Myr (Evernden & Richards 1962).

This later proved to be somewhat ironic, since as sea-floor magnetic anomaly patterns and bathymetric data accumulated, along with the advent of morphological fits of continents in the late 1960s and early 1970s, the pole position derived from the Prospect Dolerite (and some other poles from south-eastern Australia) appeared, upon reconstruction, to be divergent from Jurassic poles from other Gondwana continents. The samples collected by Boesen *et al.* (1961) were subsequently treated to more rigorous cleaning (Schmidt 1976), isolating directions significantly different from directions found by the earlier investigation. Pole positions determined from these new directions were found to be in close agreement with those from rock units from other continents (e.g. Karoo and Ferrar Dolerites).

It has been demonstrated that particularly pertinacious secondary magnetizations have been responsible for the initial failure to isolate the original direction of magnetization in a number of rock bodies from south-eastern Australia. The Gibraltar Syenite and Gingenbullen Dolerite, for instance, also investigated by Boesen *et al.* (1961), were later shown to be heavily overprinted (Schmidt 1976). Recently it has been shown that the Milton Monzonite, Hornsby Breccia and Patonga Claystone (Narrabeen Chocolate Shale of Irving 1963) also carry substantial magnetic overprints, dating from about 90 Myr ago (Schmidt & Embleton 1981; Embleton & McDonnell 1980).

Another feature that these rock bodies have in common is their *reversed* primary magnetization, facilitating the recognition of the overprint magnetization. Overprints have so far only been found with normal directions, thus they have been readily distinguished from reversed primary directions. Since the Prospect Dolerite is Jurassic in age, and other rock bodies near the south-eastern seaboard of Australia have apparently been overprinted in the Cretaceous (at about 90 Myr), it was conjectured that the Propsect Dolerite may have been overprinted at this time. The major difference between this rock body and the others which have been shown to possess overprints, is the polarity of the primary magnetization, of the Prospect Dolerite which is the same as that of the surmised overprint.

Originally the Prospect Dolerite was sampled from three quarries, which recently

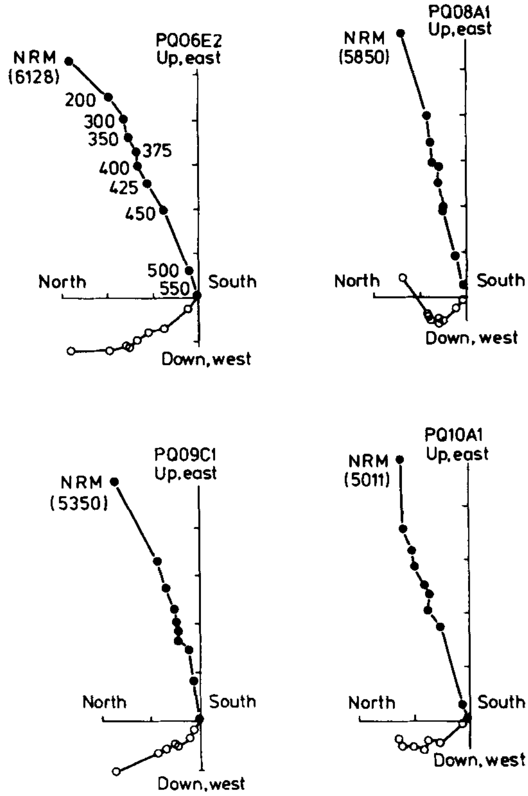

Figure 7. Orthogonal demagnetization plots from specimens of Prospect Dolerite. Note the suggestion, albeit faint, of the presence of two components.

coalesced to form a single large quarry. Between five and seven cores from each of ten sites have been collected from different bench levels throughout this quarry. The samples represent both fine- and coarse-grained varieties of the dolerite.

One specimen from each core was subjected to thermal demagnetization, and a further specimen from each site was subjected to AF demagnetization. Fig. 7 shows some representative orthogonal plots of thermal demagnetization data. NRM intensities generally varied from 3000 to 6000 mA m^{-1}. The vertical projections show very little change in (apparent) inclination, but the horizontal projections reveal a slight break in slope (reflecting a change in the declination) around the mid-temperature range.

Since a range of grain sizes is represented, it was expected that the behaviour to thermal demagnetization of some sites would be distinctive, thus sites have been defined as individual groups for this study. Although differences in behaviour between these groups is reflected by the linearity spectra, a salient feature of most spectra is a trough between 300 and 400°C, although the trough is not always pronounced. Nevertheless, there are generally two peaks in the spectra corresponding to two linear segments, that is a two component system (cf. Fig. 2). This is apparent whether the distance ratio parameter or the eigenvalue ratio (actually $1-\sin$ (MAD)) method is used. The comparison of the linearity spectra calculated by maximizing these two parameters is shown in Fig. 8. Also shown for comparison is the simple three point, or windowed (as opposed to the maximized), calculated spectra from

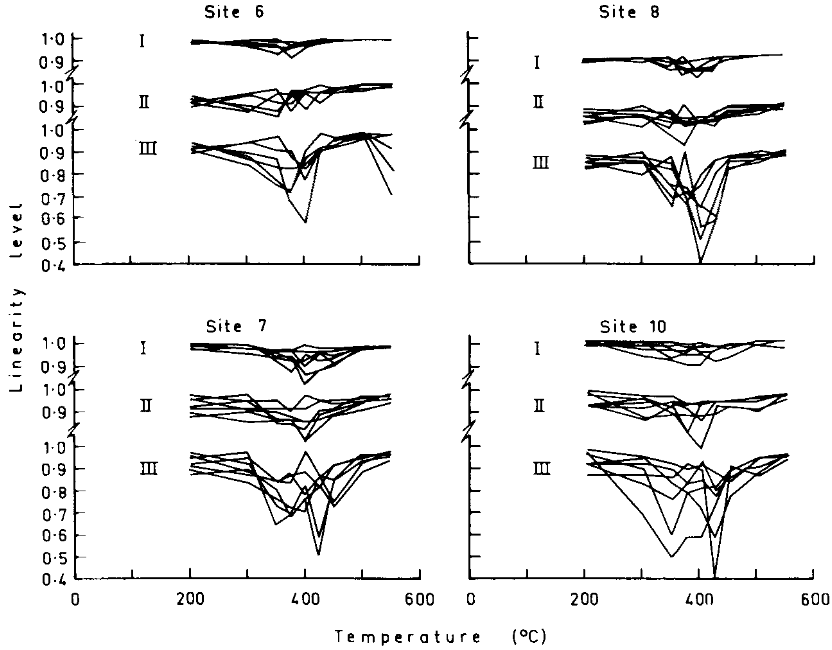

Figure 8. Linearity spectra from samples of four sites from the Prospect Dolerite, each showing two distinct plateau regions reflecting two components of magnetization. I – maximizing distance ratios, II – maximizing eigenvalue ratio parameter (1 – sin (MAD)), and III – three point moving window eigenvalue ratio parameter.

the eigenvalue ratios. All three spectra clearly show similar features, with the windowed eigenvalue ratio method being the most sensitive, as would be expected. But for the purposes of defining linear segments from demagnetization data any of the methods should suffice (cf. mean values Table 3). For those concerned with computation time, the windowed parameter (either distance or eigenvalue ratio) is obviously faster.

Some sites revealed three peaks in their spectra, but on closer inspection it was seen that one peak yielded mean directions with large confidence half-angles. These were neglected, since in all circumstances they were not significantly different from one of the mean directions associated with the other temperature peaks, with corresponding lower confidence half-angles. Thus all sites revealed two linearity peaks, the lower temperature peaks ranging from 200 to 400°C, while the higher temperature peaks range from 450 to 550°C. Table 3 lists the directions from each site associated with these linearity peaks. The linearity peaks quoted are from the maximized distance ratios. Also listed in Table 3 are the mean directions derived from the eigenvalue ratio method of defining the linearity. Both maximized and windowed derivations are given. It is apparent that no method gives a result significantly different from the others. The site mean low temperature (200 to 400°C) direction is Dec. = 9.7°, Inc. = −74.5° and an $\alpha_{95} = 8.2°$, while the site mean high temperature (450–550°C) direction is Dec. = 322.1°, Inc. = −74.9° with an $\alpha_{95} = 3.7°$. Moreover, these two directions are significantly different since their cones of confidence do not intersect.

The mean direction of magnetization first derived from the Prospect Dolerite after AF demagnetization to 15 mT was Dec. = 359°, Inc. = −81° (Boesen *et al.* 1961) with an $\alpha_{95} = 6.8°$ (calculated from 18 specimens), which is 6.8° and 9.6° away from the low

Table 3. Summary of palaeomagnetic results from the Prospect Dolerite (33.8°S, 150.9°E) (symbols and abbreviations as for Table 1).

a) Low temperature linearity peak

Site	T(°C)	N	Direction Dec(°)	Inc(°)	R	α_{95}(°)	Pole Lat(°S)	Long(°E)
1	300	6	350.2	-84.6	5.933	7.8	44.3	153.4
2	300	6	33.4	-55.1	5.869	11.0	62.6	74.3
3	400	5	301.7	-65.2	4.779	18.5	44.8	205.4
4	300	5	25.2	-82.5	4.828	16.2	46.8	141.8
5	300	5	334.0	-84.8	4.907	11.8	42.9	157.1
6	200	6	26.5	-63.4	5.760	15.0	66.8	97.5
7	200	7	10.1	-63.8	6.409	19.9	76.0	120.3
8	300	7	11.6	-68.6	6.855	9.5	70.0	129.6
9	375	5	20.2	-80.2	4.962	7.5	51.3	140.5
10	200	7	18.2	-76.4	6.740	12.8	57.6	136.2
Mean		10	9.7	-74.5	9.745	8.2	60.1	142.4 (A_{95}=13.4°)
			*3.4	-74.1	9.764	7.9	61.8	148.5 (A_{95}=13.0°)
			†11.6	-75.1	9.726	8.6	59.6	141.5 (A_{95}=13.8°)

b) High temperature linearity peak

Site	T(°C)	N	Dec(°)	Inc(°)	R	α_{95}(°)	Lat(°S)	Long(°E)
1	450	6	332.1	-74.9	5.982	4.1	57.0	175.0
2	450	6	348.1	-69.8	5.872	10.9	68.4	170.3
3	500	5	312.8	-75.3	4.973	6.3	49.0	182.2
4	540	5	325.4	-76.2	4.960	7.7	53.2	175.6
5	450	5	333.5	-84.6	4.965	7.2	43.2	157.4
6	500	6	319.0	-68.2	5.963	5.8	55.7	197.6
7	550	7	312.6	-74.9	6.846	9.8	49.2	183.2
8	550	7	307.9	-69.2	6.958	5.0	48.7	197.3
9	550	5	298.7	-76.7	4.972	6.4	42.3	181.4
10	550	7	333.5	-74.8	6.946	5.8	57.6	174.3
Mean		10	322.1	-74.9	9.947	3.7	53.0	179.6 (A_{95}=6.4°)
			*319.1	-75.4	9.962	3.2	51.5	179.7 (A_{95}=5.5°)
			†318.2	-75.8	9.952	3.5	51.3	178.5 (A_{95}=6.2°)

*As derived from maximizing the eigenvalue ratio parameter (1-sin (MAD)).
†As derived from windowing, or three point, eigenvalue ratio parameter.

temperature and high temperature directions respectively given above, but plotting approximately mid-way between the two. The mean direction derived after higher AF (30 mT) cleaning of Dec. = 306°, Inc. = −71° with an α_{95} = 7.0° from nine samples (recalculated from Table 3 of Schmidt 1976) is 18.3° from the low temperature direction given above, but only 6.1° from the high temperature direction. This latter difference is less than the half-angles of the cones of confidence, indicating that the directions after applying rigorous AF and thermal demagnetization are not significantly different. Similarly the directions derived from the low AF and low thermal demagnetization are not significantly different from each other. The point to be emphasized is that the low stability and high stability magnetizations *are* distinct.

While much of the above considerations might seem superfluous it is essential to show that from any viewpoint the Prospect Dolerite is seen to carry two similar, yet distinct, magnetizations. It is worth emphasizing that these conclusions tend to be independent of the method, being insensitive to the linearity parameter chosen. This confirms the earlier suspicion that like many other rock bodies near the seaboard of south-eastern Australia, the Prospect Dolerite has been magnetically overprinted. The age of this magnetizing episode is late Mesozoic, thus vindicating the early claim of a Mesozoic age for the dolerite on the basis of what is shown here to be a predominantly secondary, or overprint magnetization.

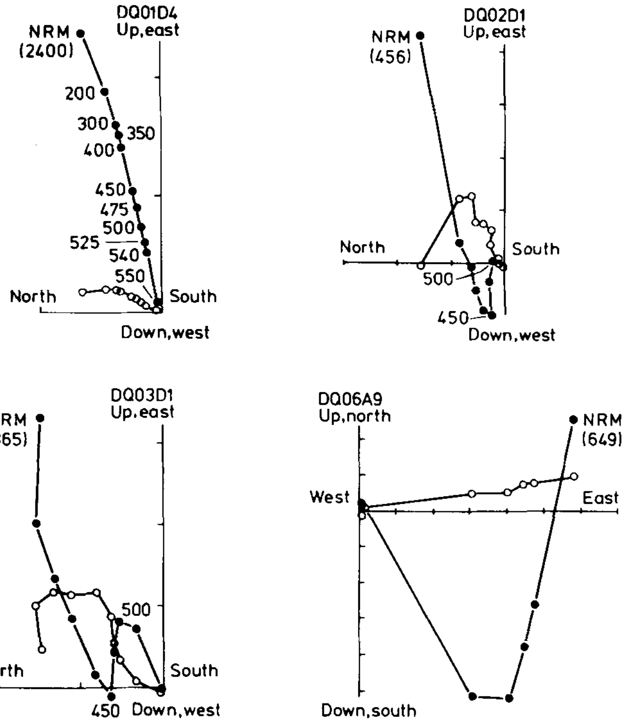

Figure 9. Orthogonal demagnetization plots from specimens of Dundas Breccia, showing single, predominantly two, and three components.

DUNDAS BRECCIA PIPE

The quarry at Dundas, 16 km west of Sydney, has long been abandoned and reclaimed for recreational activities. Now only a small portion of the 1.5 ha outcrop remains. The outcrop is largely basaltic, being deeply weathered in places. Six sites consisting of three or four block samples (drilling being impractical) were collected from fresh nodules. Initially one specimen from each block was subjected to thermal demagnetization, revealing the varied behaviour shown by the orthogonal plots (see Fig. 9). Many specimens within the same site behaved quite differently.

Although the linearity spectrum of specimen DQ01D4 is uniformly high, those for other specimens from site 1 show many peaks and troughs. In fact, the mean linearity spectrum using the specimens of site 1 as a group revealed peaks at 200, 400, 500 and 550°C. However, while other specimens from site 1 might not have behaved as ideally as DQ01D4, there did not appear to be any reason for justifying further subdivision of the site into smaller groups for the LSA, since the orthogonal plots from the other specimens showed predominantly a single component. On closer inspection of the mean directions derived from the four peaks, none were found to be significantly different, so the best estimate may be taken as the mean with the smallest α_{95}, which corresponds to the 400°C peak (see Table 4).

The linearity spectra of site 2 suggest that specimens from this site have acted in a disorderly fashion. A perusal of the orthogonal projections disclosed the reason for this behaviour. Specimen DQ02D1 from site 2 shows two well-defined linear trends (Fig. 9), however, a complication exists because neither of these linear trends directly approaches the origin, implying that the specimen possesses a third, more stable magnetic component.

Table 4. Summary of palaeomagnetic results from the Dundas Breccia pipe (33.8° S, 151.1° E) (symbols and abbreviations as for Table 1).

Site	T(°C)	N	Direction Dec(°)	Direction Inc(°)	R	α_{95}(°)	Pole Lat(°S)	Pole Long(°E)
a) Low temperature linearity peak								
1	400	4	9.6	−70.3	3.960	10.7	68.3	135.9
2	200	2	339.5	−71.1	1.994	−	64.0	177.9
3	300−350	4	16.5	−78.7	3.941	13.0	54.3	140.7
6	300	3	276.0	−71.9	2.745	47.3	41.7	192.3
Mean		3	345.7	−76.7	2.951	19.5	57.7	162.1 (A_{95}=35.6°)
b) High temperature linearity peak								
2	500	2*	80.6	60.3	2.000	−	15.3	201.4
3	475	1*	79.6	59.9	−	−	14.5	201.4
4	500	4	97.5	68.4	2.992	7.73	30.2	196.5
5	525	3	114.3	68.8	2.956	18.5	40.5	198.4
6	500	3	80.6	69.6	2.978	13.2	21.4	190.3
Mean		3	97.7	69.5	2.989	9.1	30.7	194.8 (A_{95}=15.7°)

*These specimens have been excluded from the mean, being from single samples (see text).

The other specimens from site 2 vaguely paralleled this behaviour, but their higher temperature components have not been thermally isolated. It is apparent that the blocking temperature spectra of these components are overlapped. There would therefore seem to be justification in subdividing this site for LSA, perhaps by processing more specimens from each sample, and reducing the group level to the sample. That is, a number of specimens from one sample would constitute a group.

After performing the above operation, only data from sample DQ02D gave internally consistent results. Conventionally, the data from individual specimens are combined to give a sample result, and these results are then combined to give a site (or mean sample) result, but for site 2 the results from two specimens from the one sample (DQ02D1) have been combined to represent the site, since only data from this sample were repeatable, implying that the original assumption of a homogeneous group has been violated. The stability spectra of the magnetic components in the other three samples were overlapped, leading to inconsistent linearity spectra and poorly defined intervals. However, the results from site 2 are cited for interest and have not been included in the final analysis (Table 4).

Specimens from site 3 behaved very similarly to those of site 2. Two specimens showed almost identical orthogonal projections (represented by DQ03D1 in Fig. 9), clearly showing three magnetic components. Moreover, the directions of the least and the most stable magnetization can be seen to be the same. As discussed later, this is probably not simply a coincidence, but highly diagnostic of the origin of magnetization of some specimens, particularly those from sites 2 and 3. The group level adopted for site 3 was consequently the sample, with two further specimens from each sample being processed. These extra results confirmed the presence of three distinct magnetizations in these samples. The linearity spectra of specimens from samples DQ03C and DQ03D show an overall three component pattern (cf. site 3, Fig. 10). The directions given in Table 4 from site 3 for the higher temperature component is from one specimen only from sample DQ03D, because although it was clear that other specimens possessed a three component magnetization, the two high temperature components in these specimens have not been isolated. This situation is similar to that for site 2 in that the site is not homogeneous and the high temperature result has

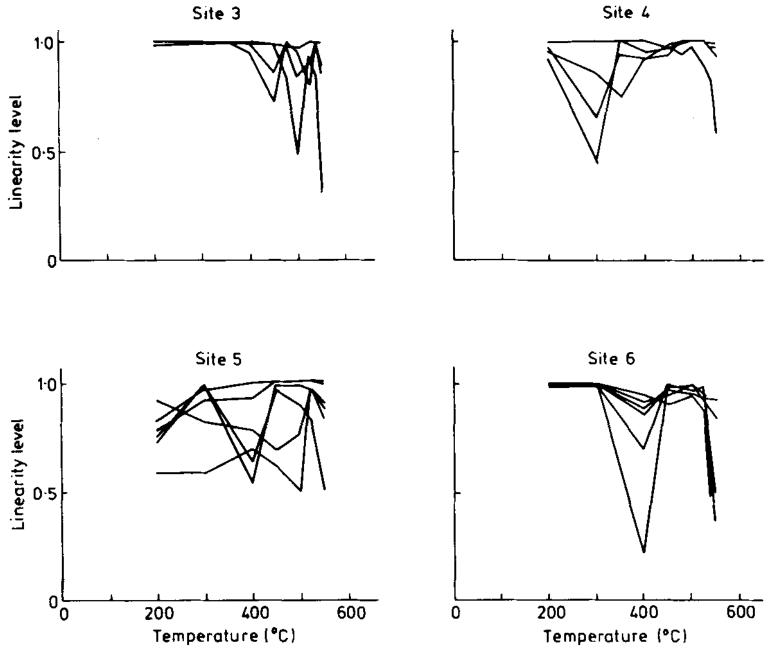

Figure 10. Linearity spectra from samples of four sites from the Dundas Breccia. Most samples reveal two peaks while others show three. Low linearity levels reflect the simultaneous demagnetization of two components with similar stability.

Site 4 showed considerable variation between samples (Fig. 10), with three samples being dominantly magnetized in the direction of the high temperature component of sites 2 and 3. Applying LSA to the site as a whole yielded peaks at 200 and 500°C. The mean sample directions gave values of $\alpha_{95} = 43$ and 29° respectively, indicating that the behaviour of different specimens is certainly not as homogeneous as that of samples from the other studies, but rejecting one direction from the high temperature group reduced the α_{95} from 29 to 8° (Table 4). No such purging of the low temperature direction estimated was possible and the low temperature directions have therefore been rejected. No further specimens from site 4 were processed.

The linearity spectra from six specimens (two from each of three samples) from site 5 reflect their paired behaviour (Fig. 10). Two specimens from one sample reveal a well-defined trough, two specimens from another sample show a broader, less distinct trough, while the remaining two specimens from the third sample show a steady increase towards unity between 500 and 600°C. This variation in behaviour clearly suggests that the LSA ought to be applied to groups of specimens from the same samples, as for sites 2 and 3. The results listed in Table 4 shows that the high temperature component has been isolated in all three samples. However, as for site 4, no consistent low temperature directions were found.

Specimens of samples from site 6 varied more by degree than by kind, as reflected by the similar linearity spectra from six specimens (two per sample) in Fig. 10. All specimens possessed two dominant magnetic components which yielded two well-defined plataeux in the mean linearity spectrum around 300 and 500°C. Again the high temperature component (corresponding to the 500°C peak) has been accurately resolved. There was evidence from the orthogonal plots (e.g. specimen DQ06A9, Fig. 9) that three components are also present, as in samples from other sites. These, however, have not been resolved since they do not form linear segments, rather they are inferred by the high temperature component not demagnetizing directly to the origin. These results are listed in Table 4.

Discussion

The results from the Marsden Park Breccia clearly indicate that this rock body possesses a single component of magnetization. There is evidence though, that the nearby St Marys Breccia is carrying a two component magnetization, with the low temperature component being overwhelmingly dominant. The direction of this low temperature component is similar to the direction of the magnetization of the Marsden Park Breccia, in itself a low temperature magnetization since its unblocking temperature range is mostly less than 500°C. As previously mentioned, the Hornsby Breccia has also been shown to carry a low temperature magnetization, which has been interpreted as a viscous partial thermo-remanent magnetization (VPTRM), resulting from a period of magnetic overprinting during the Cretaceous (Schmidt & Embleton 1981). Although the directions of these low temperature breccia magnetizations are undoubtedly similar, there generic origin is equivocal. For instance, the directions and pole positions from the low temperature magnetizations from the Marsden Park and St Marys breccias, are actually significantly different. By themselves this could be interpreted to indicate that they are entirely unrelated, but in the light of the obvious magnetic overprinting of other nearby rock bodies, the circumstances ought to be examined carefully before passing judgment. The following relevant facts are offered for consideration. The Milton Monzonite possesses overprint magnetizations with laboratory unblocking temperatures (T_{UB}) in excess of 450°C, and since the magnetic carrier in the Milton Monzonite has been shown to be magnetite (Schmidt & Embleton 1981) it seems probable that other magnetite bearing rocks (close to the sea-board) might also be similarly overprinted. The Hornsby Breccia certainly accords with this, possessing an overprint with T_{UB} above 400°C and a high temperature magnetization with T_{UB} up to 550°C. Moreover, the only sample to possess T_{UB} in excess of 500°C from the St Marys Breccia is clearly carrying two magnetizations, closely resembling the magnetizaion of the Hornsby Breccia. This single high temperature direction from the St Marys Breccia is Dec. = 82°, Inc. = 57°, strongly suggesting these two breccias not only formed at the same time (late Jurassic), but have been overprinted at about the same time (mid-Cretaceous). It therefore seems reasonable to be sceptical of nominating a magnetization as original when characterized by T_{UB} less than 500°C with directions close to others which are undoubtedly overprints.

The results from the Prospect Dolerite reveal that this body possesses a primary magnetization which has undergone partial overprinting at a similar time to the breccia pipes and other rock units in the Sydney Basin. This is consistent with its age of formation (168 Myr) and the fact that magnetite with T_{UB} in excess of 550°C is the dominant magnetic carrier. One aspect of these results which exemplifies the objectivity of the LSA is the relative errors associated with the low temperature (overprint) direction and the high temperature direction. Although a more subjective analysis might have defined the mean directions of the components reasonably accurately, it is very likely the errors would be underestimated. The LSA avoids this, and allows a meaningful statistical estimate to be performed. This is obviously desirable in any circumstance, but particularly so when the directions being compared are similar. That the error in determining the overprint direction is larger than that of the high temperature component, may be reconciled by the relative stabilities of the two components. The least stable (overprint) magnetization will probably be most affected by noise, such as stray magnetic fields, both in the laboratory or from lightning.

The three components of magnetization resolved in two samples from the Dundas Breccia pipe, along with abundant evidence from other samples of the presence of three components, at first suggest that this breccia has suffered a more complex geological history than any of the other bodies examined. However, several relationships exist which elucidate this complication. Firstly, when the third component is resolved, its duration is indistinguishable from that of the first component, and secondly, when the third component is not resolved its stability spectrum is overlapped with part (or all) of the spectra of the two other components. Furthermore, the direction of the first and third component is very similar to that of the overprint components from other bodies, while the second component closely parallels the high temperature components of other breccia pipes. It is therefore proposed that the third component is a chemical remanent magnetization (CRM) imparted during a time of elevated temperatures, perhaps from the exsolution of titanomagnetite. This simultaneously offers an explanation for the direction of the third component and its high stability. Indeed co-existing titanomagnetite and magnetite have been identified in a number of samples from Dundas from their $k-T$ (susceptibility versus temperature) curves. The curves were generally irreversible, particularly for site 3, indicating that chemical instability (exsolution?) at high temperatures was common. That magnetite is present in pristine samples is, however, evidenced by a marked isotropic point at $-155°C$. Only the overprint component was detected in samples from site 1, although T_{UB} greater than 550°C were observed, suggesting that the magnetite in this site was formed at the time of overprinting, and the surviving titanomagnetite has been thermally reset. In the other sites, however, at least some of the magnetite seems to have been original, because some of the high temperature remanence has survived the overprinting episode. The magnetization of the Dundas Breccia therefore seems to consist of a low temperature ($< 450°C$) VPTRM + CRM overprint, and a high temperature ($> 450°C$), presumably original, TRM. The T_{UB} of this latter component and of the CRM are predominantly overlapped.

Conclusions

From the foregoing studies, LSA has been shown to accomplish the original intention of objectively resolving between closely directed magnetizations. At least with the present data the method seems to be independent of the linearity parameter used. It is also worth emphasizing that the procedure of maximizing the linearity of segments ensures that any systematic bias introduced during the routine search is effectively eliminated. Therefore, given a homogeneous set of specimens, LSA can be used to rapidly reduce a large body of data to its basic elements. The linearity spectrum directly reflects the homogeneity of the group, and affords a qualitative valuation of the consistency of the data. However, it is probably naive to consider that homogeneous groups of specimens are always obtainable, and at times the objectivity is compromised in the interests of expedience. For instance, LSA could only be applied with success directly to two (sites 1 and 6) of the six sites sampled from the Dundas Breccia. This is attributable, not only to the variability within the groups of specimens analysed, but also to the overlapping of their T_{UB} spectra. It sometimes proved necessary to examine individual specimens and reject or accept their analyses on their individual merit. However, other techniques which have been devised to extract magnetization directions from overlapped components, such as the Hoffman-Day method, are no more successful than LSA in this instance because the first and third components are similarly directed. That is, planes defined by both the first and second, and the second and third vector combinations, are very similar, so the definition of their intersection is ill-conditioned.

The magnetic signatures of the rock bodies studied here, reflect the thermal history of the region as documented previously (Schmidt & Embleton 1981). It is prudent to point out that the present interpretation of the magnetization of the Marsden Park Breccia as an overprint is circumstantial. If this breccia is actually as young as the time of overprinting, then its

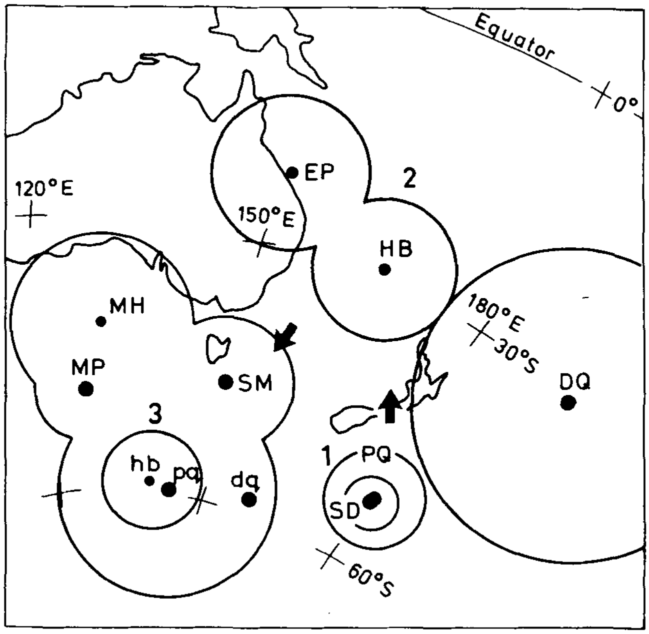

Figure 11. Pole positions from Sydney Basin intrusives showing three groups. These are interpreted to correspond to three major geological events in the basin: (1) intrusion of igneous hypabyssal rocks at around 180 Myr, (2) intrusion of breccia pipes at around 140 Myr, and (3) uplift and erosion associated with rifting at around 100 Myr.

magnetization may be considered as being original. Nevertheless, the St Marys, Dundas and Hornsby breccias all appear to be formed during the late Jurassic, and to have been partially-overprinted during the mid-Cretaceous. Fig. 11 shows palaeomagnetic pole positions from Mesozoic Sydney Basin intrusives. They fall into groups broadly corresponding to: (1) early Jurassic basic intrusives (~ 180 Myr); (2) late Jurassic diatremes or breccia pipes (~ 140 Myr); (3) mid-Cretaceous overprinting (~ 100 Myr) associated with the onset of rifting in the Tasman Sea.

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