The Palaeomagnetism of some Hypabyssal Intrusive Rocks from South Victoria Land, Antarctica

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Summary

The palaeomagnetic pole positions obtained from a study of the directions of magnetization of dolerite sheets and dykes from South Victoria Land lie in what is nowadays the South Pacific.

1. Introduction

The collection of the rock specimens, the palaeomagnetic properties of which are described in this paper, formed part of the work of the Victoria University of Wellington Antarctic Expedition (1958–9) to the Wright Valley area of South Victoria Land, Antarctica. The physical measurements were made at the Australian National University. The Wright Valley is inland from the Wilson Piedmont Glacier on the western shore of the Ross Sea (Figure 1).

The magnetic properties of specimens from two quartz dolerite sheets and from a series of older basic and acid dykes are described. The directions of magnetization of the specimens are all normal (that is, in the same sense as the present Earth's magnetic field) and have declinations to the south-west with inclinations of between 40° and 75°, the inclinations of the older dykes being lower than those of the dolerites.

The age of the dolerite sheet intrusives is uncertain but they have been regarded by some geologists as being approximately contemporaneous with the Mesozoic dolerite intrusives and basalt flows which inject or cover the Gondwana beds in India and the southern continents. The pole position consistent with the direction of magnetization of the dolerite specimens is in the South Pacific Ocean, significantly different from the present pole and from the pole positions obtained from the dolerites and basalts from the other southern continents.

2. Experimental methods

Samples were taken at a number of localities, the geographical co-ordinates of which are given in Table 1. At each locality samples have been taken at one or more sites. In the case of the sheets a site is at a certain level within the sheet; in the case of dykes separate sites refer to individual dykes. One or two separately orientated samples were taken from each site, which were usually cliff faces, and from each sample between one and five disk specimens have been cut. Altogether 79 specimens cut from 37 samples have been studied.

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The intensity (R_n) and direction of magnetization of each disk sample was determined with an astatic magnetometer, using the methods described by Collinson & others (1957). The accuracy of orientation of the specimens is 3°–5°, and the measurement of the direction of magnetization may introduce an additional error of up to 2°. Intensities of magnetization are accurate to about 5 per cent. Declinations (D) are reckoned clockwise from geographic north and inclinations (I) are given relative to the horizontal. It is assumed that the rocks have not been tilted since emplacement. The mean direction of the magnetizations of the specimens obtained from each site is given in Table 1 and the north-seeking directions of the individual specimens are plotted as stereographic projections in Figures 2 and 3. The plane of these projections is the horizontal and GN signifies geographic north. The direction of the present geomagnetic field ($D = 155°$, $I = -83°$) is denoted by F and of the dipole field (0°, $-84°$) by P.

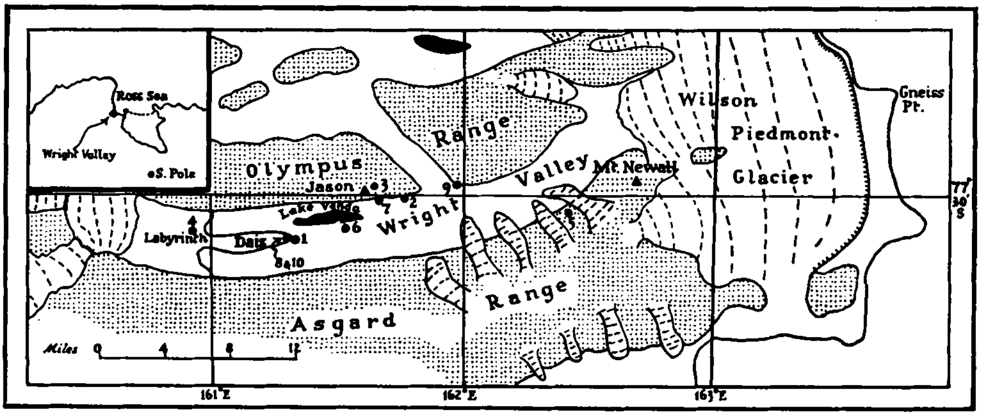

Fig. 1.—Sketch map of the Wright Valley area of South Victoria Land. Glaciers are indicated by dotted lines and land over 2 500 ft by stippling. Localities are indicated by dots, the numbering of which is consistent with that in Table 1.

Specimens from each geological unit have been tested in the laboratory for magnetic stability by subjecting them to alternating magnetic fields at 50 c.p.s. in the absence of a steady field. The specimens were placed in a spinner so that they were demagnetized in all directions by a single treatment, in a method similar to that described by Creer (1959). The direction and intensity of magnetization of the specimens were measured after demagnetization in alternating peak fields of 37, 75, 112, 149, 224, 298, 373, 447, 596 and 745 oersted. These tests indicate whether the primary thermoremanent magnetization, acquired at the time the rock cooled through its Curie point, has been affected by subsequent isothermal magnetization of the softer magnetic components. Such secondary components are likely to have a low coercivity, so that the specimens containing appreciable secondary components will be demagnetized more readily than those containing only the primary magnetization. In addition, if the secondary component is at an angle to the primary one, the direction of magnetization after partial demagnetization will differ from the original direction.

Measurements of the initial susceptibility (σ) of these specimens were made, using an astatic magnetometer, by applying to them a steady field of 0·54 oersted. To determine their saturation remanent magnetization (R_s), specimens were placed

Table 1

Site mean directions

The declination D is reckoned east of geographic north and the inclination I is the angle to the horizontal. R_n is the mean remanent volume intensity e.m.u. per $\mathrm{cm}^3 \times 10^{-4}$.

Geological Unit	Locality No.	Geographical co-ordinates	Locality description	Site No.	No. of Samples	No. of Specimen	D deg.	I deg.	R_n
Lower dolerite sheet	1	77° 32′·3 S 161° 19′ E	Dais, alt. 1 500 ft	1a	2	2	246	−74	0·27
			1 650 ft	1b	2	2	289	−70	2·72
			1 400 ft	1c	1	3	130	−84	0·32
			1 700 ft	1d	1	3	182	−76	3·23
			1 850 ft	1e	1	1	232	−76	3·59
			1 950 ft	1f	1	5	176	−80	1·36
	2	77° 30′·0 S 161° 48′ E	South-east flank of Jason, alt. 1 900 ft	2a	1	2	265	−71	0·96
				2b	2	3	264	−66	0·83
				2c	1	1	247	−62	0·96
Upper dolerite sheet	3	77° 29′·8 S 161° 38′ E	Near summit of Jason, alt. 5 800 ft	3a	1	3	259	−74	12·06
	4	77° 31′·9 S 160° 56′ E	Labyrinth, alt. 3 500 ft	4a	1	3	278	−74	4·08
	5	77° 30′·8 S 162° 25′ E	South side of Wright Valley, near Mt Newall alt. 5 200 ft	5a	1	4	257	−66	0·06

Table 1—*continued*

Geological Unit	Locality No.	Geographical co-ordinates	Locality description	Site No.	No. of Samples	No. of Specimen	*D* deg.	*I* deg.	R_n
Basic dykes in grey granite	6	77° 31′·6 S 161° 28′ E	Middle of Wright Valley, south of Lake Vanda, alt. 470 ft	6a	1	1	222	−57	0·01
				6b	2	5	247	−55	0·02
				6c	1	3	237	−44	0·04
				6d	1	2	237	−40	0·05
				6e	2	4	242	−50	0·03
	7	77° 30′·3 S 161° 40′ E	South flank of Jason, alt. 1 700 ft	7a	1	5	241	−55	0·29
				7b	1	1	244	−52	0·34
				7c	2	3	239	−63	0·01
				7d	2	3	212	−68	0·08
				7e	1	4	231	−70	0·06
Basic dykes in pink granite	8	77° 32′·3 S 161° 18′ E	Dais, alt. 2 100 ft	8a	1	3	311	−76	0·68
				8b	2	5	211	−74	0·16
				8c	1	1	252	−71	0·12
Acid dykes in grey granite	9	77° 29′·2 S 161° 58′ E	East of Jason, alt. 1 400 ft	9a	2	4	280	−50	0·10
Acid dykes in pink granite	10	77° 32·3′ S 161° 18′ E	Dais, alt. 2 100 ft	10a	2	3	303	−64	0·57

in increasing magnetic fields, the remanent intensity being measured at intervals until a constant value was obtained. Incremental magnetic fields in the opposite direction were now applied to the specimens until their remanent magnetization was nullified. The field (H_c) at which this occurs is the coercivity of the saturation remanent magnetization. The values of these properties, and of the intensity of the natural remanent magnetization (R_n), are given in Table 2.

Table 2

Magnetic properties

The following magnetic properties are given for the same samples as are listed in Figure 4: R_n is the volume intensity of the natural remanent magnetization, in e.m.u. per cm^3.; σ is the initial volume susceptibility, that is, the ratio of the intensity of magnetization induced by an external field to the strength of that field, in this case 0·54 oersted; R_s is the saturation remanent magnetization; H_s is the field in oersted required for saturation; H_c is the coercivity in oersted of the saturation remanent magnetization.

Site of specimen	$R_n \times 10^{-4}$	$\sigma \times 10^{-4}$	$R_s \times 10^{-4}$	H_s	H_c
1a	0·29	0·56	48·0	4600	610
5a	0·06	0·25	27·5	3 500	650
1f	1·62	10·15	806·0	3 500	580
8b	0·18	0·32	>40·0	>7 000	1 130
6b	0·03	0·18	2·8	5 900	1 220
9a	0·11	0·14	36·5	4 800	740

3. Geology

Topographical and geological surveys of the area were carried out by the Expedition (Webb & McKelvey 1959; McKelvey & Webb 1960). The rock nomenclature used below is that due to Harrington (1958). Throughout the area the basement complex comprises Ross System metamorphosed sediments and Admiralty System intrusives, all probably of pre-Cambrian age. More than 5 000 ft of Beacon Group sediments lie non-conformably upon a peneplained surface of the basement. Sheets and sills of Ferrar Dolerites intrude both the basement rocks and the Beacon Sediments. A similar geological succession continues south for at least 700 miles to the Queen Maud Ranges, lat. 86° S (Gould 1935).

In the Wright Valley the Ross System metamorphics, which are confined to the eastern half of the valley, include marble, schist and granulites. The Admiralty System intrusives are exposed as far west as Dais (long. 161° 15′E) and comprise an older series of porphyritic granites, gneissic granites and pure gneisses (referred to here for convenience as the "grey" granite), intruded by a younger sheet-like body of "pink" granite. Both the Ross metamorphics and the Admiralty granites are intruded by a complex of basic and acidic dykes. Two major dolerite sheets, between 600 and 1 500 ft thick, persist through the area. One of these lies wholly within the basement; the other, over most of the area, is intruded at the unconformity between the basement and the overlying Beacon sediments, but at a few localities upward flexures of the sheet expose the Beacon–basement contact. The sills and sheets intruding the Beacon sediments are thinner and do not have as great a lateral extent.

The unconformity between the basement rocks and the Beacon sediments is exposed at 5000 ft in the eastern Olympus and Asgard Ranges. It dips at a low angle to the west and at the inland ice plateau edge stands at approximately 3500 ft. Similarly the two major dolerite sheets also have a small westerly dip.

The persistent westerly tilt of the sub-Beacon peneplain, of the Beacon sediments and of the later dolerite sheets may be the result of large-scale block faulting. However, the tilt is small, about 3°, and no allowance has been made for it to the n.r.m. vectors given below. There has been no folding of the basement or the overlying Beacon sediments in the area.

Examination of thin sections of specimens from the sheets showed that they are typical quartz dolerites with the exception of the specimen from site 1e which is an acid rock of granophyric aspect. The acid dykes sampled are of aplitic type, and the basic dykes are doleritic with abundant quartz and show signs of deuteric alteration. In all cases the outlines of the ore minerals are clear and sharp and there is no evidence of weathering.

The age of the granites and the dykes is not known but is pre-Mesozoic. The age of the Beacon Sandstones is also uncertain but probably lies within the limits of Upper Palaeozoic and Triassic. The dolerite intrusives are post-Beacon Sandstone and are probably Mesozoic. The value of the palaeomagnetic results suffers from inadequate dating of the formations but it is hoped that this dating can be improved in the near future.

4. The natural remanent magnetization

From the lower dolerite sheet specimens were taken at nine sites in two localities, numbered **1** and **2** in Figure 1. The directions of magnetization of all specimens are plotted in Figure 2. Specimens from five sites have directions of magnetization significantly different from the Earth's field and from the dipole field. Specimens from three sites (1c, 1d, 1f) have directions close to the Earth's field. The direction of the specimens from site 1e was significantly different from the present field, but the magnetization contains an appreciable secondary component. The mean direction of the samples from these four sites is 187°, −81°, and the divergence of 4° from the present field is not significant.

In the upper dolerite sheet one sample was taken from each of localities 3, 4 and 5 (Figure 1). The directions of specimens from these sites is shown in Figure 2. All of these are significantly different from the present Earth's field.

The directions of magnetization of specimens from ten basic dykes at two localities in the grey granite (localities **6** and 7, Figure 1) are shown in Figure 3, together with the directions from three basic dykes in the pink granite (locality **8**), and from two acid dykes, one in the grey granite (locality **9**), the other in the pink granite (locality **10**). All these directions differ significantly from the direction of the present Earth's field.

The mean intensity of magnetization at each site is given in Table 1. These vary by three orders of magnitude, the intensity of the dykes generally being an order of magnitude less than that of the dolerites. One sample of grey granite had an intensity of magnetization of less than 10^{-7} e.m.u./cm^3 and the direction could not be measured. Ohe quartzite sample from the Beacon Sandstone had an intensity of $2{\cdot}62 . 10^{-6}$ and an inclination relative to the bedding (which is horizontal) of 64° which is much less than the present Earth's field.

5. Magnetic stability

Apart from those of specimens at the four sites in locality 1, the individual directions of magnetization all diverge from the present Earth's field. Table 3 gives the mean direction of the dolerite sheets and of the basic dykes in the grey granite. The divergence of these directions from the present field and from the dipole fields exceeds the error ($P = 0{\cdot}05$) by a factor of three or more. This deviation test is evidence for the stability of the directions of magnetization.

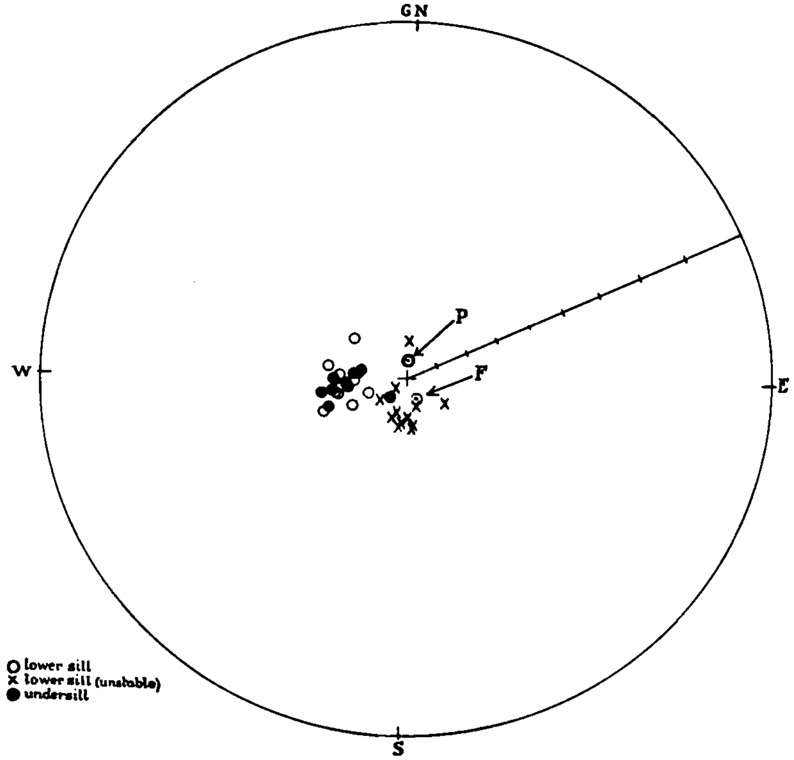

FIG. 2.—Directions of magnetization in the dolerite sills. Specimens from the lower sill are indicated by circles (stable specimens) and by crosses (direction along the present Earth's field and unstable specimen 1e). Specimens from the upper sill are indicated by dots. A stereographic projection is used in this figure and in Figures 3 and 5, and the directions are plotted on the upper hemisphere.

Alternating field demagnetization curves have been obtained for 13 specimens. An example from each geological unit is given in Figure 4. In all cases, except those for the specimens with direction along the Earth's field, and the specimen from site 1e, the intensity of magnetization was not reduced by more than one-quarter by treatment in an alternating field of 150 oersted. In the remaining specimens (e.g. Figure 4 (1f)) the intensity of magnetization was reduced by a factor of three in the same field. It may be noted that with the specimens of curves 1a and 8b the intensity of magnetization increases after demagnetization in small fields, while the direction remains unchanged. The reason for this increase is obscure but it is consistent with the presence of a subordinate, low-coercivity component of magnetization opposed in direction to that of the dominant component.

The associated changes of the directions of magnetization after partial demagnetization are shown in Figure 5. Where the initial direction of magnetization diverged from the present field the directions of the magnetization remaining after treatment in fields of up to 370 oersted were little changed, except with the specimen from site 1e. In some cases (e.g. specimen from site 1a) the direction remained unchanged in fields of 750 oersted. However, the directions of magnetization of those specimens whose initial direction was close to the present field and of the one from site 1e, changed significantly in fields of less than 200 oersted.

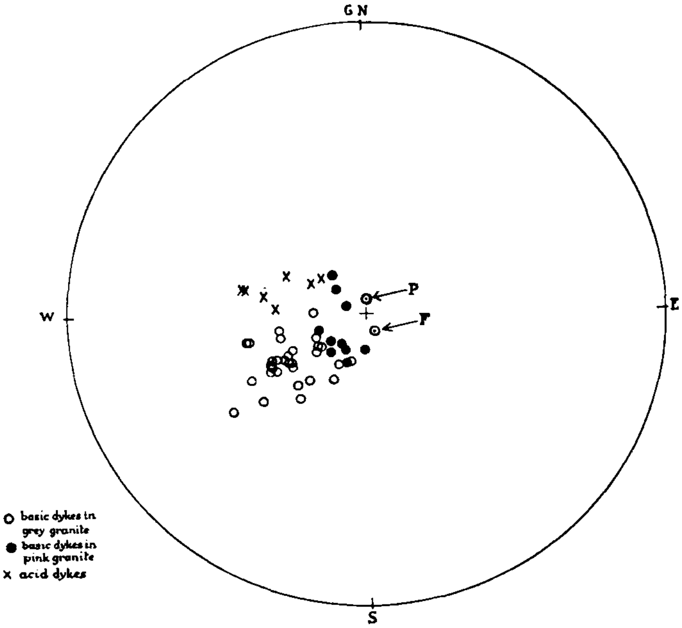

Fig. 3.—Directions of magnetization in the basement dykes. Specimens from 10 basic dykes in the grey granite are indicated by circles; specimens from 3 basic dykes in the pink granite by dots and from two acid dykes by crosses.

6. Analysis

From the evidence discussed above it may be supposed that with the exception of samples from sites 1c, 1d, 1e and 1f, the specimens from these intrusions acquired their direction of magnetization parallel to the direction of the Earth's magnetic field existing at the time they cooled through their Curie points. The specimens from sites 1c to 1f very probably have a secondary magnetization along the present Earth's field, and provide no information about the ancient field. They are not considered further.

The two dolerite sheets were intruded at different times and for each sheet it is likely that the time taken for the Curie point to pass from the margin to the centre was about 500 years (Jaeger 1957). Thus the direction of magnetization of the stable samples from 8 sites, which span 250 ft in the lower sill and 600 ft in the upper sill, may have averaged out the secular variation. Similarly the directions of the magnetization of the 10 basic dykes in the grey granite are likely to have recorded the direction of the field over a considerable period, since the dyke swarm sampled at locality 7 cuts the dykes sampled at locality 6. Assuming that the secular variation is fully represented in the scatter of directions observed, and that the main Earth's field was a geocentric dipole, the ancient pole positions appropriate to the periods when these sills and dykes cooled through their Curie points may be calculated from their mean directions of magnetization. These mean directions, which are given in Table 3 have been computed as a mean of the directions at the 8 sites in the sheets and from 10 basic dykes, giving each site unit weight. The directions at each site are themselves means of several observations (see Table 1). It is noteworthy that the scatter of directions of magnetization between sites in the sheets (standard deviation 10°) is comparable with that obtained in the Tasmanian dolerites (9°) (Irving 1956).

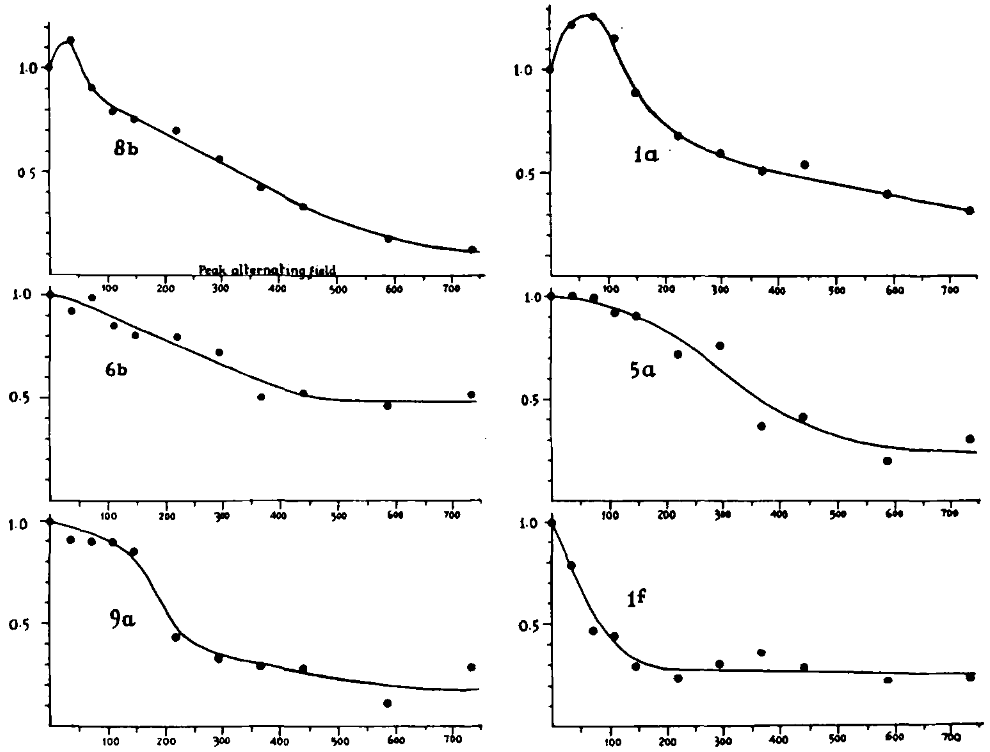

FIG. 4.—Alternating field demagnetization curves.

(1a) Lower dolerite (stable); (5a) upper dolerite; (1f) lower dolerite (initial magnetization parallel to the present Earth's field); (8b) basic dyke in pink granite; (6b) basic dyke in grey granite; (9a) acid dyke in grey granite. The numbers refer to the sites from which the specimens were taken. The ordinate gives the ratio of the intensity of magnetization remaining after treatment in the peak alternating field in oersted recorded along the abscissa, to the natural remanent magnetization, R_n.

A similar analysis has not been made of the results from the basic dykes in the pink granite or from the acid dykes because the data are insufficient.

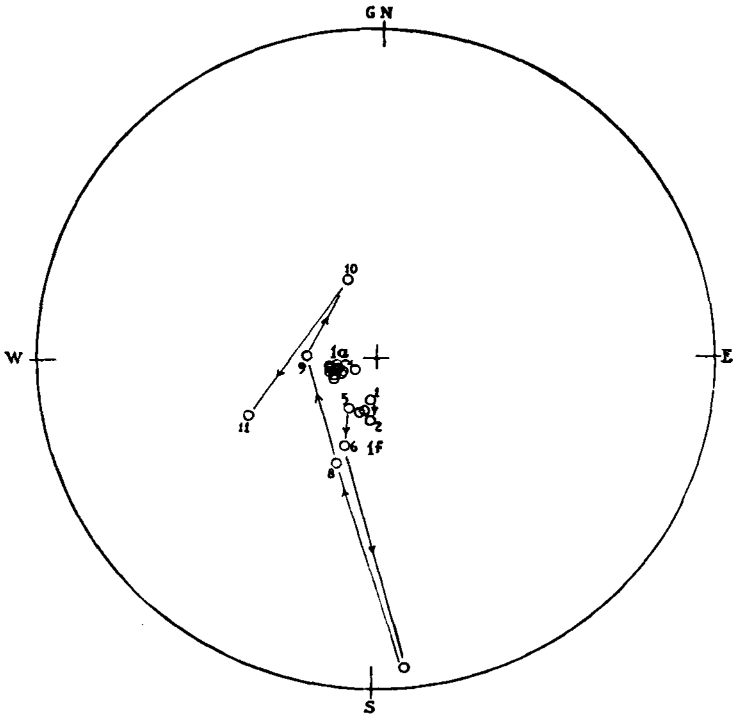

FIG. 5a

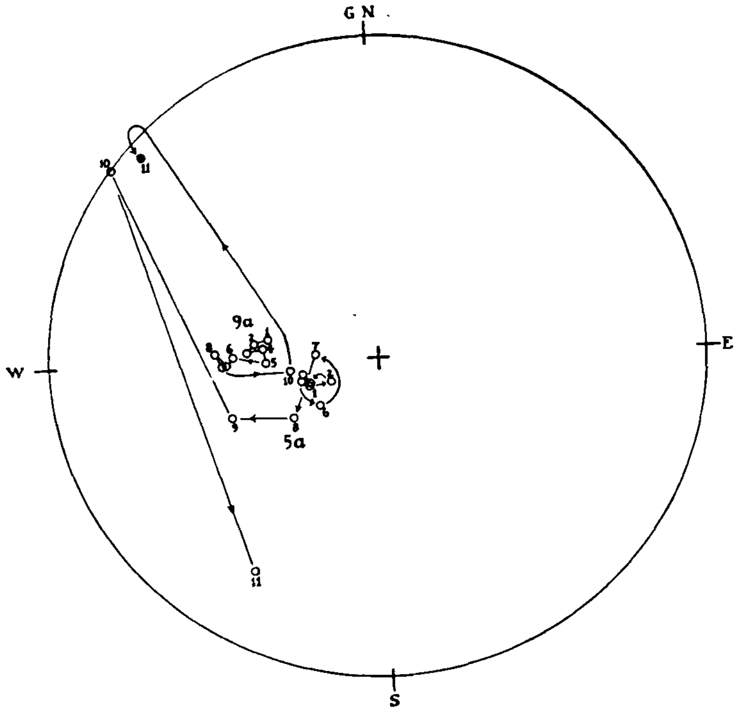

FIG. 5b

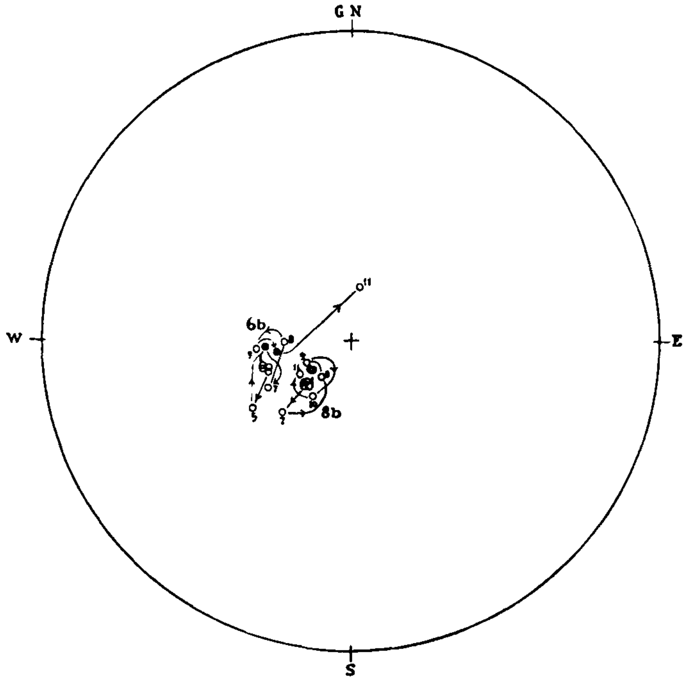

Fig. 5c

Fig. 5.—Changes of direction of remanent magnetization produced by treatment in alternating magnetic fields.

The three stereograms in this figure give the directions observed in the six specimens whose demagnetization curves are shown in Figure 4. The numbering is as in Figure 4. Points labelled 1 are the directions of the natural remanent magnetization. Points labelled 2–11 are the directions after treatment in alternating fields of 37, 75, 112, 149, 224, 298, 373, 447, 596 and 745 oersted respectively. Where possible the directions after successive increasing demagnetizations are linked, but in some cases the changes in direction are so small that this is not possible without confusion. For the same reason it has not been possible to number all points.

Table 3

Mean directions of magnetization and pole positions

N denotes the number of sites, the individual directions of which are given in Table 1. *D* and *I* are the declination and inclination of the resultant direction of magnetization computed by giving each site unit weight. *R* is the length of the resultant. α is the semi-angle of the cone of confidence at $P = 0{\cdot}05$ (Fisher 1953). ΔF and ΔP are the divergences of the mean direction from the present Earth's field (155°, −83°) and from the dipole field (0°, −84°) respectively. The southern hemisphere pole positions are specified by latitude and longitude and the errors $d\psi$ and $d\chi$ are in the direction of and at right angles to the co-latitude, respectively.

Geological unit	*N*	Mean direction of magnetization				Pole position		$d\psi$	$d\chi$	Divergences	
		D	*I*	*R*	α	Lat.	Long.			ΔF	ΔP
Dolerite sills	8	262	−70	7·889	7	51° S	132° W	10	12	23	21
Basic dykes in grey granite	10	237	−56	9·832	7	29° S	149° W	7	10	32	38

7. Comparison with other results

Pole positions for the dolerite sheets and the basic dykes are plotted in Figure 6. The pole for the dykes is in a lower latitude than that for the sheets. The dykes pre-date the sheets, so that this change of pole position is in accord with the results from Australia, North America and Europe where, with few exceptions, the divergence of the palaeomagnetic pole from the present pole increases with time, at least for periods back to the early Palaeozoic. Since these results were obtained, pole positions from other Antarctic dolerite intrusion have been reported by Turnbull (1959) and Blundell & Stephenson (1959). They are 58° S, 142° W, 54° S and 136° W respectively, and agree very well with our result from the dolerite sills.

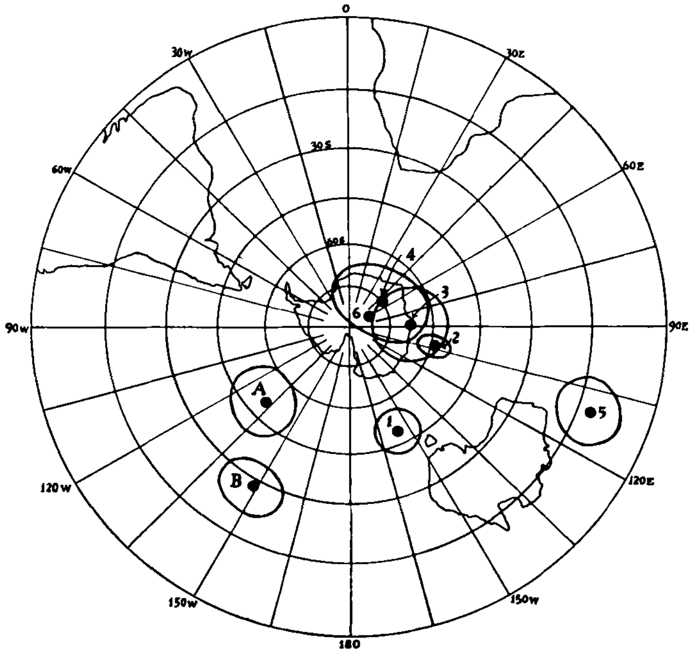

FIG. 6.—Pole positions relative to the present distribution of continents. The pole positions are numbered as follows: (A) dolerite sills of Wright Valley; (B) basic dykes of Wright Valley; (1) Tasmanian dolerites (Irving 1956); (2) Karroo basalts of Rhodesia (Nairn 1955); (3) the average pole from the dolerite sills and baked contact rocks in the mines of Estcourt and Winkelhaak, South Africa (Graham & Hales 1957, see Irving 1959); (4) Karroo dolerites, surface samples, South Africa (Graham & Hales 1957); (5) Rajmahal traps of Bihar, India (Clegg & others 1958); (6) Serra Geral lavas and baked Botacatu Sandstones of Uruguay (Creer 1958). The map is a stereographic projection.

The pole positions from dolerites, basalts and associated baked sediments from India and the southern continents, relative to the present distribution of continents, are also shown in Figure 6, the formations being listed in the legend. The poles given by the African and South American rocks do not differ greatly from each other, but both diverge appreciably from those given by the Indian rocks and the Tasmanian and Antarctic dolerites, which themselves are not consistent.

The age relationships of these dolerites and basalts are not well known. In most cases they intrude or overlie Triassic beds, which fix their lower limit. Their upper limit, however, is less satisfactorily determined. In some cases, like the Rajmahal traps, interbedded fossil-bearing sediments give the age as almost certainly Jurassic, while in others such as the Tasmanian dolerites, the upper limit could extend into the Lower Tertiary. The age of the Antarctic dolerites is even less well determined. However, it seems probable that all of these rock formations date from the Jurassic or later Mesozoic.

The divergence of the pole positions could be due to several causes:

(a) relative movement of the continents since the time of formation of these rocks;

(b) polar wandering during the time spanned by these rock formations;

(c) the Earth's magnetic field not being a dipole at the time that these rocks acquired their magnetization; and

(d) the invalidity of the correlation of the present directions of magnetization with the field at the time at which the rocks cooled.

At present we cannot decide with certainty between these; in fact, all may be responsible in part for the divergences observed. However, in connexion with the first possibility it is of interest to test the extent to which these pole positions are consistent with reconstructions of the past distribution of the continents derived from other evidence. Clearly, if our procedures and the reconstruction are correct then pole positions, previously divergent, should unify.

Many such reconstructions are available, but the one chosen here is that due to Du Toit (1937), because it was the first reconstruction accompanied by a good map. The pole positions calculated in accordance with du Toit's distribution of the Gondwanaland continents in the late Palaeozoic are given in Figure 7. The poles from India, South America and Tasmania are close together, while those from Antarctica and Africa are some distance away. With this distribution of

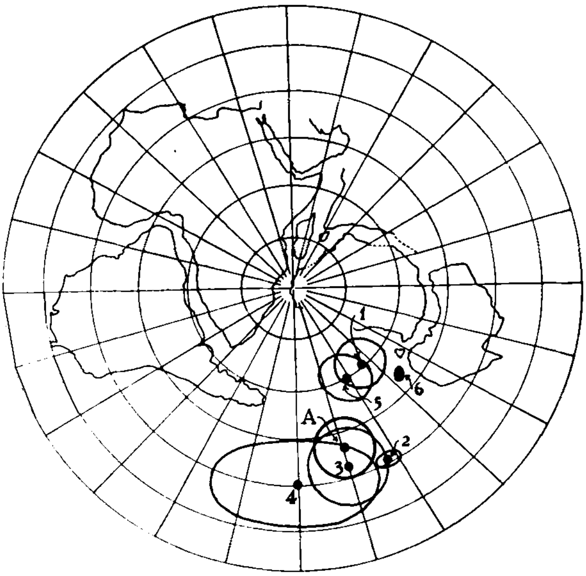

Fig. 7.—Pole positions relative to du Toit's reconstruction of Gondwanaland. The poles are labelled as in Figure 6. The continental outlines are taken from du Toit (1937), Figure 7, p. 58, who used an equal-area projection.

continents, the average angular separation of the poles, taken two at a time, is 24° and the dispersion, calculated by the method of Fisher (1953) is given by $k = 25$. The corresponding figures for the pole positions relative to the present distribution of the continents (Figure 6) are 52° and $k = 4{\cdot}6$ so that du Toit's reconstruction substantially improves the fit of these pole positions. The divergences remaining in Figure 7 could be caused by the rock formations in the various continents not being exactly contemporaneous. It must also be noted that du Toit's reconstruction refers to the Palaeozoic while the formations here discussed are Mesozoic and it is possible that the break-up of Gondwanaland had already begun at the time of their formation.

8. Acknowledgments

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