THE MAGNETISATION OF THE MESOZOIC DOLERITES OF TASMANIA

By

E. IRVING
National University, Canberra

(WITH 5 TEXT FIGURES)

(*Communicated by Professor S. Warren Carey*)

ABSTRACT

The Mesozoic dolerites of Tasmania have an almost vertical magnetisation. The magnetic pole consistent with this magnetisation is situated 10° S.E. of Tasmania. The stratigraphical record of Australia at this time suggests climatic conditions indicating a high geographical latitude agreeing with the high geomagnetic latitude, and this provides qualitative evidence in support of the supposition that some time in the later Mesozoic the geomagnetic field, when averaged out over several thousand years, was approximately coincident with the axis of rotation.

1. INTRODUCTION

Igneous rocks extruded over a land surface or injected into pre-existing formations at temperatures of over 1000° C acquire a "thermo-remanent" magnetisation in the direction of the geomagnetic field on cooling down to normal temperatures. If this direction remains unchanged throughout subsequent geological time the rock is said to be magnetically stable, and the measured directions of magnetisation may be used to determine the direction of the Earth's magnetic field in the past and thus also the approximate position of the geomagnetic pole. It has been shown previously that palaeomagnetic evidence (Hospers (1955)) and the comparison of this with palaeoclimatological data (Irving (1956)) suggests that the geomagnetic field when averaged out over several thousand years has been coincident with the Earth's axis of rotation. These new results from Tasmania are shown to be consistent with this view. The results are compared with palaeomagnetic data from Europe and their relevance to the theory of continental drift is discussed.

In addition to the directions of magnetisation, the intensity of magnetisation and susceptibility of the rocks have been measured and these are given in Table III.

2. THE TASMANIAN DOLERITES

The dolerites are intrusive through folded Precambrian to Lower Devonian rocks and into 2000 to 4000 feet of flat-lying sediments of Lower Permian to Upper Triassic age (possibly late Carboniferous to Lower Jurassic) where they take the form of transgressive sheets and sills. Their original extent prior to denudation was probably about 15,000 square miles and their average thickness about 1000 feet (Edwards, 1942). The enclosing sediments are tilted at low angles, usually not more than 10°; this was caused largely by Lower Tertiary block faulting, but the intrusion of the dolerite may have contributed in some areas. The direction of tilt varies but a dip of about 5° towards the south-west seems to be dominant. A statistical mean of the dips might be expected to be in this direction at a small angle. No correction has been applied to the magnetic results since regional mapping has not been sufficiently complete to allow reliable corrections to be made. A small error may have been introduced through this assumption.

The dolerites have a tholeiitic composition. Their petrography has been described previously by Edwards (1942) and Jaeger and Joplin (1955).

The youngest sediments cut by the sills are Upper Triassic and possibly in some cases Lower Jurassic in age. Intrusion was completed before the epeirogenic faulting of the Early Tertiary, and the dolerite was deeply dissected before the deposition of the Tertiary (probably lower Tertiary) lake sediments which in places overlie them. The sills therefore date from the Jurassic or Cretaceous.

3. The Directions of Magnetisation

It has been noticed previously (Jaeger and Joplin (1955)) that several bore-cores in dolerite from the Great Lake area have almost vertical magnetisation. The present work demonstrates that this is generally characteristic of all the Tasmanian sills.

Sampling and Measurement. In some rock formations whose magnetic properties have been studied it is often necessary (because of poor exposure or the rarity of suitable rock types) to limit the observations to certain horizons from which many samples are collected in order to obtain an accurate mean result. In contrast, the Tasmanian dolerites are well exposed and are always suitable for magnetic study; clearly the best way of obtaining accurately the average magnetisation of all the intrusions is to spread the samples as evenly as possible through their thickness and areal extent. The thirty collection sites, mostly quarries and road-cuttings, from which fresh material can be obtained are distributed over the dolerite outcrop covering an area of about 9000 square miles (Figure 1). Two samples have been obtained at each site. Orientation is by standard geological methods. Small cylinders $\frac{7}{8}''$ in height and diameter are machined from these samples with non-magnetic tools, orientation being preserved during the process.

The magnetisation of the rock cylinders is measured by an astatic magnetometer, which has been built by the author and is housed in a special non-magnetic hut at the Australian National University, Canberra. The instrument is set in Helmhotz coils which eliminate the Earth's magnetic field, and is responsive to vertical field gradients, the sensitivity being $3{\cdot}69 \times 10^{-7}$ gauss per cm. per mm. deflection, these deflections being observed by means of lamp and scale. The period is 2·5 seconds. The cylinder is held in a goniometer device at about 5 or 6 cms. beneath

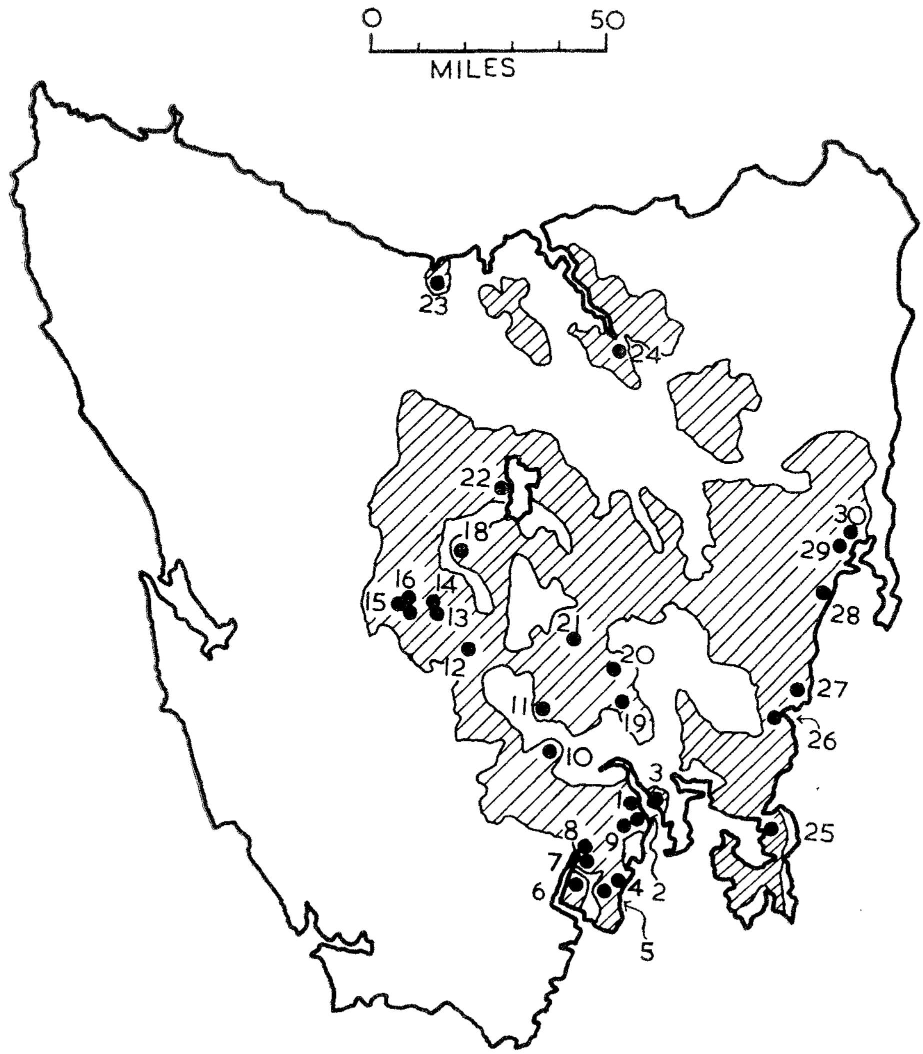

FIG. 1.—*The distribution of sampling sites.* The localities are numbered as in Table III and the area of the dolerite outcrop is shaded. The locality south of 16 should be numbered 17.

the magnetometer, and may be adjusted to the angle at which maximum response from the instrument is obtained. The instrument is so arranged that the angles of dip and declination can then be read directly from the goniometer scales, and from the magnitude of the deflection the magnetic intensity can be calculated. The susceptibility is measured by applying fields to the specimen by the Helmhotz coils. The short instrumental period allows very rapid measurement, each specimen requiring about three minutes. It can be shown experimentally that when the distance from the magnetometer is greater than 4·5 cms. it is adequate to represent the magnetisation by a dipole situated at the geometrical centre of the rock cylinder, the direction of the dipole being parallel to the mean magnetisation and its strength equal to the total intensity. The complications due to the shape of the specimen and the inhomogeneity of magnetisation which have been discussed previously (Irving (1954)) do not arise.

The direction of magnetisation in these cylinders is measured to an accuracy of 3° and the field orientation is correct to 5°, but these errors are random and will be to a large extent lost in the mean of pairs of samples at each site. The average difference in direction between these pairs is 13° (see Table III).

The directions of magnetisation. The directions are specified by the angles of dip, θ, and declination, ϕ, with respect to the north-seeking polarisation. With x, y and z-axes respectively North, East, and downwards, θ is the angle between the direction and the horizontal or xy-plane, and ϕ is the angle between the x-axis and the projection of the direction on this plane. Declination is measured clockwise of geographic North, and the dip is regarded as negative when above, and positive when below, the horizontal.

The directions at each site, as a mean of two samples, are given in Table III and plotted in Fig. 2. The vertical component of magnetisation is always upwards (normal) and no reversals occur. The mean dip θ_m and declination ϕ_m from all sites is obtained from the formulae

$$\tan \theta_m = Z/(X^2 + Y^2)^{\frac{1}{2}}, \quad \tan \phi_m = Y/X,$$

where $X = \Sigma \cos \theta \cos \phi$, $Y = \Sigma \cos \theta \sin \phi$, and $Z = \Sigma \sin \theta$.

The scatter of directions is expressed by the probable error (Watson and Irving (1955)) which is the semi-vertical angle in degrees of a cone described about the mean direction within which 50 per cent of the observations lie. This is given by

$$\text{probable error} = 67{\cdot}5\ k^{-\frac{1}{2}}$$

where N is the number of observations,

$$k = \frac{N - 1}{N - R}\ , \quad \text{(Fisher (1953))}$$

$$\text{and } R^2 = X^2 + Y^2 + Z^2.$$

The error c in defining the mean direction is obtained from the relationship (Fisher (1953)),

$$\cos c = 1 - \left\{\frac{N - R}{N}\right\} \left\{P^{-1/N-1} - 1\right\}$$

where c is the semi-vertical angle of the cone around the mean direction outside which the true mean may lie with a probability P. The mean directions θ_m and ϕ_m are given in Table I together with these parameters.

TABLE I.

The mean direction of magnetisation of the Tasmanian dolerites.

No. of sites.	ϕ_m	θ_m	R	k	Probable error.	c $P = 0{\cdot}05$
30	325	—85	29·398	48·2	10°	4°

Magnetic Stability. The following test shows that the magnetic directions in the dolerite have remained unaltered since the Lower Tertiary. At Cartwright Point south of Hobart there is a fault scarp breccia of Lower Tertiary age (Carey, S. W., private communication) containing dolerite boulders with a highly irregular arrangement (Figure 3). If the magnetisation of these dolerite boulders was imposed after formation of the breccia, the directions should be parallel from boulder to boulder, but if the directions have remained unaltered they will be widely scattered. Directions from nine boulders are plotted in Figure 4 and it can be shown statistically that these are random. Clearly the directions of magnetisation have remained unchanged since before the formation of this breccia, so there is good reason to suppose that they were acquired during cooling in the Jurassic or Cretaceous.

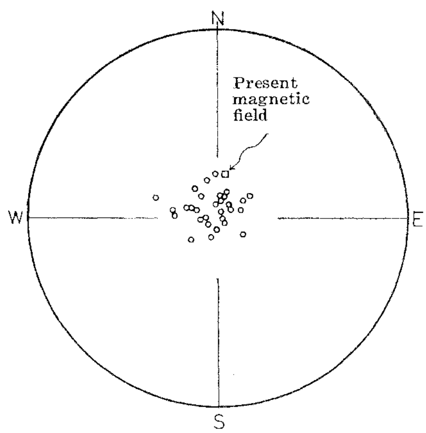

FIG. 2.—*The mean directions of magnetization at* 30 *sites in the dolerites of Tasmania.* The plane of the projection is the horizontal plane in Tasmania and the north-seeking polarisations are plotted on the upper hemisphere.

During cooling the Curie point would not be reached in all intrusions at the same time, and the fossil directions may differ due to the secular variation of the Earth's magnetic field; this may explain part of the scatter in Figure 2. It is difficult to estimate the length of this record. The emplacement of such a large volume of magma in the various sills

and the evidence of past climates from which an estimate of P can be made should be compatible with the dip measured in rocks from the same region. It has been shown previously (Irving (1956)) that the data from Europe is in as good agreement as can be expected from the qualitative nature of the palaeoclimatological data.

From the above relationship and the value of θ_m in the dolerites (Table I) the following palaeomagnetic latitudes are obtained assuming negligible relative movement between the different parts of Australia:

Tasmania 80°
Victoria 75°
South Australia 65°
South-Eastern Queensland 60°

The climate during the Jurassic and Cretaceous seems to have been generally warmer than at present, and nowhere in the world has there yet been found evidence of such profound refrigeration as occurred at the end of the Palaeozoic and in the Pleistocene. There is, however, evidence of cool conditions in Australia which is in contrast to evidence of warm conditions so widespread in other parts of the world at this time and which would therefore indicate a high geographical latitude for Australia.

1. The vegetation of the Jurassic and coal-swamps probably grew in a cool moist climate (David (1950), p. 476).
2. In western N.S.W. and South Australia there is evidence of glaciation. Large striated erratics of a great variety of rock types occur embedded in shales of Cretaceous age. (Ward (1916), Woolnough and David (1926), Kenny (1934).) These erratics were probably transported by icebergs.
3. Examples of glauberite pseudomorphed by opal (Kenny (1934)) indicate deposition in a cool shallow sea. (David (1950), p. 515.)
4. The marine invertebrates of eastern Australia have affinities with cold-water faunas (Whitehouse (1926)) although at times they are of more cosmopolitan aspect.
5. Large coral reefs and rudist lamellibranchs characteristic of the warm Tethyan sea are absent.
6. Dinosaurs, which are generally regarded as warm climate animals, lived in Australia at this time, and this would indicate that the climate was not continuously cold but that there were warm periods comparable to the warm interglacials in the Pleistocene.

The balance of the palaeoclimatological evidence suggests cool conditions during the later Mesozoic in Australia and this is consistent with the high geomagnetic latitudes given by the results from the Tasmanian dolerites suggesting that the mean geomagnetic and rotational axes of the Earth were coincident at this time.

The ancient pole position. The geomagnetic pole is that point on the Earth's surface at which the geomagnetic axis emerges, and its average position during the intrusion and cooling of the dolerite sills may be calculated from the magnetic results since the mean magnetic direction represents a line of force in the field of the geocentric dipole. The scatter in the magnetic observations will give an uncertainty to this pole position. The method of calculating this has been given previously (Irving (1956)). The uncertainty in co-latitude δp will be slightly greater than the error δm in the direction of declination. The co-ordinates and errors of the ancient pole position are given in Table II and plotted in Figure 5 (point 8).

TABLE II.

The Pole position in later Mesozoic times.

Present-day Tasmania		Ancient Pole co-ordinates		Errors $P = 0{\cdot}05$.	
Lat.	Long.	Lat.	Long.	δm	δp
42° S	147° E	50° S	157° E	1°	8°

If the correlation of geomagnetic and rotational axes is correct, this represents the position of the geographic pole relative to Tasmania at the time when the dolerites were intruded.

Comparison with results from Europe. The pole positions calculated from the magnetic directions in rocks of the same age but from different continents should be the same; if they are not, relative land movement between the sampling areas must have occurred subsequently. It is therefore interesting to compare the pole position obtained from these dolerite sills with those obtained from rocks of similar age from other parts of the world. Only results from Europe are available at the present time and it has been found convenient previously (Creer, Irving and Runcorn (1954)) to plot these ancient pole positions in the northern hemisphere, but clearly there will be complementary poles in the southern hemisphere and these are given in Figure 5.

The pole with respect to Europe has not yet been obtained at all stages in the Mesozoic, but it seems fairly certain that, at the time during which the Tasmanian dolerite sills were intruded, the pole lay somewhere in the region of what is now the South Atlantic, and at least 50° from the pole given by these dolerites. This suggests that there has been considerable relative movement between Tasmania and Europe since this time.

It would be of the greatest interest to know the magnetic directions of the Mesozoic lavas and intrusions of Antarctica (intrusions into the Beacon Sst.), South America (Sao Bento Series), South Africa (Karoo), and India (Rajmahal traps) in order to compare them with the Tasmanian results. If the reassemblies of the southern continents proposed by Wegener (1924) and Du Toit (1937) are correct, then these formations, like the Tasmanian dolerites, should disclose corresponding geomagnetic latitudes, and it should be possible to test strictly the validity of these reconstructions. These measurements ought to provide a critical test for the hypothesis of continental drift.

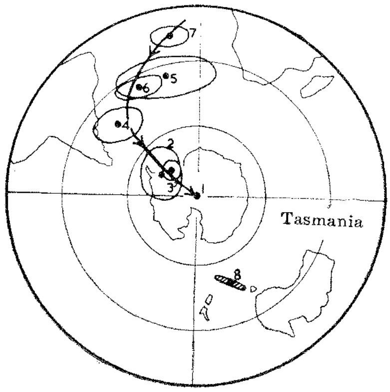

FIG. 5.—*Movement of the pole in the past.* The ancient positions of the pole are plotted on a Lambert's Azimuthal equal-area projection of the southern hemisphere. The oval regions represent the area within which the pole lay with a probability of 95 per cent. The shaded area numbered 8 is the probable pole position during the intrusion and cooling of the Tasmanian dolerites. The other poles are calculated from the results from Europe as follows:—1. Upper Tertiary and Pleistocene; 2. Oligocene; 3. Eocene; 4. Triassic; 5. Permian; 6. Devonian; 7. Cambrian.

6. Reversals of Magnetization.

In a bore-core studied by Jaeger and Joplin (1955), evidence was found of reversals of magnetization. The core is 1050 feet long and specimens from the upper half have north-seeking polarisations directed upwards (normal), and in the lower half pointing downwards opposed to the vertical component of the present Earth's field. It is argued that, if some sections had been inverted by mistake during transfer from the core barrel to the storage box, the reversed specimens would be distributed here and there all along the length of the bore-core. This is not so, the reversed specimens being confined with a few exceptions to the lower half, and it seems likely that a true reversal of direction is represented.

In the present work the pairs of specimens from 30 sites are all normally magnetized. The orientations by standard geological methods are not subject to the inversion errors as in bore-cores. If reversed magnetizations are a general characteristic of the dolerite sills such as would have arisen from reversals of the geomagnetic field during cooling, then they almost certainly would have been picked up in at least a few of these widespread sites. It seems rather likely that this bore-core reversal is due to some special Néel effect (Néel (1951)) by means of which the rock became magnetized during cooling in the opposite direction to the Earth's magnetic field. There are, however, two reasons why this cannot be regarded as evidence against the hypothesis of reversals of the geomagnetic field as proposed by Hospers (1954) who suggested that reversals of the field in the Upper Tertiary and Pleistocene occurred every 25,000 to 250,000 years. Firstly, there is strong evidence that reversals with a comparable periodicity also occurred in the late Pre-cambrian (Irving (1954)) and perhaps also in the Triassic (Clegg, Almond and Stubbs (1954)). In the intervening epochs, despite intensive study (Creer (1955)), reversals have not been recorded, and it is quite possible that they are confined to certain epochs, while at other times the geo-magnetic field maintained a steady polarity. Secondly, it is possible that the time interval between reversals is longer than that required for the intrusion and cooling of the dolerite sills, and reversed magnetizations would not therefore be "fossilized".

TABLE III. *The Magnetic properties observed at* 30 *collection sites in the dolerite sills.*

Two samples have been obtained at each site and the results from a site are given as a means of these two.

ϕ declination in degrees east of geographic north.
θ dip in degrees away from the horizontal.
δ difference in degrees in direction between two samples from the same site.
I magnetic intensity per cc. *e.m.u.* $\times$ 10^{-4}.
K magnetic susceptibility, being the ratio of the intensity of magnetization in *e.m.u.* $\times$ 10^{-4} per cc. induced by an external field to the strength of that field, in this case 0·49 oersted.

TABLE III.

No.	Collection Locality	ϕ	θ	δ	I	K
1	Quarry near Derwent Park Road, Hobart	54	—77	22	3·3	4·2
2	Quarry near Park Street, Hobart	289	—76	4	16·3	22·4
3	Cutting on the road from Hobart to the aerodrome, near Bellerive	233	—75	7	41·5	3·9
4	Quarry at Little Oyster Cove near Kettering	55	—74	16	25·8	8·4
5	Small road cutting on Woodbridge-Gardiner's Bay Road, 2 miles west of Woodbridge ...	323	—78	29	0·6	1·4
6	Cutting on road from Cradoc to Huonville, 1 mile north of Cradoc	195	—85	7	3·0	4·1
7	Road cutting 1 mile south of site 8 on Huonville-Woodstock road	280	—70	2	10·5	7·3
8	Quarry on Huonville-Woodstock road 1 mile south-east of Huonville near bend in the Huon river	202	—81	15	6·4	3·5
9	Road cutting at Neika the summit of the Huon Highway 7 miles south-west of Hobart ...	289	—61	2	1·5	0·5
10	Quarry on the Lyell Highway 200 yards N.W. of Rosegarland Hotel near Gretna	293	—79	14	3·4	8·9

No.	Collection Locality	ϕ	θ	δ	I	K
11	Quarry on the Lyell Highway 2 miles east of Hamilton	275	—71	8	9·3	2·2
12	Quarry half way along the road between Ouse and Tarraleah	124	—78	12	68·1	27·7
13	Road cuttings near Tarraleah power station	241	—85	13	15·1	3·5
14	Cutting in mountain side for the pipes carrying water to Tungatinah power station	357	—84	12	30·8	1·9
15	Cuttings at Butler's Gorge just below the main dam	268	—82	17	3·5	4·6
16	Quarry 150 yards north of the camp at Butler's Gorge	8	—88	20	1·5	0·8
17	Quarry 200 yards north of the main dam at Butler's Gorge	97	—88	20	28·8	6·2
18	Quarry 3 miles north of Bronte	48	—84	6	8·1	2·9
19	Quarry ½ mile south of Kempton	322	—74	14	12·5	4·3
20	Quarry 2 miles north of Melton Mowbray	343	—73	15	24·6	16·0
21	Quarry near Bothwell	289	—77	26	41·8	6·8
22	Cuttings along the Liawenee canal	277	—85	7	33·6	6·6
23	Quarry near Latrobe	7	—81	23	4·6	3·8
24	Cataract Gorge quarry, Launceston	39	—83	6	21·9	12·4
25	Road cutting 1½ miles south-east of Murdunna on the Arthur Highway	357	—71	11	10·4	2·2
26	Road cutting 1 mile west of Orford on the Tasman Highway	25	—77	10	10·6	1·9
27	Road cutting near reservoir just north of Triabunna	15	—79	3	11·7	10·4
28	Road cutting on Tasman Highway 2 miles south of Swansea	68	—80	18	46·1	5·8
29	Road cutting east of the Swan river bridge, Cranbrook	13	—87	12	37·9	2·6
30	Road cutting on Tasman Highway between Bicheno and Cranbrook	123	—87	8	7·7	13·5

ACKNOWLEDGMENTS

I wish to offer grateful acknowledgments to the following people: Professor J. C. Jaeger, of the Australian National University, who suggested the investigation and who read and criticised the manuscript; Professor S. W. Carey, of the University of Tasmania, who allowed me the use of the facilities of his Department, who arranged for me to use University vehicles during field-work, who provided information concerning the Cartwright Point breccia, and who gave me much encouragement; Professor S. W. Carey, Mr. M. R. Banks and Miss Edith Smith, of the University of Tasmania, who directed me to many of the exposures from which I was able to obtain suitable rock specimens.

NOTES

(i) It was remarked on page 158 that there may have been epeirogenic tilting of about 5° to the south-west during the Tertiary. This would have the effect of changing the ancient pole co-ordinates given in Table II to Lat. 55° S., Long. 148° E.; the size of the error area is not appreciably altered.

(ii) Professor P. M. S. Blackett and Dr. J. A. Clegg, of Imperial College, London, have kindly communicated the results of their measurements on four vertical bore-cords. These, of course, give the dip only. The results are as follows: bore-hole No. 5001, 30 samples, average dip 86°; No. 5002, 7 samples, average dip 84°; No. 8102, 8 samples, average dip 86°; bore-hole No. 8103, 9 samples, average dip 86°. These confirm, within the errors, the mean dip value of 85° (Table II) obtained from surface samples.

REFERENCES

CLEGG, J. A., ALMOND, M., STUBBS, P. H. S., 1954.—The Remanent Magnetism of some Sedimentary Rocks in Britain: *Phil. Mag.*, Ser. 7, vol. 45, p. 583.

CREER, K. M., IRVING, E., AND RUNCORN, S. K., 1954.—The Direction of the Geomagnetic Field in Remote Epochs in Great Britain: *Jour. Geomagn. Geoelect.*, vol. 6, No. 4, pp. 163-168.

CREER, K. M., 1955.—Thesis. Cambridge.

DAVID, SIR T. W. E. (edited and supplemented by W. R. Browne) 1950.—The Geology of the Commonwealth of Australia: Arnold, London.

DU TOIT, A. L., 1937.—Our Wandering Continents: London, Oliver and Boyd.

EDWARDS, A. B., 1942.—Differentiation of the dolerites of Tasmania: *Jour. Geol.*, vol. 50, pp. 451-610.

FISHER, R. A., 1953.—Dispersion on a sphere: *Proc. Roy. Soc.* A., vol. 217, pp. 295-306.

HOSPERS, J., 1954.—Reversals of the main geomagnetic field III: *Koninkl. Nederl. Akademie van Wetenschappen*, Amsterdam, Ser. B, vol. 57, No. 1, pp. 111-121.

——————, 1955.—Rock magnetism and polar wandering: *Jour. Geol.*, vol. 63, No. 1, pp. 59-73.

IRVING, E., 1954.—Thesis. Cambridge.

——————, 1956. Palaeomagnetic and palaeoclimatic aspects of polar wandering, to appear in vol. 33 *Geophysica pura et applicata*.

JAEGER, J. C. AND JOPLIN, G., 1955.—Rock magnetism and the differentiation of a dolerite sill. *Jour. Geol. Soc. Aust.*, vol. 2, pp. 1-19.

KENNY, E., 1934.—West Darling District. *Miner. Res. Geol. Surv. N.S.W.*, vol. 36.

NEEL, L., 1951.—L'inversion de l'aimantation permanente des roches, *Ann. Geophys.*, vol. 7, pp. 90-102.

WARD, L. K., 1916.—Stuart Range opal field. *Min. Rev. Min. Dept. S. Australia*, vol. 25, p. 36.

WATSON, G. S. AND IRVING, E., 1955.—Statistical methods in rock magnetism: to be published shortly.

WEGENER, A., 1924.—The Origin of Continents and Oceans: London, Methuen.

WOOLNOUGH, W. G. AND DAVID, T. W. E., 1926.—Cretaceous glaciation in Central Australia: *Quart. Jour. Geol. Soc. London*, vol. 82, p. 332.

WHITEHOUSE, F. W., 1926.—Cretaceous ammonoids of Eastern Australia: *Mem. Qld. Mus.*, vol. 8, p. 195.