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DEPARTMENT OF NATIONAL DEVELOPMENT
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BULLETIN 129

The Stability of Magnetisation in Basic Igneous Rocks

BY

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FOREWORD

The work described in this Bulletin was carried out between 1958 and 1961 at the Department of Geophysics, Australian National University, Canberra. During this time the author was on leave from the Bureau of Mineral Resources whilst undertaking a research scholarship with the University.

Thanks are due to the Australian National University for permission to publish the results of this work, to the staff of the Department of Geophysics for their help and co-operation in the work, and particularly to Professor J. C. Jaeger and Mr. E. Irving who were directly responsible for the supervision of the work.

SUMMARY

Special demagnetising apparatus was constructed to study the stability of several samples of basic igneous rocks from three localities in eastern Australia, particular emphasis being placed on the reliability of the directions of NRM. The direction of primary magnetisation acquired when the rocks first cooled was determined for samples at all three sites.

Mesozoic dolerite from Red Hill Dyke in southern Tasmania has little or no secondary magnetisation and the mean direction of NRM is representative of the Jurassic in Tasmania. There is no evidence of systematic error due to stress or shape, and therefore the direction of NRM is a reliable estimate of the direction of the geomagnetic field at the time of intrusion.

Devonian Nethercote basalt from southern New South Wales can be divided into two distinct groups, one in which the NRM is completely unaffected in either direction or intensity by demagnetisation in peak alternating fields of up to 1000 oersteds, and the other in which secondary magnetisation completely masks any primary magnetisation that may be present.

Tertiary basalts from southern New South Wales show a wide range of stability. The NRM consists of primary TRM and varying proportionate amounts of secondary magnetisation, which is almost certainly viscous and which was probably acquired in the present Earth's field.

The stability shown by the three rock types makes it more probable that previous palaeomagnetic results, which span a long period from Devonian to Tertiary, form a reliable record of the geomagnetic field in Australia.

The general effects of alternating demagnetising fields are also discussed and a comparison made between the theoretical predictions and the data obtained.

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1. INTRODUCTION

1.1 BACKGROUND

All new lavas are known to become magnetised in the direction of the field in which they cool. Older rocks heated in the laboratory to above the Curie temperature of their component magnetic minerals show the same phenomenon and, although there are rare cases in which rocks develop magnetisation in a direction exactly opposite to the applied field, there are no known cases in which isotropic rocks become magnetised obliquely to the field.

The direction of the natural remanent magnetisation of ancient rocks is often different from that of the present geomagnetic field; in general, the older the rocks, the greater will be the divergence (Blackett, Clegg, & Stubbs, 1960). Palaeomagnetism is the study of the history of the geomagnetic field as revealed by these 'fossil compasses'.

In many rocks, it is known that the natural remanent magnetisation is due to the original, or primary, magnetisation on which is superposed a secondary magnetisation that has been acquired since the rock was formed. Primary magnetisation in basic igneous rocks is almost invariably thermoremanent magnetisation, which is one of the most stable forms of magnetisation, and secondary magnetisation is usually a less-stable type of magnetisation. Graham (1949) has described field tests for stability and there are simple laboratory tests (such as storing the specimen with the direction of natural remanent magnetisation at an angle to the local magnetic field) which can show short-term stability. In many cases, rocks of palaeomagnetic interest are not folded so that the simplest field test is not applicable and other field tests are perhaps inconclusive. The rocks studied in this Bulletin were subjected to detailed laboratory tests in an attempt to show that long-term stability can be demonstrated even where no field evidence exists. It is presumed that a stable natural remanent magnetisation represents an ancient direction of magnetisation.

It is reasonable to suppose that by subjecting a rock specimen to demagnetising forces it will be possible to distinguish the two types of magnetisation. A direction of magnetisation may be found that is identified with primary thermoremanent magnetisation; it is then necessary to show that the direction of magnetisation acquired by an igneous rock as it first cooled represents the field direction at that time. Although it is generally true that no cases are known of rocks becoming magnetised obliquely to the applied field it has been suggested that this may occur in some special cases, for two reasons:

> The first, suggested by Graham (1955, 1956), is that in an intrusive sill, the effect of directed stress from the overlying rocks might deflect the magnetisation acquired away from the direction of the ambient field, the effect being due to magnetostriction. This has been tested in the laboratory and the results obtained, together with some field evidence, show that the effect is negligible in all the rocks studied.
>
> The second possible cause of deflection of the magnetisation has been studied by Strangway (1960). In a tabular body of rock, such as a dyke or

sill, in which one linear dimension is very much less than the other two, shape effects may cause the internal magnetising field to be different from the applied external field.

1.2 SUMMARY

This Bulletin is concerned with the investigation of the magnetic properties of some basic igneous rocks from eastern Australia and, in particular, with the testing of the reliability of the directions of natural remanent magnetisation.

The apparatus used for demagnetisation by alternating magnetic fields is described in Chapter 2, together with an explanation and some discussion of methods of treating the results obtained when demagnetising, and a brief account of other apparatus used in the experiments.

Results of measurements on three rock formations from eastern Australia are presented and discussed in Chapters 3, 4, and 5. Chapter 3 is concerned with the magnetisation of dolerite from the Red Hill Dyke in southern Tasmania and includes an account of an experiment designed to measure the effect of directed stress on thermoremanent magnetisation and isothermal remanent magnetisation and a discussion of the effect of self-demagnetising fields on the direction of magnetisation in a tabular body. The results from Tasmania and calculations based on measured intensities of magnetisation there (and elsewhere in Australia) show that self-demagnetising effects are unimportant; they may possibly become important in dykes with exceptionally high intensities of magnetisation.

In Chapter 4 results obtained from the Upper Devonian Nethercote basalts in southern New South Wales are given and Chapter 5 describes some measurements on Tertiary basalts from southern New South Wales. The locations of these rocks are shown in Figure 1.

In all cases it is possible to find the direction of the primary magnetisation acquired when the rocks first cooled. The Tasmanian dolerite has little or no secondary magnetisation and the results show that the direction obtained from the natural remanent magnetisation represents the Jurassic in Tasmania. The Nethercote basalts can be divided into two distinct classes by their behaviour in demagnetising fields. One group has a natural remanent magnetisation which is almost completely unaffected in either direction or intensity by demagnetisation in peak alternating fields of up to 1000 oersteds and which is thought to be primary magnetisation. The other group has secondary magnetisation which is much greater in magnitude than, and completely masks, any primary magnetisation that may be present. In one or two cases, it is possible to detect a primary magnetisation which is found to agree with that in stable specimens from the same sites.

The Tertiary basalts contain examples of rocks with almost undetectable secondary magnetisation and others with large secondary components of natural remanent magnetisation. Of the latter, the primary component can be detected and measured in over half the samples, a much higher proportion than for the unstable (or partially stable) Devonian basalts.

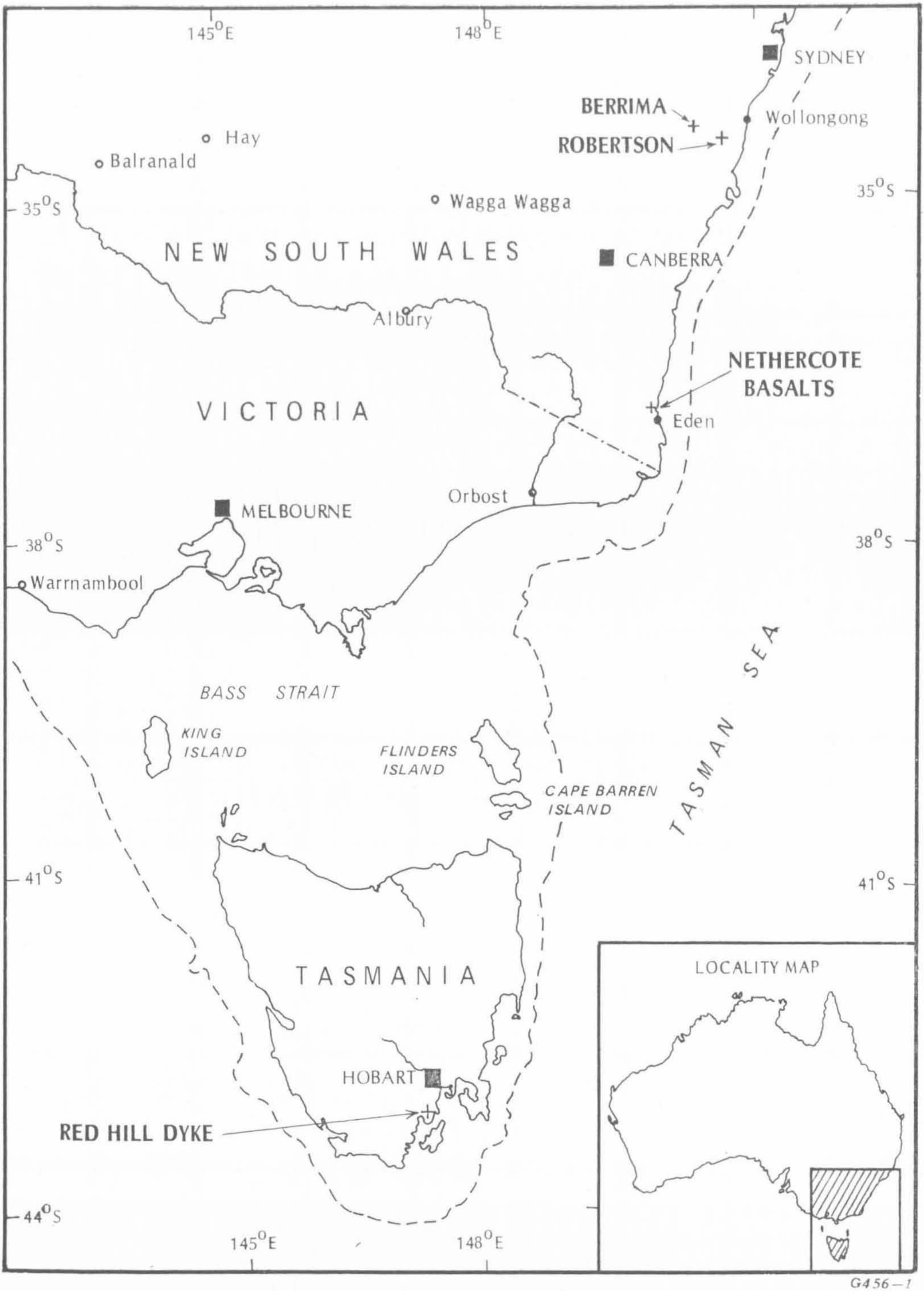

Figure 1 Map showing places from which rocks were collected

The effects of alternating demagnetising fields in general are discussed in Chapter 6 and it is shown that information about the physical basis of rock magnetism can be obtained from the results.

The stability shown by the three rock formations studied make it more probable that palaeomagnetic results previously reported, which span a long period from Devonian to Tertiary times, form a reliable record of the geomagnetic field in Australia. All these results are considered in Chapter 7 and are interpreted primarily as polar movement relative to Australia, using revised values of directions of magnetisation and time scale which are thought to be correct at the present time; there is a brief discussion of alternative presentations.

Finally, in Chapter 8, the Australian results are compared with those from other parts of the world and the implications for Earth history, generally, are discussed.

1.3 TYPES OF MAGNETISATION

The magnetisation of a body of a rock is made up of induced magnetisation and remanent magnetisation.

1.3.1 INDUCED MAGNETISATION. Induced magnetisation depends upon the strength of the applied field and the susceptibility of the rock and is reversible with no hysteresis. The magnetisation of rocks is due to ferromagnetic particles, ferromagnetic being taken to include ferrimagnetic except where a distinction is necessary; it is usual to consider induced magnetisation in terms of susceptibility rather than permeability. This is because the concentration of ferromagnetic particles is low and, in the rock as a whole, the magnetisation is of the same order as that induced in a paramagnetic substance, but possessing remanence; susceptibility is a more convenient measure. The susceptibility (κ) is the reversible magnetisation induced by a magnetic field of unit strength (one oersted). The susceptibility is measured in fields of less than an oersted and in these fields the magnetisation induced is reversible and proportional to the applied field in nearly all the rocks considered.

1.3.2 NATURAL REMANENT MAGNETISATION (NRM). The remanent magnetisation of a rock taken from the ground is called the natural remanent magnetisation. It is the magnetisation remaining when no magnetic field is applied to the rock and is acquired in one or more of the ways described below.

1.3.3 THERMOREMANENT MAGNETISATION (TRM). Thermoremanent magnetisation is the remanent magnetisation acquired when the rock cools, from a temperature above the highest Curie temperature of all of the magnetic minerals contained in it, to room temperature in a magnetic field. This is the total TRM; TRM acquired when the rock cools in a magnetic field for only part of the range between the highest Curie temperature and room temperature is the partial TRM (PTRM).

1.3.4 ISOTHERMAL REMANENT MAGNETISATION (IRM). Isothermal remanent magnetisation is acquired when a specimen is placed in a magnetic field at room temperature for a short time (counted in seconds). The field will be larger than that in which susceptibility is measured; only remanent magnetisation is included, by definition. If a specimen remains in a magnetic field at room temperature for longer periods, then in some cases the remanent magnetisation increases with time. This is viscous magnetisation. There is obviously no clear distinction between viscous magnetisation and IRM and the arbitrary time of one minute is convenient; magnetisation acquired in less than one minute is termed IRM and is normally measured after the specimen has remained in the field for five seconds or so; the increase in magnetisation when the specimen is exposed for longer periods is termed viscous magnetisation.

1.3.5 ANHYSTERETIC REMANENT MAGNETISATION (ARM). Anhysteretic remanent magnetisation is acquired by a specimen placed in a steady magnetic field, on which is superposed another periodic force—this is usually taken as an alternating magnetic field, but in this Bulletin the definition is broadened to include diurnal and annual temperature variations, mechanical vibration such as seismic waves or riveting (e.g. of ships), etc. It is usually stronger and more resistant than IRM or viscous magnetisation that have been acquired in the same steady field in the same time.

1.3.6 CHEMICAL MAGNETISATION (CRM). Chemical magnetisation is acquired when magnetic substances form in a magnetic field, either by chemical change in a pre-existing solid substance or by crystallisation from a solution (or from a melt, if this occurs below the Curie point; there are cases where it is difficult to distinguish CRM and TRM, e.g. maghemite changes to haematite before reaching its Curie point, but this difficulty does not arise in the present work).

1.4 ORDER OF MAGNETISATION

Since most rocks are found to have acquired more than one type of remanent magnetisation, it is necessary to determine the order in which each type was acquired. For convenience, three terms are used to classify the order of magnetisation; primary, secondary, and temporary. These terms, introduced by Creer (1957, 1959), are necessarily somewhat flexible (especially the secondary and temporary components) but the distinction is often quite plain; see for example the very unstable Robertson basalt (Chapter 5).

1.4.1 PRIMARY MAGNETISATION. In the case of igneous rocks, primary magnetisation is TRM acquired by the rock as it first cools from a molten state.

1.4.2 SECONDARY MAGNETISATION. Secondary magnetisation is acquired in one or more of the ways described in 1.3 in the period since the primary magnetisation was formed, up to months before measurement. It is arbitrarily distinguished from temporary magnetisation (see below) by having stability such that if a specimen having a secondary component of NRM is stored with its direction of magnetisation at an angle to the local magnetic field, the direction of the secondary component will not change appreciably in about a year or less.

1.4.3 TEMPORARY MAGNETISATION. Temporary magnetisation is (usually) IRM or viscous magnetisation acquired between the times of collection and measurement (weeks or a few months) and this component will change appreciably in a year, often in days.

1.5 STABILITY

The following definitions must be regarded as somewhat flexible in particular cases.

1.5.1 STABLE MAGNETISATION. Stable magnetisation is arbitrarily defined as: (a) magnetisation unchanged in direction in alternating fields up to 500 oersteds (peak); or (b) magnetisation that is changed in low fields (say, up to 100 to 250 oersteds) and shows a constant direction over a range of at least 100 oersteds, which is significantly parallel to that in other samples from the same site after similar treatment.

The criteria for judging when stable magnetisation can be identified with primary magnetisation are discussed later.

1.5.2 UNSTABLE MAGNETISATION. Unstable magnetisation is magnetisation effectively destroyed in alternating magnetic fields of 100 to 150 oersteds. Generally, directions of magnetisation in specimens from the same or adjacent samples will show increasing divergence as the peak alternating field is increased.

1.5.3 PARTIALLY STABLE MAGNETISATION. A partially stable rock will behave as in 1.5.1a because it has both stable and unstable components of magnetisation; the latter is more easily demagnetised and behaves as described for unstable magnetisation; the former behaves as in 1.5.1a and the compound magnetisation usually behaves as described in 1.5.1b.

1.6 MAGNETIC FIELDS

1.6.1 SATURATING FIELD. Isothermal remanent magnetisation (see 1.3.4) acquired in a strong field, such that no increase in intensity occurs with increasing magnetising fields, is called saturation isothermal remanent magnetisation (sat. IRM) and the smallest field required to produce this magnetisation is the saturating field (H_{sat}).

Figure 2a shows the hysteresis curve normally used to describe the magnetisation of a ferromagnetic substance, but the apparatus usually employed in palaeomagnetism allows only the measurement of *M-H* curves, as shown in Figure 2b, where *M* is the intensity of magnetisation in e.m.u./cm^3, and this must be remembered when magnetisation curves are considered in later chapters. The difference is explained in standard works on ferromagnetism.

1.6.2 DESTRUCTIVE FIELD. When a specimen, saturated as above, is placed in a small magnetic field directly opposed to the magnetisation, the intensity is reduced. As the reverse field is increased, the intensity of magnetisation becomes less and less until at some particular reverse field, the remanent magnetisation is zero; this value of the reverse field is the destructive field (sometimes known as the 'coercivity of remanence'). This is not the 'coercive force' as it is usually defined.

1.6.3 PEAK ALTERNATING FIELD. During demagnetisation by alternating magnetic fields, a specimen is placed in a field having a certain peak value which is then gradually reduced to zero. The peak value of the highest alternating field applied in a particular demagnetisation is called the peak alternating field ($H_p\sim$); it is $\sqrt{2}$ times the root mean square value of the highest alternating field.

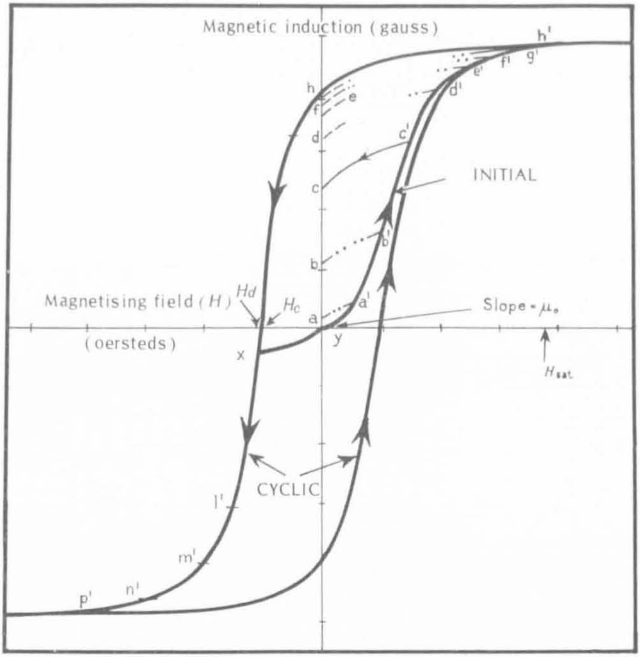

Figure 2a. Normal hysteresis curve for a ferromagnetic substance

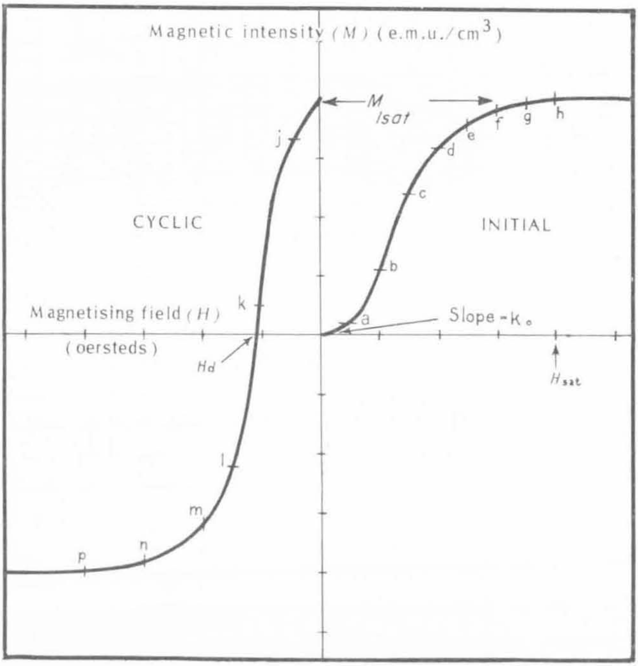

Figure 2b. Hysteresis curve for a palaeomagnetic substance

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1.7 ANALYSIS OF RESULTS

The methods used in the statistical analysis of palaeomagnetic results are based on a distribution proposed by Fisher (1953). Fisher regarded the directions as distributed around the true mean direction so that the number making an angle between θ and $\theta + d\theta$ with it, is proportional to:

$$e^{K\cos\theta} \qquad (1)$$

where K is the true value of the precision.
Fisher shows that:

$$k = (N - 1)/(N - R) \qquad (2)$$

is a good approximation for k, the best estimate of the true precision K.

A group of N measurements are combined to give the mean direction (the N measurements may be specimen directions at a site, site mean directions within a formation, and so on). The N measurements are each given unit weight and added vectorially to give the resultant R, and the direction of R is the observed mean direction. This method of analysis does not fully utilise the data and a more refined method of analysing the observations is sometimes used.

This second method is due to Watson (1956a & b) and introduces the notions of within-site and between-site precisions, which may in future help to elucidate the theoretical basis of rock magnetism. The 'analysis of precision' developed by Watson is analogous to the 'analysis of variance' of Gaussian distributions and is explained in the papers cited. The symbols used here differ somewhat from those of Watson and are now explained.

There are n_i specimens collected at the i th site and there are altogether B sites from which a total N specimens are collected, so that $N = \sum_i^B n_i$. In this Bulletin, only two levels of analysis are used as described above, but the level of analysis may vary, i.e. the n_i specimens may be from the i th sample and the overall mean be that of B samples at a site, etc. The n_i directions have a resultant r_i and the N specimens taken individually have resultant R. Following the method of Watson, we find estimates w and b of the true within-site precision parameter ω, and the true between-site precision parameter β.

A table showing the analysis of precision (Watson & Irving, 1957, p. 297) takes the form:

Source	Degrees of freedom (d.f.)	Sum of squares (s.s.)	Mean square (m.s.)	Expectation of m.s.
Between-sites (B.S.)	$2(B-1)$	$\Sigma(r_i)-R$	$\frac{\Sigma(r_i)-R}{2(B-1)}$	$\frac{\overline{W}}{2\beta} + \frac{1}{2\omega}$
Within-sites (W.S.)	$2\Sigma(n_i-1)$	$\Sigma(n_i-r_i)$	$\frac{\Sigma(n_i-r_i)}{2\Sigma(n_i-1)}$	$\frac{1}{2\omega}$
Total (for checking)	$2(N-1)$	$(N-R)$		

$$\text{where } \overline{W} = \frac{1}{B-1}\left(N - \frac{\Sigma n_i^2}{N}\right)$$

These parameters are calculated and can be used to test hypotheses about the variation of magnetisation, etc., but when quoting overall mean directions of magnetisation, pole positions, etc., the probable errors are based on Fisher's k. The calculation of k does not utilise the data completely, but it is recognised (see for example, Watson & Irving, 1957) that palaeomagnetic results at present do not warrant refined analysis when (for example) comparing results from widely separated regions, obtained perhaps by different observers from different rock types, using very different instruments. The values of b, w, etc. are given so that they are available should they prove useful in future.

1.8 LIST OF SYMBOLS

1.8.1 MAGNETIC PROPERTIES

M_n	— NRM vector (intensity and direction)
M_i	— intensity of IRM
$M_{i(300)}$	— intensity of IRM in a field of 300 oersteds
$M_{i(sat)}$	— saturation IRM
M_t	— TRM (by implication, total TRM)
$M_{t(0.6)}$	— TRM (by implication, total TRM) in a field of 0.6 oersted
$M_{t(550-525)}$	— PTRM acquired (or lost) between temperatures of 550 and 525 degrees centigrade
$M_{t(0.5)[450-200]}$	— PTRM in a field of 0.5 oersted between 450 and 200 degrees centigrade
H_{sat}	— field required (in oersteds) to produce saturation magnetisation—usually $M_{i(sat)}$
H_d	— destructive field (equivalent 'coercivity of remanence' not 'coercive force')
$H_p\sim$	— peak value of alternating magnetic field
κ	— volume susceptibility (e.m.u./cm^3)
χ	— mass susceptibility (e.m.u./g)

(Strictly, susceptibility is a tensor; in isotropic materials, it can be regarded as scalar.)

1.8.2 DIRECTIONS, POSITIONS, ETC.

D	— declination, positive clockwise from true north (TN)
I	— inclination relative to reference plane (horizontal or bedding), positive when north-seeking direction is downward

(When D or I are relative to some arbitrary direction, this will be stated.)

Components of magnetisation, etc. in usual right-handed, cartesian, geomagnetic co-ordinates:

X	— positive north (generally TN)
Y	— positive east
Z	— positive downward
ϕ	— latitude (strictly +90° at North Pole, 0° at equator and —90° at South Pole)

λ	—	longitude — 0°-360° eastabout
ψ	—	co-latitude $= \frac{1}{2} - \theta$ measured to nearest pole; as distinct from north polar distance

1.8.3 STATISTICS

D_m, I_m, etc.	—	mean values for a group of N measurements
R	—	vector resultant of group of N measurements
α	—	semi-angle of the cone of confidence about the mean direction, within which the true mean direction lies with a probability $P = 0.95$
θ	—	individual angles, either of a direction from the mean or between two directions
K	—	precision parameter of a spherical distribution (Fisher, 1953)

Generally, a group of directions is the mean of site mean directions at B sites with vector resultant R_{si}; at the i th site, the mean is from n_i samples with resultant r_i; altogether, there will be $N = \Sigma n_i$ samples and the N samples combined individually have vector resultant R_{sp}. Following Watson (1956a), the between-site and within-site precisions are b and w respectively; k, b, and w all being 'best estimates' obtained from the measurements of the true values K, β, and ω.

2. MAGNETIC CLEANING

2.1 INTRODUCTION

It is possible to treat partially stable rocks in the laboratory so as to separate and identify the direction of the stable magnetisation. At present, the two most successful methods discovered are: demagnetisation in alternating magnetic fields; and demagnetisation by cooling from some temperature above room temperature, in zero field. These two processes will be called 'magnetic cleaning' and 'thermal cleaning' respectively; the former is preferable to the cumbersome term 'demagnetisation in alternating magnetic fields'. The present study is mainly concerned with magnetic cleaning.

In magnetic cleaning, the aim is to place the rock specimen in a position where it is subjected to an alternating magnetic field, which is increased to some peak value ($H_p\!\sim$) and then decreased gradually and smoothly to zero. The first stage is for practical reasons; theoretically, a specimen could be placed immediately in an alternating field equal, or nearly equal, to the peak value required. However, because of transients, the behaviour of a coil producing an alternating field is complicated and is not reproducible during the first few cycles of current after switching on; it is better to increase the current fairly slowly to its peak value.

The procedure for studying the magnetic behaviour in demagnetising fields is: first measure the NRM of a specimen, then apply a small alternating field in the manner described and measure the magnetisation again, apply a field with a greater peak value, remeasure, and so on. The peak alternating field is increased in steps of about 50 oersteds for most rocks; the steps may be increased to 100 oersteds in later stages.

2.2 APPARATUS

The apparatus is designed to apply an alternating magnetic field of known peak value to the specimen; the field must be equal in all directions and must be able to be decreased as smoothly as possible to zero. Asymmetry in the waveform of the current producing the field and discontinuities in the rate of decrease have been known to have serious effects (Rimbert, 1958; As & Zijderfeld, 1958). The apparatus consists of a coil mounted on a trolley, which runs on a tramway. The specimen is placed in a specimen holder which spins at the centre of the field-free space produced by pairs of square Parry coils; the coil and trolley can be moved from a distance of 5 m to a position surrounding the spinning specimen so that the specimen is at the centre of the alternating-field coil. The whole apparatus is shown in Figure 3 and the separate parts are now described.

2.2.1 THE SPECIMEN HOLDER. The specimen holder can take cylindrical specimens up to 3.5 cm in diameter and 3.5 cm long. It is made of laminated plastic and fabric ('tufnol') and has a bevel gear of similar material at one end—see Figure 4a. The holder rotates about a horizontal axis within an inner frame of laminated beechwood ('permali')—see Figure 4b. A second bevel gear in the base of this inner frame engages that on the end of the specimen holder and the inner frame itself rotates about a vertical axis within a second, outer framework (Figure 4c). The whole assembly is shown in Figure 5 and, when mounted in position, just fits inside the coil (Figure 6). The inner frame is driven by the string and pulley seen in Figure 6; the pulley is fixed to the top of the inner frame (Figure 4b) and the string causes the inner frame to rotate about its vertical axis and hence the holder to rotate about its horizontal axis. The bevel gears have a ratio 15:16 and a point on the specimen when projected on to a plane performs a Lissajous figure during rotation. The specimen holder is a hollow semi-cylinder with circular ends and the specimen is held in position by the rubber O-ring seen in Figure 4a.

An electric motor is mounted on the framework of the tramway at the end remote from the specimen. This motor drives the spinner by a shaft, which is linked to a second shaft by a V-belt and variable-ratio pulleys; the second shaft drives the string and the specimen has primary rotation rates about the vertical axis of 140, 350, 525, and 700 rev/min (and therefore, secondary rates of rotation about the horizontal axis 16/15 times these).

2.2.2 PARRY COILS. The spinning specimen is at the centre of two pairs of square coils, which annul the horizontal and vertical components of the Earth's magnetic field. The coils are separated by a distance such that the second derivative of the axial field of each coil is zero at the centre of the pair. This is analagous to the 'Helmholtz position' for circular coils and was described by Parry (1957); the coils of the pair are therefore referred to as 'Parry coils'. The formulae for the field were not published, but have been calculated independently by me and are given here in Appendix 1 for reference; they were later confirmed as being identical with those of Parry.

The separation d of the Parry coils with mean side length $2a$ is:

$$d = 1.0890a \tag{3}$$

and the field due to both coils at the centre of the system is:

$$Ho = 0.814ni/a \tag{4}$$

where H is in oersteds for i in amperes and a in centimetres; n is the number of turns on each coil.

The variation of axial field along the axis is:

$$H_z = H_o + \frac{(\triangle z)^4}{4} f^{iv}(z) + \frac{(\triangle z)^6}{6} f^{vi}(z)^4 + \ldots . \tag{5}$$

$$\text{where } f^{iv}(z) = \frac{1.6i.\,\partial^4}{a\ z^4}(1 + z^2)^{-1}(2 + z^2)^{-\frac{1}{2}}$$

and z is in units of a.

The axial field, off the axis, and the field perpendicular to the axis can be calculated from the formulae in Appendix 1; some computed values are also given in the appendix.

In rectangular co-ordinates with origin at the centre of the pair, the field at a point (0.1, 0.1, 0.1) is:

$$H_z = (1 + 3.6 \times 10^{-4})H_o \tag{6}$$

In Figure 7, x, y, and z are in units of a, and the z axis is along the axis of the coils.

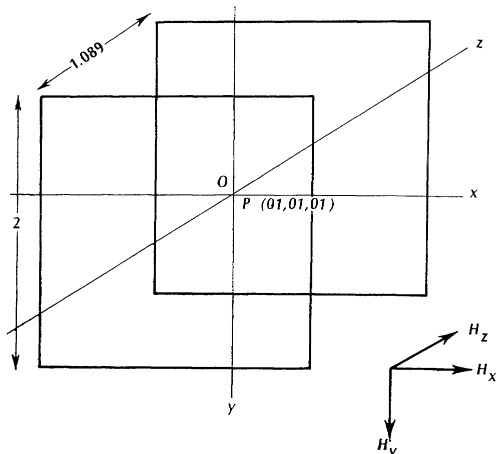

Figure 7. Coordinate axes used to describe Parry coils. Units of half-side, a ($\approx$ 100 cm). G456-2

The coils are wound on wooden formers, each with 100 turns of 18 s.w.g. enamelled copper wire, and have dimensions and carry currents as given in Table 1.

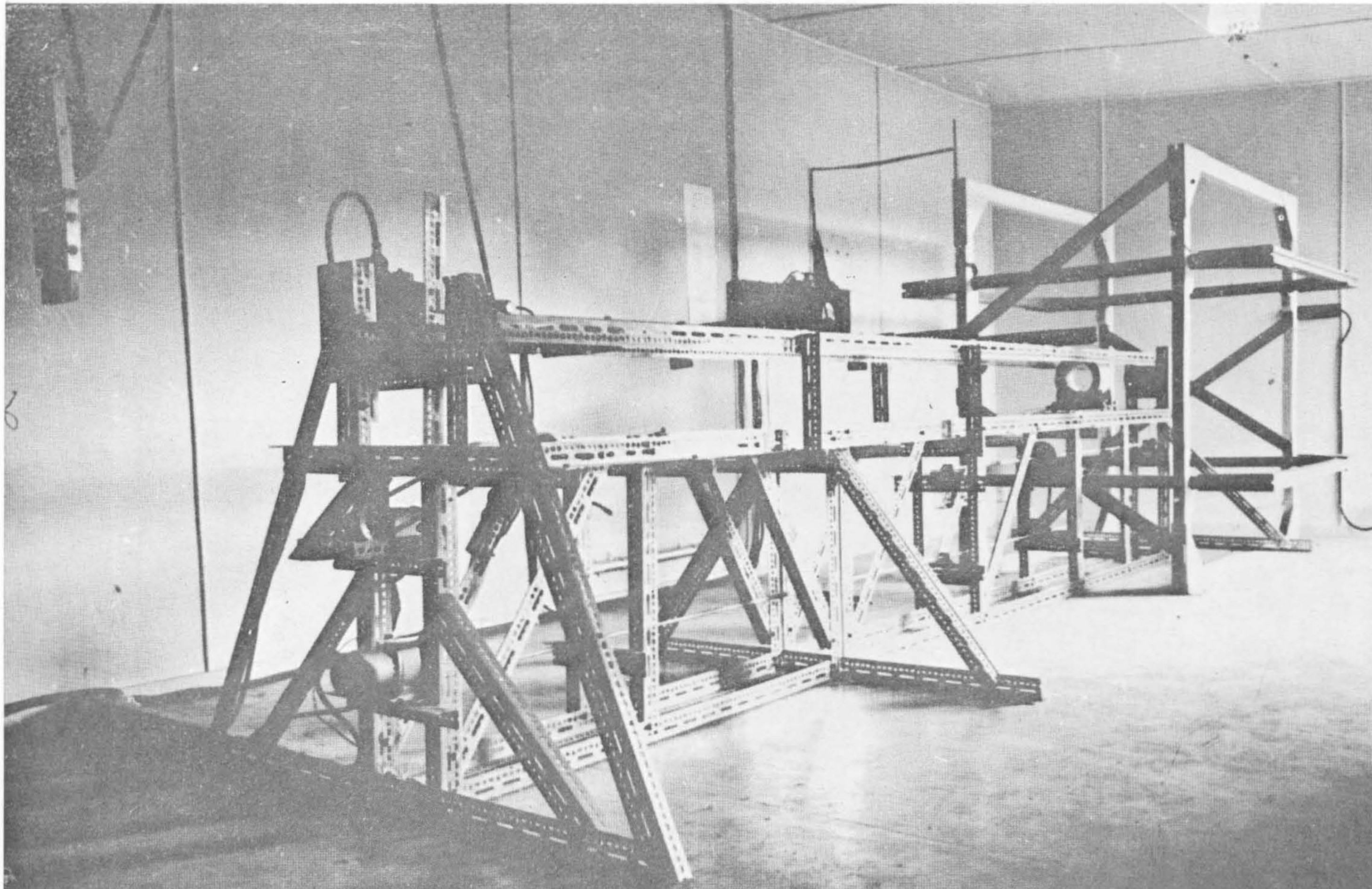

Figure 3. Magnetic cleaning apparatus.

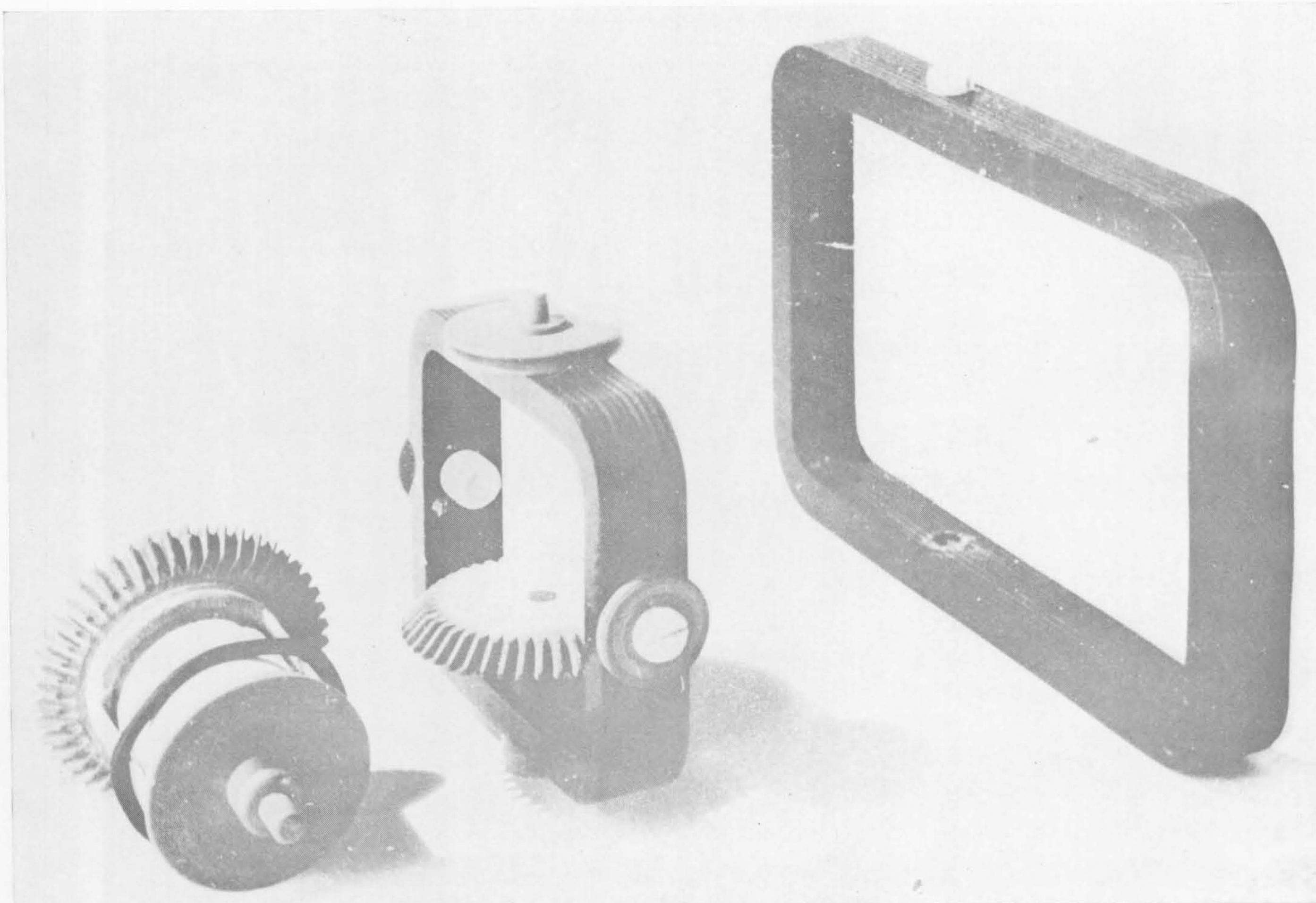

Figure 4 (a), 4 (b), 4 (c). Parts of the spinner unit.

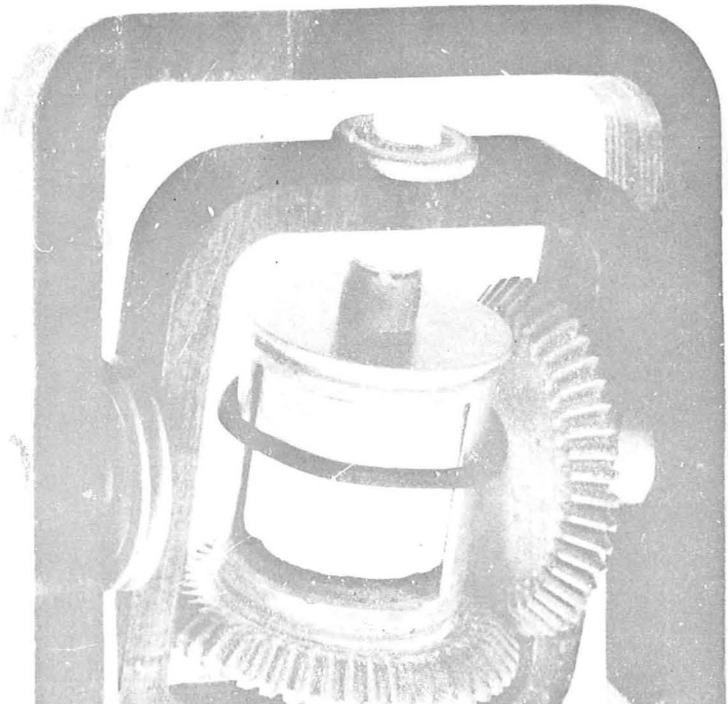

Figure 5. Spinner unit assembled.

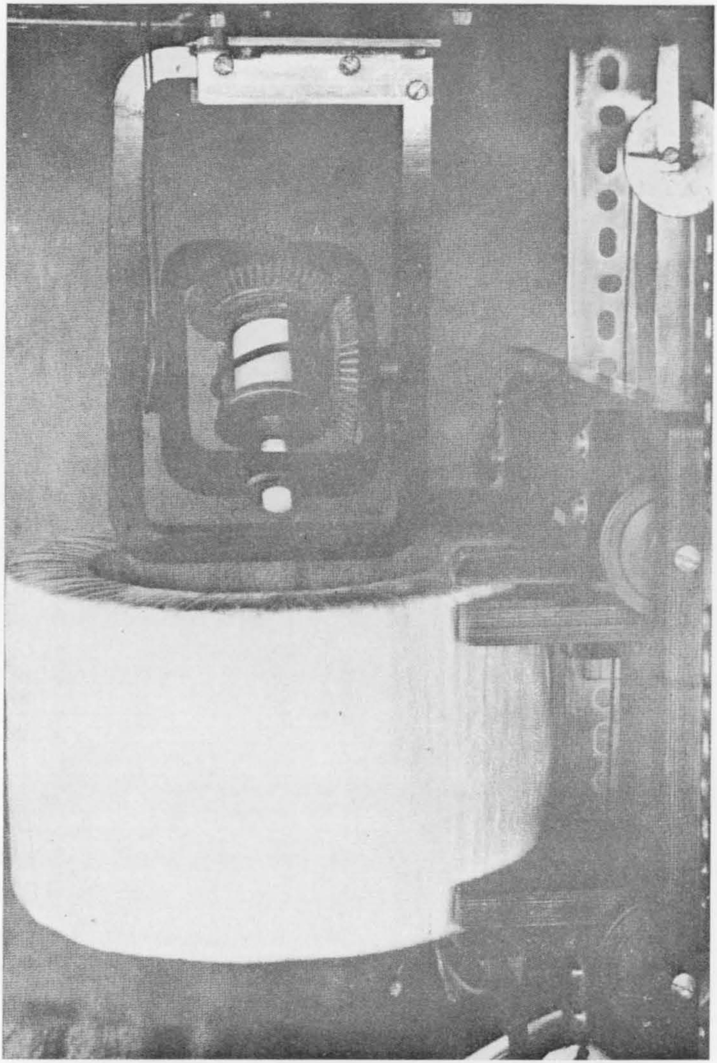

Figure 6. Spinner unit in relation to alternating-field coil.

TABLE 1. DETAILS OF COILS

Parry coils

	Coil turns	Resistance of each coil (ohms)	Side (cm)	Distance apart (cm)	Current (mA)
North/South	100	10.51	180.2	98.2	270
Vertical	100	9.76	165.9	90.4	543

Alternating field coil

Number of turns	1920	
Number of layers	20	
Internal diameter	14.7 cm	
External diameter	20.8 cm	
Length	12.5 cm	
Form factors		
α	1.41	Ratios defined in Cockcroft (1928)
β	0.85	
G_1	0.13	

The Earth's field is annulled to within 1 percent of the value at Canberra, that is to within ±500 gammas. The currents required were determined by using a dip circle for the pair of vertical-field coils and a swinging magnet for the horizontal-field coils.

2.2.3 THE ALTERNATING-FIELD COIL. The alternating-field coil is a short solenoid with 1920 turns of 18 s.w.g. enamelled copper wire and with paper insulation between each layer. There are 20 layers of 96 turns and the dimensions and electrical characteristics are given in Table 1. The dimensions are based on the factors given by Cockcroft (1928); although efficiency is not the principal consideration, the form factors give a coil efficiency, expressed as a percentage of the maximum theoretical field for the power consumed, of about 72 percent. The coil is connected to the supply mains (240 v/50 Hz) through fixed and variable transformers as shown in the circuit diagram (Figure 8). The circuit was tuned to 50 Hz with a bank of ten 2-μF condensers, connected in parallel to give

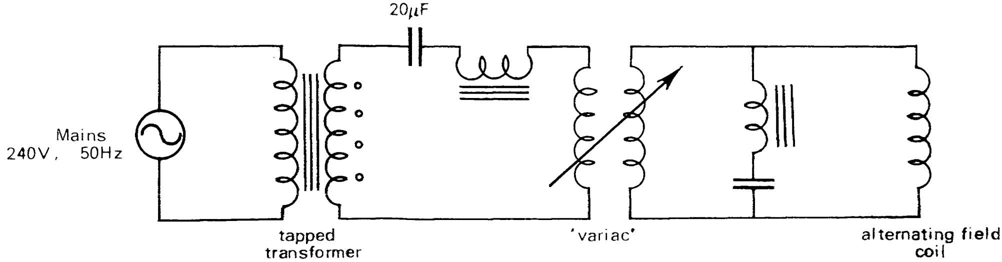

Figure 8. Schematic diagram of demagnetising circuit.

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a total capacity of 20 μF. A circuit tuned to 100 Hz is connected in parallel across the secondary winding of the 'variac'. The final result is that the impedance at 50 Hz is about 20 ohms, compared with the measured d.c. resistance of the coil, 15.6 ohms. No doubt, by more careful tuning the overall efficiency could be increased, but the power available is ample to pass more than the maximum allowable current through the alternating-field coil. The principal power loss was due to the low 'Q' of the 100-Hz shunt circuit, which allows an appreciable 50-Hz current to pass through it.

The coil has been calibrated by a.c. and d.c. methods; details are given in Table 1.

To calibrate the coil using direct current, a search coil having area-turns equal to about 2 cm^2 is placed inside the coil with its plane perpendicular to the axis of the coil. The search coil is connected to a fluxmeter and the field is measured by observing the deflection when the field coil current is reversed. Two fluxmeters have been used, one made by W. G. Pye & Co. Ltd, and the other by Cambridge Instruments Co. Ltd (Grassot type); both have been calibrated using a Cambridge Instruments Co. Ltd variable mutual inductance and compared (in strong fields) with a British Thomson Houston 'Hall effect' fluxmeter. The overall accuracy of the search coil and fluxmeter is better than 0.1 percent; the chief source of error is the accuracy of the alignment of the axes of the search coil and the field coil, which is probably accurate to about 2°; if this were the amount of misalignment, the calibration error would be 0.06 percent.

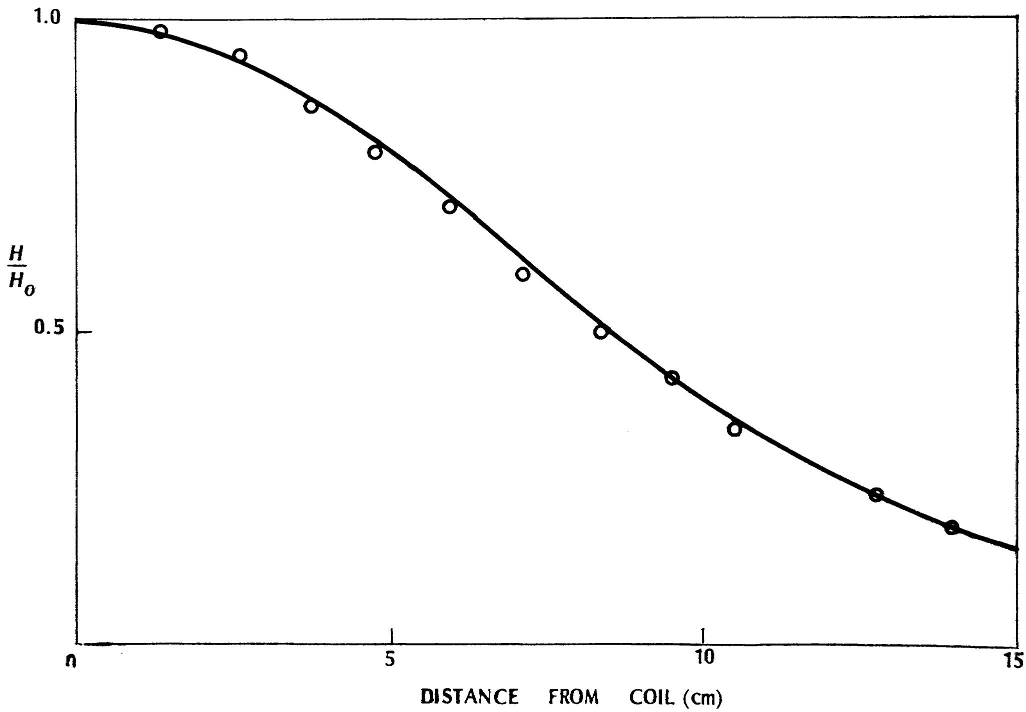

Figure 9. Field of alternating – field coil.

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The a.c. calibration was made by using the same search coil connected to a valve voltmeter and by passing alternating current through the field coil. In this case, the alignment of the search coil is easily corrected by rocking it to and fro to obtain a maximum reading.

The two calibrations agree to better than 1 percent giving:

$$H = 105 \text{ oersteds/amp} \tag{7}$$

The variation of field with distance between specimen and coil was measured by the a.c. method, up to a distance of 100 cm (the variation of field up to a distance of 15 cm is shown in Figure 9); for distance greater than 100 cm the variation was calculated using the formula:

$$\begin{aligned} H_d &= H_{100}.(100/d)^3 \\ &= (H_{100}/d^3) \times 10^6 \ (d \text{ in cm}) \end{aligned} \tag{8}$$

2.2.4 THE TRAMWAY. The control of the current through the coil by a 'variac' transformer does not allow the current (and hence the alternating magnetic field at the specimen) to be reduced to zero sufficiently smoothly. There are several ways by which a smooth reduction of the field can be achieved; that chosen is to mount the coil on a trolley, which is withdrawn along a tramway. The demagnetising coil is brought up to a position surrounding the specimen, with the full current flowing for the particular treatment required, and then withdrawn to a distance of about 5 m; the field at the specimen is then about 10^{-5} times the peak value and is reduced to zero using the 'variac' (Figure 8).

The tramway is horizontal and perpendicular to the magnetic meridian. It is made of slotted aluminium angle. Theoretically, an electrical non-conductor would be better, but any distortion of the demagnetising field due to currents induced in the aluminium tramway is undetectable in practice (it is less than 0.5 percent of the field at the centre of the coil) and the construction and maintenance is much simpler. The 'rails' of the tramway are the upturned edges of the aluminium angle; the 'gauge' is 22.86 cm (9 inches) a figure which is conveniently 'built in' by the repetition of the pattern of holes in the 'dexion'.

The trolley is made of laminated wood ('permali'). On one side, the 'tufnol' wheels have a V-groove, which fits on one rail to locate and guide the trolley; the wheels on the opposite side are flat and rest on the other rail.

Originally, the trolley and coil were moved along the tramway by an electric motor. It was found more satisfactory, for various reasons (mainly mechanical), to control the movement by hand; this form of 'motive power' permits of very fine control over the movement of the coil, which is especially important in the early stages of withdrawal.

2.2.5 ELECTRICAL SYSTEMS. There are two separate electrical circuits: direct current for the compensating Parry coils and alternating current for the demagnetising coil, the spinner motor, and other ancillary apparatus. The two circuits are controlled from two boards mounted side by side near the spinner; the top of these control boards is visible in the middle of Figure 3, above the tramway.

An ammeter is mounted in the centre of the d.c. control board and below it is a rotary switch to place the meter in either the horizontal or the vertical compensating coil circuits. The meter has two ranges: 0 to 300 mA, used with the pair of coils that compensate the horizontal field; and 0 to 600 mA, for the other pair; the range is automatically changed when switching from one circuit to the other. At the sides of the board are identical sets of terminals, one for each circuit, on-off and reversing switches, warning lights, and so on. Current is drawn from the battery of lead-acid cells used by all the instruments in the non-magnetic laboratory (Green, 1960). The circuits are separately fused near the storage battery. The wires to the control board, and those from the control board to the coils, are twisted together to reduce stray magnetic fields. A resistance near the fuses provides 'coarse' current control; two rheostats (in series) on the control panel are normally sufficient for adjusting the current to the correct value.

The a.c. control system is more complex. Two separate outlets from the main laboratory supply are used. One, near the control board, supplies the spinner motor (and the coil transport motor before this was replaced by the hand-operated device), and the other, in the next room, supplies the magnetising coil and associated equipment. All the transformer, chokes, condensers, etc. are together in this next room and the current reaches the coil by the cable seen passing round a pulley on the left of Figure 3; this pulley and two more mounted on the roof, take up and let out the cable as the trolley moves along the tramway. Once the socket supply outlet is switched on, the coil current is controlled by relays operated by switches on the control panel near the spinner. These provide for switching the coil current on and off and for raising or lowering the current by the motor-operated 'variac' (Figure 8). The current through the alternating-field coil is measured by a meter on the control panel (wired from the end of the tramway) and there is another meter with the transformers and tuning circuit components, which is not visible from the operator's position and which is provided for use when testing the circuits.

Appendix 2 gives some practical notes, intended as a guide for designing and building similar apparatus.

2.3 ANALYSIS OF RESULTS

The result of demagnetising the NRM of a specimen can be described in general terms by considering a partially stable rock specimen. This specimen may be taken to have an NRM made up of a stable TRM acquired when the rock first cooled (assuming an igneous rock) and a less stable viscous magnetisation in a direction making an angle (say) of 90° with that of the TRM. The effect of treating the specimen in alternating magnetic fields with successively greater peak values is to reduce the intensity of magnetisation (giving perhaps a curve such as is shown in Figure 10a) and to change the direction of magnetisation, as shown in Figure 10b. (In practice, intensity curves do not show the marked bend indicated in Figure 10a), but changes in direction as shown in Figure 10b have been described many times (As & Zidjerfeld, 1958; Creer, 1959; Bull & Irving, 1960; and many others). But just as the direction of magnetisation of the rock at a site is treated statistically and taken to be the mean direction of several specimens, so

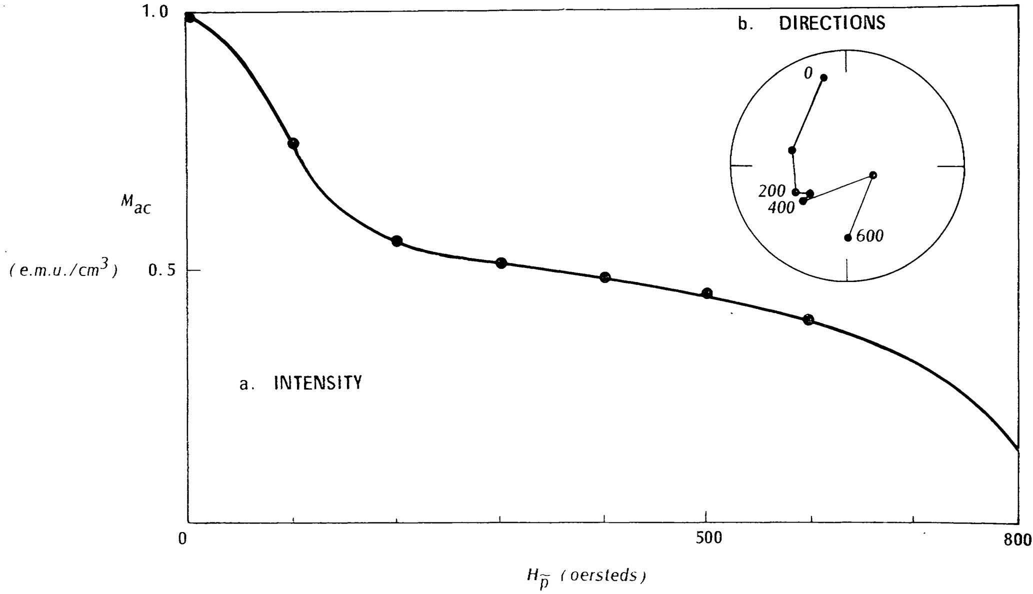


Figure 10. Hypothetical demagnetisation G456–6

it is preferable to treat the results of demagnetisation statistically. A direction of NRM in a single specimen may, or may not, represent a significant direction; one cannot tell until directions in several specimens have been measured and a mean direction and an estimate of dispersion obtained. Similarly, demagnetisation results as shown in Figure 10 may or may not represent significant directions of stable and less-stable magnetisations.

It is reasonable to suppose that a partially stable rock with an NRM made up as indicated above will have these characteristics:

(i) The primary TRM will be the same in all specimens and will be dispersed about the mean direction with precision of some value, k_T;

(ii) The viscous or other secondary magnetisation will generally be more variable, both in intensity and direction, depending upon the 'relaxation times' of the magnetic grains in the rock and of the possibly varying conditions under which the secondary magnetisation was acquired.

The result will be that the NRM will have a direction between that of the primary TRM and that of the secondary magnetisation (usually the direction of the Earth's field at the time of demagnetisation) and the varying amount of viscous magnetisation will result in a larger dispersion of the NRM. This suggests that when demagnetising several partially stable specimens from a site, the precision will increase if the secondary magnetisation is removed in preference to the primary magnetisation. Similar arguments lead to a second conclusion: that agreement between sites in the same rock formation should improve. A third applies to any significant palaeomagnetic results: that directions of magnetisation in different rock formations of similar age over a wide area and within the same continent should agree, after allowing for differences in geographic position. This is found to be the case in several instances subsequently described.

In higher demagnetising fields, the TRM will become more altered, and random magnetisations will appear (these are discussed in Chapter 6) so that the dispersion increases. It is usually found, as might be expected, that the within-site and between-site precisions are greatest after treatment in about the same alternating field. The criterion adopted for recognising the stable direction of magnetisation in a partially stable rock is: the stable direction is the mean direction of magnetisation of several specimens from a site or formation, after treatment in the alternating field for which the precision is greatest.

If this alternating field has a peak value $H_{p1}\sim$, it is better that the mean direction after treatment in $H_p\sim > H_{p1}\sim$ is taken, rather than that in $H_p\sim < H_{p1}\sim$. It will be seen later that H_{p1} will often lie between two actual measured points and the reason for this empirical rule is discussed in section 5.4.

2.3.1 STATISTICS FOR A SMALL NUMBER OF SPECIMENS. The method of assessing the optimum treatment as outlined above can lead to great economy in laboratory time if a small number of specimens from a formation (four or five are often sufficient) are taken and treated in increasing alternating fields. These few treated specimens will show the best value of demagnetising field and the remainder of the collection can then be subjected to this field immediately. However, some extension of the statistical theory of dispersion on a sphere is required.

It is desirable to be able to compare the dispersion of groups of specimens and, because the number of specimens in the groups may differ, some method of measuring the dispersion is required which is independent of the number of specimens. This is done by dividing the precision parameter k (see section 1.3.5) by a factor k_o. Watson (1956b) has given a table showing values of the resultant R_o of N ($= 5$ to 20) random vectors which will be exceeded by chance in only 5 percent and 1 percent of cases. The value of $R = R_o$ (at $P = 0.05$) is inserted in equation 2 to give k_o. Table 2 gives the values of R_o for $N = 2$ to 100. Because N is sometimes less than 5, the table has been extended down to $N = 2$, using the method given by Watson. The values of R_o for N between 20 and 100 were calculated at the same time; beyond $N = 100$, the approximations given by Watson are almost exactly correct. Also, because the precision often changes very slowly with increasing alternating fields, it was found useful to know R_o to four places of decimals. Table 2 gives R_o ($P = 0.05$, 0.01) to six figures for N between 2 and 10 and to four figures for N between 11 and 100 (the values for $N = 11$ to $N = 20$ are taken from Watson's table).

The approximation for k given above is valid only for N large and R greater than about $\frac{1}{2}N$. When these conditions do not hold, exact formulae are used. Figure 11 shows three curves of K plotted against R, for $N = 10$. Curve 1 shows the exact formula, curve 2 is for $K = N/(N - R)$, and curve 3 is for $K = (N - 1)/(N - R)$. The value of k for given values of N and R, for N between 2 and 10, can be read from Figure 11.

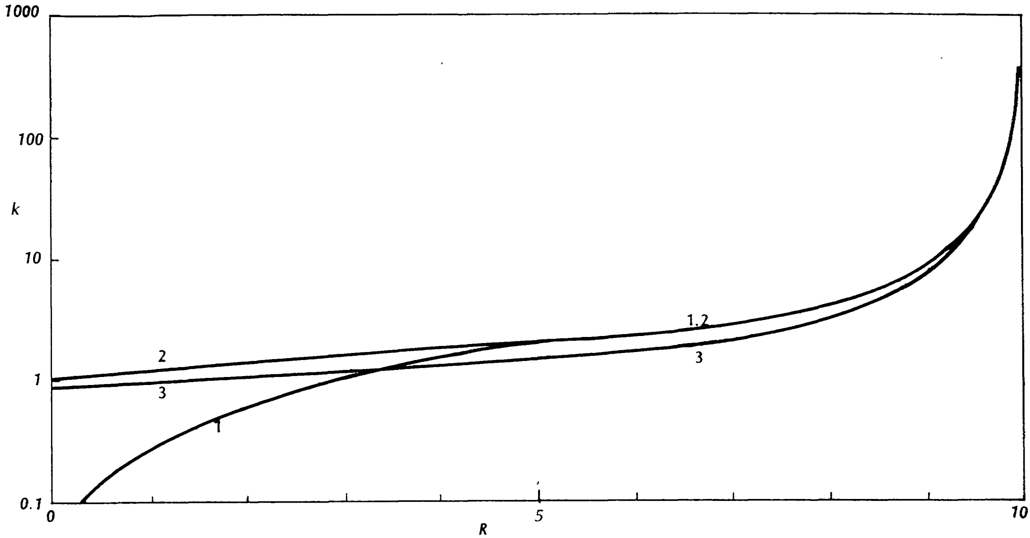


Figure 11. Relation between R and k ($N = 10$)

2.4 ASTATIC MAGNETOMETER

When specimens are demagnetised, the range of intensity between NRM and magnetisation after treatment in (say) 500 oersteds may be quite large, so that measurements of the magnetisation are made with the specimen at varying distances from the magnet system of the magnetometer. The theory used earlier (Collinson & Creer, 1960; Green, 1960) to obtain the constants of the instrument leads to small errors in the intensity values because it allows only for the forces acting to deflect the magnet nearer the specimen. The effect of the other magnet can be calculated and involves a correcting factor to divide into the amplitude of the measured deflection. The correcting factors are given in Tables 3 and 4. For the more sensitive 'sedimentary' magnetometer, two values are given, because in this case the deflections caused by the horizontal and vertical components of magnetisation are separated. If the amplitudes of the deflections due to the horizontal and vertical components are A and B respectively, then for an astatic magnetometer with the centres of the magnets 7.05 cm apart, the correcting factors are:

$$F_a = 1 + \frac{z_o^3}{(z_o + 7.05)^3} \tag{9}$$

and

$$F_b = 1 + \frac{z_o^4}{(z_o + 7.05)^4} \tag{10}$$

where z_o is the corrected distance from the lower magnet (Irving, 1954). The corrected amplitudes are then: $A_c = A/F_a$; $B_c = B/F_b$. (The value $8F_b$ is tabulated because B is derived from the sum of differences totalling $8B$. It is therefore simpler to calculate $B_c = 8B/8F_b$). On the less sensitive 'igneous' magnetometer, the magnetic intensity is measured always with the specimen rotated in such a way that the magnetisation is horizontal, and only one correcting factor is needed, F_a as in equation 9, but with 6.74 replacing 7.05.

TABLE 2. SIGNIFICANCE POINTS OF R

R_o is the length of the resultant of N unit vectors oriented at random which will be exceeded with a probability $P = 0.05$ or 0.01.

N	R_o ($P = 0.05$)	R_o ($P = 0.01$)	N	R_o ($P = 0.05$)
			51	11.49
2	1.94936	1.98997	52	11.60
3	2.61831	2.83359	53	11.71
4	3.10319	3.48995	54	11.82
5	3.50079	4.02323	55	11.93
6	3.85324	4.48004	56	12.04
7	4.17811	4.88782	57	12.15
8	4.47976	5.26255	58	12.25
9	4.76208	5.61211	59	12.36
10	5.02847	5.94082	60	12.46
11	5.29	6.25	61	12.57
12	5.52	6.55	62	12.67
13	5.75	6.84	63	12.77
14	5.98	7.11	64	12.87
15	6.19	7.36	65	12.97
16	6.40	7.60	66	13.07
17	6.60	7.84	67	13.17
18	6.79	8.08	68	13.27
19	6.98	8.33	69	13.37
20	7.17	8.55	70	13.46
21	7.36		71	13.56
22	7.53		72	13.65
23	7.70		73	13.75
24	7.87		74	13.84
25	8.03		75	13.94
26	8.19		76	14.03
27	8.35		77	14.12
28	8.50		78	14.21
29	8.65		79	14.31
30	8.80		80	14.40
31	8.95		81	14.49
32	9.09		82	14.58
33	9.23		83	14.66
34	9.37		84	14.75
35	9.51		85	14.84
36	9.64		86	14.93
37	9.78		87	15.01
38	9.91		88	15.10
39	10.04		89	15.19
40	10.17		90	15.27
41	10.29		91	15.36
42	10.42		92	15.44
43	10.54		93	15.52
44	10.67		94	15.61
45	10.79		95	15.69
46	10.91		96	15.77
47	11.02		97	15.86
48	11.14		98	15.94
49	11.26		99	16.01
50	11.37		100	16.10

For $N > 10^3$:

N	R ($P = 0.05$)
10^n (n odd)	$5.1 \times 10^{\frac{1}{2}(n-1)}$
10^n (n even)	$1.6 \times 10^{\frac{1}{2}n}$

Notes: (1) There may be an error of 1 in the last figure;

(2) Values of R_o for $10<N<20$ taken from Watson (1956b).

TABLE 3. CORRECTING FACTORS FOR 'SEDIMENTARY' MAGNETOMETER

Z_o (cm)	F_a	$8F_b$	Z_o (cm)	F_a	$8F_b$
			6.6	.8870	7.563
			6.7	.8843	7.549
			6.8	.8816	7.535
			6.9	.8790	7.521
3.5	0.9635	7.903	7.0	.8763	7.507
3.6	.9614	7.896	7.1	.8737	7.493
3.7	.9592	7.888	7.2	.8710	7.479
3.8	.9570	7.880	7.3	.8684	7.464
3.9	.9548	7.871	7.4	.8657	7.450
4.0	.9526	7.863	7.5	.8630	7.435
4.1	.9503	7.854	7.6	.8604	7.421
4.2	.9480	7.845	7.7	.8577	7.406
4.3	.9456	7.835	7.8	.8551	7.391
4.4	.9432	7.826	7.9	.8524	7.376
4.5	.9408	7.816	8.0	.8498	7.361
4.6	.9384	7.806	8.1	.8472	7.346
4.7	.9360	7.795	8.2	.8445	7.332
4.8	.9335	7.785	8.3	.8419	7.316
4.9	.9310	7.774	8.4	.8393	7.301
5.0	.9285	7.763	8.5	.8367	7.286
5.1	.9260	7.752	8.6	.8341	7.270
5.2	.9235	7.740	8.7	.8315	7.255
5.3	.9210	7.729	8.8	.8289	7.240
5.4	.9184	7.717	8.9	.8263	7.224
5.5	.9158	7.705	9.0	.8237	7.209
5.6	.9132	7.693	9.1	.8211	7.194
5.7	.9106	7.680	9.2	.8185	7.178
5.8	.9080	7.668	9.3	.8160	7.163
5.9	.9054	7.655	9.4	.8134	7.147
6.0	.9028	7.643	9.5	.8109	7.131
6.1	.9002	7.630	9.6	.8083	7.116
6.2	.8976	7.616	9.7	.8058	7.100
6.3	.8949	7.603	9.8	.8033	7.085
6.4	.8923	7.590	9.9	.8008	7.069
6.5	.8896	7.576	10.0	.7982	7.053

Z_o (cm)	F_a	$8F_b$	Z_o (cm)	F_a	$8F_b$
10.1	.7957	7.038	14.6	.6933	6.346
10.2	.7933	7.022	14.7	.6913	6.331
10.3	.7908	7.006	14.8	.6892	6.316
10.4	.7883	6.991	14.9	.6872	6.301
10.5	.7858	6.975	15.0	.6852	6.287
10.6	.7834	6.959	15.1	.6832	6.272
10.7	.7809	6.944	15.2	.6812	6.258
10.8	.7785	6.928	15.3	.6792	6.243
10.9	.7761	6.912	15.4	.6772	6.229
11.0	.7737	6.897	15.5	.6752	6.214
11.1	.7713	6.881	15.6	.6733	6.200
11.2	.7689	6.865	15.7	.6713	6.186
11.3	.7665	6.849	15.8	.6694	6.171
11.4	.7641	6.834	15.9	.6675	6.157
11.5	.7617	6.818	16.0	.6655	6.143
11.6	.7594	6.803	16.1	.6636	6.129
11.7	.7570	6.787	16.2	.6617	6.114
11.8	.7547	6.772	16.3	.6598	6.100
11.9	.7524	6.756	16.4	.6579	6.086
12.0	.7500	6.740	16.5	.6561	6.072
12.1	.7478	6.725	16.6	.6542	6.058
12.2	.7455	6.709	16.7	.6523	6.044
12.3	.7432	6.694	16.8	.6505	6.030
12.4	.7409	6.678	16.9	.6486	6.017
12.5	.7386	6.663	17.0	.6468	6.003
12.6	.7364	6.648	17.1	.6450	5.989
12.7	.7341	6.632	17.2	.6432	5.975
12.8	.7319	6.617	17.3	.6414	5.962
12.9	.7296	6.601	17.4	.6396	5.948
13.0	.7274	6.586	17.5	.6378	5.934
13.1	.7252	6.571			
13.2	.7230	6.556			
13.3	.7208	6.540			
13.4	.7187	6.525			
13.5	.7165	6.510			
13.6	.7143	6.495			
13.7	.7122	6.480			
13.8	.7100	6.465			
13.9	.7079	6.450			
14.0	.7058	6.435			
14.1	.7037	6.420			
14.2	.7016	6.405			
14.3	.6995	6.390			
14.4	.6974	6.375			
14.5	.6954	6.360			

Diff.	1	2	3	4	5	6	7	8	9
6	1	1	2	2	3	4	4	5	5
8	1	2	2	3	4	5	6	6	7
10	1	2	3	4	5	6	7	8	9
12	1	2	4	5	6	7	8	10	11
14	1	3	4	6	7	8	10	11	13
16	2	3	5	6	8	10	11	13	14
18	2	4	5	7	9	11	13	14	16
20	2	4	6	8	10	12	14	16	18
22	2	4	7	9	11	13	15	18	20
24	2	5	7	10	12	14	17	19	22
26	3	5	8	10	13	16	18	21	23
28	3	6	8	11	14	17	20	22	25

TABLE 4. CORRECTING FACTORS FOR 'IGNEOUS' MAGNETOMETER

Intensity derived from formula has to be divided by F_a. Alternatively, use value of z_e^3 instead of z^3, where $z_e^3 = z^3/F_a$ and $F_a = 1 - [z/(z + 6.74)]^3$.

z	z_e^3	F_a	z	z_e^3	F_a
5.9	228.2	0.900	10.0	1271	0.786
6.0	241.2	.896	10.1	1314	.784
6.1	254.2	.893	10.2	1358	.782
6.2	267.8	.890	10.3	1402	.779
6.3	281.8	.887	10.4	1448	.777
6.4	296.4	.884	10.5	1495	.774
6.5	311.5	.882	10.6	1544	.772
6.6	327.1	.879	10.7	1593	.769
6.7	343.3	.876	10.8	1643	.766
6.8	360.0	.873	10.9	1695	.764
6.9	377.4	.871	11.0	1748	.762
7.0	395.3	.868	11.1	1802	.759
7.1	413.8	.865	11.2	1857	.757
7.2	432.9	.862	11.3	1913	.754
7.3	452.6	.859	11.4	1971	.752
7.4	473.0	.857	11.5	2030	.749
7.5	494.1	.854	11.6	2090	.747
7.6	515.8	.851	11.7	2151	.745
7.7	538.1	.848	11.8	2214	.742
7.8	561.2	.846	11.9	2278	.740
7.9	585.0	.843	12.0	2343	.737
8.0	609.4	.840	12.1	2410	.735
8.1	634.6	.837	12.2	2478	.733
8.2	660.6	.835	12.3	2548	.730
8.3	687.3	.832	12.4	2619	.728
8.4	714.8	.829	12.5	2691	.726
8.5	743.0	.826	12.6	2765	.723
8.6	772.1	.824	12.7	2840	.721
8.7	802.0	.821	12.8	2917	.719
8.8	832.7	.818	12.9	2996	.717
8.9	864.2	.816	13.0	3075	.714
9.0	896.6	.813	13.1	3157	.712
9.1	929.9	.810	13.2	3240	.710
9.2	964.0	.808	13.3	3324	.708
9.3	999.1	.805	13.4	3411	.705
9.4	1035	.802	13.5	3499	.703
9.5	1072	.800	13.6	3588	.701
9.6	1110	.797	13.7	3679	.699
9.7	1149	.795	13.8	3772	.697
9.8	1188	.792	13.9	3867	.695
9.9	1229	.789	14.0	3963	.692

3. MAGNETISATION OF RED HILL DYKE

3.1 INTRODUCTION

Before the development of techniques for testing the stability of the remanent magnetisation of rocks in the laboratory (in particular, by demagnetising in alternating magnetic fields) a great many palaeomagnetic surveys were made in which there was little more than a presumption of stability. The Tasmanian dolerites are an important group of rocks which have been extensively studied, but for which the only evidence of stability comes from a Tertiary breccia that contains dolerite boulders near Hobart; they are therefore very suitable for careful laboratory study of stability. This has been done on rock samples from Red Hill Dyke in southern Tasmania because its petrology and geological setting has been extensively studied. It exhibits a range of differentiated rock types which is greater than usual for the Tasmanian dolerites; they range from chilled margins, considered to represent the average composition of the injected magma, to a silicic differentiate, granophyre. Also, a dyke-like intrusion provides a contrast to the more usual sill-like body and makes possible a comparison of results with those from a fairly detailed set of observations from the Mount Wellington Sill (see section 3.5.2). Since this work began, the age of rocks from the dyke has been measured by the potassium-argon method and the palaeomagnetic results from these particular rocks now form an important reference point in the measurements made on Australian rocks.

The Mesozoic dolerite of Tasmania has intruded Permian and Triassic sediments, generally in the form of extensive flat-lying sills some hundreds of metres thick. It provides excellent material for palaeomagnetic measurements, being strongly magnetic and readily accessible, both by natural means and by artificial, the latter mainly due to large-scale hydroelectric schemes. A provisional age for Red Hill Dyke of 167$\pm$ m.y. from potassium-argon measurements (McDougall, 1961) is in excellent agreement with previous estimates of probably Jurassic age (Banks, 1958). There is every reason to believe that all the dolerite is part of a single intrusion.

The dolerite sills may have once covered an area of 40,000 km^2, but erosion has reduced this to about 15,000 km^2, and the original average thickness was about 300 m (Edwards, 1942). The sills transgress upwards and downwards (Carey, 1958) and in places the dolerite forms dyke-like intrusions (one of which is Red Hill Dyke), about 2 km wide, situated some 15 to 30 km south-southwest of Hobart. Palaeomagnetic results from the dolerite have been described by Jaeger and Joplin (1955) and Almond, Clegg, and Jaeger (1956) and results of a regional survey are described by Irving (1956, 1963). The composition and mineralogy have been discussed in many papers, the more important of which are Edwards (1942), Jaeger and Joplin (1955), and McDougall (1960).

Intensive geological studies by McDougall (1960) have made available a wealth of geological and petrological information about Red Hill Dyke, which is representative of the dolerite as a whole. In Irving's earlier regional survey (Irving, 1956) samples were collected from outcrops over the whole of Tasmania, two or three samples at each site. It would be extremely laborious to make a thorough examination of every rock sampled by Irving and so a detailed study has been made of one particular area, and the results can then apply to the regional

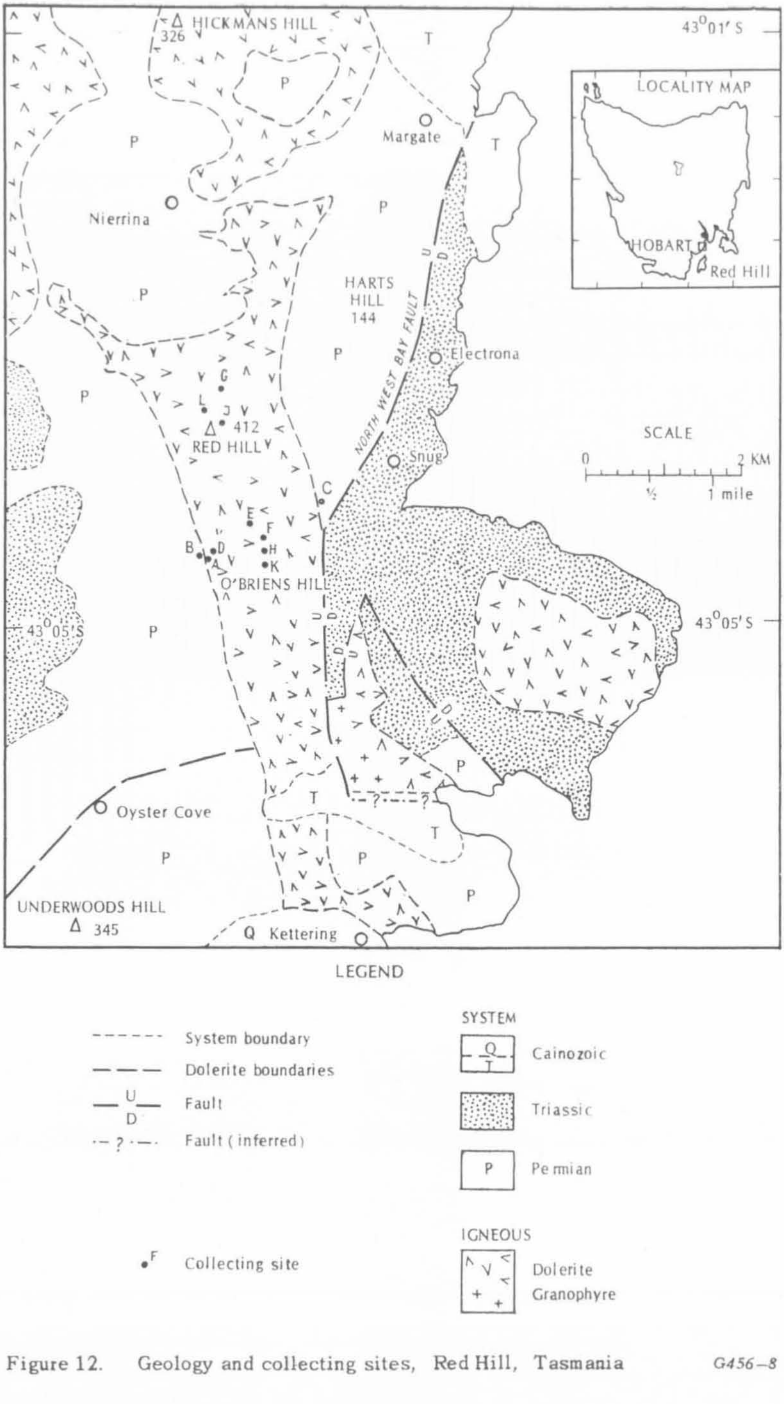


Figure 12. Geology and collecting sites, Red Hill, Tasmania *G456–8*

survey as a whole. The evidence suggests that the natural remanent magnetisation now existing represents thermoremanent magnetisation acquired when the dolerite first cooled in the direction of the Jurassic geomagnetic field. Reconnaissance gravity and magnetic traverses have also been made over Red Hill Dyke, by McDougall and Stott. An account of some of this work has been given by McDougall (1960) and further reference is made below (section 3.7).

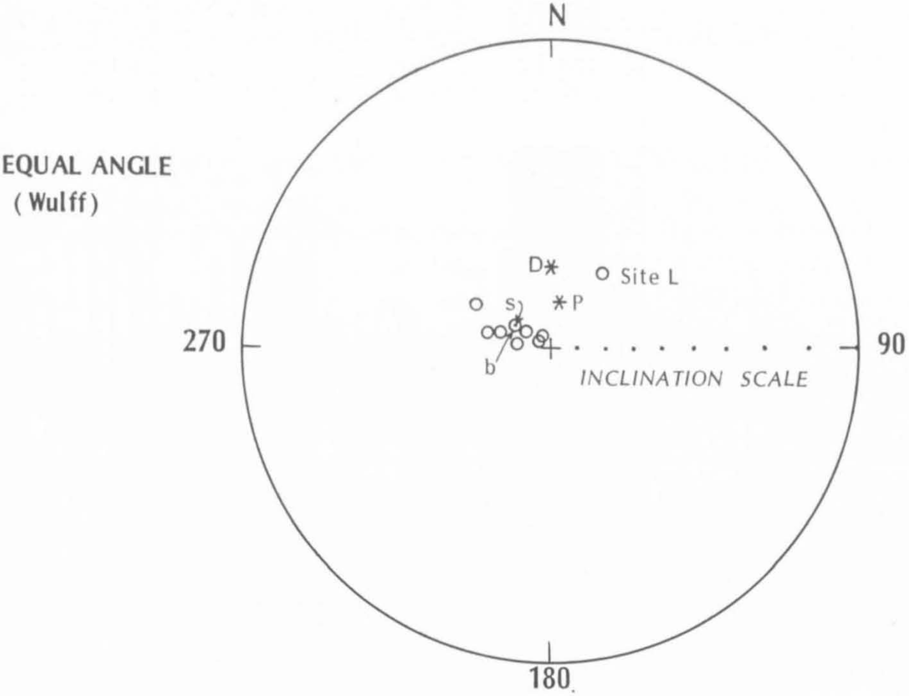
3.2 GEOLOGY

The geology of Red Hill Dyke has been fully described by McDougall (1960). The following is a brief summary of that part of the geology that is relevant to this study.

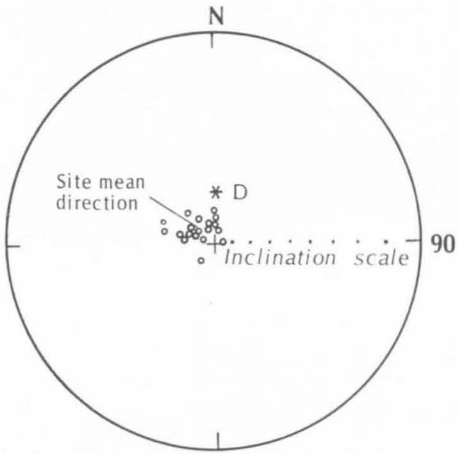
As elsewhere in Tasmania, the dolerite of the Red Hill area is intrusive into flat-lying Permian and Triassic sediments, although in this particular area it is mainly in the Permian beds. The form of the intrusion is essentially that of a dolerite sheet about 400 m thick, which is gently transgressive upwards through the Permian sequence from east to west. Arising out of the roof of this sheet is the large Red Hill Dyke, an almost vertical dyke of dolerite up to 1500 m wide, which can be traced north and south of the area studied for a total length of over 10 km. The dyke extends upwards from the underlying sheet for over 350 m and the field relations clearly show that the intrusion was roofed by sediments. A geological map is shown in Figure 12.

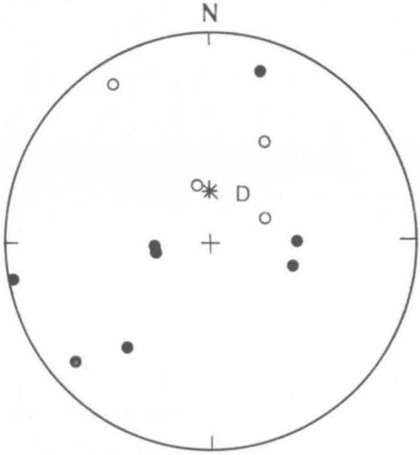
The dolerite magma was liquid at the time of emplacement, except for a few percent of micro-crystals of pyroxene, and at the contacts with the intruded sediments it was chilled to a very fine-grained rock or in some cases to a glass. Analyses of such dolerites will give a close approximation of the composition of the original magma. The dolerite magma is tholeiitic and is similar to the Mesozoic dolerites of the Karroo, Brazil, Antarctica, and Palisades. During the cooling and crystallisation of the dolerite, marked differentiation took place, which gave rise to a series of rocks with a wide range of composition. Only the upper part of the Red Hill Dyke is exposed so that all the rocks found are more silicic than the chilled dolerites. From the chilled contacts in the lowest exposed section, towards the central parts of the Red Hill Dyke, progressively more silicic quartz-dolerites are found; towards the summits of Red Hill or O'Briens Hill, the dolerite grades into fayalite granophyre and finally into silicic granophyre. These differentiates are markedly enriched in iron, silica, and alkalies and impoverished in magnesium, calcium, and aluminium, compared with the original magma. The differentiation in Red Hill Dyke is more extreme than that previously found by Edwards (1942) in his study of several other Tasmanian dolerite intrusions.

The magnetic minerals are of the magnetite-ilmenite series and form from 1 percent to about 10 percent of the rock by volume. The composition of the magnetic mineral seems uniform throughout the dyke; the magnetic grains usually show 50 percent almost pure magnetite (Curie point 550 to 570°C) and 50 percent of slightly magnetic ilmenite (Curie point about 150 to 250°C), which occur as separate exsolution lamellae. About 5 percent (by volume) of the opaque mineral content is pyrite, but this will not materially affect the magnetic properties. The modal analyses quoted later assume that all the opaque mineral is magnetite-ilmenite. No samples have been collected from the (atypical) small pegmatites which occur.



a. *The nine dolerite sites*





b. *Specimens at site B*

c. *Specimens at site C*

LEGEND

✱D	Present dipole field	●	Positive inclination
✱P	Present actual surface field	s	Mean direction of dolerite using sites
o	Negative inclination	b	Mean direction of dolerite using specimens

Figure 13. Site mean directions, Red Hill Dyke *G456–9*

3.3 RESULTS

Samples representative of all types of dolerite have been collected at nine sites within the dyke and samples of baked sediments were taken from the contacts at both sides of the dyke. The sites are shown in Figure 12; site descriptions are given in Table 5.

3.3.1 NATURAL REMANENT MAGNETISATION. Mean directions of magnetisation at each site are given in Table 6 together with other statistical parameters (Fisher, 1953). The site mean directions of the nine dolerite sites are plotted in Figure 13a. Giving unit weight to each mean they have the mean:

$$D_m = 308.6^\circ;\ I_m = -76.6^\circ$$

Excluding site L (see discussion) the mean direction is:

$$D_m = 293.6^\circ;\ I_m = -74.7^\circ$$

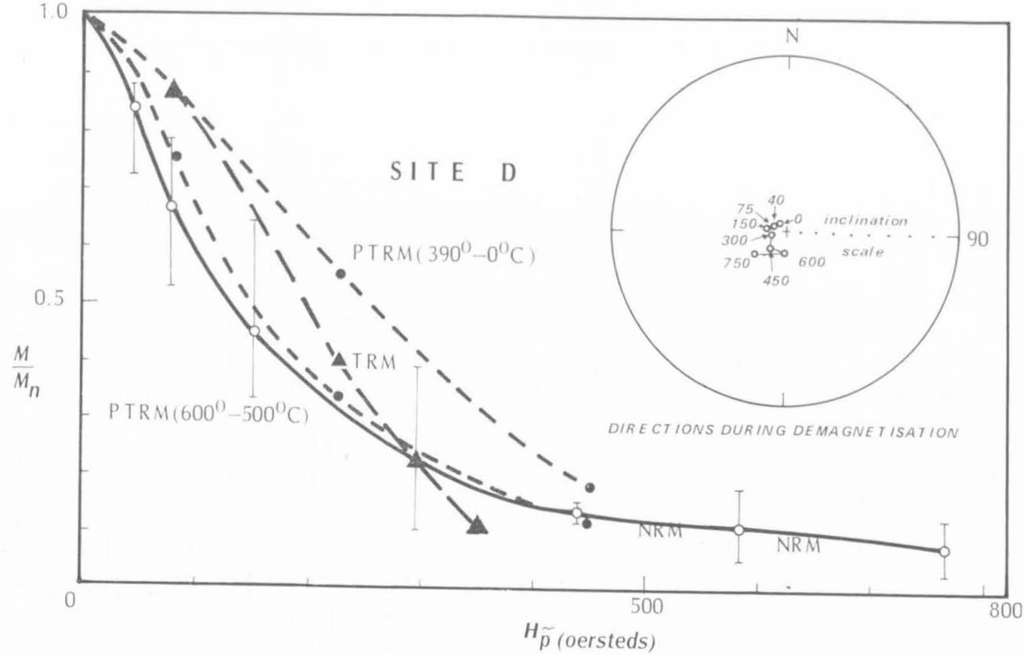
The baked sediments at site B are weakly magnetised, but give a good cluster of directions (see Figure 13b) with mean:

$$D_m = 310;\ I_m = -79$$

At site C, the rocks are more weakly magnetised and the directions are almost random (Figure 13c), probably owing to the measurement errors arising from the weak remanent magnetisation and the much greater susceptibility. Nowhere was it possible to get samples that formed a complete section extending from the dolerite contact to the unbaked sediments.

3.3.2 DEMAGNETISATION IN ALTERNATING MAGNETIC FIELDS. Some of the specimens at five sites, including fine-grained dolerite from near the contact at site C and coarse granophyre from sites J and K, were demagnetised in alternating magnetic fields up to 900 oersteds peak value, successive treatments having peak fields increasing in steps of about 40 to 80 oersteds at first, and by 150 to 300 oersteds later. Three to six specimens were treated from each site and the mean results are given in Table 7. The changes in intensity of magnetisation expressed as the ratio of remaining to initial intensity (M/Mn), and the corresponding directions are given in Figure 14; the range of values of NRM are given for site D, which is typical of all the sites. Some demagnetisation curves were obtained in a similar manner for TRM, IRM, and PTRM and are shown in Figure 14.

3.3.3 MAGNETIC PROPERTIES. On several specimens, measurements were made of: saturation isothermal remanent magnetisation; TRM in the Earth's field (0.6 oersted); susceptibility; destructive field; and 'minimum intensity'. The mean results for each site are given in Table 8. In this, and in all similar measurements described in later chapters, values of saturating IRM, saturating field, and destructive field were obtained by measuring the remanent magnetisation initially, and then after applying a steady field of about 300 oersteds, and subsequently after applying successively larger fields of up to about 5000 oersteds in the same direction the steady field was then applied in the reverse direction and the magnetisation measured after applying fields of 300 up to 5000 oersteds. Sample *M-H* curves obtained in this way are shown in Figure 15. The 'initial' curve is for a specimen having only NRM, or one that has been demagnetised; the 'cyclic' curve is for a saturated specimen, in which the saturation IRM has been reversed several times.



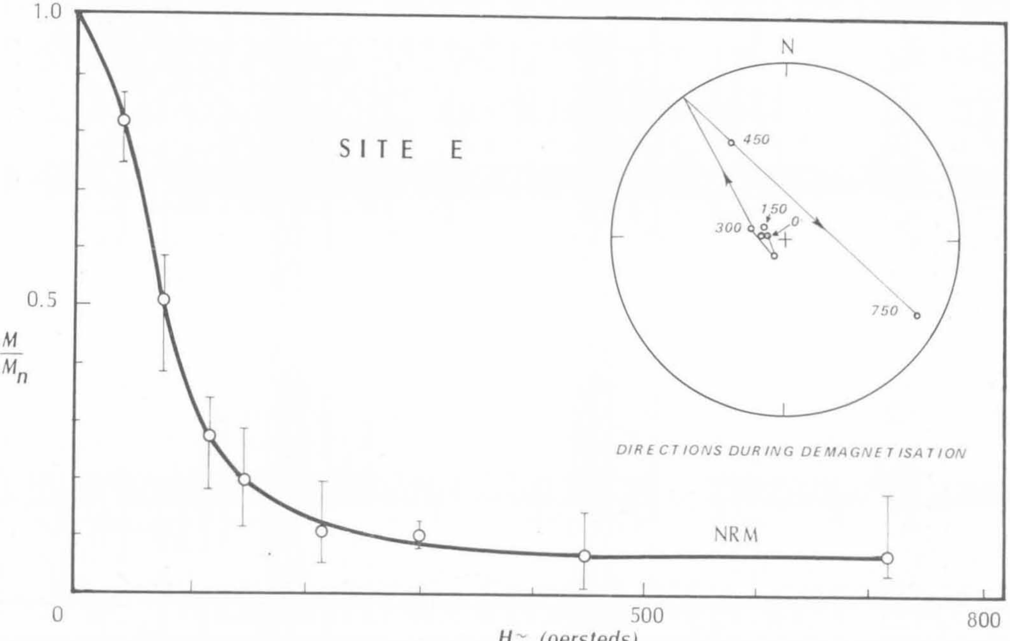
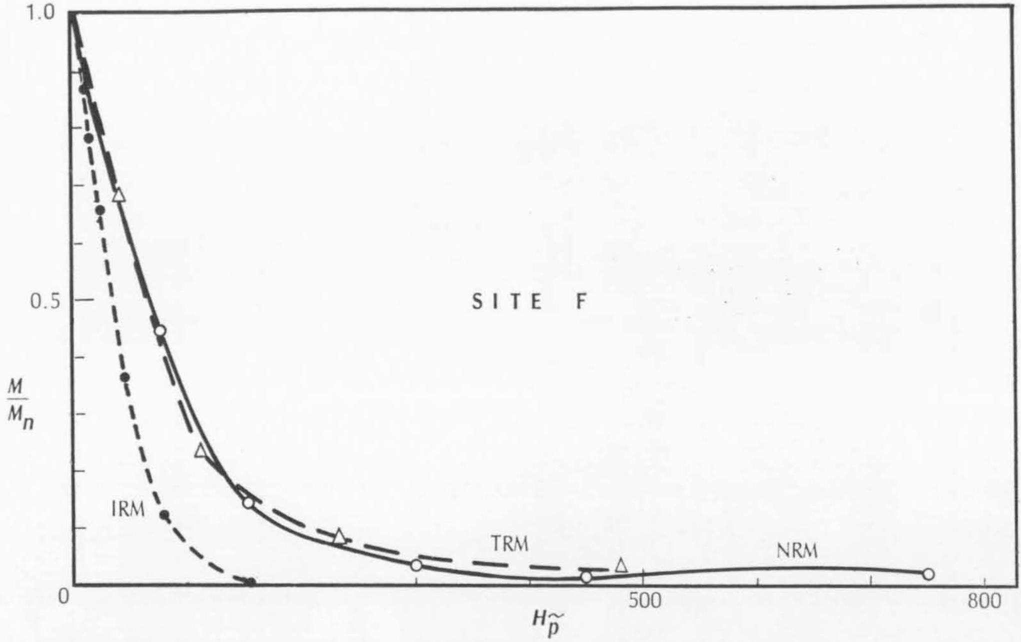


Figure 14a. Demagnetisation curves, Red Hill Dyke, Sites D and E G456–10



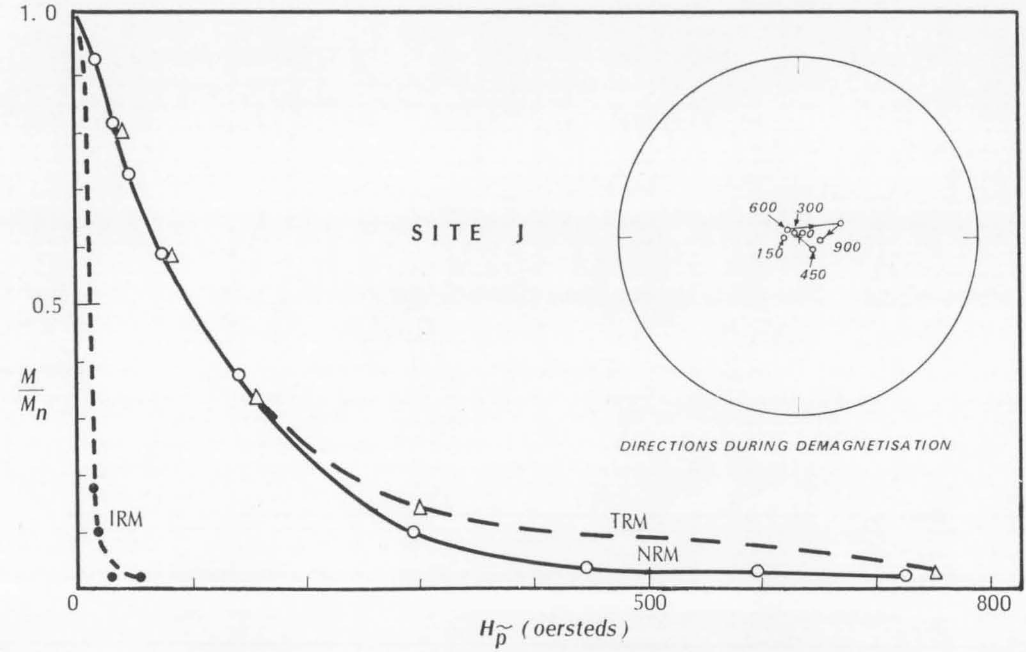


Figure 14b. Demagnetisation curves, Red Hill Dyke, Sites F and J G 456–11

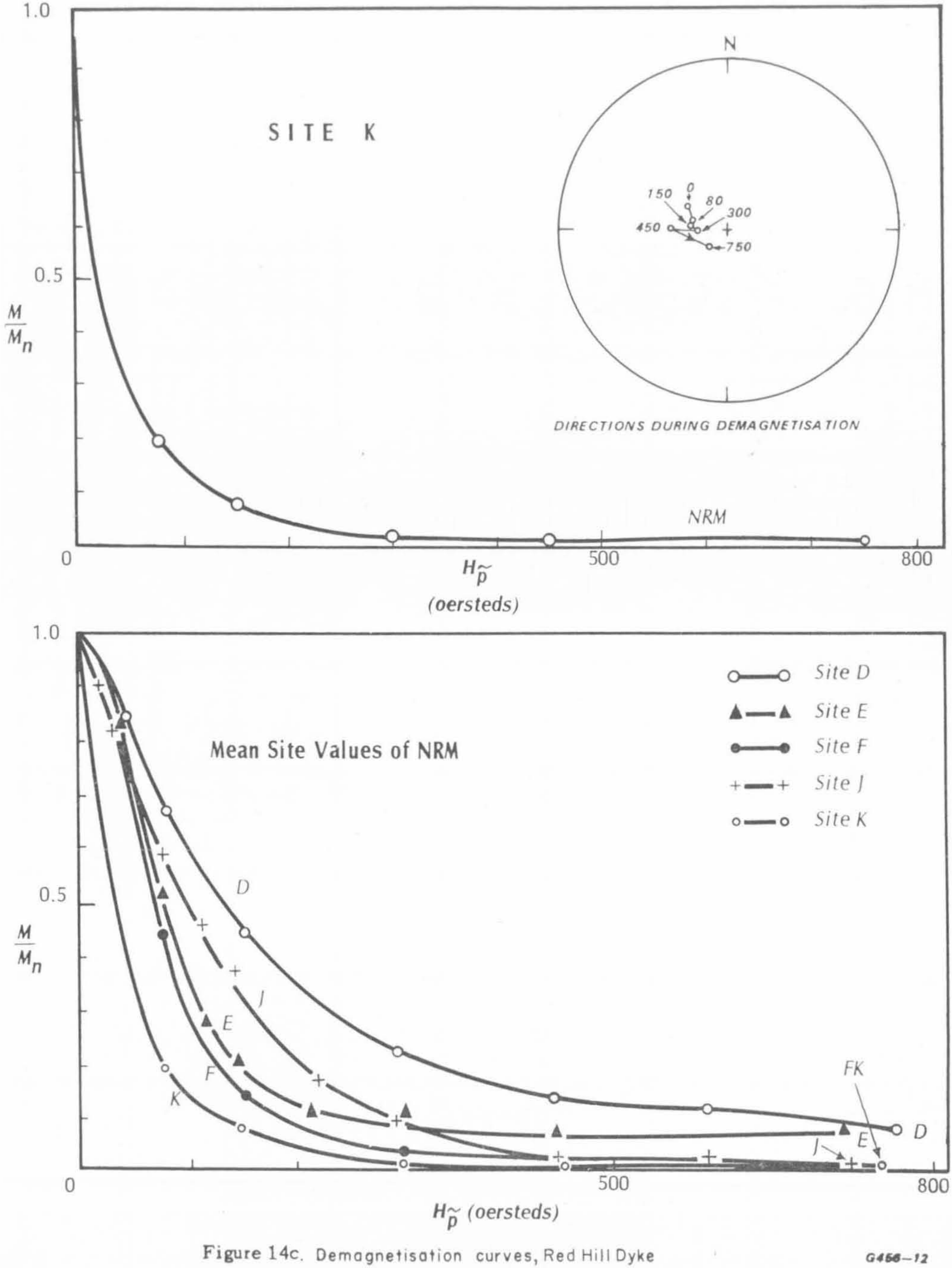


Figure 14c. Demagnetisation curves, Red Hill Dyke

G456—12

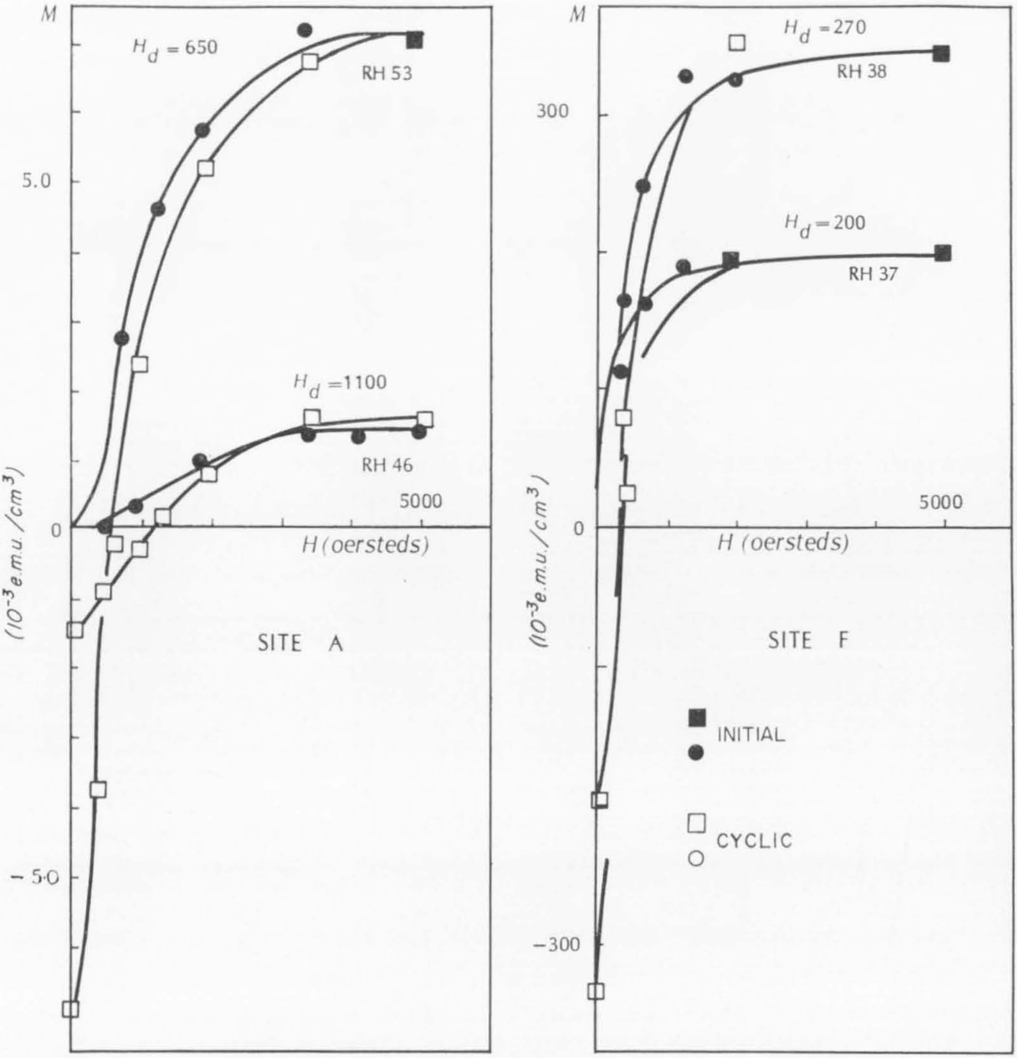


Figure 15. $M - H$ curves for Red Hill Dyke specimens G456–13

3.3.4 EFFECT OF PRESSURE. Some laboratory experiments were made in which rocks acquired magnetisation in the Earth's field under directed stress, using the apparatus described in Chapter 2. The results are given in Table 9 (Stott & Stacey, 1960). The second group are rocks from Red Hill Dyke; the two other groups are of dolerite from near Great Lake in central Tasmania.

TABLE 9. EFFECTS OF PRESSURE ON SPECIMENS OF TASMANIAN DOLERITE

Site	No. of specimens	Load applied (kg/cm^2)	Type of magnetisation	Angle of field to axis of load (degrees)	Mean angle of magnetisation (degrees)	Standard deviation of individual angles from mean (degrees)
(1) Core from bore 5001, Great Lake	13	0	TRM	46	46.5	2.9
	13	1,000	TRM	46	45.5	2.5
(2) Red Hill Dykesite E	4	0	IRM	49	49.8	0.5
	4	500	IRM	49	48.8	1.9
(3) Core from bore 5001—previously heated specimens from (1)	6	800	IRM	49	50.0	1.3

3.4 THE NATURAL REMANENT MAGNETISATION

3.4.1 DIRECTION OF MAGNETISATION. The mean direction of the nine dolerite sites from Red Hill Dyke (Table 6 and Figure 13a) are in good agreement with each other, except for site L. The angle θ between the direction at this site and the mean of the nine sites is 34°. The probability of this site coming from a formation with the mean direction $D_m = 308$; $D_m = -77°$, and with $N = 9$; $R = 8.71$ (see section 3.3.1) is:

$$P(\theta > 34°) = 0.0012;$$

the site is excluded on statistical grounds.

The remaining eight sites give:

$D_m = 293.6°$; $I_m = -74.7°$; $N = 8$;
$R = 7.9004$; $k = 70$; $\alpha = 6.7°$.

This direction makes an angle of 21° with the Earth's present field. The probability of the true mean direction being that of the present field is about 10^{-13}, so that the mean direction is significantly different from the present field (and even more significantly different from the dipole field). The direction at site L is closer to the present field (but deviates in a direction opposite to that of the other eight sites) and it might be that the rock is partially stable; however, the evidence from laboratory experiments does not reveal any difference in behaviour of the magnetisation from that of the other rocks and the most probable explanation is that the rock has been subjected to local earth movement.

The analysis of precision using the directions of the 92 specimens at eight sites is given below:

Source	Degrees of freedom	Sum of squares	Mean square
Between-sites	14	1.0610	0.0758
Within-sites	168	1.0308	0.0061

$B = 8$; $N = 92$; $R_{sp} = 89.91$; $r_i = 90.96$; $w = 82$; $b = 80$.
See section 1.8.3 for definition of symbols.

These values of within-site and between-site precisions are very similar to those found in the regional survey (Irving, 1956; Watson & Irving, 1957).

3.4.2 DISTRIBUTION. The specimen distribution is in agreement with Fisher's distribution with a probability greater than $P = 0.95$. The individual angles of 92 specimens at eight sites are distributed about the mean, in azimuth, within 45° sectors, clockwise from north: 12; 13; 21; 7; 7; 9; 16; 7; and deviations from the mean, in five ranges, each of 4°, between 0° and 20°, a sixth range for $\theta > 20°$, are: 7; 31; 21; 19; 2; 12. The chi-squared test is applied to these results; the test shows that the deviations from the mean in the second set appear to be significant, but this is entirely due to the excessive number having $\theta > 20°$. It is perhaps reasonable to assume an occasional gross error in measurement and to exclude the last group. The observed numbers are then in extremely good agreement with the expected distribution for 92 results: 12; 32; 22; 18; 6; and the chi-squared test shows no significant difference at the 5 percent level.

The dispersion of the results from Red Hill Dyke and the Tasmanian dolerite validly represents estimates of the same true dispersion K, for $k_{TD}/k_{RH} = 1.6$ (Watson & Irving, 1957, p. 292) and $F_{170,14} = 1.7$ at the 5 percent level (where F is the variance ratio).

The comparison of mean direction of the eight Red Hill Dyke sites with that from eighteen sites in southern Tasmania (Irving, 1956) gives a calculated value of $F = 2.54$, to be compared with the tabulated value with $F_{2,48} = 3.19$ at the 5 percent level (Watson, 1956a, p. 157), so that the mean directions appear to represent the same true mean.

To sum up, the samples from Red Hill Dyke have directions of magnetisation with a Fisherian distribution, the scatter is not significantly different from that of the Tasmanian dolerites as a whole, but the mean direction is significantly different from the direction of the Earth's present field.

3.4.3 DEMAGNETISATION BY ALTERNATING FIELDS. It was explained in section 2.3, that the removal of unstable magnetisation from the NRM of a rock, and the leaving of some stable magnetisation still present in a group of specimens from a formation should normally result in:

(a) Reduced scatter at any particular site;

(b) Reduced variation of between-site directions.

Table 7 in section 3.3.2 shows the results obtained when specimens from five sites are demagnetised in alternating magnetic fields. These show that only at site L (from near the contact) does the precision increase; at the others, it remains constant for values of $H_p\sim$ up to between 100 and 400 oersteds (the value varies from site to site) and then decreases until at $H_p\sim = 750$ oersteds the directions are widely scattered. The results are displayed graphically in Figure 16, where k is plotted against $H_p\sim$.

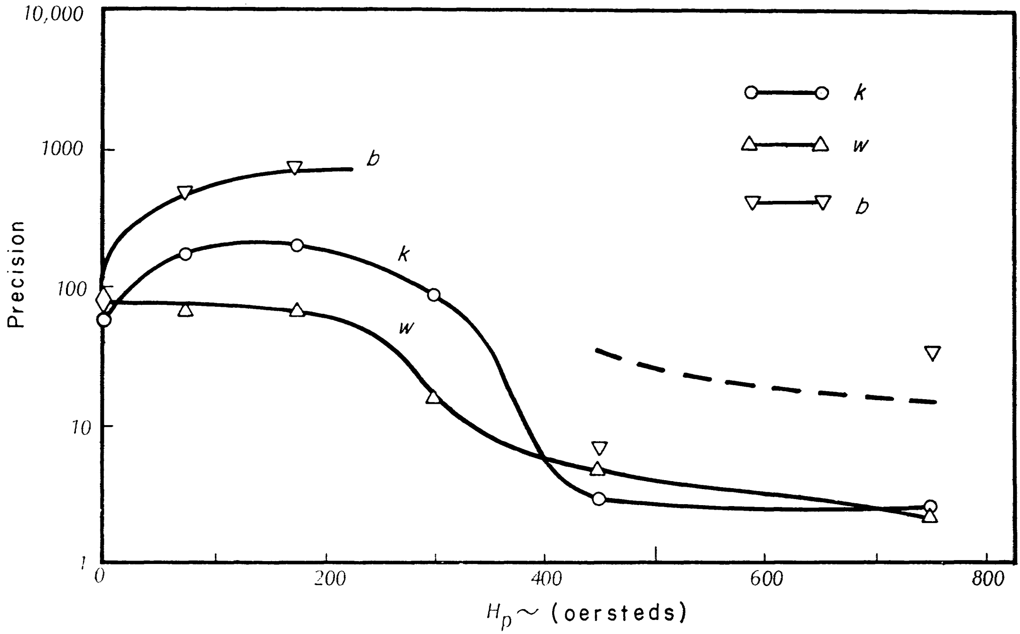


Figure 16. Variation of precision with demagnetising field

The agreement in direction between sites increases slightly up to 150 oersteds and then decreases rapidly after 300 oersteds. The increase in precision is not very large and it is apparent that there is either very little or no unstable magnetisation. For example, to test that the two directions—(i) the initial value; (ii) after 150 oersteds—represent the same direction of magnetisation, we have

$$(N\text{-}2) . \frac{(R_0 + R_{150} - R)}{(N\text{-}R_0\text{-}R_{150})} = 0.49$$

which has to be compared with $F_{2,16} = 3.63$ at the 5 percent level (Watson, 1956b). The angle between M_n and M_{150} is only 3.8°, well within the cone of confidence, with $P = 0.95$. Even the direction after 750 oersteds is less than 20° away from that at 150 oersteds.

3.5 DEFLECTION OF MAGNETISATION

3.5.1 MAGNETOSTRICTION. Magnetostriction is the change in dimensions which occurs when a body becomes magnetised. In rock magnetism, the term 'magnetostriction' has been used indiscriminately for all effects relating stress and magnetisation.

Graham (1955, 1956) suggested that magnetostriction in rocks which are intrusive in the form of tabular bodies might cause a deflection of the magnetisation away from the direction of the magnetic field prevailing at the time the magnetisation was acquired. The Tasmanian dolerites have just this form, and the near-vertical magnetisation might possibly be the result of such an effect. The results of laboratory tests, given in Table 9, show that axial loads of up to 1000 kg/cm^2 have no measurable effect. This pressure corresponds to a depth of burial of about 3000 m. Experiments in which specimens acquired TRM show results similar to those in which the specimens acquired IRM. One specimen (not a dolerite) was chemically altered during heating, but showed no deflection. This specimen must have acquired a magnetisation with components of TRM and CRM —more details are given by Stott and Stacey (1960). In the case of the Tasmanian dolerite, the magnetisation is thought to be TRM, so only the effect relating to TRM concerns this discussion. A short note by Hall and Neale (1960) gives results which show small deflections of up to 8° due to directed stress; however, the specimens concerned were extremely fine-grained dolerite. The dolerite from which the results given in section 3.3.4 were obtained had a grain size of about 200 μm (average linear dimension), whereas Hall and Neale obtained appreciable deflections only in rocks with grain size less than 100 μm. In Tasmania, such rocks would be found only at the chilled margins, which form an insignificant proportion of rocks sampled, and in Table 6 such rocks (site A) have a direction very close to the mean of the whole collection. It is important also to note that Hall and Neale used anisotropic specimens (Stott & Stacey, 1961); the effect of anisotropy can be quite large. Laboratory experiments demonstrate that magnetostriction is not likely to be important in connection with TRM of isotropic rocks (Stott & Stacey, 1960, 1961; Kern, 1961).

3.5.2 SELF-DEMAGNETISING EFFECT. Strangway (1961) has reported results from Canadian diabase (dolerite) dykes, which suggest that their magnetisation was deflected toward the plane of the dyke and, as a corollary to this, that the most stable magnetisation was due to the magnetic minerals with the lowest Curie point temperatures. A deflection such as this is theoretically predicted; it is due to self-demagnetising and Lorentz field effects, but it would not seem to be important in the case of most magnetised rocks. For an infinite tabular body (Figure 17) being magnetised in an external field H_e, the internal field H_i is given by:

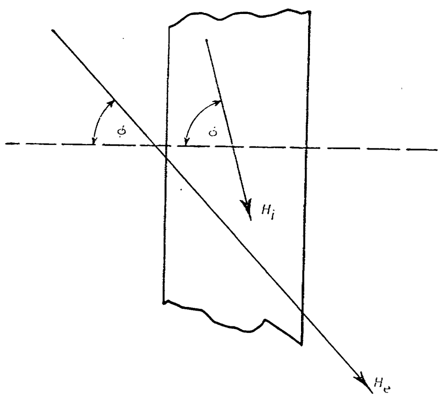


Figure 17. Self de-magnetising effect of a tabular body

G456—15

(i) for H_e perpendicular to plane of dyke,
$H_i = H_e - 4\pi M$
where M is the intensity of magnetisation of the rock parallel to H_e.

(ii) for H_e at angle ϕ to dyke
$H_i = H_e - 4\pi M . \sin \phi$.

In the Earth's field ($H_e \simeq 0.5$ oersted) the effect will not become appreciable for M less than 10^{-2} e.m.u./cm^3, averaged over the dyke. (This section was written prior to the appearance of Strangway's full results, but his figures confirm my conclusion, although by a rather different approach.) At Red Hill, only at site J does M_n reach this value; the average value of M will be 10^{-4} e.m.u./cm^3 or less. To see if the effect is present the results from Red Hill Dyke can be compared with those from Mount Wellington Sill, about 15 km to the north. These are tabular bodies with contrasting attitudes: Mount Wellington Sill is nearly horizontal and Red Hill Dyke almost vertical.

In the usual geomagnetic co-ordinates, let Red Hill Dyke be in the XZ plane; Mount Wellington Sill in the XY plane; and let the true field direction (H_o) when the dolerite cooled have a direction $D = 319°$; $I = -81°$ (H_o is the mean direction of the Tasmanian dolerite). The direction H_o makes an angle of about 7° with the plane of Red Hill Dyke and 78° with that of Mount Wellington Sill, and the shape effect (if present) would tend to deflect the magnetisation to a direction $D = 0$; $I = -90°$ for Red Hill Dyke (M_{RHD} in Figure 18) and a direction (319, 0) for Mount Wellington Sill (M_{MWS}). Figure 18 shows these directions plotted on an equal-angle stereographic projection, together with the mean of eight site mean directions at Red Hill Dyke, and of eleven at Mount Wellington Sill. There is no significant difference; if there is any deflection at all, it is in the direction opposite to that predicted.

It is difficult to comment on Strangway's results, but one can think of several alternative explanations; certainly the effect is unimportant in Tasmania. An important factor in Strangway's dykes is the existence of a stable, low Curie point mineral; this must be an uncommon state of affairs when combined with high intensities of magnetisation. As far as Tasmanian dolerite is concerned, no complete investigation has been made, but two points can be stated:

(1) There are in general, two main magnetic minerals with T_c = about 250°C and 550°C.

(2) Over 90 percent of M_n remains after heating to 450°C and cooling in zero field.

This means that most of the NRM (which has been shown to be stable) has $T_c > 450°$; that is, the stable magnetisation is mainly due to the high Curie point mineral (there is no evidence as to the stability of the low Curie point mineral).

3.6 CONCLUSIONS

The NRM of the dolerite at Red Hill Dyke is due to TRM acquired when the rock cooled (170 m.y. ago). Although magnetic cleaning improves the precision of the result, it does not significantly alter the mean direction of magnetisation. There is evidence that there is no systematic error due to stress or shape, and therefore that the direction of NRM is a reliable estimate of the direction of the geomagnetic field at the time of intrusion.

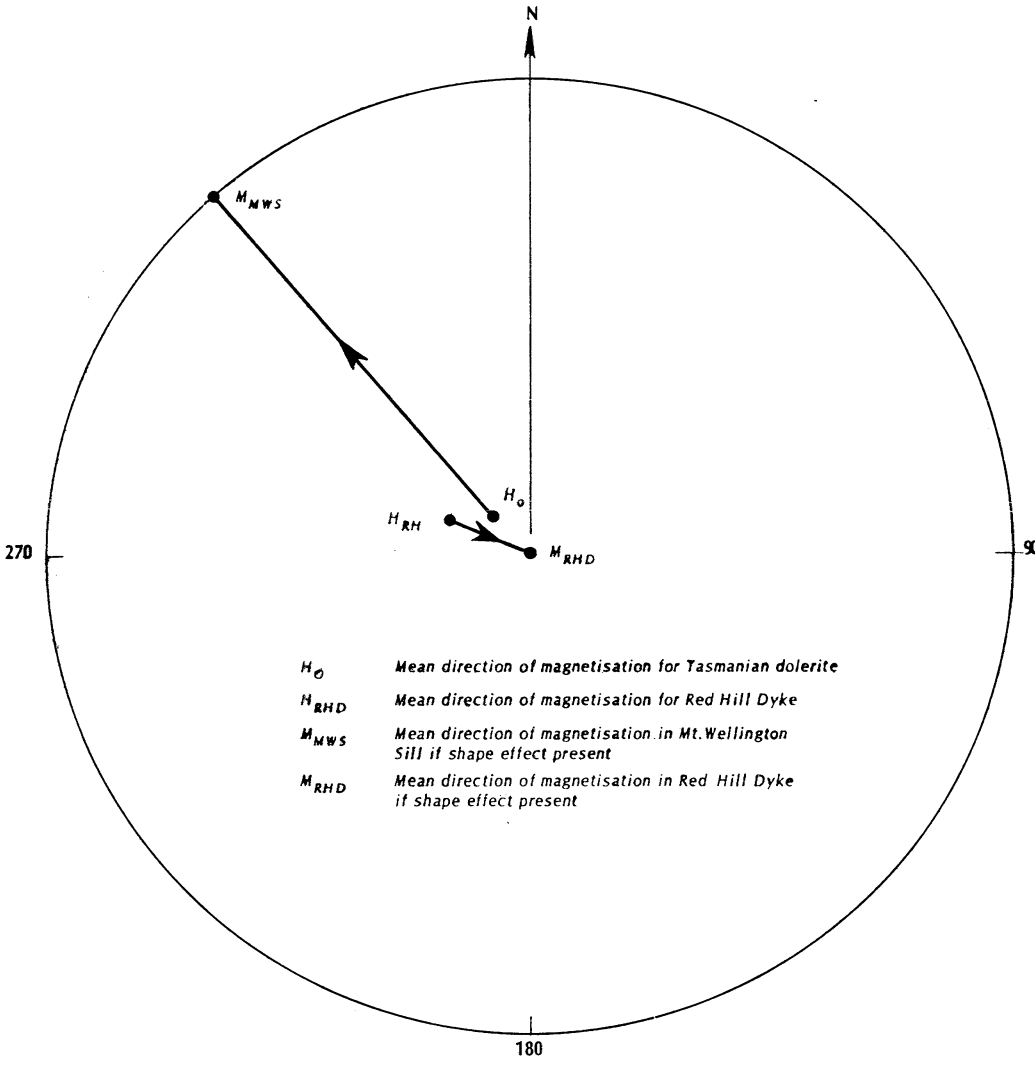


Figure 18. Test for the shape effect at Red Hill Dyke and Mount Wellington Sill G 456–16

3.7 GRAVITY AND MAGNETIC SURVEY

The results of reconnaissance gravity and magnetic surveys over Red Hill Dyke have been described by McDougall and Stott (1961). These surveys were undertaken whilst McDougall was studying the geology and petrology, and the form of the intrusion given earlier in this chapter is based to some extent on these surveys.

The gravity measurements fit reasonably well to a geologically realistic situation. There are discrepancies, noted by McDougall and Stott (1961; see especially p. 13) and the results and cross-sections presented are a compromise between the needs of geology (more dolerite) and geophysics (less dolerite). The nature of the terrain and quality of the observations make any more detailed interpretation unprofitable.

It is pertinent to consider briefly the magnetic results. When the paper was written, one possible reason for the uselessness of the magnetic measurements (though not then stated) was thought to be that all the observations were at stations along traverses which followed man-made tracks. These tracks, of various ages and degrees of dilapidation, were presumably made from dolerite boulders from the vicinity of the track; this meant that randomly directed magnetised rock was in close proximity to the magnetometer. Calculations show that boulders in the roadbed could conceivably annul the effect of the rest of the dyke because of their close proximity to the magnetometer. This explains why the magnetic observations can be used only to differentiate dolerite from sediments and accounts for the large and rapid variation in vertical magnetic force from station to station.

Since then, similar results have been found on traverses that did not follow roads or tracks (R. Green, private communication) and, although the explanation suggested may be true as far as the Red Hill area is concerned, it may also be an example of a more general phenomenon (which Green calls "the presence of 'non-magnetic' dolerite"). No explanation is attempted; the possible existence of this paradox is suggested for future study. However, if it is found that the magnetic anomaly over an isolated body of uniformly magnetic rock (or over rock with known, regular variations) is not the same as that calculated from classical potential theory, this may be disappointing in some respects, but it provides an explanation of the successful interpretation of magnetic anomalies in terms of susceptibility alone, even when remanent magnetisation of similar magnitude to, but different direction from, induced magnetisation is also present.

These more recent reflections make the original explanations of the magnetic results (McDougall & Stott, 1961) implausible; at present, it seems best to acknowledge the situation as puzzling, and to await more data.

TABLE 5. SITE DESCRIPTIONS

POSITION	ROCK DESCRIPTION
Site A: West contact, bed of Snug River, left bank. 0 to 1 m from contact (altitude: 70 m)	Chilled dolerite, usually very fine-grained holocrystalline, sometimes devitrified glass. Grain size $\approx$ 0.01 mm, small amount iron ore as crystals. (See M172)*
Site B: Same site as A, 0 to 2 m from contact (70 m)	Baked sediments
Site C: East contact, from roadside, about 15 m above bed of Snug River (70 m)	Baked sediments
Site D: About 15 to 30 m from west contact, in bed of Snug River (70 m)	Fine to medium-grained quartz dolerite. Mainly pyroxene and plagioclase with hosostasis of quartz and potash feldspar. Iron ore about 2%. (M212)
Site E: Melville Creek (north side of Snug River valley) (about 65 m)	Medium-grained quartz dolerite. (Between M9 and M209)
Site F(i): Centre of Red Hill Dyke in bed of Snug River (about 65 m)	Coarse-grained quartz dolerite. (M210)
Site F(ii): Centre of dyke, on roadside on north flank of O'Briens Hill (140 m)	Coarse-grained quartz dolerite. (M221)
Site G: Poverty Gully Creek, north of Red Hill (175 m)	Fayalite granophyre, mainly clinopyroxene and olivine, basic plagioclase, quartz and potash feldspar. (M384)
Site H: Centre of dyke on north flank of O'Briens Hill (230 m)	Fayalite granophyre, just above transition from quartz dolerite. (M223)
Site J: Summit of Red Hill (410 m)	Granophyre. Elongate crystals of pyroxene and plagioclase, abundant quartz and potash feldspar, up to 10 percent iron ore. (M19)
Site K: Near summit of O'Briens Hill (310 m)	Granophyre. (M176)
Site L: North flank of Red Hill, about 400 m NW of summit (175 m)	Granophyre. (M162)
Site M: Various sites: east flank of Red Hill, Margate, etc.	Unaltered sediments, Permian and Triassic

* Numbers 'M172' etc. refer to specimen numbers in McDougall (1960). The specimens referred to are either from the same site as those collected for this palaeomagnetic survey, or from nearby.

TABLE 6. SITE MEAN DIRECTIONS OF NATURAL REMANENT MAGNETISATION

Site	S	N	D_m	I_m	R	k	α
(a) *Dolerite:*							
A	3	10	301	−75	9.75	36	8
D	7	25	321	−84	24.83	140	3
E	5	9	279	−77	8.96	202	4
F	7	13	287	−70	12.93	161	3
G	2	5	283	−66	4.97	159	6
H	6	12	302	−79	11.89	100	4
J	3	9	299	−86	8.78	36	9
K	4	9	299	−58	8.86	57	7
L*	3	8	37	−58	7.88	57	7
Mean dolerite (9 sites)			309	−77	8.71	27	10
Dolerite (excluding site L)			294	−75	7.90	70	7
(b) *Baked sediments:*							
B	6	23	310	−79	22.60	55	4
C	4	12	315	+37	2.4		

At each site, N specimens are measured, cut from S samples; site mean directions, declination D_m (east of true north) and inclinations I_m (negative for north-seeking direction upward) are calculated by Fisher's method (Fisher, 1953) on specimens; R is the magnitude of the resultant vector; k the estimate of precision; α the semi-angle of the cone about the mean in which the true mean direction lies with $P = 0.95$; formation means are calculated from site means.

TABLE 7. SITE MEAN DIRECTIONS DURING DEMAGNETISATION AT FIVE SITES

Site	N	D_m	I_m	R	a_{95}	D_m	I_m	R	a_{95}	D_m	I_m	R	a_{95}
	Field:		NRM				75 oersteds				150 oersteds		
D	5	318	−84	4.96	8	289	−81	4.98	5	286	−79	4.98	5
E	5	286	−78	4.99	4	281	−76	4.95	8	298	−76	4.95	8
F	6	286	−70	5.97	5	287	−72	5.97	5	288	−71	5.94	8
J	3	308	−85	2.92	25	272	−79	2.89	30	270	−75	2.90	28
K	4	301	−61	3.96	11	288	−66	3.94	13	273	−67	3.96	11
	5 Sites:	296	−76	4.93	10	284	−75	4.98	6	282	−74	4.98	5
Mean													
	23 Specs:	295	−75	22.5	4	285	−75	22.6	4	284	−74	22.6	4
k			60				173				204		
w			88				68				67		
b			79				470				705		
	Field:		300 oersteds				450 oersteds				750 oersteds		
D	5	257	−81	4.96	7	221	−76	4.80	18	228	−67	4.56	27
E	5	291	−68	4.29	35	319	+48	2.43	··	118	+7	0.8	··
F	6	286	−68	5.78	14	279	−75	5.72	16	300	−40	3.21	73
J	3	299	−84	2.88	31	131	−78	2.94	22	71	−63	2.35	87
K	4	265	−70	3.86	20	271	−53	3.05	62	227	−73	2.95	67
	5 Sites:	280	−75	4.96	8	292	−67	3.59	56	161	−83	3.32	64
Mean													
	23 Specs:	280	−74	21.6	8	281	−72	15.4	22	256	−78	11.3	32
k			89				2.8				2.4		
w			15				4.4				2.0		
b			∞				6.7				32		

TABLE 8. AVERAGE MAGNETIC PROPERTIES

Site	Mn	κ	$M_{i(sat)}$	$M_{t(0\cdot6)}$	H_d	H_{sat}	M_{min}	$M_{min(t)}$
A	0.0068	0.058	3.67		900	5000		
B	0.0032	0.0113						
C	0.0003	0.015						
D	0.17	0.19	27.5	1.70	270	1500	0.010	0.020
E	1.30	1.30	150		215	1200	0.09	
F	3.43	1.69	240	6.94	250	1450	0.024	0.19
G								
H	3.76	4.15						
J	21.0		1020	20.2	280	2000	0.24	0.56
K	4.83	3.86					.027	
L	0.98		160	4.27				

All measurements of M and κ are in units of 10^{-3} e.m.u./cm^3; H in oersteds.

4. MAGNETISATION OF THE NETHERCOTE BASALTS

4.1 INTRODUCTION

Devonian rocks occur in a narrow strip along the southern coast of New South Wales, about 15 km wide, between Twofold Bay and Merrimbula. Brown (1930, 1931) distinguishes three stages: the Eden stage, the oldest of the three stages; the Yalwal stage; and the Lambie stage, all of which are thought to be Upper Devonian, on the evidence of marine fossils. The Nethercote basalts are lava flows (some may be intrusions) in the Yalwal stage; they are interbedded with fossiliferous red sediments. The sediments are magnetically unstable, but palaeomagnetic results have been obtained from the lavas (Green, 1960). There is negligible folding and the only evidence of stability was the existence of 'reverse' magnetisation at some sites and a 'normal' direction far removed from the present field direction; some of the samples were obviously very unstable.

The samples collected by Green (1960), and some from another five sites, have been tested for stability in the laboratory. It is not possible to present these results uniformly, as is done with the other results, in Chapters 3 and 5, because of accidental destruction of some of the records. The surviving measurements are shown site by site.

Table 10 gives the site descriptions and shows the relation between the sites mentioned here and those of Green (1960). All the sites are marked in Figure 19.

4.2 RESULTS OF MAGNETIC CLEANING

Because the measurements made and the methods of magnetic cleaning used in the early part of this research were not always those which were afterwards found to give the best results, the decision on whether or not a particular rock sample gives a direction of primary magnetisation cannot be made using the criteria adopted in other chapters. The results which showed evidence of stability are summarised in this chapter.

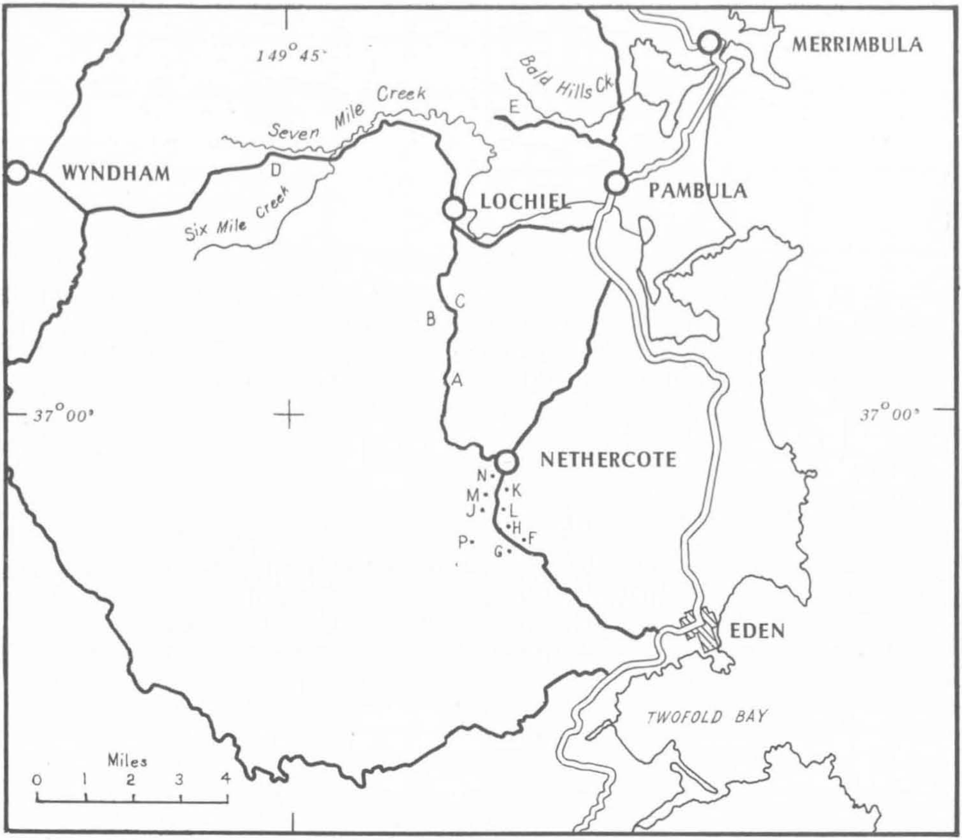


Figure 19 Location of collecting sites for specimens of Nethercote basalt

G456—17

4.2.1 SITES A-D. The results did not show evidence of a primary direction of magnetisation. Most of the specimens showed an increase in intensity in alternating magnetic fields of about 375 oersteds peak value. This may be due to spurious magnetisation acquired during magnetic cleaning (most of these measurements were made before the demagnetising apparatus was in its final form, i.e. before the 100-Hz filter was added, etc.). In many cases, the NRM of the specimens was directed at more than 90° to the present field and the increase in intensity may have been due to removal of secondary or temporary components of reversed magnetisation.

4.2.2 SITES E, G, K, L, AND P. Three or more specimens from at least two samples from each of these sites were submitted to alternating magnetic fields of about 375 oersteds peak value and gave the results shown in Table 11. They are remarkable in that the NRM is almost unaffected by this treatment. The exceptional stability of some of these rocks is shown in Table 12, where one specimen from each of sites K and P show changes in magnetisation less than about

5° in direction and 10 percent in intensity when 'demagnetised' in fields of up to 1000 oersteds peak value. (See also section 4.2.6.)

4.2.3 SITE F. The results of magnetically cleaning one specimen from each of three samples are shown in Table 13. The mean values have been calculated twice, once using all three specimens, and once using the first two only.

4.2.4 SITE H. Results from a specimen from each of three samples at this site are given in Table 14.

4.2.5 SITES J, M, AND N. The surviving results are too fragmentary to be considered in detail. At site J, there is a suggestion of a primary direction at about $D = 0$; $I = -25°$ in an alternating field of 600 oersteds. At site *M*, there is possibly some primary magnetisation with $D = 200°$, $I = -20°$ at $H_p\sim = 70$ oersteds; and at site N, with $D = 0°$, $I = -15°$ at 150 oersteds.

4.2.6 SITE P. Results at site P, additional to those included in section 4.2.2 above, are shown in Table 15 and will be discussed separately (see section 4.4.1).

4.3 MAGNETIC PROPERTIES

Values of susceptibility, saturation IRM, and destructive field are shown in Table 16.

4.4 DISCUSSION

The variations in the treatment given to specimens from the Nethercote basalts does not allow a uniform presentation of the results, as was mentioned earlier. Selection of specimens showing stable directions of magnetisation is made more difficult because their behaviour is also variable in a way completely different from the other rocks studied. For example, compare the remarkable stability of the direction and intensity of specimen E58.3 from Site P (Table 12) with specimen E42 from Site F (Table 13). In the first case, the direction changes only by two or three degrees and the intensity by 10 percent (which could very well be due to measurement error); in the second, the intensity drops by a factor of 200 and the direction by about 30°, but this is remarkably small in the circumstances. There are intermediate cases, and there are some cases where the intensity increases fivefold.

The results in 4.2.1 have been selected from the complete data. Results have been included when treatment of several specimens from a site in a particular demagnetising field reduces the dispersion. In many cases, results of one treatment only are available, and even where the dispersion increases slightly in say 300 oersteds, the result is included as showing more *prima facie* evidence of stability. Rocks which show almost no change in intensity and direction when subjected to demagnetisation in 500 to 1000 oersteds are also included. All specimens showing increases in intensity are excluded, irrespective of other considerations, except that very stable specimens showing apparent increases of less than 10 percent are included.

The results regarded as stable are summarised in Table 17 and Figure 20, which give the directions of the NRM, and directions after optimum demagnetisation. The NRM values are taken from Green (1960). The NRM values are

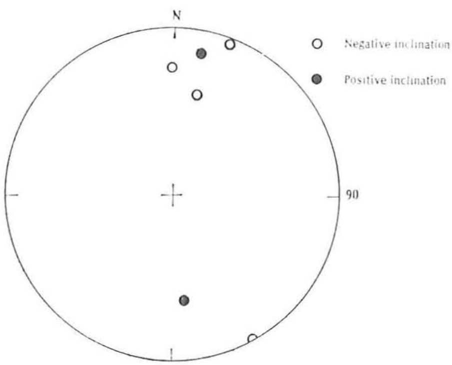


Figure 20. Directions of stable magnetisation after cleaning. Nethercote basalts.

taken from Green (1960). The NRM values are from seven sites and washed values from six (including five of Green's sites and one other). There is good agreement between Green's mean (5,—23) and the new value (2,—10), which is based on different criteria of stability. It is disappointing that the washed values are not less scattered (the dispersions, 15, and 14, are essentially the same), but the new values are more likely to be correct because of the more complete testing. The two sites that were regarded as stable by Green but not by the author are not necessarily unstable. The partial evidence available now merely indicates a 'not proven' verdict—very likely a retesting of these sites would prove them stable.

TABLE 10. SITE DESCRIPTIONS, NETHERCOTE BASALT

Site	(Site) (Green, 1960)	Location
A	—	Back Creek road from Nethercote to Lochiel; about 3½ miles south of Lochiel; road cutting near top of hill
B	—	Back Creek road; about 1½ miles south of Lochiel; in creek bed near road bridge (west of road)
C	—	As B; east of road
D	—	Pambula-Wyndham road; 350 yds west of Six-mile Creek, in creek bed below road; about 5 miles west of Lochiel
E	—	Bald Hills road from Pambula; near head of Bald Hill Creek
F	1	Road cutting; first (highest) outcrop on road from Eden
G	—	Road cutting below F; opposite farmhouse
H	2	Right bank of Nethercote Creek; to west of first bridge from Eden
J	3	As Site H, to east of bridge (downstream)
K	5	Bed of Nethercote Creek; about 1 mile south of township
L	4	Bed of Nethercote Creek; about ¾ mile north of K
M	—	Bed of Nethercote Creek; about midway between K and N
N	6	Bed of Nethercote Creek; immediately south of township
P	7	Landslide Creek, west of sites H and J

TABLE 11. SITE MEAN DIRECTIONS AT SITES E, G, K, L, AND P

Site	NRM					$H_p\sim = 375$ oersteds				
	D_m	I_m	N	R	α	D_m	I_m	R	α	M/M_n
E	216	—63	6	5.995	2	215	—64	5.994	2	0.99
G	170	+18	6	5.960	6	175	+25	5.966	6	0.87
K	20	—10	3	2.871	30	21	—1	2.990	9	0.95
L	0	—43	3	2.962	17	37	—46	2.934	23	
P	169	—16	4	3.998	3	169	—23	3.967	10	1.00

M/M_n is the ratio of remaining to initial NRM after treatment in an alternating field of 375 oersteds.

TABLE 12. DIRECTION AND INTENSITY OF MAGNETISATION OF TWO SPECIMENS FROM SITES K AND P

	Specimen E51.1 Site K			Specimen E58.3 Site P		
$H_p\sim$ (oersteds)	D	I	M (10^{-6} e.m.u./cm^3)	D	I	M (10^{-6} e.m.u./cm^3)
0	19	—3	80.3	170	+21	385
45	—	—	—	170	+19	368
65	21	+1	82.6	—	—	—
80	—	—	—	169	+19	380
170	—	—	—	169	+19	383
290	21	+3	76.4	172	+19	379
585	22	+1	74.8	—	—	—
645	—	—	—	169	+23	390
1050	22	—2	74.6	169	+23	414

TABLE 13. RESULTS OF MAGNETIC CLEANING OF SAMPLES FROM SITE F

Sample No.	NRM (O)			$H_p\sim = 180$			$H_p\sim = 330$			$H_p\sim = 615$			$H_p\sim = 1080$		
	D	*I*	*M*	*D*	*I*	*M*	*D*	*I*	*M*	*D*	*I*	*M*	*D*	*I*	*M*
E40	30	—30	36.5	24	—15	31.7	25	—13	30.8	17	—7	28.1	14	—4	24.4
E41	41	+1	44.6	29	—2	30.4	33	+6	25.4	34	—11	14.2	349	+1	13.2
E42	34	+55	22.90	35	+45	165	38	+46	92.6	18	+38	51.6	25	+27	11.6
Mean value ($N = 3$)	35	+7		29	+9		31	+13		23	+6		9	+8	
R		2.45			2.70			2.72			2.75			2.82	
Mean for E40 and E42 only	36	—15	40	26	—8	31	29	—3	28	26	—9	21	2	—1	19
R		1.92			1.98			1.97			1.98			1.95	

M is magnetic intensity in units of 10^{-6} e.m.u./cm^3 after demagnetisation in peak alternating field, $H_p\sim$ oersteds.

TABLE 14. SAMPLES FROM SITE H

Sample	O (NRM)			$H_p\sim = 120$			$H_p\sim = 735$			$H_p\sim = 1050$		
	D	*I*	*M*	*D*	*I*	*M*	*D*	*I*	*M*	*D*	*I*	*M*
E45	10	—58	409	15	—43	233	14	—31	66	73	—65	52
E46	9	—35	369	8	—33	334	12	—31	165	1	—18	129
E47	4	—2	110	14	—3	36	125	—28	19	108	—18	15
Mean	7	—32	296	12	—26	201	44	—43	83	60	—45	65
R		2.761			2.871			2.20			2.176	

M is magnetic intensity in units of 10^{-6} e.m.u./cm^3 after treatment in peak alternating field, $H_p\sim$ oersteds.

TABLE 15. RESULTS FROM FIVE SPECIMENS FROM SITE P

$H_p \sim$	D	I	R ($N = 5$)
0	122	—73	2.04
340	143	—28	2.64
600	168	+9	2.96
1050	158	+36	4.50

The values of D and I are the mean values for specimens E57.1, E58.3, E59.1.2, E59.1.3, and E59.2.2 after treatment in $H_p \sim$ oersteds.

TABLE 16. MAGNETIC PROPERTIES (INDIVIDUAL SPECIMENS)

Specimen and site	M_n	K	$M_{i(sat)}$	H_d	H_{sat}
E44(G)	0.03	0.06	10	(5000)	—
E46(H)	0.33	1.00	190	4000	1200
E49(J)	0.06	0.09	—	—	—
E52(L)	—	0.08	8	(5000)	—
E58(P)	0.38	0.07	38	5000	1250
E59(P)	0.27	1.56	208	4000	500

M_n, K, and $M_{i(sat)}$ are in units of 10^{-3} e.m.u./cm^3 and H_d and H_{sat} are in oersteds.

TABLE 17. SITE MEAN DIRECTIONS OF STABLE MAGNETISATION, NETHERCOTE BASALTS

Site		NRM*		After cleaning	
(Green's No.)		D_m	I_m	D_m	I_m
F	1	33	—5	8	+8
G	—	—	—	175	+25
H	2	351	—18	12	—26
—	3	13	—32		
—	4	0	—43		
K	5	19	—11	21	—1
N	6	349	—31	359	—16
P	7	349	—18	152	0
Mean:		5	—23	2	—10
		$R = 6.60$; $k = 15$; $\alpha = 16°$		$R = 5.63$; $k = 14$; $\alpha = 16°$	

* Values taken from Green (1960)

5. MAGNETISATION OF SOME TERTIARY BASALTS IN NEW SOUTH WALES

5.1 GENERALITIES

Scattered throughout the eastern fringe of Australia are numerous basalt flows; they are known to be of Tertiary age, but in nearly all cases there is no convincing evidence that places any closer time limit upon their age. Some attempt has been made to distinguish between upper and lower Tertiary on the basis of weathering, but only in Victoria do sediments occur between the flows and allow more exact dating.

One of the earliest palaeomagnetic surveys in Australia was of these Victorian basalts, the 'Older' and 'Newer Volcanics' (Green & Irving, 1958; Irving & Green, 1957). The Older Volcanics have a direction of magnetisation significantly different from those of the present actual surface field or the present dipole field; the Newer Volcanics do not, and this provides a basis on which other Tertiary basalts can be assigned to the upper or lower Tertiary. However, although measurements of NRM have proved successful in a few cases, many of the Tertiary basalts in New South Wales show unstable, or partially stable, magnetisation and this chapter describes the magnetic cleaning of rocks from two sites that exhibit the two extremes of stability and instability.

5.2 THE ROCKS

The rocks are all flat-lying flows of olivine basalt and the samples were collected from artificial exposures, generally road cuttings. Results from these sites have been reported in three published papers. The collecting site at Berrima is on the Hume Highway, 5 km northeast of Berrima and is the same as site 2 of Irving, Stott, and Ward (1961) and site D1 of Boesen, Irving, and Robertson (1961). At Robertson, the rock samples are from three localities (R1, R2, R3) within an area about 3 km across and are the same as those included in site 3 of Irving, Stott, and Ward (1961) and sites D2 of Boesen, Irving, and Robertson (1961). The sites are shown in Figure 21.

At Berrima, the rocks are from a single lava flow; at Robertson they may be from two or three flows, not long separated in time. The magnetic minerals form from about 1 to 5 percent (by volume) of the rock, and are of the magnetite-ilmenite series. The grain size is of the order 100 μm (linear dimension as seen in thin section). However, there is some variation, which may be related to differences in magnetic behaviour. Rocks collected at Berrima seem to be isotropic (no measurements of magnetic anisotropy have been made), but at Robertson some of the samples seem obviously anisotropic when seen in thin section, and this may influence the magnetic properties.

The method of magnetic cleaning described here has since been applied to similar rocks from six other sites in New South Wales by other members of the Department of Geophysics, Australian National University (see Irving, Stott, & Ward, 1961); the results of these are included here in Table 19 and are discussed later, since the results obtained from two sites must be considered within the framework of other results from rocks adjacent in space and time.

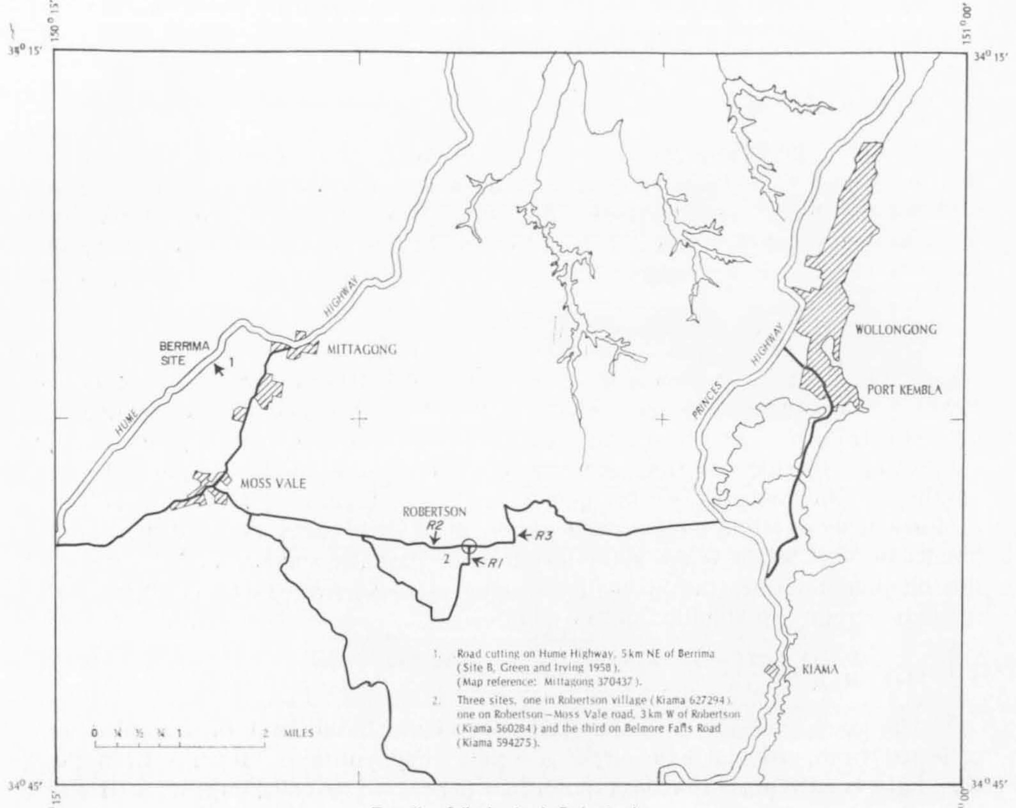


Figure 21. Collecting sites for Tertiary basalts.

5.3 RESULTS

The measurements of NRM and the magnetisation after magnetic cleaning on seven samples from Berrima and on six samples from Robertson are summarised in Table 18. Figure 22 shows the changes in direction during cleaning for the Berrima specimens.

Mean values of some other magnetic properties are given in Table 20.

5.4 STABILITY

The mean results show that when the specimens are treated in a field of 150 oersteds at Berrima and 300 oersteds at Robertson, the dispersion is least and the mean directions are more nearly the same in comparison with the values for NRM. Furthermore, when considered in relation to specimens from the six other sites in New South Wales (Table 19) the directions after treatment suggest that a stable primary component is present in the direction of the average geomagnetic field during the time at which these lavas cooled; this field corresponds to a southern hemisphere pole at 63°S, 137°E.

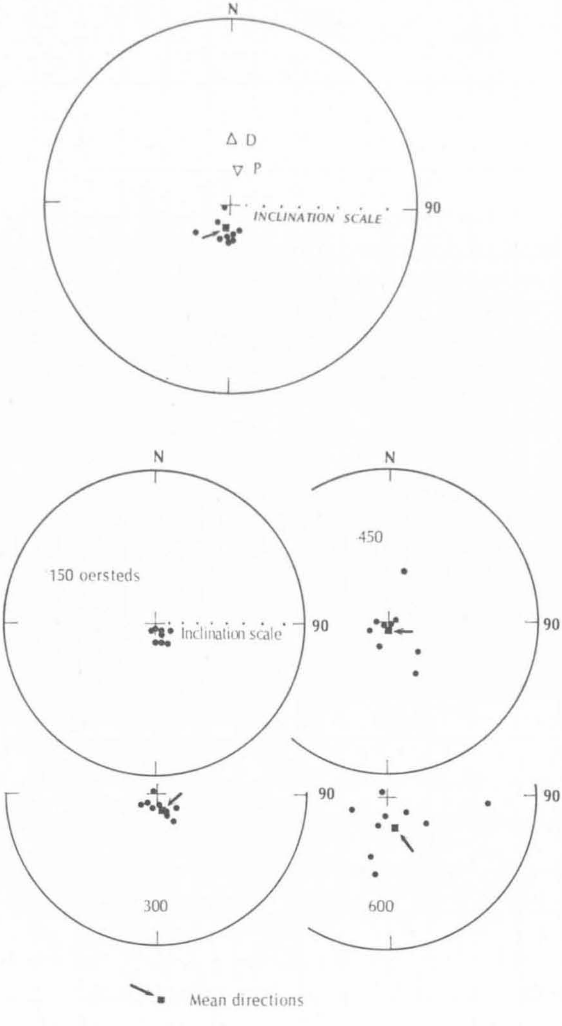


Figure 22. Directions at Berrima G456-20

However, these two sites discussed represent the extremes of the eight sites in New South Wales. At Berrima, there is very little secondary magnetisation and the mean direction of NRM is not significantly different from that of the stable, primary magnetisation. The specimens from Robertson have secondary magnetisation which is over 90 percent of the NRM and probably this is the maximum for it to be possible to detect and measure a more stable primary magnetisation. This is because of what may be called 'noise' from the demagnetised grains in the specimen. This is discussed in Chapter 6, but is briefly outlined here.

From Table 18 (Robertson) it can be seen that intensity of NRM is reduced to about a thirtieth of its value after treatment in 300 oersteds. Thus, under these conditions, there is present in a demagnetised state at least 30 times (and almost certainly more) the magnetic material producing the remanent direction. This 'demagnetised' material is in fact magnetised, but with no net resultant magnetisation on the average. However, there are several reasons why it will in practice have a net resultant, and this is included in the measured remanence; there is a point when the amount of 'demagnetised' material is so large that the randomly directed net resultant becomes comparable to any 'stable' magnetisation still present and this point is probably approached in these specimens.

The results from Robertson are analysed more completely in Table 21, which shows the results of demagnetisation at the three sites, R1, R2, and R3, separately (they were combined together in Table 18). The precision is broken down into within-site and between-site precisions by the method (Watson & Irving, 1956) outlined in Chapter 1. This table shows the significant mean direction after treatment in 300 oersteds and the results demonstrate that the demagnetised field can be considerably higher than the optimum value without seriously affecting the mean. In this case, giving each site unit weight, the 'best' value is in fact 450 oersteds rather than 300 (the value probably lies between these figures) but the difference in the means (242,78) and (277,84) is small. Even after treatment in 600 oersteds, the mean direction (234,61) lies within the circles of confidence of the means at 300 and 450 oersteds; this is not true of the mean direction of NRM.

5.5 MAGNETIC VISCOSITY

Materials placed in a steady magnetic field at a constant temperature sometimes show an increase of magnetic moment with time, over and above the reversible and irreversible magnetisations (susceptibility and IRM) that are produced almost instantaneously by the field (see Chapter 1). Viscous magnetisation in iron was investigated in the last century; more recently, it has been studied by Street and Woolley (1952) in technically important magnetic substances, and in magnetite powder by Shimizu (1960). Magnetic viscosity (sometimes called 'magnetic after-effect', although this term includes other phenomena connected with susceptibility and permeability) can be explained in terms of the 'relaxation times' of the magnetic domains; the theory as it applies to rocks is discussed by Néel (1955). The results described in section 5.3 show that the Robertson basalts have large secondary components of magnetisation, and some preliminary measurements showed them also to have appreciable temporary components of magnetisation, as defined in Chapter 1. The specimens are very suitable for experiments on magnetic viscosity in natural rock samples.

5.5.1 RESULTS. Four specimen discs from Robertson and two from Berrima, for comparison, were demagnetised in an alternating field of 900 oersteds, and the remaining magnetisation was measured. They were then placed in a fixed position in the local geomagnetic field (0.6 oersted) and the magnetisation was measured at intervals of three months or so. The results for small values of time t are not reliable because some specimens were so unstable that an appreciable part of the viscous magnetisation acquired in a few hours or days was lost during the few minutes that they were in zero magnetic field whilst being measured.

The results can be expressed by the relation:

$$\triangle M = \text{const} + V \log t \qquad (11)$$

where $\triangle M$ is the change of magnetisation in time t (i.e. $\triangle M$ is the viscous magnetisation produced). The slope V has been called the 'magnetic viscosity coefficient' by Shimizu (1960). In the Rayleigh region of magnetisation, the instantaneous moment M, induced by a field H is $M = aH + bH^2$ and Shimizu shows that in this region, V is related to the S_v of Néel (1955); V is proportional to bHS_v where b is the same as that in the first Rayleigh relation, and the theoretical formula of Néel is:

$$M = M_o + CS_v\,(Q + \log t) \qquad (12)$$

where C is the irreversible susceptibility at the point (M_o,H) of the hysteresis cycle, Q is a numerical constant of the order of 40 or 50, and S_v has the dimensions of a magnetic field and is characteristic of the material.

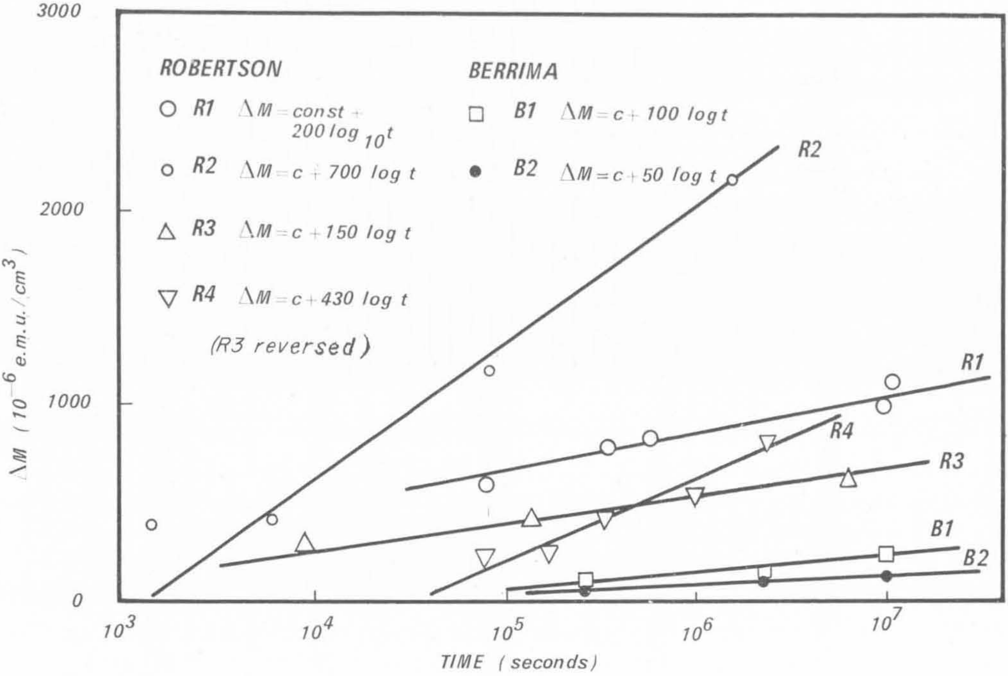


Figure 23. Viscous magnetisation G456–21

Figure 23 shows the results in terms of equation (11); $\triangle M$ is measured in units of 10^{-6} e.m.u./cm^3 and t in seconds. The constant term arises from the initial remanent magnetisation and may be regarded as arbitrary. One specimen from Robertson was turned through 180° after it had acquired some viscous magnetisation in the reverse direction (Line R5)—the two processes are not necessarily independent.

Measurements were not made over a time long enough to extrapolate the results with any accuracy, but qualitatively, the Robertson rocks acquire more viscous magnetisation than those from Berrima. Rough calculations show that the specimen R1 in Figure 23 would acquire a moment of more than half the measured NRM in 30 million years; B1 from Berrima would acquire about 10 percent of the NRM (see Chapter 6).

5.6 CONCLUSIONS

The Tertiary basalts of New South Wales show a wide range of stability. The NRM consists of primary TRM and varying proportionate amounts of secondary magnetisation, which is almost certainly viscous. The secondary component is probably acquired in the present Earth's field, although this cannot be established from the results of magnetic cleaning. The reason for this is that the primary direction is almost directly opposed to the present field direction so that the resultant direction of NRM may move along any great circle passing through these directions.

There are several ways to calculate the direction of secondary magnetisation; the secondary magnetisation removed between 0 and 150 oersteds at Berrima has a direction (0,+72) and that removed between 0 and 300 oersteds at Robertson has a direction (49,+1). These figures are for net magnetisation removed, which inevitably is a mixture of primary and secondary magnetisation. The secondary direction could possibly be found by taking the net direction removed to be composed of primary and secondary magnetisation in the proportion by which TRM and IRM are reduced in these fields. However, there is no reason to suppose this is correct and for reasons given above, even a true answer would have little meaning, and so no further analysis is attempted.

The result given earlier, that a pole at (137°E, 63°S) represents the average geomagnetic field in eastern Australia, follows from the assumption that a direction of primary magnetisation has been found, and is that given in Table 19. This direction indicates a lower Tertiary age, by comparison with the Older Volcanics of Victoria. The similar dispersion of the Older Volcanics may indicate that a similar period of time is sampled in both cases, but the evidence on this point is not conclusive. If the conclusion be accepted, the evidence from Victoria is for a period of 10 to 20 million years during the lower Tertiary.

Of the eight sites discussed in this chapter, Robertson is not only the least stable, it is considerably less stable than any of the other sites and is not typical of the basalts as a whole and probably represents, approximately, the least stable rock in which the primary component can be detected. As was the case at Nethercote, the reason for this instability, and for the variation in stability, will not be known until more geological and mineralogical information becomes available. Magnetic cleaning is a means of detecting unstable components; the discovery of the cause must await more evidence and more detailed study.

TABLE 18. MEAN DIRECTIONS AND INTENSITIES DURING CLEANING

$H_p\sim$	D_m	I_m	R	k	M_m
Berrima					
0 (NRM)	187	76	10.78	44	6.9
150	164	79	10.92	177	3.7
300	165	79	10.85	68	1.9
450	184	84	10.09	11	1.3
600 (N = 10)	171	70	7.75	4	1.2

These values are from 11 individual specimens (except at 600 oersteds, when there are 10 specimens) from 7 rock samples.

$H_p\sim$	D_m	I_m	R	k	M_m
Robertson					
0 (NRM)	228	37	3.42	1.3	21.0
150	294	70	5.23	1.7	1.6
300	240	75	8.43	3.9	0.8
450	250	81	7.65	3.0	0.4
600 (N = 10)	231	60	6.55	2.6	0.6

These values are from 11 individual samples (except at 600 oersteds, when there were 10 specimens) from 6 rock samples.

D_m and I_m are mean values of declination and inclination; M_m is the mean intensity (in units of 10^{-3} e.m.u./cm^3), after treatment in peak alternating field $H_p\sim$ (oersteds).

TABLE 19. MEAN SITE DIRECTIONS FROM SIX OTHER SITES IN NEW SOUTH WALES

(Irving, Stott, & Ward, 1961)

Collection sites	Lat. S.	Long. E.	S	N	Mean directions of NRM				Mean directions after treatment in alternating fields				Pole position (primary magnetisation)	
					D_m	I_m	R	k	D_m	I_m	R	k	Lat.	Long.
Nimmitabel	36° 30′	149° 16′	3	4	167	+59	3.50	6	166	+88	3.63	8	40	150E
Liverpool Ranges	31° 38′	151° 41′	2	4	57	—12	3.94	54	140	+47	3.92	41	55	126W
Yarrowitch	31° 15′	151° 58′	7	16	274	+46	13.32	6	219	+60	15.35	23	57	91E
Ebor	30° 25′	152° 20′	3	5	190	+60	4.41	7	191	+62	4.53	8	74	122E
Armidale	30° 31′	151° 39′	6	10	166	— 3	7.78	4	199	+45	9.46	17	73	55E
Myall Creek	29° 47′	150° 44′	3	5	92	+84	4.94	65	209	+82	4.88	33	44	140E

S is the number of samples and N is the number of specimens cut from these. Mean site directions of NRM and the mean directions after removal of the secondary and temporary components are given. The lavas are flat-lying and no correction for geological tilt is necessary. D is the declination east of true north, I is the inclination positive downwards, R is the resultant and k is Fisher's (1953) precision parameter. The mean pole is 63S, 137E ($N = 8$, $R = 7.21$, α (P0.05) $= 20°$).

TABLE 20. AVERAGE MAGNETIC PROPERTIES

Site	M_n	K	$M_{t(sat)}$	$M_{t(0\cdot6)}$	H_d	H_{sat}	M_{min}
Berrima	4.9	0.43	130	5.0	225	1700	0.3
Robertson (1)	10	1.52	380	2.5	265	1400	—
Robertson (2)	15	0.46	105	1.0	165	600	—
Robertson (3)	23.6	0.46	140	—	190	800	—
Robertson (mean)	18	0.72	190	2.0	200	900	0.17

Magnetic intensities and susceptibility are in units of 10^{-3} e.m.u./cm^3; magnetic fields in oersteds.

TABLE 21. ANALYSIS OF PRECISION DURING MAGNETIC CLEANING OF SAMPLES FROM THREE SITES AT ROBERTSON

	NRM				150 oersteds				300 oersteds				450 oersteds				600 oersteds			
Site	*D*	*I*	*R*	*k*	*D*	*I*	*R*	*k*	*D*	*I*	*R*	*k*	*D*	*I*	*R*	*k*	*D*	*I*	*R*	*k*
R1 ($N = 4$)	221	+22	2.37	1.8	241	+48	3.80	15	233	+38	3.77	13	232	+56	3.55	6.7	262	67	1.86 ($N = 3$)	1.7
R2 ($N = 4$)	351	—79	0.36	1	345	65	1.62	1.3	20	80	2.88	2.7	342	74	1.82	1.4	242	34	2.63	2.2
R3 ($N = 3$)	247	+68	1.63	1.5	29	22	1.63	1.5	54	84	2.97	69	63	76	2.94	36	173	70	2.67	6.1
Mean (sites) ($B = 3$)	237	15	1.23	1.1	345	65	2.22	2.6	242	78	2.65	5.8	277	84	2.78	9.1	234	61	2.76	8.4
Mean (specimens) ($N = 11$)	228	37	3.42	1.3	294	70	5.23	1.7	240	75	8.43	3.9	250	81	7.65	3.0	231	60	6.55 ($N = 10$)	2.6
w				1				2				6				3				3
b				—				9				9								

6. THE MAGNETISATION OF ROCKS

6.1 INTRODUCTION

During the last thirty years or so, magnetic theory has been developed to a point at which many of the experimental results can be explained. The impetus to the recent rapid advance in ferromagnetism has been the need for, and discovery of, new magnetic materials. Theoretical progress, however, has inevitably been greatest in connection with technically important magnetic materials, mainly because of the large amount of observational data available, and the special problems of rock magnetism have not received sufficient attention for many of the phenomena to be explained. In some respects, neither theory nor experiment is ever likely to give complete satisfaction for palaeomagnetism—one of the more important aspects is the possibility of long-term stability of magnetisation (over hundreds of millions of years) and by its very nature, this will never be proved.

The magnetic properties of rocks are discussed by Néel (1955) in a paper which is perhaps the first to apply modern magnetic theories directly to rocks. Néel showed that the observations could be largely explained by assuming the magnetisation to be due to an agglomeration of single-domain magnetic particles in a non-magnetic matrix. It was known that most of the particles are far too large to be single domains and, although Néel did consider the effect of multidomain particles and thereby explained some phenomena not explicable on the single domain theory, other phenomena now became inexplicable. Despite these difficulties, the Néel theory is of great importance, and other attempts to explain rock magnetism (Stacey, 1958, 1959, 1961; Verhoogen, 1959) suffer the same defect of providing explanations of only some of the phenomena.

It is now apparent that in many ways, the magnetisation of rocks behaves as though it is due to a mixture of single and multidomain particles. Recent theoretical ideas accept this, although the origin of the hard 'single-domain type' magnetisation is ascribed to several causes. It should be mentioned that, in the case of rocks containing haematite, it is possible for the magnetisation to be due only to single-domain particles, because the critical maximum size for a single domain is much larger than for magnetite.

6.2 ROCK MAGNETISM

The more relevant points of three recent theories are now set out; but the original papers should be consulted for details.

6.2.1 NÉEL'S THEORY. A paper by Néel (1955) in which he considers problems of rock magnetism includes most of the relevant theory; although Néel returned more recently to this problem, the 1955 paper is the latest of his work on the broad topic of rock magnetism to be published and it is taken here as the exposition of Néel's theory.

After reviewing the necessary basic ideas in the theory of ferromagnetism and ferrimagnetism, which can now be found in any of the more recent textbooks, Néel goes on to consider some practical aspects in detail.

Single-domain theory predicts that TRM is much more stable than the IRM acquired in the same field; this agrees with experiment, but leads to the conclusion that TRM is independent of the applied field, H. However, taking reasonable account of thermal agitation, Néel finds that:

$$M_{(o)} = vM_{s(o)} \tanh[(vM_{s(T)}H_T)/kT] \qquad (13)$$

where $M_{(o)}$ is the TRM at room temperature; M_s is the spontaneous (saturation) magnetisation at the temperature concerned; T is the 'blocking' temperature, i.e. the temperature at which the critical diameter is equal to the actual diameter of the ferromagnetic grains; v is the volume of grains per unit volume; and k here is Boltzmann's constant. The terms 'blocking' temperature and 'critical diameter' refer to concepts introduced by Néel. Each single-domain grain has a 'relaxation time' (the time for the magnetisation to reverse—there are usually only two anti-parallel directions of stable magnetisation within a single domain), which is dependent on the size, shape, and temperature. Because the variation in relaxation time changes rapidly with volume and temperature, e.g. in iron, the relaxation time changes from 10^{-1} to 10^{-9} seconds when v/T changes from about $3\text{x}10^{-21}$ to $7\text{x}10^{-21}$, then at a particular temperature, there is a well-defined diameter for which larger particles will retain their magnetisation more or less indefinitely, whilst smaller particles will quickly be magnetised in any applied field, H. Furthermore, over a range of particle sizes, there will still be a fairly small range of temperature in which the magnetisation (TRM) is acquired. In an assemblage of grains of equal size, there is a definite blocking temperature, some few degrees below the Curie point, at which all the TRM is acquired; in a more realistic case where there is a range of grain sizes, there will be a spectrum of blocking temperatures, each associated with those particles having the corresponding critical diameter.

For small values of the magnetising field H_T at temperature T, equation (13) shows TRM to be proportional to the field.

Considering larger, multidomain grains, Néel obtained the expression:

$$M_{(o)} = 2H_T^{\frac{1}{2}}H_c^{\frac{1}{2}}/N \qquad (14)$$

where $M_{(o)}$ is the TRM at room temperature; H_c is the coercive force at room temperature and N is the demagnetising factor. In this case, TRM is proportional to $H_T{\frac{1}{2}}$. It is possible to modify this expression to make $M_{(o)}$ proportional to H_T (as is found experimentally) by making assumptions, theoretically reasonable but experimentally unverifiable, about the magnetising process.

Both single and multidomain theories predict that remanent magnetisation will decay proportionally to the logarithm of time after the magnetising force ceases (and in the case of IRM, the amount of magnetisation acquired will vary similarly with the length of time the field is applied). The constants involved depend on rather indeterminate factors and the experimental data, in any case, are too meagre to decide their values.

In case of temperature, two hypotheses have been proposed for multidomain grains. Néel regards decay as being caused by a fluctuating field due to thermal agitation, which enables a domain wall to overcome barriers to its movement; the probability of this happening is based on thermodynamic energy considerations. Street and Woolley (1949) suggest that thermal agitation may affect the height of the barrier to be crossed and hence the energy required to move the domain wall. The first hypothesis leads to a viscosity coefficient which varies as the square foot of the temperature; the second to a direct relationship; whereas such experimental results as are available lie close to a variation with $T^{\frac{3}{4}}$.

6.2.2 STACEY'S THEORY. Stacey (1958) proposed that at the blocking temperature, the crystalline anisotropy and magnetostriction coefficients equal zero, and only magnetostatic effects control the magnetisation. This leads to an expression:

$$M_{(o)} = \frac{H_T M_{s(o)}}{N M_{s(T)}} \cdot \frac{1}{1 + N\kappa_o} \qquad (15)$$

where κ_o is the susceptibility at room temperature and the other symbols are as before.

In a later paper Stacey (1959) proposed that multidomain grains are made up of rod-shaped domains. Stacey shows that this leads to a lower energy than the lamellar domains assumed by Kittel (1949) and Néel (1955). (This is not to be taken to imply that either Kittel or Néel thought lamellar domains existed. It is impossible to calculate an actual domain structure, except in simple cases such as the 'picture frame', but Kittel pointed out that the domains must arrange themselves to make the least magnetic energy and, as an example, showed lamellar domains were a possible method of doing this in a perfect cubical grain. Stacey showed that rods were even better, but nobody imagines that either will actually occur in nature).

The magnetically, very hard component of TRM is postulated as due to 'pseudo-single domain' behaviour of small grains which are, however, too large to be true single-domain grains (Stacey, 1961). It is also suggested that within a single grain, from a consideration of the magnetic energy involved, the domain size decreases towards the edges. This gives rise to a spectrum of demagnetising fields and Stacey gives the results of calculations based on grains with simple geometrical shapes (spheres and cubes).

6.2.3 VERHOOGEN THEORY. Verhoogen (1959) draws attention to the fact that TRM in rocks is very variable, so that it is impossible to predict the value in particular cases. For example, the intensity of TRM acquired by rocks having the same composition is unpredictable and whilst part of this may be due to different grain size, etc., not all of the variation can be explained in this way. Verhoogen concludes that the unexplained variation is suggestive of a structure-sensitive property. That some part of the TRM in many rocks can resist demagnetising in alternating fields of over 500 oersteds must also be considered. Both of these can be explained by postulating that some of the TRM arises from stressed regions surrounding dislocations. Verhoogen calculates the size, shape, and number of such regions necessary to explain the hard component of TRM and finds them consistent with what is known from other experiments.

In other words, effects apparently due to small single-domain grains can occur without the actual occurrence of particles with sufficiently small physical dimensions. Verhoogen concludes that the stable part of the NRM should depend on the number of dislocations per unit volume and should therefore be greater in rapidly cooled rocks (extrusives, chilled margins) than in slowly cooled plutonic rocks.

6.3 EXPERIMENTAL RESULTS AND THEORETICAL PREDICTIONS

It is often difficult to reconcile experimental results in rock magnetism with theoretical predictions. In almost every case, theoretical calculations are based on such drastic simplifying assumptions (equal grain size, spherical grains, and so on) as to make any quantitative comparison with natural rock specimens impossible. Although qualitative comparison may be made, this is commonly 'qualitative' to such an extent that it is impossible to decide between conflicting predictions on crucial matters. It seems too, that because of the variations in the magnetic behaviour of rocks, especially between distant localities (there does seem to be a certain similarity in the behaviour of rocks from a particular area, even though they be of different ages), theoretical predictions based on data gathered in one part of the world are nullified by data from elsewhere.

For example, the statement ". . . TRM is commonly greater in the chilled margins of a lava flow than in its interior" (Verhoogen, 1959) is not true of the rocks from Red Hill Dyke (Chapter 3). Admittedly, this is not a lava flow, but the argument should apply equally (if not more so) because the variation in cooling time between the chilled margins and the interior is much greater. In fact, the statement quoted must apply very locally, because it has been generally found ". . . that in extensive work on hypabyssal dolerite intrusives . . . and plutonic intrusions of gabbro . . . few cases of instability have been found, whereas instability in basalts is very common . . ." (Irving, Stott, & Ward, 1961).

6.3.1 THERMOREMANENT MAGNETISATION. It is generally agreed that the primary magnetisation of igneous rocks is due to TRM acquired when the rock cooled and that TRM is the most stable form of magnetisation (see, for example, Nagata, 1961; Chapter 9). Subsequently, two processes can, and do, take place: the original (primary) TRM will decay with time; the rock acquires a secondary magnetisation, commonly viscous magnetisation, possibly in a direction different from that of the primary TRM. Changes in the chemical or physical state, reheating, and so on, may also occur, giving rise to other kinds of secondary magnetisation, but apparently this has not occurred in the rocks studied in this Bulletin.

The decay of TRM over geologic time is not known. Qualitatively, it is known that TRM may persist for periods of the order 10^9 years and a decrease in intensity proportional to log*t* seems reasonable. This type of decay (and growth), can be observed with IRM in the laboratory and gives rise to viscous magnetisation (discussed later), but it has never been observed in the case of TRM. The general observation that older rocks tend to have smaller values of NRM may be a consequence of this decay; however, there are other possible explanations, for example a change in the magnitude of the Earth's field.

The important point is whether or not the decay of TRM involves a change in direction, as well as a reduction in intensity. Stacey (1958) suggests that in multidomain grains, the self-demagnetising field of each domain will be several times stronger than the external geomagnetic field and that decay involves no change in direction, because the internal field is exactly opposed to the magnetisation. However, because TRM acquired in fields of the order of one oersted is a tenth or less of the saturation remanent magnetisation, it follows that the remanence is due to the vector resultant of the net magnetisation of individual grains and that there is only slight preponderance of grains magnetised in the half of the complete solid angle nearer to the applied field. Most of the grains will have randomly directed magnetisation and, although internal fields may be most important, the external field will tend to demagnetise preferentially those grains with magnetisations opposed to the ambient field.

Even if the demagnetisation process is not controlled by self-demagnetising fields, it is reasonable to suppose that decayed TRM will have randomly directed magnetisation in the absence of any other controlling factor. It may be argued that the external field during the decay will be a controlling factor, but this, and the effect mentioned in the previous paragraph, is really viscous magnetisation.

There is no reason to suppose that the decay of primary TRM alone affects the direction of NRM.

6.3.2 SECONDARY MAGNETISATION. It is well established that in some rocks, the NRM measured is the resultant of an original magnetisation acquired when the rock was formed and magnetisation acquired since that time. The terms 'primary', 'secondary', and 'temporary' components introduced by Creer (1957) have been used in this Bulletin and are defined in Chapter 1. There are several kinds of secondary and temporary magnetisation, but in the rocks considered, only viscous magnetisation (and possibly anhysteretic magnetisation due to lightning or temperature changes) is important. Anhysteretic magnetisation behaves in a similar way to viscous magnetisation, i.e. its resistance to demagnetisation is intermediate between TRM and IRM and although magnetisation by lightning currents may be detectable by the field relationships of the directions of NRM (Rimbert, 1958; Graham, 1961), it is unlikely that other forms of anhysteretic magnetisation will be easily distinguishable from viscous magnetisation. There is no evidence that the Tasmanian dolerite has undergone any chemical change or been reheated since its formation and it is safe to assume that the NRM is due to TRM from the time of cooling, together with (in some cases) an insignificant amount of viscous magnetisation that has been acquired since.

The samples collected from Red Hill Dyke show a very stable magnetisation. The results show that some less stable component is sometimes present, but it was impossible to measure any viscous component acquired in the laboratory. It could well be that there is some secondary magnetisation in the direction of the present actual surface field or the present dipole field, but the amount is well under 10 percent and can be disregarded.

The basalts from Nethercote need further study to find out the reasons for the extraordinary stability in some samples and the extreme instability in others. Although the wide range of stability in specimens from the same site may prove to have some interesting cause, it is more probable that the reason is simply that they come from different lava flows and this will have to await more detailed geological mapping; at the moment this will be assumed and the local variation in stability is of little interest. Some of the basalts show signs of deuteric alteration. In this area, 'spilitic' lavas have been found and if this means that they were extruded under the ocean it is possible that this is the cause of the alteration. At the moment there is insufficient data to decide whether or not deuteric alteration is associated with magnetic stability—there is an impression that altered rocks are more stable, but this is not established.

However, if deuteric alteration is caused by saltwater, it will take place when the lava flows are formed, although possibly at a low temperature. Any CRM produced would be controlled by pre-existing or co-existing magnetic minerals; this may conceivably cause a reversal of NRM, but it is not likely to affect the direction (disregarding sign). The results given in Chapter 4, therefore, record the Upper Devonian geomagnetic field, but perhaps the existence of reversals is not proved from these particular results. There is undoubtedly secondary magnetisation that is not CRM present in some of the specimens discussed and there is not definite evidence that CRM is present in any specimen and for the moment, no more can be said.

The Tertiary basalts of New South Wales (Chapter 5) are a good example of rocks in which secondary magnetisation, probably viscous, is present to a varying extent. At Berrima it is almost completely absent and at Robertson it almost completely masks the primary magnetisation.

In these three formations, and in many others elsewhere in Australia, there is evidence that the most important type of secondary magnetisation is viscous magnetisation. This is probably true of most basic igneous rocks from most parts of the world—perhaps excluding Africa (for example) where local circumstances (i.e. the greater incidence of thunderstorms) may make anhysteretic magnetisation or IRM a more prominent disturbing factor. In the following sections, attention is concentrated on rocks having a primary TRM and secondary viscous magnetisation, because this is the commonest case in rocks of palaeomagnetic interest.

6.3.3 VISCOUS MAGNETISATION. The elementary experimental observations of viscous magnetisation in Chapter 5 are reported because there seems to be no other account of magnetic viscosity in natural rock specimens. The results given by Creer (1959) involve magnetic viscosity, and results similar to those in Chapter 5 could probably be derived from his observations. It is simpler to have results which can be used directly.

The observations on rock specimens agree with the theoretical prediction that the viscous moment is proportional to log$t$, t being the time (in seconds in the experiments) during which the magnetising field is applied. It must be admitted that the results given in Chapter 5 do not brilliantly illustrate a relation of the form $A = B + C \log D$. The results are scattered and it is likely, should a different relation be proposed, that they would fit equally well; obviously a more extended series of observations is needed. However, they do not contradict the hypothesis, for which there is other evidence, and the magnitude of the viscosity coefficient S is reasonable, compared with the results of Shimizu (1960). Shimizu's experiments are closest to nature (as far as rock magnetism is concerned) of any so far reported. Values of S given in Chapter 5 are of the order 1/10 to 1/100th of the values found by Shimizu, who used magnetite. The values should be proportional to the magnetisation (and hence to the concentration of magnetite) and the rocks contained about 1 to 10 percent magnetite.

Shimizu found a log$t$ relation and it is reasonable to assume that this theoretical prediction is in accordance with experimental results. As to the magnitude of S, probably the best that can be said is: "generally speaking, the . . . results are in qualitative agreement . . ." (Shimizu, 1960; p. 136). However, it is comforting to agree with Shimizu that ". . . TRM of igneous rocks ought to [retain their] initial condition during their whole life . . ." (Shimizu, 1960). In the least stable rocks from Robertson, it is calculated that viscous magnetisation might account for 50 percent of the NRM. Even if experiments over a longer period of time confirm these results, it is impossible to prove that viscous growth or decay of magnetisation will continue at the same rate for millions of years. The relaxation times of grains by Néel's theory is critically dependent on grain size; a small change in size can change the relaxation time by many orders of magnitude. Possibly the magnetic grains in a rock include a fraction whose relaxation time makes them stable for ever (i.e. $>10^9$ years) and that only some of the grains can acquire viscous magnetisation at ordinary temperatures. It is likely that a situation arises eventually in which, as it were, the viscous magnetisation becomes 'saturated', a position when all the grains of appropriate size have become magnetised, and the remainder never will; at this point no further change will occur unless the field changes, or some such event occurs; with constant ambient conditions, the viscous growth (or decay) of magnetisation will decrease as it approaches 'saturation'. This question must remain unsettled for the present; even in the least favourable case, however, it appears that viscous magnetisation does not preclude stability in some rocks for at least 10^9 years, a period ample enough for palaeomagnetism for many years to come.

6.3.4 MISCELLANEOUS TOPICS. It has been necessary previously in this chapter to confine comparison of theoretical predictions and experimental results to minor points or to make qualitative comparisons only. Some of the topics omitted are now mentioned together with the reasons why direct comparison is not possible.

Firstly, no investigation of the variation of TRM with applied field has been made because facilities were not available when most of this work was done and in any case it is established that in fields below one oersted, TRM is directly proportional to the field (see for example, Nagata, 1961; p. 151), so that it is no longer of interest to confirm this yet again, unless it be done incidentally in connection with other studies.

The intensity of TRM is related to the coercive force in Néel's theory. There is some experimental evidence of this (Nagata, 1961; p. 159), which, as so often happens in geophysics, is in disagreement with theoretical predictions, but for several reasons it is not profitable to investigate the relation using natural rock samples. The theoretical relation derived depends on several other factors, particularly grain size, and consequently there is a specific relation only for a particular grain size. Rocks normally contain grains with a range of sizes and the problems of calculating the theoretical values, of relating some measured parameter to grain size and similar factors, are formidable. Even were the calculations practicable, there remains the fact that the coercive force or destructive field measured on a specimen is a 'bulk' value; all that happens when the destructive field is measured is that after the specimen is magnetised to saturation, a reverse field is applied, such that part of the magnetic minerals are magnetised in the opposite direction with a total intensity equal to another part which is still magnetised in the original direction. This point has not been realised by many workers, especially in the USSR, who place excessive trust in steady field demagnetisation as a test for stability. This value for the destructive field does not bear any simple relation to the real value for individual grains. (Similar arguments apply to coercive force). The relation is better tested using artificial samples of uniform grain size, such as the experiments of Gottschalk (1935) with magnetite powder, or Kobayashi (1961), who used a copper-cobalt alloy.

Equally fruitless is any precise comparison with equation 10 of Stacey (1958), which relates the TRM to the proportion of magnetic mineral in a rock and to the susceptibility (and of course, it is equally fruitful to test the relation using artificial specimens). In this case, the difficulties already mentioned are augmented by the fact that iron occurs in other common rock-forming minerals such as pyroxenes and these are strongly paramagnetic. This paramagnetism is large enough to affect the susceptibility but has no effect on the remanence, and there is no simple relation between the relative amounts of paramagnetic and ferromagnetic minerals.

There are other topics for which there are similar obstacles to any quantitative comparison and the remainder of this chapter is devoted to considering the stability of NRM in basic igneous rocks and the demagnetising of specimens in alternating fields.

6.4. STABILITY OF NRM

The magnetic properties of rocks depend upon so many factors that it is helpful firstly to discuss NRM in the light of the data from Red Hill Dyke given in Chapter 3. The rock samples concerned have a wide variation in many factors which are probably relevant to magnetic properties, but the chemical composition of the magnetic minerals (one of the more important sources of variation of magnetic properties) is constant, even though the chemical composition of the bulk rock changes.

The most obvious variables in the samples from Red Hill Dyke are the proportion of magnetic mineral, the average grain size, and range of grain size. The amount of magnetic mineral will affect the intensity of magnetisation acquired in given circumstances and the grain size will (probably) affect the decay of magnetisation, after it is acquired.

The proportion of ore minerals varies irregularly from specimen to specimen; ore content tends to increase towards the upper (and more silicic) part of the dyke, but a sample from near the contact at a low altitude (and therefore more basic) may contain more iron ore than a specimen of granophyre from the summit of Red Hill. This makes it difficult to discover any relation between magnetic intensity and ore content. However, using the data in Table 8 and in Tables 2 and 9 of McDougall (1962), it is possible to obtain approximately:

$$M_{i(\text{sat})} = 13 \text{ (volume proportion of magnetite) e.m.u./cm}^3$$
$$= 0.13 \text{ (volume percentage of magnetite)}$$
$$M_{t(0.6)} = 0.25 \text{ (volume proportion of magnetite) e.m.u./cm}^3$$

In these expressions, remember that 'magnetite' means the ore mineral, which is about 50 percent magnetite and 50 percent of practically non-magnetic ilmenite;

that the density of the rock is about 3 g/cm^3; and that $M_{i(\text{sat})}$ is saturation IRM, which is probably less than half the intensity of saturation magnetisation. Bearing these points in mind, and realising that uncertain and unknown variables may involve correction factors of two or more, we can compare the first of the expressions given above with equation (4-14) given by Nagata (1961; p. 137). The agreement is remarkable and, I hasten to add, probably fortuitous—the constant for specific intensity is about 3 times 13 = 39; the two other factors are approximately equal and opposite, so that this value is to be compared with Nagata's empirical figure of 47 for Japanese rocks.

The average saturation IRM is about 50 times the TRM intensity acquired in 0.6 oersted and this lies within the 'normal' range of the ratio.

An important result which does not depend on the proportion of magnetic mineral is that the ratio $M_{t(0.6)}/M_n$ varies in a fairly regular fashion from a value of 1/15 at the chilled margins to about 1 in some of the most silicic and coarsest rocks (that is, the ratio decreases with increasing grain size and/or silica content).

This implies that the most slowly cooled rocks (i.e. the coarsest and most silicic) have the greatest stability of TRM acquired during cooling, which contradicts Verhoogen's assertion quoted earlier. It is unlikely that the bulk chemical composition, or grain size, is dominant—the grain size present, for example, is sufficiently large to show a decrease of 'retentivity' with increase in size, and probably the most important controlling factor is rate of cooling. This would encourage exsolution lamellae of ilmenite to divide the more-magnetic fraction (essentially magnetite) into very small portions and this is probably the source of the hard component of magnetisation. Exsolution will be greatest in the rocks that cool the slowest and the hypothesis is reasonable and involves no assumptions about unknown factors. Excellent photographs of some of the iron ore particles have been reproduced by McDougall (1960). They suggest that the dominant magnetite is in the form of small cubes, side length of the order of the distance between two ilmenite lamellae. It is very likely that some of these cubes have linear dimensions of about 0.01 μm and hence, are single domain particles. This explanation of a hard part of the NRM seems most likely in the present state of the art—at least in part; it is not suggested that the several alternative proposals do not play some part.

It is impossible to assume that at the top of Red Hill (site J) the primary TRM has not decayed in 170 m.y., so that the fact of the NRM being equal in magnitude to $M_{t(0.6)}$ can be taken as meaning only that when the dolerite cooled, the geomagnetic field had a strength not less than the present value.

Secondary magnetisation is negligible and appears to have an average direction (200,0). However, the small amount of unstable magnetisation makes this uncertain. It does not seem to be due to the present geomagnetic field but, since the NRM is extremely stable, any viscous secondary magnetisation is likely to be more stable than usual and this direction could be the resultant of viscous magnetisation acquired in the geomagnetic field during the last reversal (180, + 60) and a component now being acquired (0, —60) which has so far only about equalled the component acquired in the reversed direction of the present field. It is emphasised that the secondary magnetisation is so slight and the uncertainties correspondingly large that such conjectures can only be speculative.

Another aspect of the greater stability of rocks that cool the slowest (i.e. more silicic rocks) is that the precision of directions of magnetisation in the rocks at site D, near the chilled margin, increases when washed in 150 oersteds; the precision at sites F, J, and K (the more silicic rocks) is virtually constant, and at E (less silicic) it decreases. Again, this is an isolated result based on a small number of specimens (five), and the fact is merely noted.

Perhaps the constant precision at site E after magnetic cleaning in 75 and 150 oersteds, combined with the observations at the other four sites, indicates that the direction of the primary component is not affected in fields up to 150 oersteds. Similar remarks apply to the Robertson site of the Tertiary basalts of New South Wales described in Chapter 5. Six of the eight sites discussed show an increase in precision at 150 oersteds and, of the other two, Robertson has a more or less constant precision in fields of 0, 75, and 150 oersteds (Robertson, is in many ways anomalous; certainly it is atypical, as has been pointed out in Chapter 5).

6.4.1 MAGNETIC CLEANING. Whatever the origin of stable and unstable magnetisation the results given earlier demonstrate that basic igneous rocks can have NRM made up of hard and soft components, the soft components being those preferentially removed by demagnetisation in alternating magnetic fields.

Firstly, consider how the two components are separated and the directions measured. It has been, and still is, the practice of some experimenters to take the results specimen by specimen, and to assume the stable component is present only when variation of direction and intensity with increasing alternating fields is absent over some particular range of values of the demagnetising field, or when the variation is much less than in fields less than or greater than these values. A recent example is Graham (1961) but there are many others. It is no doubt true in the cases studied so far that this method gives the desired result, but the method using a combination of results from a group of specimens, explained earlier in this Bulletin, is preferable. In many cases where the 'single specimen' method is used, the increased precision at the chosen demagnetising field is cited in support. However, I contend that the latter is the main evidence for accepting the validity of the results. The measurements on a single specimen are irrelevant, in precisely the same way as a single measurement of NRM does not represent the magnetisation of rock formation. This point is emphasised, perhaps unduly so, because it is 'bad' physics that has somehow crept into the subject; it is unnecessary in most cases (in other words, there will be special cases where the 'single specimen' method is necessary and each case has to be treated on its own merits, but these are special cases and should be rare), and it seems extraordinarily difficult to eradicate. The reasons why the 'single specimen' method of magnetic cleaning ever came to be considered, especially when it is universally accepted that NRM results must be based on measurements of several specimens, is one of the many mysteries of palaeomagnetism.

Secondly, consider whether the identification of the hard component with primary magnetisation is justified. There is an impressive amount of evidence that TRM is the most stable form of magnetisation. (It is impracticable to give a complete list of references. Koenisberger was probably the pioneer and two papers (Koenisberger, 1938a & b) review the facts known at that time. For the rest, reference to Nagata (1961), in particular Chapters 5 and 12 and the references therein, will provide sufficient of the experimental observations). All theories agree that this is the case—of course they must do, in the light of the evidence. Recently, CRM has been shown to be almost as stable as TRM (Doell, 1956; Martinez & Howell, 1956; Haigh, 1957; Kobayashi, 1959; Nagata, 1961; Chapter 6), but although the resistance to demagnetisation can be almost equal to that of TRM, the intensity of CRM acquired in a particular magnetic field is less than TRM. The magnetisation of rocks at site J in Chapter 3 of this Bulletin cannot be CRM and there is, therefore, a strong presumption that no Tasmanian dolerite has CRM; nor is there any evidence that any of the other rocks possess CRM and this type of magnetisation will not be considered.

Qualitatively, the various theoretical predictions agree that IRM, viscous magnetisation, and anhysteretic magnetisation should be less stable than TRM and there have been several calculations of the shape of the demagnetisation curve of an assemblage of single domain particles and its dependence on grain shape, volume, alignment, and so on (Néel, 1950; Stoner, 1948). Stacey (1961) has dealt with the demagnetisation of rocks in a quantitative way, but restricted to a rather improbable situation where the rock contains multidomain grains which are of equal size and which are either spherical or cubical. However, some calculated demagnetisation curves (Stacey, Figure 3) show some of the features found experimentally. The principal features are a great dependence on grain shape (cubical grains are more resistant than spheres and irregular shapes are probably even more resistant) and a limiting value of demagnetising field (depending on grain size) below which no demagnetisation occurs. The first prediction cannot be tested on the available data, but it is possible that some evidence will be obtained from natural rock specimens. The second prediction is not supported by any results from rocks, but it must be remembered that because of the range of grain sizes, some will have critical fields less than the lowest demagnetising field used and so the results in Chapters 3 to 5 are not necessarily inconsistent with this hypothesis.* Obviously, more work is required before any detailed comparison can be made.

A consequence of Stacey's theory is the anisotropy of susceptibility induced by alternating fields. Briefly, the susceptibility of rock when demagnetised by spinning the specimen about two axes in an alternating field (Chapter 2) will differ from that of a rock magnetised when stationary, and in the latter case the susceptibility is greater in a direction parallel to the demagnetising field than in a perpendicular direction. Denoting the three susceptibilities by κ_0, $\kappa_{//}$, and $\kappa_{\perp}$, Stacey finds the relation:

$$\kappa_0 = 1/3\ (\kappa_{//} + 2\kappa_{\perp}) \qquad (16)$$

* Some recent preliminary calculations based on Stacey's theory (Stacey, 1961) indicate that the 'critical field' for particles with linear dimensions greater than 50 μm is less than 50 oersteds. This order of grain size is likely to form an important fraction of the magnetic mineral in most rocks.

A few measurements of this have been made and they show a slightly greater value for $\kappa_{//}$ than for $\kappa_{|}$, the difference is slight and an accurate check of equation (16) was not possible.

A point worth mentioning is that caution is necessary in applying the rules for accepting NRM values as given by Nagata (1961, p. 280). These rules as a whole are an admirable basis on which to judge a particular result, but high values of the ratio $M_n/M_{t(0\cdot5)}$ should not be uncritically accepted as an indication of stability. Experience has shown that, generally, in rocks having secondary viscous magnetisation, the least stable rocks have the highest relative NRM. It is easy to see qualitatively that this follows from the fact that the least stable rocks acquire viscous magnetisation most easily and hence will have a proportionately greater NRM relative to primary TRM, whether or not the TRM component in the NRM has decayed. An example of this is shown in Figure 24 where $\log\kappa_n$ (κ_n being the precision of the NRM) is plotted against $\log M_n/M_{i(\text{sat})}$ for the Tertiary basalts of Chapter 5 (from Tables 19 and 20). $M_{i(\text{sat})}$ can be taken

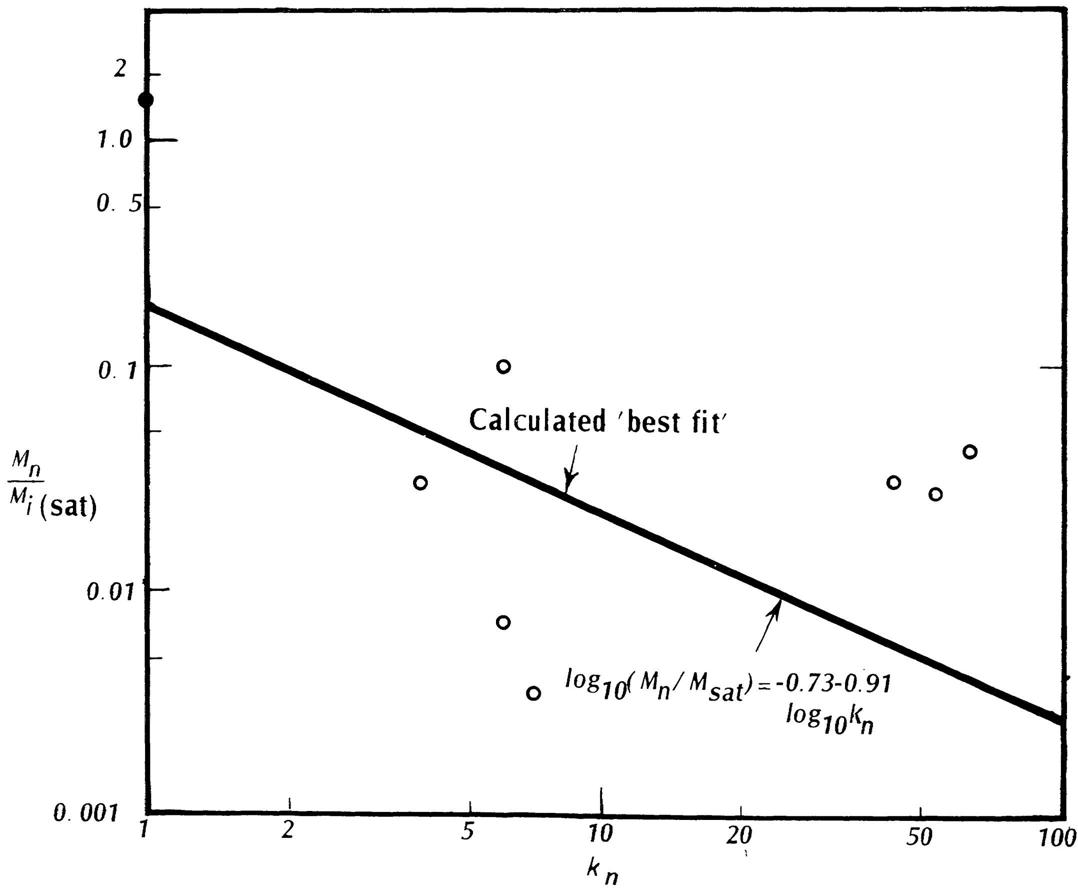


Figure 24. Relation between M_n and precision. G456–22

proportional to $M_{t(0.5)}$, on the average. Although the points are scattered, there is a clear relation between them, such that higher values of κ_n are associated with lower values of $M_n/M_{i(sat)}$, and high values of κ_n indicate most stability.

6.5 SOME OTHER ASPECTS OF MAGNETIC CLEANING

There are some features of magnetic cleaning that are not related to the NRM of rocks alone. One of these topics, the frequency of the alternating field and the rate of rotation of the specimen, was discussed in Chapter 2.

concept of 'minimum intensity' arises from the production of "stray magnetisations" during cleaning (Creer, 1959) or "disturbing magnetisations" (As & Zijderveld, 1958), which have been ascribed to imperfections in experimental techniques. When these imperfections (steady fields, harmonics) are eliminated, the effects are reduced and so part of the stray magnetisation probably is caused by these factors, but even when all causes thought to be responsible are eliminated, an unexplained remnant persists (the first quotation above, by Creer, is an example).

In a magnetised rock possessing NRM, TRM in the present field, or any intensity of similar magnitude, this minimum intensity is usually a fraction of the saturation remanence and an even smaller fraction of the saturation magnetisation. This is easily explained of course by the domain theory of ferromagnetism—essentially it was the explanation of how magnetic substances could exist in a demagnetised or partially magnetised state that led to the idea of domains. The magnetisation in such a situation can be thought of as a combination of a small fraction of the magnetic mineral magnetised in the net resultant direction with most of the magnetic grains having random directions. Because the domains are always spontaneously magnetised at ordinary temperatures it follows that an 'unmagnetised' magnetic grain will generally possess a small resultant magnetic moment, and, in turn, the resultant of these grains, in the rock as a whole, will not be zero. In this discussion, the term 'unmagnetised' is used to denote a condition known generally, and used elsewhere in this Bulletin, as 'demagnetised'. The term is used because part of the argument is that 'demagnetised' is not necessarily 'non-magnetic', i.e. 'unmagnetised' is not always 'demagnetised' if the latter means having zero magnetic moment.

For an 'unmagnetised' grain or rock, a zero resultant is most probable; small net moments are almost as probable, but the probability of large deviations from a zero resultant is small. However, because the 'unmagnetised' fraction is much larger than the 'magnetised' part, the absolute magnitude of the net moment of the 'unmagnetised' grains may be comparable with that of the 'magnetised' grains. During magnetic cleaning, the demagnetisation by alternating magnetic fields proceeds in two ways: some of the magnetised grains are demagnetised and are added to the 'unmagnetised' fraction; at all times, the 'unmagnetised' part is altered by the magnetic field insofar as there is a rearrangement of the domains. In effect, after each treatment, the 'unmagnetised' part is a new assembly of randomly directed unit vectors, and statistical fluctuations will produce resultant magnetic vectors which vary in direction and intensity. With each treatment, more and more of the magnetic grains are added to the 'unmagnetised' fraction, the number in the 'magnetised' fraction decreases, and the chance will be greater that the resultant intensity of the 'unmagnetised' fraction will have a significant effect on, or even exceed in magnitude, that of the 'magnetised' fraction.

The probability distribution of the sum of randomly directed vectors was given by Lord Rayleigh in two papers (1880, 1919).

Assume the specimen has n 'unmagnetised' grains and that the average moment of these r_o is that for which the probability that the resultant r of the n random vectors is $P(r, r_o) = 0.5$ (the magnitude changes by less than a factor of two if the 95% level is chosen, i.e. $P(r, r_o) = 0.05$). The same situation applies within each grain, except that it is perhaps more probable that the domains are magnetised antiparallel, that is, the sum is of unit vectors having values +1 or —1 only, at random. The difference is not important: for n random unit vectors, $r_o = 0.89n^{\frac{1}{2}}$; for unit vectors ± 1, $r_o = 0.83n^{\frac{1}{2}}$ (a condition is that the values +1 and —1 are equally probable). Taking the real situation to lie between these situations, then if there are n_2 domains of equal moment m, on the average in each of n_1 'unmagnetised' grains in a specimen, the average resultant of the 'unmagnetised' grains will be: $M_r = 0.7m(n_1.n_2)^{\frac{1}{2}}$. The saturation moment will be: $M = n_1.n_2m$; and the saturation remanence $M_{i(sat)}$ will be about $\frac{1}{2}M$. Approximately then, $M_{i(sat)}/M_r = 0.7(n_1.n_2)^{\frac{1}{2}}$; the measured value of M_{min} is probably greater than M_r (Irving, Stott, & Ward, 1961), so that it is reasonable to assume that:

$$\frac{M_{i(sat)}}{M_{min}} = 0.5(n_1.n_2)^{\frac{1}{2}}$$

This expression, applied to one of the Tertiary basalts of New South Wales (see Table 19) gives a value of about 10^7 domains per cm^3 (the difference between this value and 2×10^7 given by Irving, Stott, & Ward (1961) arises from the difference in the degrees of approximation). Similarly, the Tasmanian dolerites give values between 10^7 and 10^8 domains per cm^3, $M_{i(sat)}/M_{min}$ having values between 1500 and 10,000. At Berrima and Robertson, the ratio is smaller, 100 to 600, and as far as Robertson alone is concerned, this could explain the greater difficulty in detecting the primary magnetisation. The number of domains per cm^3 is about 10^4 to 10^5; the grain size and proportion of magnetic mineral is similar to those in samples from Red Hill; hence, one might say that the average moment per domain, *m,* was much larger at Robertson, and the statistical fluctuation, or 'noise', proportionately greater. However, this argument applies even more to Berrima, where $M_{i(sat)}/M_{min} = 100$, but where the magnetisation is very stable.

The following inferences can be made:

1. The average moment per domain, and hence the average size of domain, is larger in the rapidly cooled basalts. This supports the argument that, generally, stable magnetisation and hard components are more common in slowly cooled rocks and are probably due to exsolution (of ilmenite).

2. The apparent absence of any correlation between the number of domains and the stability or 'noise' is probably because the bulk of $M_{i(sat)}$ and M_{min} is due to a number of large particles which are a large proportion of the total magnetic mineral by volume (or weight), but a very small

proportion by number. They will tend to cause the 'soft' components, but their number is so small (that is, only several per cm^3) that large variations between samples, or between lava flows, will occur.

This theory of minimum intensity, like some of the topics discussed earlier, needs verification from experiments with artificial specimens of known grain size. However, although the estimates may be an order of magnitude or more in error, the effect must be present; the figures quoted suggest that it is present, that it is large enough to be measurable, and that it can obscure stable moments; it then places a lower limit on the amount of primary magnetisation (compared with $M_{i(sat)}$) that can be measured.

6.6 CONCLUSIONS

There is still much to be learned about magnetic cleaning, but it is clear that the method is capable of detecting and measuring the more stable direction of magnetisation in a rock which is magnetically unstable or partially stable. It is conceivable that in some circumstances an incorrect result may be obtained (reheating, CRM), but this would be present in the NRM initially. It is unlikely, that is, that the demagnetisation as such will introduce errors. The stray magnetisations mentioned in the previous section do not affect the mean of a group of specimens; they are an additional reason for not using the 'single specimen' method.

7. PALAEOMAGNETIC RESULTS FROM AUSTRALIA

7.1 INTRODUCTION

The methods of magnetic cleaning developed during the course of this work have been used by others in the Department of Geophysics, Australian National University on other rocks from eastern Australia. In some cases, rock collections made earlier, and for which results had already been published, have been re-examined and new values for the direction of stable primary magnetisation derived. These do not generally differ greatly from earlier published values, but there were some rocks collected for which, previously, no results could be given because of obvious instability; some of these have been found to be partially stable rocks, and a reliable direction of primary magnetisation can now be found by magnetic cleaning. The results of washing some Tertiary basalts from New South Wales, additional to those measured by the author have been given in Chapter 5. The latest values from these, and some other rocks measured in the Department of Geophysics are given in Table 22.

7.2 RESULTS

All formations studied and listed in Table 22 have been shown to be stable by laboratory tests—chiefly by magnetic cleaning, but in the case of some of the sediments, by thermal cleaning. One exception is the Victorian Tertiary volcanics, for which there is field evidence of stability (Irving & Green, 1957; Green & Irving, 1958).

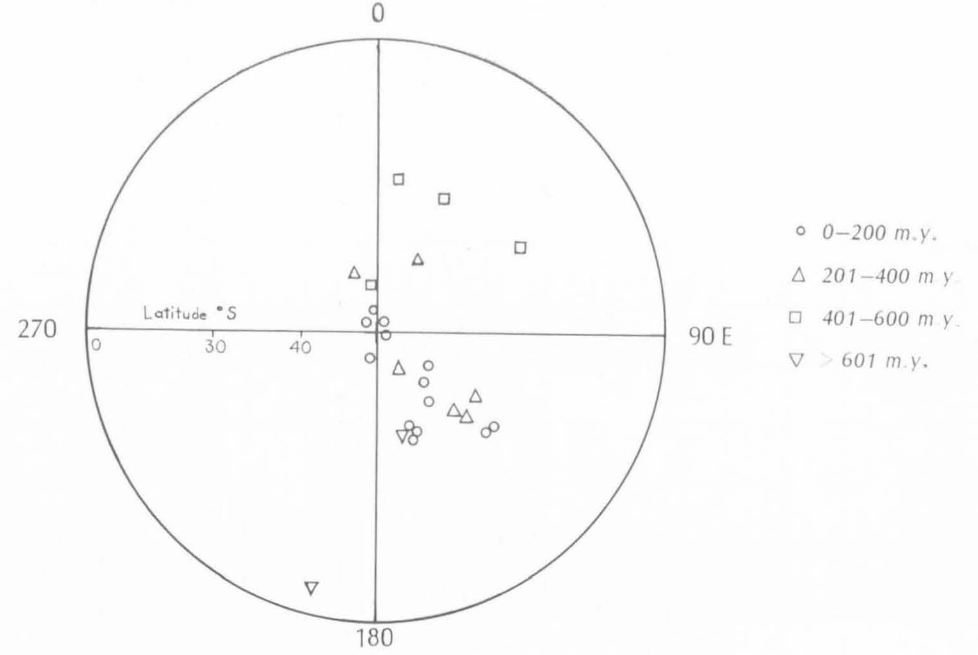


Figure 25. The past pole positions relative to Australia G456–23

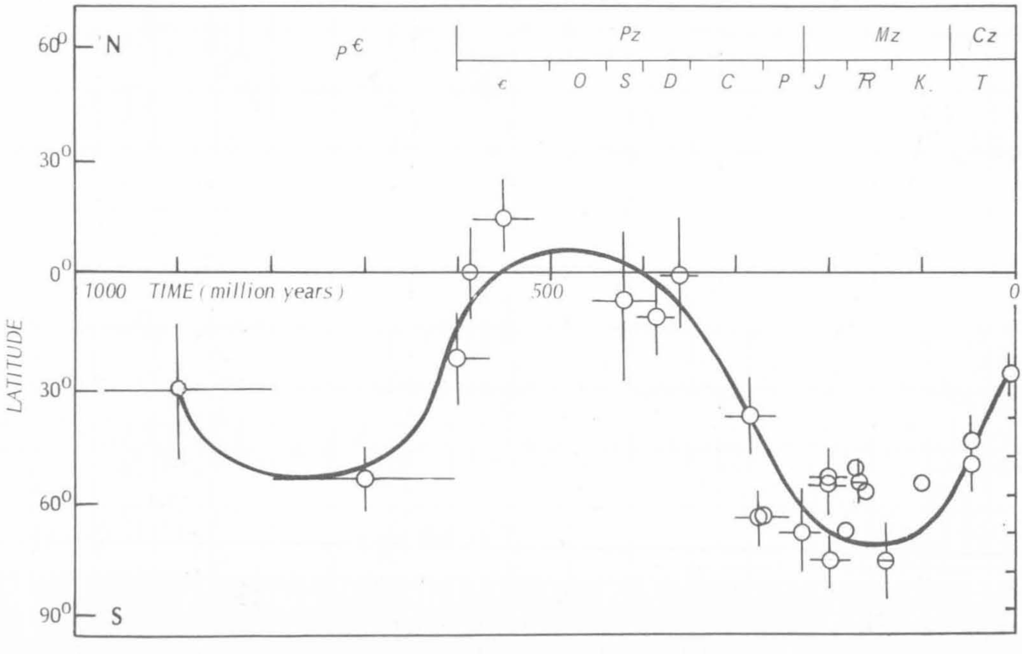


Figure 26. The past latitude of Alice Springs, from palaeomagnetic measurements.

G456–24

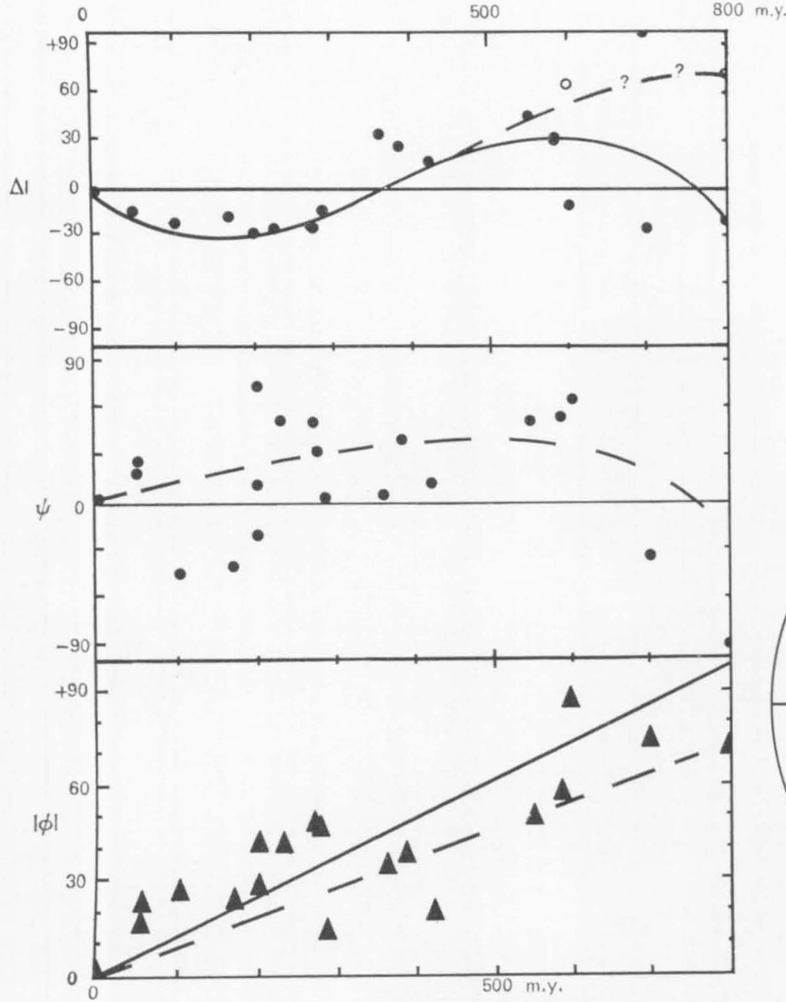


Figure 27a Palaeomagnetic parameters after Blackett, Clegg, and Stubbs (1960).

G456–25

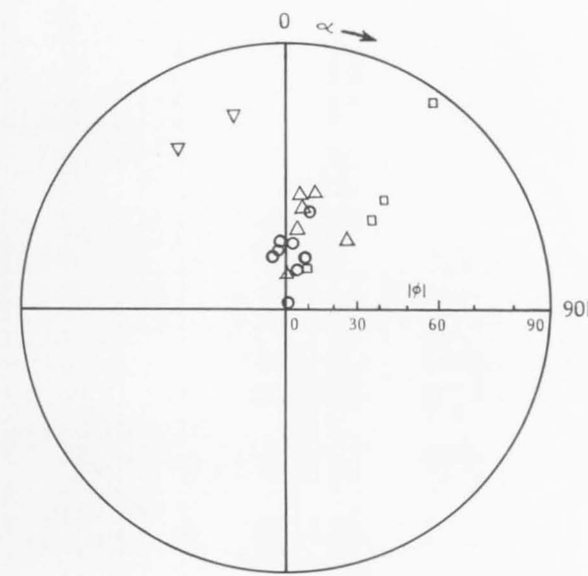


Figure 27b. Blackett et al (1960) parameter α

G456–26

Recent developments in radioactive methods of age determination have made it possible to determine the age of basic igneous rocks, which are most suitable for palaeomagnetic work. A programme of age determination has been vigorously pursued in the Department of Geophysics and this, combined with new evidence of magnetic stability, has now provided several results which are virtually 'fixed-points' in measurements of the history of the magnetic field in Australia.

The figures given in Table 22 show significant changes in the geomagnetic field relative to Australia during the last 400 million years or so. The earlier results are less reliable, both as to age and to direction, but they are consistent with the later results.

The results are shown in Figure 25 as a series of pole positions and in Figure 26 they are expressed as the geomagnetic (= geographical) latitude of Alice Springs (representing the centre of the continent). The Holmes (1960) time scale is used in Figure 26; the vertical line through each point shows the limits due to error in the mean direction measured ($P = 0.95$), and the horizontal line indicates the errors in dating. A somewhat arbitrary system has been adopted for the time errors. Radiometric ages are shown having 5 percent error; formations dated stratigraphically have been assigned an error $\pm$ 20 m.y. for those younger than Carboniferous; $\pm$ 35 m.y. for those from the base of the Cambrian to Devonian age; and $\pm$ 100 m.y. for older rocks. Formations classified as Lower Cambrian (600 to 550 m.y.) and late Upper Proterozoic have the errors cut off at 600 m.y

The interpretation of the results given below is naturally hypothetical, but the data on which it is based can be considered reliable as far as our present knowledge allows.

7.2.1 ALTERNATIVE PRESENTATION OF THE RESULTS. Blackett, Clegg, and Stubbs (1960) attempted to discuss palaeomagnetic results without necessarily invoking the geocentric axial dipole field hypothesis. To do this, the results cannot be presented as in Figures 25 and 26, so Blackett and his colleagues defined parameters ΔI, ψ , ϕ, and α (for details of the definitions, see: Blackett, Clegg, and Stubbs, 1960). The values of these parameters are given in Table 23 and are plotted in Figure 27; they correspond to Table 3 and Figures 4a to 4d and 7c of Blackett, Clegg, and Stubbs, but with more reliable and additional data. Each formation has also been assigned the most probable age in accordance with the data available using the Holmes (1960) time scale. (I have been unable to reconcile all the values in Table 23 with those given by Blackett, Clegg, and Stubbs. It appears that in some cases they have reversed D (or I), but not I (or D) and their Appendix I does not resolve this problem).

Whichever presentation is preferred, Blackett and his colleagues are undoubtedly right when they state ". . . there are now a sufficient number of . . . results . . . to provide overwhelming evidence that the remanent magnetic vectors of rocks do . . . change in a systematic way with geological age . . .". However, those who also agree that ". . . use of pole positions . . . leads to needless complication" (Blackett, Clegg & Stubbs, 1960) will proceed no further. In this chapter, only Australian results are considered, so that a pole position can be regarded merely as a geometric representation of a direction of magnetisation. Both methods give a unique point from a particular result and it is immaterial whether the point be confined within rectangular cartesian co-ordinates or the circle of a stereographic projection.

7.3 DISCUSSION

In Figure 26, a smooth curve has been drawn by eye and the points lie reasonably close to these lines. Some additional points, not included in Table 22, have been included in Figures 25 and 26 from Irving (1964, Appendix). Several features are evident:

(1) From some time in the Carboniferous, about 300 m.y. ago, until the Tertiary, the magnetic inclination is consistently steeper than at present. The Mesozoic results suggest a distinct 'pause', as it were, in the polar movement, with a comparatively rapid change to present-day conditions starting only in the lower Tertiary.

(2) During the Palaeozoic, especially the middle Palaeozoic, up until about 400 m.y. ago, the inclinations were less than at present. The Palaeozoic results in general, are not so complete and the stability evidence from pre-Devonian is not so good as from later rocks (although by no means absent), but the stability and age of the Nethercote basalts and younger rocks are well established.

(3) There was a rapid change in the inclination of the magnetic field from low values, about 400 m.y. ago, to high values, about 300 m.y. ago.

The results also show a fairly rapid change in inclination during the last 100 m.y. or so, which both simplifies and complicates earlier ideas. Whereas previously there was evidence of a rapid movement of the pole in Devonian to Carboniferous times, it was a singular event, perhaps explainable in terms other than those of polar wandering or continental drift, or for that matter, any hypothetical cause for the systematic change in the direction of magnetisation with geological age. Now, it is more probable that the geomagnetic field in Australia has changed fairly quickly over a period of about 100 m.y., because it is known to have done so on at least two occasions. But this does not in any way explain why this should happen.

7.4 STRATIGRAPHIC CORRELATION

There is one feature of the results which is world-wide but particularly relevant to Australia. It is known that from time to time in the past, the Earth's magnetic field has reversed; details of this, such as apparently rapid and frequent reversals separated by periods of relative calm, are beyond the scope of this work, but although both polarities occur during most geological periods, results from Permian rocks everywhere show reversed polarity. The position of the upper limit of the 'reversed' period is accurately known at the Permian type-section in the USSR (Khramov, 1959) and very conveniently coincides with the Permo-Triassic boundary, at least within the stratigraphic limits that this can be placed.

The special interest of this precise and world-wide datum is that in Australia, and all Gondwana continents, palaeontological correlation with the northern continents is not very accurate during this period, because of the very different fossils that are found. Even within Australia, the relative ages of beds found in the several Permian sedimentary basins are not always known, because there are many freshwater sediments and volcanic rocks. The palaeomagnetic determination of this Permo-Triassic boundary will be of considerable value in determining these ages and, since in many cases the boundary occurs in volcanic rocks, there is reason to hope that suitable stable rocks can be found.

The lower limit of the magnetic reversal in the Carboniferous will be equally important when the precise position is known.

In the future, other reference levels of this sort will be discovered and it should be noted that the time taken for the geomagnetic field to reverse is thought to be of the order 10^3 years, which is practically instantaneous on the geologic time scale and incomparably more accurate than any fossil evidence.

7.5 CONCLUSIONS

There is broad agreement between the palaeomagnetic latitude (Figure 26) and other evidence, such as glaciations during the Permo-Carboniferous and reef limestones in the Devonian. This evidence has been given by Irving and Green (1958) and there have been no new developments in Australia since then. During the last few years, palaeomagnetic results have inspired renewed interest in polar wandering and continental drift and some of the standard geological climatic indicators have been critically re-examined and fresh ideas developed. One of the more interesting proposals is that aeolian deposits can show the direction of the prevailing winds and that the 'trade winds' have always existed, approximately in the latitudes they are today. When suitable rocks are found in the right places, directions of the palaeomeridian can be found and this method has produced promising results from Europe and North America (Opdyke & Runcorn, 1960). Unfortunately, aeolian deposits have not been recognised in Australia.

At present, palaeoclimatology is in an active state and this is not the moment to attempt to foretell the eventual outcome. As far as Australia is concerned, the immediate interest in palaeomagnetism will be concerned with stratigraphic correlation, discussed in section 7.4. The question of continental drift is discussed in the next chapter, but it may be noted that when outstanding problems concerned with the determination of absolute movement are solved, Australia will be one of the more interesting areas to be studied. To anticipate a little, it seems likely that continental movement will be found to have taken place, and the results shown here indicate that Australia has undergone a more complicated movement than some other regions. The tectonic relations of Australia, New Zealand, New Guinea, and the neighbouring islands also show peculiar features. However, more results from here and elsewhere are required before more definite conclusions can be reached.

TABLE 23. ALTERNATIVE PRESENTATION OF PALAEOMAGNETIC RESULTS FROM AUSTRALIA

Pole number	ΔI	Ψ	ϕ	α
1	—2.6	3.0	3.0	26.2
2	—15.6	17.3	17.1	16.5
3	—19.6	26.0	22.6	19.4
4	—24.0	314.0	25.8	—8.2
5	—24.5	11.0	24.8	4.5
6	—26.5	359.0	26.5	—0.35
7	—20.0	319.0	23.0	—14.7
8	—30.5	217.0	37.8	—3.9
9	—27.8	11.0	28.3	6.3
10	—26.8	52.0	—41.9	10.4
11	—23.9	50.0	—47.9	14.0
12	—26.6	33.0	—47.1	8.1
13	33.4	5.0	33.6	8.2
14	25.5	40.0	38.4	42.2
15	17.5	12.0	19.3	26.7
16	44.8	51.0	49.0	44.8
17	27.8	53.0	57.4	43.5
18	—11.5	63.0	87.4	35.1
19	—26.5	—37.0	—74.4	—15.3
20	—23.2	270.0	—71.8	—35.2

For details of terminology, see Blackett, Clegg, and Stubbs (1960).
(Pole numbers correspond to Table 22).

TABLE 22. PALAEOMAGNETIC RESULTS FROM AUSTRALIA

Pole number	Formation	Direction of magnetisation		Pole (Southern hemisphere)		Latitude Alice Springs	Age	Reference
		D	*I*	Long. (°E)	Lat. (°S)	(°S)	(m.y.)	
1	Newer Volcanics, Victoria	3	—60	102	86	27	5	1
2	Older Volcanics, Victoria	17	—73	123	67	46	45	1
3	Tertiary basalts, NSW	26	—72	137	63	50	~45	3,9
4	Cygnet, Tasmania	314	—85	158	50	57	100	5,10
5	Gingenbullen, NSW	191	80	144	53	59	~160	4,10
6	Prospect, NSW	359	—81	151	57	53	170	4,10
7	Tasmanian dolerite (Regional)	319	—81	160	51	56	170	2,9
8	Gibraltar, NSW	27	—86	146	41	70	180	4,10
9	Brisbane Tuff, Qld	35	—84	143	39	72	200	7
10	Upper Marine, NSW	67	81	169	27	55	230	7
11	Lower Marine, NSW	110	80	172	38	55	270	7
12	Kuttung, NSW	270	—84	164	32	55	275	7
13	Nethercote basalts NSW (a)	5	—23	340	65	1	(b) 360	8,9
14	Murrumbidgee 'red beds', NSW	40	—29	29	58	12	(b) 385	8
15	Igneous rocks, ACT	12	—37	352	71	8	(b) 420	7
16	Elder Mount Sandstone, NT	231	—15	8	34	—14 (14N)	(b) 550 (ϵ)	7
17	Antrim Plateau basalts, NT & WA	53	—2	26	36	0	(b) 585 (ϵ)	7
18	Buldiva quartzites, NT	243	38	59	30	23	(b) 600 (Bu)	7
19	Nullagine lavas, WA	143	64	162	51	55	(b) 700 (Bu)	7
20	Edith River volcanics, NT	90	48	194	6	31	(b) 900 (Bl)	7

NOTES:

(a) Calculated using original results, reference 8.

(b) Stratigraphic dates only; numerical age is approximate.

References:
1 Irving and Green, 1957;
2 Irving, 1956 and 1963;
3 Irving, Stott, and Ward, 1961;
4 Boesen, Irving, and Robertson, 1961;
5 Robertson and Hastie, 1962;
6 Robertson, 1963;
7 Irving and Green, 1958;
8 Green, 1961;
9 this Bulletin;
10 Evernden and Richards, 1962.

Latitude of Alice Springs (23.5°S; 134°E) determined graphically.

8. MAGNETIC RESULTS FROM OTHER CONTINENTS

The main emphasis of the work described in this Bulletin has been on the stability of the NRM of basic igneous rocks; on the recognition, detection, and elimination of unstable components of NRM and the measurement of the true direction of the stable component; on the question of whether a cooling igneous body could acquire TRM in a direction non-parallel to the prevailing field; and on related topics. The earlier chapters contain these results and general conclusions were presented in Chapter 6. Chapter 7 dealt with the palaeomagnetic aspects in relation to Australia and this final chapter attempts to place the results in a more general context—firstly, the palaeomagnetic, and secondly the more physical aspects of rock magnetism.

8.1 PALAEOMAGNETIC RESULTS

Two notable trends recently are:

1. The ever-increasing amount of reliable palaeomagnetic data makes more and more certain what was apparent some time ago, that results from rocks of the same age within the same continent generally agree well with each other, but that, certainly in pre-Tertiary times, the results from different continents do not agree. If the results are expressed as ancient pole positions then, in general, the older rocks have poles more divergent from the present pole and the poles from different continents deviate more from each other.

2. The increasing acceptance by recent geophysical and geological writers of the validity of the palaeomagnetic results and polar wandering, and an open mind regarding the almost inevitable conclusion of relative continental movement.

It is impossible to examine Figure 28, which shows Mesozoic and Tertiary pole positions, without thinking of the possibility of continental drift. Two features are immediately striking. Firstly, the pole, relative to a particular continent, has moved towards its present position from nearer that continent, or in other words, all the continents appear to have been moving away from a pole fixed in its present position. Secondly, the pole path for each continent is a curve, and all the curves have approximately the same shape. Either each continent has been moving away from a pole fixed in its present position for the last 200 m.y. or so, or else the pole has wandered, presumably along a path of the general shape common to nearly all of them; at the same time, the continents have drifted apart latitudinally. The uncertainty in calculating poles, mainly because of the possible rotation of the continents, has been used in attempts to avoid the need for the concept of polar wandering and/or continental drift. However, no amount of rotation, for example of the Tasmanian dolerite, will make the ancient pole coincide with the present one, so that the idea of polar wandering seems inevitable. The similarity of the curves of Figure 28 may suggest the second alternative of polar wandering plus drift as more likely. Movement, either translation or rotation, of continents plus polar wandering has occurred; the relative probabilities of rotation and translation are unknown in the absence of plausible mechanisms for either.

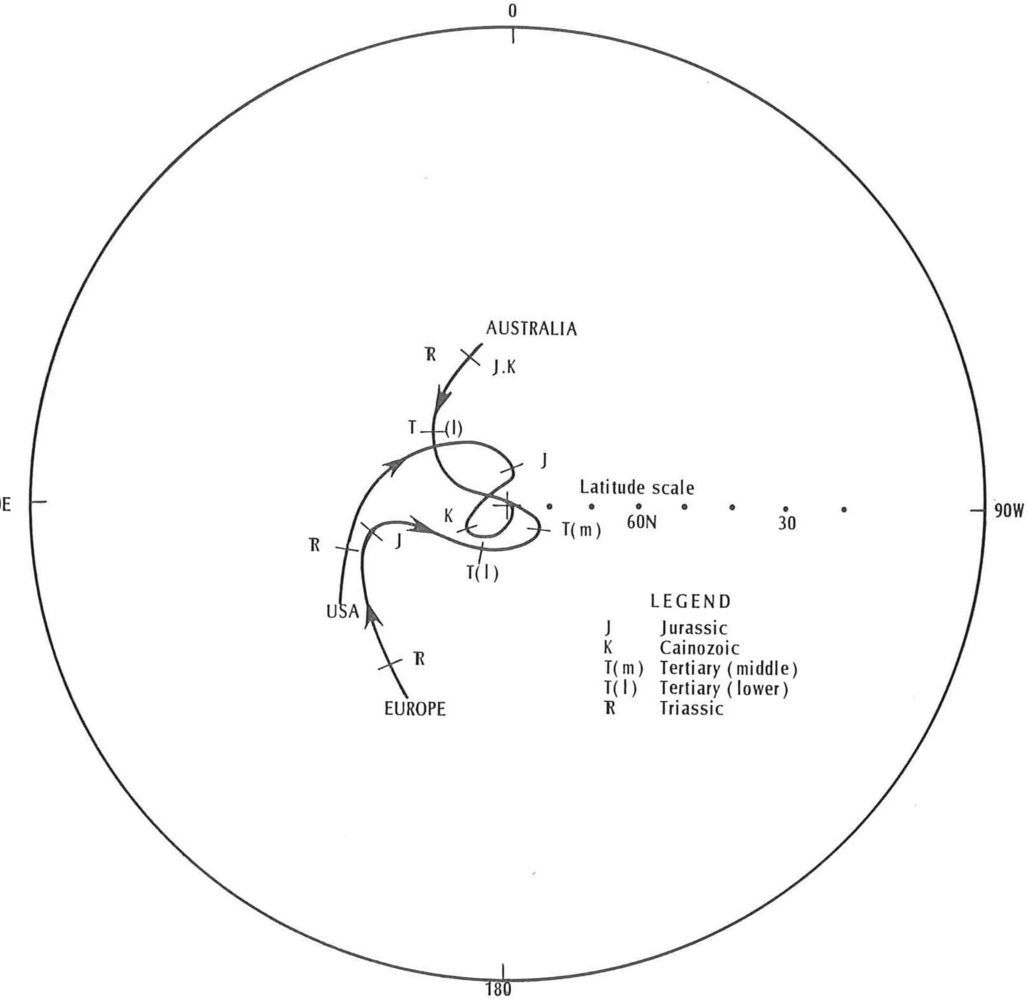


Figure 28. Mesozoic and Cainozoic pole paths – Australia, Europe, and USA G 456–27

The first alternative, of universally 'pole-fleeing' continents moving along a meridian, with similar lateral movements by all at certain times, must not be rejected solely because it requires more assumptions. The second alternative, that the 'highest common factor' of the apparent movement is due to polar wandering and only partly due to continental drift, is possibly preferable, as it requires less independent causes. However, phenomena such as the westward drift of the non-dipole components of the geomagnetic field and the circulation of the atmosphere show that correlated movement over at least a hemisphere is a common occurrence. If continental drift is accepted, it is plausible that a steady drift toward the equator was intermittently combined with latitudinal drift, common to all continents (the forces that caused either being as yet unknown), together with the same independent motion required by polar wandering.

Although there are not enough results to decide which, if either, of the two is more correct, or to resolve the problem of the unrestrained degree of freedom (rotation/translation), it is possible to hope that many outstanding puzzles will be solved soon. Is it not being unduly pessimistic to say that the problem of latitudinal motion is forever insoluble? Certainly, the analogy drawn by Blackett, Clegg, and Stubbs (1960) between finding the palaeo-longitude of continents and of an ancient mariner, implies hope—for reliable chronometers were eventually built and the ancient mariner's problem was solved.

8.2 ROCK MAGNETISM

The last few years have been years of consolidation in rock magnetism. Much effort is being made to ensure that palaeomagnetic results are reliable. As an example, in a way similar to that in which, in earlier chapters, an attempt was made to investigate possible disturbances of the magnetic directions in tabular intrusions, so also there have been enquiries into the magnetisation of sediments. Experiments have shown that if sediments possess detrital remanence (DRM) due to the magnetic particles contained, an 'inclination error' ought to occur. There is abundant field evidence that this does not occur in practice (see Blackett, Clegg, & Stubbs, 1960) and in some cases, at least, it seems that the magnetisation is mainly CRM acquired during cementation, the particles passing through a stage of 'superparamagnetism' to very stable CRM, probably due to single domains of haematite (Creer, 1961).

Magnetic anisotropy has been a topic much studied recently. This has two aspects: as a tool for studying rock fabrics; and as a possible source of error in palaeomagnetism. The first shows promise of becoming very useful, and work on the latter so far has not led to any great doubts about the validity of results from the type of rocks normally used for palaeomagnetism.

Progress has been made in studies of the magnetic properties of the principal minerals and this makes it easier to select the most suitable specimens for measurement.

8.3 CONCLUSION

Although the evidence for continental drift is not conclusive, there is at the moment no satisfactory alternative explanation of the results of palaeomagnetic measurements. These can be summed up as showing, in general, concordant results from within continents and discordant results between continents, the discrepancy increasing in older rocks. There are exceptions of course, and these are often unduly emphasised by opponents of continental drift; in fact, these results form only a small part of the results as a whole.

Critics commonly confuse estimates of the error of palaeomagnetic results with reliability and there are at least two reasons why this is fallacious. In the first place, although nearly all results are calculated by Fisher's method (Fisher, 1953), there is not unanimity on the unit vectors used to find estimates of the mean direction and the errors involved. There are several possible variants, the most frequent being to add together individual specimen (or sample) directions and to add site mean directions. Taking Table 7 as an example, it can be seen that both methods give essentially the same mean direction, but the former gives a much smaller estimate of the angular error in the mean. Using site mean directions may overestimate the angular errors, but certainly the use of sample directions can seriously underestimate them, especially when different numbers of specimens are collected at several sites within a rock formation. A second reason is that even where identical methods are used, and to be truly comparable this implies collecting and measuring, as well as statistical methods, there is no reason why a more precise result is more reliable. There are many possible reasons why dispersion in directions of magnetisation occur and the effects are almost entirely unknown, but to take a simple example, a direction from two or three sites for which there is evidence of stability may have an estimated angular error of 20°, nevertheless this would be more reliable than a result from a hundred sites with no stability evidence, even though the estimated angular error in this case is only one or two degrees.

There has been activity in other branches of geology and geophysics regarding the question of continental drift. Renewed interest in palaeoclimatology has been mentioned in Chapter 7; evidence of relative movements of the order of 1000 km, probably during the Tertiary era, has been found in the Pacific Ocean off North America; it is suggested that movements of this magnitude, or more, have occurred along major fault zones in Scotland, the United States, and New Zealand. All in all, recent discoveries have favoured the idea of continental drift and although, individually, the results are not conclusive, taken together they almost, if not quite completely, overwhelmingly support the hypothesis.

The argument is often used that continental rocks are mechanically weaker than the oceanic crust so that this movement is physically impossible. However, if and when the evidence that movement has occurred becomes incontrovertible, this argument is an expression of ignorance, rather than an objection to continental drift.

For the moment, the task of palaeomagnetism is to provide more data and to ensure that it is reliable data, by methods akin to those described earlier in this Bulletin which were applied to basic igneous rocks.

It seems to be fashionable nowadays to be unduly pessimistic about the results of some experiments. Whilst caution is admirable, it is surely unreasonable to cast doubts upon the whole structure of palaeomagnetism from experimental results which show a possible source of error, more especially when the experimenter has probably gone to a deal of trouble to obtain just those specimens that show to the greatest extent the peculiar properties he wishes to study. It may be a regrettable consequence of a particular experiment that one or two results previously reported become suspect, but of much greater importance (usually) that a vastly larger number of results can be accepted with more confidence. The present seems a time to have great hopes for the future, rather than regret for the past.

In 1956, Graham wrote:

> "The data are tantalizing, but they must be greatly amplified and strengthened. We must look for wide regional consistencies in the magnetiza-

tion pattern of rocks of varied types in varied settings, and we must gain accurate and ample knowledge of the processes by which rocks are magnetized".

The years which have elapsed since then have failed to bring about an ample understanding of the ways in which rocks become magnetised, although much has been discovered, but the regional consistency of palaeomagnetic results has been amply demonstrated.

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APPENDIX 1

PARRY COILS

The exact formulae are given for the field at a point (x, y, z) in cartesian co-ordinates, with the z axis along the axis of the coil pair and with the origin at the centre of the coil pair, the coils being in the 'Parry position', i.e. $\frac{\delta^2 H_z}{\delta_z{}^2} = 0$

The field parallel to the axis is:

$$\frac{a}{i} H_z = \frac{(1+x)(1+y)}{[(1+x)^2 + z_1{}^2][(1+x)^2 + (1+y)^2 + z_1{}^2]^{\frac{1}{2}}}$$

$$+ \frac{(1+x)(1-y)}{[(1+x)^2 + z_1{}^2][(1+x)^2 + (1-y)^2 + z_1{}^2]^{\frac{1}{2}}}$$

$+$ 2 terms with $(-x, +y)$; $(-x, -y)$;

$+$ 4 terms with x and y transposed

$+$ 8 terms with z_1 replaced by z_2.

(16 terms in all)

$$z_1 = (0.5445 + z); \; z_2 = (0.5445 - z);$$

x, y, and z are in units of a, the length of half the coil side; i is in abamperes and H in oersteds (if a in cm). Note that the field at a point (x, y, z) is the vectorial sum of the fields due to each side calculated separately from the Biot-Savart law. This is (presumably) the same as that due to a rectangular magnetic shell, but it is difficult (if not impossible?) to calculate the solid angle subtended by a rectangle at point (x, y, z).

The fields perpendicular to the axis parallel to x (or y) axis are:

$$\frac{a}{i} H_x = z_1 \frac{(1+y)}{[(1+x)^2 + z_1{}^2][(1+x)^2 + (1+y)^2 + z_1{}^2]^{\frac{1}{2}}}$$

$$+ \frac{(1-y)}{[(1+x)^2 + z_1{}^2][(1+x)^2 + (1-y)^2 + z_1{}^2]^{\frac{1}{2}}}$$

$+$ 2 terms in $-x$

$+$ 4 terms in $-z_2$

(8 in all)

(Units as for axial field)

Similarly for H_y with x and y transposed.

N.B. z_1 and z_2 have opposite signs, in contrast to axial field, i.e. if z_1 $(0.5445 + z)$; then $z_2 = -(0.5445 - z)$ and vice-versa.

The axial field for values of (x, y, z) between 0 and 0.1 times a have been computed and are given in the next few pages. a is approximately 100cm, therefore a value of x, y, or z of 0.01 in the list is approximately 1 cm. The field has been calculated over a sixteenth of the whole space; the rest is obtained by symmetry. The final column, H_z (exp), is the field in exponential form with all eight figures retained.

x	y	z	H_z	H_z (exp)
.00	.00	.00	8.143717	.81437172E+01
.01	.00	.00	8.143718	.81437182E+01
.02	.00	.00	8.143717	.81437178E+01
.03	.00	.00	8.143715	.81437156E+01
.04	.00	.00	8.143709	.81437098E+01
.05	.00	.00	8.143698	.81436980E+01
.06	.00	.00	8.143676	.81436760E+01
.07	.00	.00	8.143639	.81436398E+01
.08	.00	.00	8.143584	.81435842E+01
.09	.00	.00	8.143503	.81435034E+01
.10	.00	.00	8.143389	.81433898E+01
.01	.01	.00	8.143718	.81437180E+01
.02	.01	.00	8.143717	.81437176E+01
.03	.01	.00	8.143715	.81437150E+01
.04	.01	.00	8.143709	.81437096E+01
.05	.01	.00	8.143697	.81436978E+01
.06	.01	.00	8.143675	.81436758E+01
.07	.01	.00	8.143639	.81436396E+01
.08	.01	.00	8.143583	.81435838E+01
.09	.01	.00	8.143503	.81435030E+01
.10	.01	.00	8.143389	.81433894E+01
.02	.02	.00	8.143717	.81437172E+01
.03	.02	.00	8.143714	.81437146E+01
.04	.02	.00	8.143709	.81437092E+01
.05	.02	.00	8.143697	.81436972E+01
.06	.02	.00	8.143675	.81436750E+01
.07	.02	.00	8.143638	.81436388E+01
.08	.02	.00	8.143583	.81435830E+01
.09	.02	.00	8.143502	.81435020E+01
.10	.02	.00	8.143388	.81433882E+01
.03	.03	.00	8.143712	.81437128E+01
.04	.03	.00	8.143707	.81437070E+01
.05	.03	.00	8.143694	.81436948E+01
.06	.03	.00	8.143673	.81436730E+01
.07	.03	.00	8.143636	.81436362E+01
.08	.03	.00	8.143580	.81435806E+01
.09	.03	.00	8.143499	.81434992E+01
.10	.03	.00	8.143385	.81433856E+01
.04	.04	.00	8.143700	.81437008E+01
.05	.04	.00	8.143689	.81436890E+01
.06	.04	.00	8.143666	.81436666E+01
.07	.04	.00	8.143630	.81436304E+01
.08	.04	.00	8.143574	.81435742E+01
.09	.04	.00	8.143492	.81434926E+01
.10	.04	.00	8.143379	.81433792E+01
.05	.05	.00	8.143676	.81436764E+01
.06	.05	.00	8.143654	.81436542E+01
.07	.05	.00	8.143617	.81436172E+01
.08	.05	.00	8.143561	.81435614E+01
.09	.05	.00	8.143479	.81434794E+01
.10	.05	.00	8.143365	.81433658E+01
.06	.06	.00	8.143631	.81436316E+01
.07	.06	.00	8.143594	.81435948E+01

x	y	z	H_z	H_z (exp)
.08	.06	.00	8.143538	.81435384E+01
.09	.06	.00	8.143456	.81434566E+01
.10	.06	.00	8.143342	.81433422E+01
.07	.07	.00	8.143558	.81435580E+01
.08	.07	.00	8.143501	.81435010E+01
.09	.07	.00	8.143418	.81434184E+01
.10	.07	.00	8.143304	.81433044E+01
.08	.08	.00	8.143444	.81434440E+01
.09	.08	.00	8.143361	.81433616E+01
.10	.08	.00	8.143246	.81432462E+01
.09	.09	.00	8.143278	.81432784E+01
.10	.09	.00	8.143163	.81431630E+01
.10	.10	.00	8.143046	.81430464E+01
.00	.00	.01	8.143717	.81437178E+01
.01	.00	.01	8.143718	.81437182E+01
.02	.00	.01	8.143718	.81437181E+01
.03	.00	.01	8.143717	.81437170E+01
.04	.00	.01	8.143713	.81437130E+01
.05	.00	.01	8.143702	.81437026E+01
.06	.00	.01	8.143682	.81436827E+01
.07	.00	.01	8.143649	.81436493E+01
.08	.00	.01	8.143596	.81435967E+01
.09	.00	.01	8.143519	.81435195E+01
.10	.00	.01	8.143409	.81434098E+01
.01	.01	.01	8.143718	.81437182E+01
.02	.01	.01	8.143718	.81437183E+01
.03	.01	.01	8.143717	.81437173E+01
.04	.01	.01	8.143712	.81437129E+01
.05	.01	.01	8.143702	.81437028E+01
.06	.01	.01	8.143682	.81436828E+01
.07	.01	.01	8.143649	.81436495E+01
.08	.01	.01	8.143596	.81435969E+01
.09	.01	.01	8.143519	.81435193E+01
.10	.01	.01	8.143409	.81434098E+01
.02	.02	.01	8.143718	.81437184E+01
.03	.02	.01	8.143717	.81437172E+01
.04	.02	.01	8.143713	.81437130E+01
.05	.02	.01	8.143702	.81437027E+01
.06	.02	.01	8.143682	.81436828E+01
.07	.02	.01	8.143649	.81436493E+01
.08	.02	.01	8.143596	.81435965E+01
.09	.02	.01	8.143519	.81435190E+01
.10	.02	.01	8.143409	.81434093E+01
.03	.03	.01	8.143715	.81437158E+01
.04	.03	.01	8.143711	.81437119E+01
.05	.03	.01	8.143701	.81437014E+01
.06	.03	.01	8.143681	.81436817E+01
.07	.03	.01	8.143648	.81436480E+01
.08	.03	.01	8.143595	.81435953E+01
.09	.03	.01	8.143517	.81435173E+01
.10	.03	.01	8.143407	.81434077E+01

x	y	z	H_z	H_z (exp)
.04	.04	.01	8.143707	.81437074E+01
.05	.04	.01	8.143697	.81436971E+01
.06	.04	.01	8.143676	.81436767E+01
.07	.04	.01	8.143642	.81436429E+01
.08	.04	.01	8.143590	.81435902E+01
.09	.04	.01	8.143512	.81435123E+01
.10	.04	.01	8.143402	.81434020E+01
.05	.05	.01	8.143686	.81436860E+01
.06	.05	.01	8.143666	.81436664E+01
.07	.05	.01	8.143632	.81436321E+01
.08	.05	.01	8.143579	.81435791E+01
.09	.05	.01	8.143500	.81435009E+01
.10	.05	.01	8.143390	.81433907E+01
.06	.06	.01	8.143645	.81436458E+01
.07	.06	.01	8.143611	.81436117E+01
.08	.06	.01	8.143558	.81435582E+01
.09	.06	.01	8.143479	.81434799E+01
.10	.06	.01	8.143369	.81433693E+01
.07	.07	.01	8.143577	.81435772E+01
.08	.07	.01	8.143523	.81435235E+01
.09	.07	.01	8.143444	.81434446E+01
.10	.07	.01	8.143333	.81433339E+01
.08	.08	.01	8.143469	.81434696E+01
.09	.08	.01	8.143390	.81433903E+01
.10	.08	.01	8.143279	.81432791E+01
.09	.09	.01	8.143310	.81433106E+01
.10	.09	.01	8.143199	.81431990E+01
.10	.10	.01	8.143086	.81430868E+01
.00	.00	.02	8.143716	.81437168E+01
.02	.00	.02	8.143719	.81437196E+01
.04	.00	.02	8.143721	.81437211E+01
.06	.00	.02	8.143703	.81437034E+01
.08	.00	.02	8.143634	.81436342E+01
.10	.00	.02	8.143469	.81434691E+01
.02	.02	.02	8.143722	.81437222E+01
.04	.02	.02	8.143723	.81437238E+01
.06	.02	.02	8.143705	.81437058E+01
.08	.02	.02	8.143636	.81436364E+01
.10	.02	.02	8.143471	.81434711E+01
.04	.04	.02	8.143725	.81437252E+01
.06	.04	.02	8.143706	.81437067E+01
.08	.04	.02	8.143637	.81436370E+01
.10	.04	.02	8.143471	.81434712E+01
.06	.06	.02	8.143687	.81436878E+01
.08	.06	.02	8.143616	.81436169E+01
.10	.06	.02	8.143450	.81434501E+01
.08	.08	.02	8.143545	.81435452E+01
.10	.08	.02	8.143376	.81433768E+01
.10	.10	.02	8.143206	.81432064E+01

x	y	z	H_z	H_z (exp)
.00	.00	.04	8.143701	.81437010E+01
.02	.00	.04	8.143713	.81437133E+01
.04	.00	.04	8.143743	.81437432E+01
.06	.00	.04	8.143772	.81437727E+01
.08	.00	.04	8.143771	.81437713E+01
.10	.00	.04	8.143694	.81436941E+01
.02	.02	.04	8.143725	.81437252E+01
.04	.02	.04	8.143755	.81437551E+01
.06	.02	.04	8.143784	.81437847E+01
.08	.02	.04	8.143782	.81437828E+01
.10	.02	.04	8.143705	.81437053E+01
.04	.04	.04	8.143785	.81437850E+01
.06	.04	.04	8.143814	.81438141E+01
.08	.04	.04	8.143811	.81438118E+01
.10	.04	.04	8.143733	.81437336E+01
.06	.06	.04	8.143842	.81438424E+01
.08	.06	.04	8.143839	.81438393E+01
.10	.06	.04	8.143760	.81437601E+01
.08	.08	.04	8.143834	.81438344E+01
.10	.08	.04	8.143754	.81437541E+01
.10	.10	.04	8.143671	.81436716E+01
.00	.00	.06	8.143633	.81436330E+01
.02	.00	.06	8.143660	.81436603E+01
.04	.00	.06	8.143737	.81437376E+01
.06	.00	.06	8.143846	.81438462E+01
.08	.00	.06	8.143956	.81439562E+01
.10	.00	.06	8.144024	.81440245E+01
.02	.02	.06	8.143688	.81436880E+01
.04	.02	.06	8.143764	.81437649E+01
.06	.02	.06	8.143873	.81438736E+01
.08	.02	.06	8.143983	.81439832E+01
.10	.02	.06	8.144051	.81440514E+01
.04	.04	.06	8.143841	.81438418E+01
.06	.04	.06	8.143949	.81439499E+01
.08	.04	.06	8.144058	.81440589E+01
.10	.04	.06	8.144126	.81441264E+01
.06	.06	.06	8.144057	.81440572E+01
.08	.06	.06	8.144165	.81441653E+01
.10	.06	.06	8.144231	.81442315E+01
.08	.08	.06	8.144272	.81442720E+01
.10	.08	.06	8.144336	.81443369E+01
.10	.10	.06	8.144399	.81443994E+01
.00	.00	.08	8.143449	.81434498E+01
.02	.00	.08	8.143499	.81434991E+01
.04	.00	.08	8.143641	.81436410E+01
.06	.00	.08	8.143858	.81438585E+01
.08	.00	.08	8.144123	.81441234E+01
.10	.00	.08	8.144393	.81443936E+01
.02	.02	.08	8.143548	.81435482E+01

x	y	z	H_z	H_z (exp)
.04	.02	.08	8.143690	.81436901E+01
.06	.02	.08	8.143907	.81439078E+01
.08	.02	.08	8.144172	.81441720E+01
.10	.02	.08	8.144442	.81444421E+01
.04	.04	.08	8.143832	.81438320E+01
.06	.04	.08	8.144049	.81440490E+01
.08	.04	.08	8.144312	.81443128E+01
.10	.04	.08	8.144582	.81445821E+01
.06	.06	.08	8.144265	.81442656E+01
.08	.06	.08	8.144528	.81445281E+01
.10	.06	.08	8.144795	.81447959E+01
.08	.08	.08	8.144789	.81447896E+01
.10	.08	.08	8.145055	.81450554E+01
.10	.10	.08	8.145319	.81453190E+01
.00	.00	.10	8.143065	.81430658E+01
.02	.00	.10	8.143142	.81431420E+01
.04	.00	.10	8.143366	.81433669E+01
.06	.00	.10	8.143722	.81437229E+01
.08	.00	.10	8.144183	.81441835E+01
.10	.00	.10	8.144709	.81447090E+01
.02	.02	.10	8.143218	.81432188E+01
.04	.02	.10	8.143443	.81434430E+01
.06	.02	.10	8.143799	.81437994E+01
.08	.02	.10	8.144259	.81442594E+01
.10	.02	.10	8.144785	.81447850E+01
.04	.04	.10	8.143667	.81436674E+01
.06	.04	.10	8.144023	.81440231E+01
.08	.04	.10	8.144482	.81444823E+01
.10	.04	.10	8.145007	.81450071E+01

x	y	z	H_z	H_z (exp)
.06	.06	.10	8.144377	.81443776E+01
.08	.06	.10	8.144835	.81448358E+01
.10	.06	.10	8.145359	.81453591E+01
.08	.08	.10	8.145292	.81452928E+01
.10	.08	.10	8.145813	.81458137E+01
.10	.10	.10	8.146332	.81463326E+01
.10	.10	.10	8.146332	.81463326E+01
.40	.10	.10	8.090993	.80909930E+01
.70	.10	.10	7.197207	.71972075E+01
1.00	.10	.10	3.489154	.34891546E+01
.40	.40	.10	8.034781	.80347810E+01
.70	.40	.10	7.153235	.71532359E+01
1.00	.40	.10	3.484389	.34843891E+01
.70	.70	.10	6.386253	.63862536E+01
1.00	.70	.10	3.083324	.30833247E+01
1.00	1.00	.10	1.290229	.12902290E+01
.10	.10	.50	7.870612	.78706122E+01
.40	.10	.50	8.360158	.83601581E+01
.70	.10	.50	10.801480	.10801480E+02
1.00	.10	.50	3.339897	.33398976E+01
.40	.40	.50	8.825240	.88252404E+01
.70	.40	.50	11.196796	.11196796E+02
1.00	.40	.50	3.609800	.36098000E+01
.70	.70	.50	13.288703	.13288703E+02
1.00	.70	.50	4.883964	.48839648E+01
1.00	1.00	.50	1.227844	.12278440E+01

APPENDIX 2

NOTES ON DESIGNING MAGNETIC CLEANING APPARATUS

The apparatus for magnetic cleaning has been described in section 2.2, but the description does not always explain why a particular arrangement of a component was chosen. After the apparatus was designed and built, several requests for details were received and, for future reference, the notes that follow are intended as a practical guide to the construction of the apparatus, to show which parts were designed specifically and which parts were chosen because the components happened to be available. This kind of information is normally excluded; however, because of the interest already shown and especially because in this field physical apparatus is often built by geologists, it is thought to have some value and is included here with the tentative suggestion that similar accounts be considered in other publications in interdisciplinary sciences such as geophysics.

The demagnetising field is produced by a 'short solenoid' and for such a coil with given overall physical dimensions and power consumption, the field is almost independent of the size of wire used in winding. The choice is mainly controlled by:

(a) Ease of winding

(b) Self-inductance of finished coil

(c) Voltage and frequency of the available power supply.

The frequency used will nearly always be about 50 Hz and the voltage can easily be transformed so that the choice is governed by balancing (a), which requires thicker wire, against (b), which requires thinner wire (this increases the self-inductance and so reduces the capacity of the condensers needed to tune to mains frequency). Experience has shown that thicker wire (within reason) is better and, although the capacity of the tuning condensers will be greater and therefore more costly, the voltage developed across them is less. The same voltage (which is much greater than the applied voltage) is developed across the coil terminals and a lower value makes the apparatus safer in case of accidents. Note too that a definitely lethal quantity of electricity can be stored on the condensers. These are covered to avoid accidental contact, but in addition all switching is done in the primary circuit of the variable transformer; there are no switches in the secondary circuit, hence there is always a complete electrical circuit to allow the condensers to discharge.

Square Parry coils are preferable to Helmholtz coils in regard to ease of construction and erection. Calculations show little difference in the degree of field uniformity, but the list of values given in Appendix 1 shows that the contours of field strength have a definite trend toward a rectangular or cubical shape for the region of uniform field, whereas two or three orthogonal Helmholtz pairs produce a spheroidal region. In this particular instance it is no great advantage, but often it happens that a uniform field is needed over a rectangular piece of apparatus and the Parry coils would be more suitable. In the general case, the advantages of Parry coils outweigh a very slight loss in uniformity and only in special circumstances are Helmholtz coils superior.

Within the limits of 150 to 700 rev/min the speed of rotation has no effect on the demagnetisation. All these rates of rotation are a small fraction of the alternating frequency. Intuitively, a rotation frequency nearly equal to the mains frequency is undesirable because of possible synchronisation and the other alternative is to rotate at rates greater than a few thousand rev/min. There is no theoretical advantage in using rotations greater or less than the current frequency. An isolated discovery was made some thirty years ago that, with a stationary specimen, demagnetisation was increasingly effective (i.e. 'complete' demagnetisation) when the frequency of the current was increased to 300 Hz, but that beyond 300 Hz, there was no change. Graham (1961) reports that 'better' results were obtained using 500 Hz instead of 50 Hz; rotation rates are not specified, but are presumed similar to those used here. There is no evidence about much greater rotation rates—probably some kind of turbine would be needed, which would involve considerable mechanical problems. These few inconclusive remarks indicate some of the possibilities for future investigations.