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PALAEOMAGNETIC INVESTIGATIONS IN THE FALKLAND ISLANDS DEPENDENCIES

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ABSTRACT

A STUDY has been made of the remanent magnetism of more than 400 samples collected from 104 localities in Graham Land and several of the nearby islands. The directions of the remanent magnetism of these samples have been measured and analysed in the standard manner. The stability of the magnetism has been investigated by tests involving the storage of specimens and their partial demagnetization in alternating magnetic fields. The study was restricted to the investigation of igneous rocks as the few sediments available for collection were found to be too weakly magnetic to be measurable. The magnetism of Tertiary and Recent lavas, collected from 12 localities, and of Andean intrusive rocks (late Cretaceous to early Tertiary age) from another 12 localities, is aligned on average along the axial geocentric dipole field direction, but both normally and reversely magnetized rocks have been found. The stability and the dispersion of magnetic directions indicate the remanent magnetism was probably acquired when the rocks were first formed. The magnetism of the Upper Jurassic Volcanic Group and the older intrusives (? Lower Palaeozoic) has been found to be either unstable or widely scattered in direction. It is suspected that the intrusion of the Andean suite so affected all the pre-existing rocks as to destroy their original magnetism. From these results it is possible to infer the condition of the Earth's past magnetic field only in connection with the Andean and younger rocks. This is that the Earth's magnetic field in the region of Graham Land has been, on average, in the same direction as the axial geocentric dipole field, or its exact reverse, since the intrusion of the Andean suite. Unfortunately there is no information from pre-Andean rocks in this area that can be used for comparison with the interesting results obtained elsewhere in Antarctica.

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I. INTRODUCTION

MANY rocks contain some ferromagnetic minerals, usually titaniferous magnetite or hematite, in small quantity, and these minerals are capable of retaining a magnetism for a long time. Palaeomagnetism forms the study of such remanent magnetism in rocks.

A remanent magnetism may originate in one of the following ways:

i. As a *thermo-remanent magnetism* (T.R.M.) acquired by an igneous rock on cooling from above the Curie Point of the ferromagnetic mineral in the rock.
ii. As a *detrital magnetism* acquired by a sediment during deposition, resulting from the alignment of ferromagnetic particles along the prevailing field.
iii. As a *chemical remanent magnetism* (C.R.M.) acquired during some chemical change which involves the growth of magnetic minerals within the rock.
iv. As an *iso-remanent magnetism* (I.R.M.) acquired by a rock lying in a weak magnetic field at normal temperatures for some length of time, or by being subjected to a strong magnetic field such as that associated with lightning.

The *natural remanent magnetism* (N.R.M.) retained by the rock and measured in the laboratory may have arisen from any of the above, but from the nature of the rock and the properties of the N.R.M. it can generally be ascertained in which way the magnetism was acquired. Detrital magnetism is only found in sediments and is usually very weak. Forces other than magnetic ones also help to orientate the grains during deposition so the resultant magnetism is not necessarily aligned along the ambient field direction. A C.R.M. is generally acquired during consolidation or induration of a sediment or as a secondary magnetization acquired in an igneous rock subjected to chemical alteration. The types of magnetism listed above have been observed directly in the laboratory and with rocks that are at present being formed. It has to be presumed that circumstances similar to those described above applied earlier in the Earth's history and that ancient rocks were magnetized in one or more of these ways.

The remanent magnetism of a rock formed from either a T.R.M., detrital magnetism or a C.R.M. is often particularly stable against demagnetization, because the average coercivity of the ferromagnetic constituent is high (usually >200 oersted) and because fields of comparable value are required to demagnetize it. Since it is seldom that ancient rocks have been subjected to fields of this magnitude (unless struck by lightning), it is likely that the direction of a remanent magnetism may be preserved, relative to the co-ordinates of the rock when it formed, for millions of years. Thus, if the stability of the N.R.M. of an ancient rock can be demonstrated, its direction when measured in the laboratory should be that of the field prevailing at the locality when the rock formed. The stable N.R.M. directions of rock samples of the same age, collected from numerous localities, should thus determine the Earth's magnetic field at the time the rocks formed.

For this method to be used to deduce the configuration of the Earth's field at various known times in the past it is essential to demonstrate that the N.R.M. direction does give the field direction when the magnetism was acquired and that the magnetism was acquired when the rock formed. Sometimes it is possible to make use of the geological relationships to demonstrate the stability of the N.R.M., but usually there is no such field test available. In the laboratory some test of stability can be made by demagnetizing the N.R.M. in successively higher alternating magnetic fields. The greater the field necessary to demagnetize the N.R.M., the greater is the average coercivity of the magnetic material and the greater is the stability of the magnetism. This a.c. demagnetization test may also have the effect of removing any secondarily formed spurious magnetization of lesser stability, thus revealing an original stable magnetism which might otherwise have been masked. Such secondary magnetizations could arise from partial chemical alteration of the magnetic materials during the later history of a rock or as a result of weathering. A general account of all the tests of stability in current use has been given by Cox and Doell (1960) in a recent review of palaeomagnetism. Since it is not the intention here to do more than set the present work in perspective, the reader is referred to the above paper and also those of Irving (1959, 1960) for a more comprehensive account of recent research in palaeomagnetism.

The use of rock magnetism to investigate the Earth's past field began in Britain over ten years ago and since then this research has extended to world-wide proportions. It became clear at an early stage that the Earth's past field had not always had the same configuration as at present. The Earth's present field is made up of several parts, the most important being one of geocentric dipolar character whose axis of magnetization is marked on the Earth's surface by the geomagnetic poles. Superimposed on this are regional features, which change slowly from year to year, and rapid field changes of extra-terrestrial or atmospheric origin. Observatory studies have shown that the geomagnetic poles, situated at present about 1,500 miles from the geographical poles, slowly change their position from year to year, and this is known as the secular variation. Records of the secular variation have been kept in London and Paris for 400 years, and there is some indication from them that the geomagnetic poles circle round the geographical poles. Theoretical explanations of the origin of the dipole part of the Earth's field are concerned with magneto-hydrodynamic motions of the Earth's core and all require that the average position of the dipole axis should be coincident with the axis of the Earth's rotation.

Measurement of the N.R.M. directions of Quaternary and Recent lava flows from many parts of the world has revealed that on average the magnetic field during this time has been that of an axial geocentric dipole, so that averaged over some thousands of years the geomagnetic pole positions coincide with the geographical poles. These data therefore lend support to the theoretical explanations of the origin of the dipole field. The N.R.M. is always directed northwards and with an inclination (I) determined according to the latitude (δ) of the locality by the relationship

$$\tan I = 2 \tan \delta, \qquad (1)$$

being downward in the Northern and upward in the Southern Hemisphere.

Measurements of Tertiary rocks have revealed a significant departure from this situation. Numerous examples have been found in which the N.R.M. direction is exactly reverse to the dipole field direction. In such cases it must be presumed either that the rock became magnetized in a direction opposed to the prevailing field or else that the polarity of the Earth's magnetic field has reversed at various times in the past. Although it has been demonstrated that certain rocks can be magnetized in a direction opposed to the ambient field, there is also considerable evidence in favour of polarity reversals of the Earth's field. The most recent reversal has been correlated with the Plio-Pleistocene boundary, but this has not yet been firmly established.

Taking account of the polarity reversals, the Earth's field during the Tertiary appears from most results to be axially dipolar, and the dipole relationship given in equation (1) is maintained. However, several exceptions to this general rule have recently been discovered and are still unexplained.

The N.R.M. directions of pre-Tertiary rocks are widely variable and geomagnetic pole positions calculated from them, using the dipole relationship, are spread over the globe often at large angles from the geographical poles. Their distribution is not random. The geomagnetic pole positions of rocks from Western Europe lie over Eastern Asia, in chronological order in such a way that a polar path can be drawn through them ending at the geographical pole in the late Tertiary. North American rocks produce a similar result, except that the polar path lies consistently to the west of the European one. Rocks from other continents provide further polar paths of similar form, but displaced from one another. Data from continents other than Europe and North America are still sparse, due to lack of sampling, but they are being rapidly supplemented.

The displacement of the geomagnetic polar paths relative to various continents has been interpreted as due either to a non-dipolar character of the Earth's field in the past or to a large number of experimental errors by many independent investigators or to relative displacement of the continents. Evidence so far indicates that the N.R.M. directions of contemporaneous rocks from within a single continent are consistent with a dipole field but not enough data are available to establish this point firmly. Errors of observation and secular variation effects can account for some of the discrepancies between continents but not all. Interest has therefore been reawakened in the hypotheses of past continental displacements, which have been in existence in geological thought for more than a century.

Hypotheses concerning lateral displacements of the continents have been put forward in order to explain the former distributions of plants and animals, climates, structural arrangements and stratigraphic relationships. These hypotheses have been concerned with superficial features rather than with the physical properties of the outer parts of the Earth, and have been severely criticized for lack of adequate motivation. No satisfactory forces capable of displacing the continents to the required extent have so far been discovered. Most of the hypotheses are variants upon the theme developed by du Toit from the original idea of Wegener. In this it is supposed that two primaeval continents, Laurasia and Gondwanaland, formed in antipodal positions. Some time later these continents were disrupted and the various fragments drifted over the globe to become the present continents. The fragments of Laurasia are supposed to be Asia, Europe and North America and those of Gondwanaland are Africa, South America, Australia, India and Antarctica. The dislocation of the continents is thought to have taken place in the Mesozoic Era and may have occurred in several stages. The break-up of Gondwanaland, according to this hypothesis, would have been the more spectacular since the movements of the fragments (of India in particular) are thought to be greater than those of Laurasia.

Evidence derived from palaeomagnetic data has a particular bearing on the hypotheses of continental drift, since it is entirely independent of the geological arguments that have been put forward so far. Research into the magnetism of rocks from South America (Creer, 1958), Africa (Nairn, 1956; Graham and Hales, 1957), Australia (Irving, 1956*a*) and India (Clegg and others, 1958) is already well advanced, but in order to understand the situation in the Southern Hemisphere it is also necessary to have data from Antarctica. It was with this object in mind that the work described in this report was undertaken. Several small-scale studies were being made at the same time in Antarctica and the results of these are already published (Blundell and Stephenson, 1959; Nagata and Shimizu, 1959; Turnbull, 1959; Bull and Irving, 1960). Though they are of considerable interest, all are restricted by the limited time ranges that could be sampled and the lack of adequate material for sampling.

The Graham Land area, in principle, allows the widest choice of rock to be sampled within a single sector of the continent, because the availability and accessibility of rock outcrops is better than elsewhere and the geological record is more complete. A simplified outline of the succession in this area is given in Table I. The Graham Land peninsula is structurally a continuation of the Andean mountain chain of

TABLE I

GEOLOGICAL SUCCESSION IN GRAHAM LAND (AFTER ADIE, 1953)

Approximate Age (million years)	*Period*	*Rock Type*
0–5	Recent to Pliocene	Deception Island Volcanics (interbedded lavas and agglomerates)
35	? M. Miocene	James Ross Island Volcanic Group (olivine-basalt lavas, tuffs and agglomerates)
70	Late Cretaceous to Early Tertiary	Andean Intrusive Suite (gabbro-diorite-granite)
140	U. Jurassic	Volcanics (interbedded lavas, tuffs and agglomerates)
	M. Jurassic	"Mount Flora Beds"
300	? Carboniferous	Trinity Peninsula Series (greywackes and shales)
450	? Lower Palaeozoic	Older intrusives
>600	Precambrian	Basement Complex

South America and is connected to it through the island arc of the Southern Antilles (Scotia Arc). The greater part of Graham Land is made up of the Andean Intrusive Suite, which predominates over all other rock types. The most suitable rocks for palaeomagnetism studies are the igneous formations, but useful information can be obtained from the sediments if they contain sufficient magnetic material.

II. EXPERIMENTAL PROCEDURE

A. Field Programme and Sample Preparation

1. *Sampling scheme*

Magnetic measurements are normally carried out on cylindrical specimens cored from samples of rock which have been orientated in the field during removal from a particular site. In the analysis of the measurements it is possible to make use of the distribution of the magnetic directions of individual specimens within a single sample, of mean directions of magnetism of the samples within a site and of sites within the full extent of the formation. The "within sample" variation of magnetic directions is an indication of the uniformity of magnetization of the rock on a small scale and of the accuracy of orientating individual specimens within a sample. Igneous rocks are generally very uniformly magnetized on this scale and, since orientation of the specimens can be made accurately, the dispersion on this level is usually small. The variation between samples at a particular site is in part due to errors in orientating the samples during collection, to local movements of the rocks, which are small if the sampling is done carefully, and to local variations prevailing at the time the rock was first magnetized. With an igneous rock it can generally be assumed that all the material at a particular site within a single formation was magnetized at the same time on cooling down through the Curie Point during consolidation, so that only a small dispersion in the directions of this primary magnetization would be expected within a site. However, from one site to another it cannot be assumed that the magnetism was acquired at exactly the same time, and some dispersion due to the secular variation would be expected. Variation of magnetic directions between sites, resulting from geological tilting of one relative to another subsequent to formation could also be expected. Watson and Irving (1957) have pointed out that in order to estimate the mean magnetic direction of a formation most economically it is best to take one sample from each of a large number of sites uniformly distributed throughout the formation. In practice, to guard against gross experimental error, to test for magnetic instability and to assess "within site" scatter, which may be of interest in itself, it is best to collect several samples from each site visited.

The collection of rocks from Graham Land was planned on these lines with the aim of sampling as fully as possible each of the major units indicated in Table I. Due to the restricted time available, the collection was largely confined to coastal sites, but in subsequent years geologists of the Falkland Islands Dependencies Survey have supplemented the collection with samples from the more remote outcrops. Altogether over 400 samples have been collected from 104 sites. Whenever time allowed, more material than was strictly necessary was collected, since return visits were not feasible; therefore, not all the material collected has been used subsequently.

2. *Method of sampling*

Each sample of rock was orientated in a standard manner. Before removing it from an exposure, several horizontal lines were marked with a felt-nibbed pen on vertical surfaces using a spirit level. On the upper surface of each sample an arrow was drawn pointing towards magnetic north as given by a compass held nearby. The markings were later made more permanent by painting and varnishing. The possibility of very strong local variations in the magnetic field affecting the compass was allowed for by taking bearings on local prominences, and equipment for plane table survey was carried. Unexpectedly, no anomalous deviations were recorded. A map of magnetic variation in the Graham Land area, compiled by the Directorate of Overseas Surveys, allows the correction of magnetic orientations to true north. Samples were numbered according to the standard Survey system used for geological specimens, except the prefix π was used to denote a palaeomagnetic sample instead of the station initial letter. For example, π.72.3 refers to sample 3 collected at site π.72. Most of the samples collected were rather larger than necessary and usually weighed about 10 lb., so that subsidiary experiments could be carried out in the laboratory without the need for further collections.

Detailed station lists of the sampling localities are housed in the Geology Department, University of Birmingham.

3. *Sample preparation*

Measurement of the magnetic properties of rocks is facilitated if the rock samples are of some simple geometric shape and standard size; for convenience, it is usual to core out cylindrical or cubic specimens from each of the samples. Apparatus existing in the Geophysics Department was designed for measurements on cylindrical specimens 2 cm. high and 2 cm. in diameter, as previous experience had shown this to be a convenient size. The samples of rock were suitably orientated and set in Plaster of Paris, which allowed the orientation markings to be preserved whilst the samples were cored with a diamond drill. The markings were then transferred to the cylindrical specimens thus obtained. A specimen could be orientated in this way relative to the sample with an estimated accuracy of 2°.

Preliminary experiments showed that a reasonable indication of the direction of magnetism of a sample was given by the mean of measurements on two specimens. In order to reduce the time taken to prepare and measure many cylindrical specimens a number of samples were prepared for direct measurement by setting each in a cubic Plaster of Paris mould of 18 cm. side orientated in such a way that one pair of faces of the cube lay parallel to the horizontal markings on the sample and with the north arrow marked on the upper face of the cube. This procedure reduced the overall time of sample preparation and magnetic measurement, but the large heavy cubes proved clumsy to handle and the saving was not great. The direction of the N.R.M. could be measured easily but not the intensity. Also, stability tests by demagnetizing in alternating fields could not be carried out. In view of these disadvantages the use of large cubes was abandoned and the 2 cm. cylinders were preferred.

B. Laboratory Apparatus

The main aim in a palaeomagnetic survey is to determine the average direction of the magnetic field in a given region at various times in the past. It is therefore necessary to measure the direction of the N.R.M. of every specimen and, if possible, its intensity of magnetization, and to test the magnetism for stability. There are two ways of measuring direction and intensity of magnetization, and both have been used in these investigations. One method makes use of a spinning magnetometer, the other an astatic magnetometer. Several tests of magnetic stability must be carried out in the laboratory to determine the reliability of the N.R.M. directions as being representative of the direction of the field prevailing when the rock formed. One test merely requires the remeasurement of the N.R.M. after a suitable time interval, generally 2–3 weeks, with the specimens stored in the reversed direction from their natural orientations. Another more informative test involves the partial demagnetization of the N.R.M. in successively higher alternating fields, and this requires subsidiary demagnetizing apparatus. A comparison of the intensity of the N.R.M. with a T.R.M. produced in the laboratory gives an indication of the total decay of the N.R.M. intensity or the change in field intensity, so that a non-magnetic furnace is valuable in such studies.

1. *Spinning magnetometer*

An instrument working on this principle was built at Birmingham by D. H. Griffiths (1953, p. 46–59) who has already published a full description. A magnetic moment of 10^{-4} e.m.u., which for a 2 cm. cylindrical sample is equal to an intensity of 2×10^{-5} e.m.u./cm.^{3}, could be measured with ease on the Birmingham spinning magnetometer in about 6–8 min. Since the intensity measurement was dependent on the calibration of an amplifier gain, the absolute value of the intensity of magnetization could only be given with 10 per cent accuracy. For the more strongly magnetized specimens, measurements could be made most easily and speedily using this instrument.

2. *Astatic magnetometer*

Several astatic magnetometers have been described in detail (Blackett, 1952; Collinson and others, 1957), and the equipment at Birmingham is essentially similar to the instrument designed by J. A. Clegg for use at Imperial College, London. The main magnets, made from "Alcomax IV", are each 4 mm. long and 2 mm. square in cross-section, and are attached to an aluminium beam 25 mm. apart. Two 36 s.w.g. "Vicalloy" wire trimming magnets improve the astatism. Helmholtz coils surround the instrument to nullify the Earth's field. The magnet system is suspended by a quartz fibre of approximately 5 μ diameter rigidly supported at its upper end. No Müller or similar suspension is necessary. The period of the system is 20 sec., when slightly underdamped and in zero field, and readings of deflections of the system can be taken at 15 sec. intervals. The instrument is housed in a wooden hut, secluded from magnetic and mechanical disturbances, and the temperature in the hut is thermostatically controlled. Shortly after astatization the instrument was capable of measuring a moment of 10^{-6} e.m.u., which gave a deflection of 1 cm. on the scale at a distance of 1 m. from the magnet system, but this sensitivity was reduced to 5×10^{-5} e.m.u. after 2 years. This was found to be sufficient for the satisfactory measurement of all the specimens of igneous rocks.

In practice, the specimen was turned round beneath the magnet system and readings were taken after each 90° rotation. It was placed inside a cubic "Perspex" box on the outside of each face of which is a cover slip acting as a mirror. The box was placed vertically below the magnet system and was aligned by using the reflection of a light beam off each of its faces in turn. The box was rotated 6 times below the magnetometer, sitting on each face in turn, so that altogether 24 readings were taken. A repeat reading was taken each time to allow for linear instrument drift. The specimens were rotated at one of three set distances beneath the magnet system, which were intercalibrated. In this way intensities as well as directions of magnetization could be measured consistently from one specimen to another. Absolute calibration of the magnetometer was effected by passing a measured current through a small coil of known cross-section in place of the specimen. The 24 readings were computed to give four independent estimates of each of the three major components of the magnetization, and on averaging out, these estimates reduced the effect of non-uniform magnetization within the specimen and improved the accuracy of the measurement.

Provision was made under the magnetometer for a "Perspex" table to support the 18 cm. cubic specimens well below the magnet system. Like the cylinder specimen holder the turntable could be manipulated from a table 1 m. away from the instrument. From this position the operator could control the specimen and read the scale recording deflections of the magnet system. The experimental procedure with the large cubes was identical to that for the cylindrical specimens. The astatic and spinning magnetometers were intercalibrated.

3. *A.c. demagnetization apparatus*

A description of the main features of this apparatus has been given by Creer (1959). Fig. 1 illustrates the Birmingham equipment. It was found from early tests at Birmingham that, if the magnetism concerned was to be effectively randomized in direction, it was necessary for the reduction of the applied alternating field to zero to be made very smoothly and for there to be no constant field present; these factors considerably influenced the design. The alternating field was applied by passing 50 c./sec. mains a.c. through a solenoid. The solenoid was designed to provide peak fields up to 1,400 oersted, uniform to within 0·5 per cent within a volume 5 cm. in diameter and 5 cm. long, and sufficiently large to house a specimen. Within these limitations, the dimensions of the solenoid were arranged for minimum power dissipation for a given field at the centre. Fig. 1a shows the coil dimensions. It was made of 20 layers of 18 s.w.g. copper wire, about 150 turns per layer, to give a total of 3,010 turns. The solenoid has a resistance of 15Ω and an inductance of 0·17 H. A peak field of 1,400 oersted was obtained at the centre with a current of 6·8 amp. (r.m.s.) which could be maintained for up to 5 min. without serious overheating. The coil was calibrated for both d.c. and a.c. fields and was the same for both. The coil was in series with a 60 μF condenser to provide a circuit tuned to 50 c./sec. and to cut out unwanted d.c. from the mains. The maximum demagnetizing current was adjusted by means of a "Variac" variable transformer and the current was reduced to zero with a liquid variable resistance shown in Fig. 1b. In this, two copper electrodes in a copper sulphate solution provided a resistance of about 10Ω when both were completely immersed. The copper sulphate solution was then syphoned off, uncovering the upper electrode. The current decreased to zero, as the resistance increased to infinity, in a near linear way by suitable arrangement of the syphoning rate and the shape of the upper electrode. Since only the liquid moved the decrease in current was made particularly smooth. It was arranged for the complete decrease to last about 3 min. Helmholtz coils surrounded the demagnetizing solenoid to back off the Earth's field. To reduce the effect of other extraneous constant fields and to allow demagnetization of the specimen uniformly in all directions the specimen was spun inside the solenoid simultaneously about two axes perpendicular to that of the coil. An air turbine provided the drive so that the motor could be well removed from the apparatus. The specimen was spun at a rate of about 3 c./sec. about one axis which was linked to the other in the ratio 9 : 19. These periods of rotation were long compared with the alternating field but short compared with the decay time of the field.

The apparatus has been used successfully with currents up to 4 amp. (r.m.s.) giving a peak field of 800 oersted, but for higher currents it was necessary to vary the transformer as well, which gave a less smooth decay, in order to avoid overheating the electrodes of the variable resistance. In practice, the rocks investigated have been demagnetized almost completely in fields of less than 800 oersted.

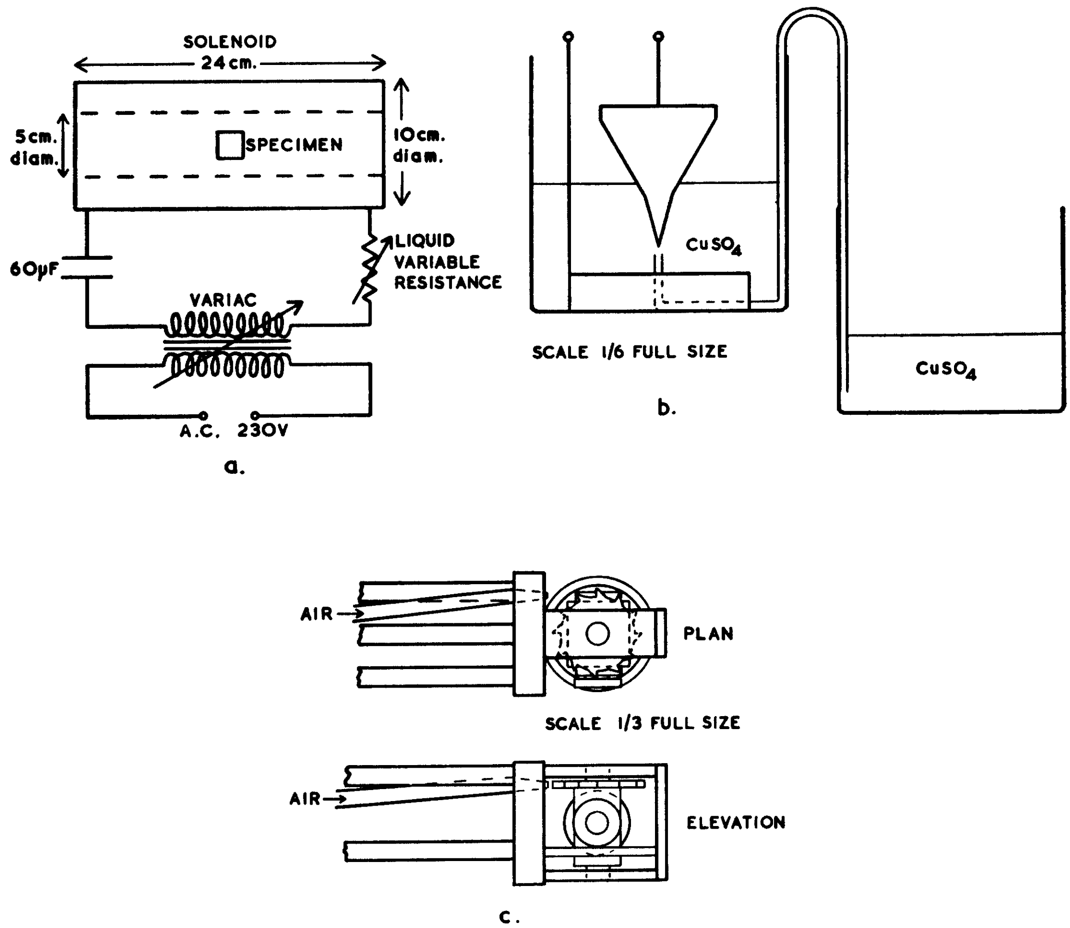

FIGURE 1
A.c. demagnetization apparatus.
a. The solenoid and electrical circuit.
b. The liquid variable resistance.
c. The specimen holder.

4. *Non-magnetic furnace*

The furnace used for producing a T.R.M. in specimens consists of a non-inductively wound "Nichrome" wire coil, capable of taking 100 W and bedded in a "Sindanyo" (commercial asbestos sheet) framework. The specimen was heated in air. The heating element, which is slightly magnetic, was removed while the specimen cooled in the Earth's field.

C. METHODS OF ANALYSIS

The directions of the N.R.M. of a group of specimens are usually scattered axially symmetrically about some mean value. These directions can be represented by unit vectors radiating from a point, the outer ends of which all stand on a sphere of unit radius, and as such can be plotted either on a stereographic or an equal area projection. The mean direction is calculated by averaging the direction cosines of the individual vectors, giving unit weight to each. Fisher (1953) suggested that an appropriate mathematical analysis of the distribution of these vectors could be made by assuming a probability function

$$P = \frac{\kappa}{4\pi \sinh \kappa} \cdot e^{\kappa \cos \theta}, \qquad (2)$$

where θ is the angle between an individual vector and the mean, and κ is a precision parameter representing the spread of the vectors around the mean. The distribution is generally found to be a good estimate of the actual dispersions of the N.R.M. directions of stably magnetized rocks. Watson (1956) and Watson and Irving (1957) have elaborated upon the statistical analysis introduced by Fisher (1953).

If there are N magnetic directions in the group, then, treated each as unit vectors, their vectorial sum is given as a resultant of magnitude R. The best estimate (k) of the precision parameter (κ) is given by

$$k = \frac{N-1}{N-R}. \tag{3}$$

i. Fisher (1953) introduced an estimate of the accuracy of the calculated mean direction, known as the circle of confidence of radius α, and given by

$$1-\cos\alpha = \frac{N-R}{R}\left\{\left(\frac{1}{P}\right)^{\frac{1}{N-1}}-1\right\} \tag{4}$$

such that the calculated mean may differ from the true mean direction by an angle not exceeding α with a probability $(1-P)$. It is usual in palaeomagnetic work to choose $P = 0{\cdot}05$, and in this report the angle α refers to the limit of error of the calculated mean with 95 per cent probability.

ii. Watson and Irving (1957) have given a combined analysis of the distribution of a set of groups of vectors. If there are W_i samples from the ith of B sites, so that the total number of samples is $N = \sum_{i=1}^{B} W_i$, and if the resultant of the magnetic directions of samples at the ith site is R_i and the resultant for all N samples is R, then the best estimate of the precision parameter (ω) of the dispersion of magnetic directions of samples within a site is given by

$$\frac{1}{\omega} = \frac{N-\sum_1^B R_i}{\sum_1^B W_i - B}, \tag{5}$$

and the precision parameter (β) between sites is given by

$$\frac{\overline{W}}{\beta}+\frac{1}{\omega} = \frac{\sum_1^B R_i - R}{B-1}. \tag{6}$$

$\overline{W}$ is the weighted average of W_i given by

$$\overline{W} = \frac{1}{B-1}\left\{N-\frac{\sum_1^B W_i^2}{N}\right\}. \tag{7}$$

The precision parameter (k) of the full set of magnetic directions is given by

$$\frac{1}{k} = \frac{1}{N\omega}+\frac{1}{B\beta}. \tag{8}$$

This treatment is valid only for large values of ω and β, i.e. >10, and can be applied not only to the distribution of the N.R.M. directions of a set of N samples taken from B sites but also to a set of N specimens cut from B samples, or possibly a set of N sites in B localities.

This analysis accounts for random errors in the directions about some mean value but not for any systematic errors or for linear distributions of the vectors on the unit sphere.

iii. Irving (1956*b*) has given the calculation of a geomagnetic pole position from the N.R.M. direction at a given locality based on the hypothesis that the Earth's main field is equivalent to that of a geocentric dipole.

For a locality with colatitude c and longitude d, at which the magnetic direction has a declination ϕ east of true north and inclination I, the colatitude a of the geomagnetic pole is given by

$$\cos a = \cos c \,.\, \cos p + \sin c \,.\, \sin p \,.\, \cos\phi, \tag{9}$$

where

$$\cot p = \tfrac{1}{2}\tan I. \tag{10}$$

The longitude b of the geomagnetic pole is given by

$$\sin(b-d) = \frac{\sin p \,.\, \sin \phi}{\sin a}, \tag{11}$$

and if the circle of confidence about the magnetic direction has radius α, then an error oval equivalent to this can be drawn about the geomagnetic pole position with a semi-axis in the direction of the site given by

$$\delta p = \tfrac{1}{2}\,\alpha\,(1+3\cos^2 p), \tag{12}$$

and the semi-axis perpendicular to it is given by

$$\delta m = \alpha \,.\, \frac{\sin p}{\cos I}. \tag{13}$$

III. RESULTS OF THE MAGNETIC MEASUREMENTS

MEASUREMENTS of the N.R.M. of the greywacke facies sediments of the Trinity Peninsula Series and the Middle Jurassic sediments from Mount Flora, Hope Bay were not possible because the intensities of magnetization were too weak to produce measurable deflections of the astatic magnetometer. The investigations were therefore restricted to a study of the magnetism of the igneous rocks.

A. TERTIARY AND RECENT VOLCANIC ROCKS

The directions of the N.R.M. of Tertiary lavas from Deception Island, King George Island and near Hope Bay have been measured. Together with a dyke of probable Tertiary age from Danco Island they form an interesting group.

The most thorough investigation has been carried out at Deception Island where seven lava flows were sampled at eight sites (Fig. 2). According to Hawkes (1961), the lava from site π.84 is a member of the Fumarole Bay Volcanics, the earliest represented on the island. The other samples are all from lavas thought to have been erupted subsequent to the formation of the main caldera which has given the island its present shape. The lava from site π.88 belongs to the Neptunes Bellows Group and the others to the later Pendulum Cove Group. None of the very recent lavas were sampled, because their highly scoriaceous tops prevented the collection of suitable material. The Deception Island volcanic rocks are of recent origin, although no absolute dating has yet been possible. It would seem that the sampling covers a range of time at least comparable with the period of secular variation or even longer. The Danco Island dyke (O.923) was sampled by G. J. Hobbs and, although it could be dated only as post-Upper Jurassic, it is likely to be of Tertiary age.

TABLE II

RESULT OF STORAGE TESTS ON TERTIARY LAVAS FROM POINT THOMAS, KING GEORGE ISLAND

Site	*Number of Samples*	*Change in Magnetic Inclination in Each Sample brought about by Storage for One Month Orientated Upside Down*
Gπ.1	4	34°, 8°, 1°, 4° (also large scatter of N.R.M. directions)
Gπ.2	5	15°, 31°, 2°, 4°, 18°
Gπ.3	5	1°, 0°, 1°, 2°, 1°
Gπ.4	4	5°, 29°, 22°, 12°

The lava from site Gπ.3, collected by J. S. Bibby, was the only one of four sampled from King George Island to show any stability of N.R.M. The change in the inclination of the N.R.M. brought about in each sample as a result of storage upside down for one month is shown in Table II. On this evidence all the lavas except Gπ.3 showed gross instability and were subsequently disregarded.

The James Ross Island Volcanic Group was sampled at three localities near Hope Bay by J. Ashley who has since completed the magnetic measurements on them (Ashley, 1962). These are tentatively dated as Middle Miocene from fossil evidence in the sediments above and below.

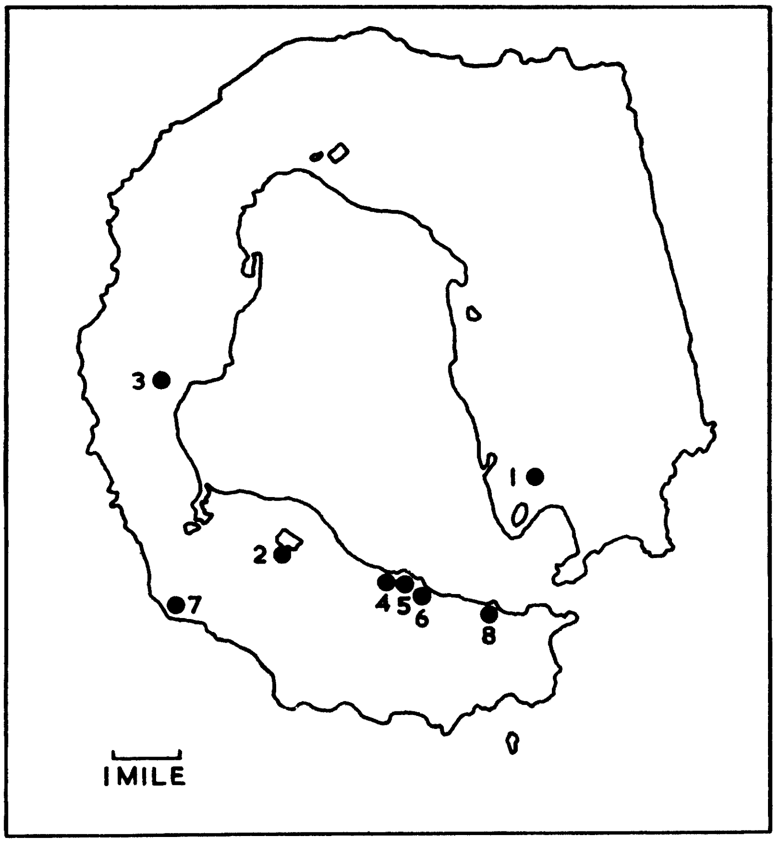

FIGURE 2

Map of Deception Island showing the sampling sites of the Tertiary volcanic rocks.

1. Site π.82.	3. Site π.84.	5. Site π.86.	7. Site π.88.
2. Site π.83.	4. Site π.85.	6. Site π.87.	8. Site π.104.

The results of all these magnetic measurements are summarized in Table III and Fig. 3a. Two of the three lavas of the James Ross Island Volcanic Group are reversely magnetized but all the other rocks are magnetized normally. In the statistical analysis of these results the mean N.R.M. directions of the reversely magnetized lavas have been turned back to normal directions. There is no evidence to suggest whether the reversal is due to a reversal of the Earth's field or to some self-reversal mechanism in the rock. When heated and given a T.R.M. in the laboratory, specimens from the Beak and Corrie Island lavas all became normally magnetized. Apart from the reversed N.R.M. of the two lavas all the results given in Table III show a grouping of magnetic directions more or less about the theoretical axial dipole field direction. The Deception Island lavas and the James Ross Island lavas have been analysed separately but using the variance test of Watson (1956, p. 157) it has been found that they are not significantly different and can be treated together. In view of this and the absence of any clear knowledge of the relative ages of the groups of lavas from the various localities, all the Tertiary rocks have been grouped together for analysis. This is shown in Table IV. In most cases only two or three specimens were measured from each sample, but in order to compare the dispersion at various levels, 26 specimens were measured from the five samples from site O.923. From Table IV it appears that the dispersion between samples within a site is greater than that between sites, and it was therefore necessary to measure several samples in order to obtain a precise mean site direction. The "within site" dispersion, in the

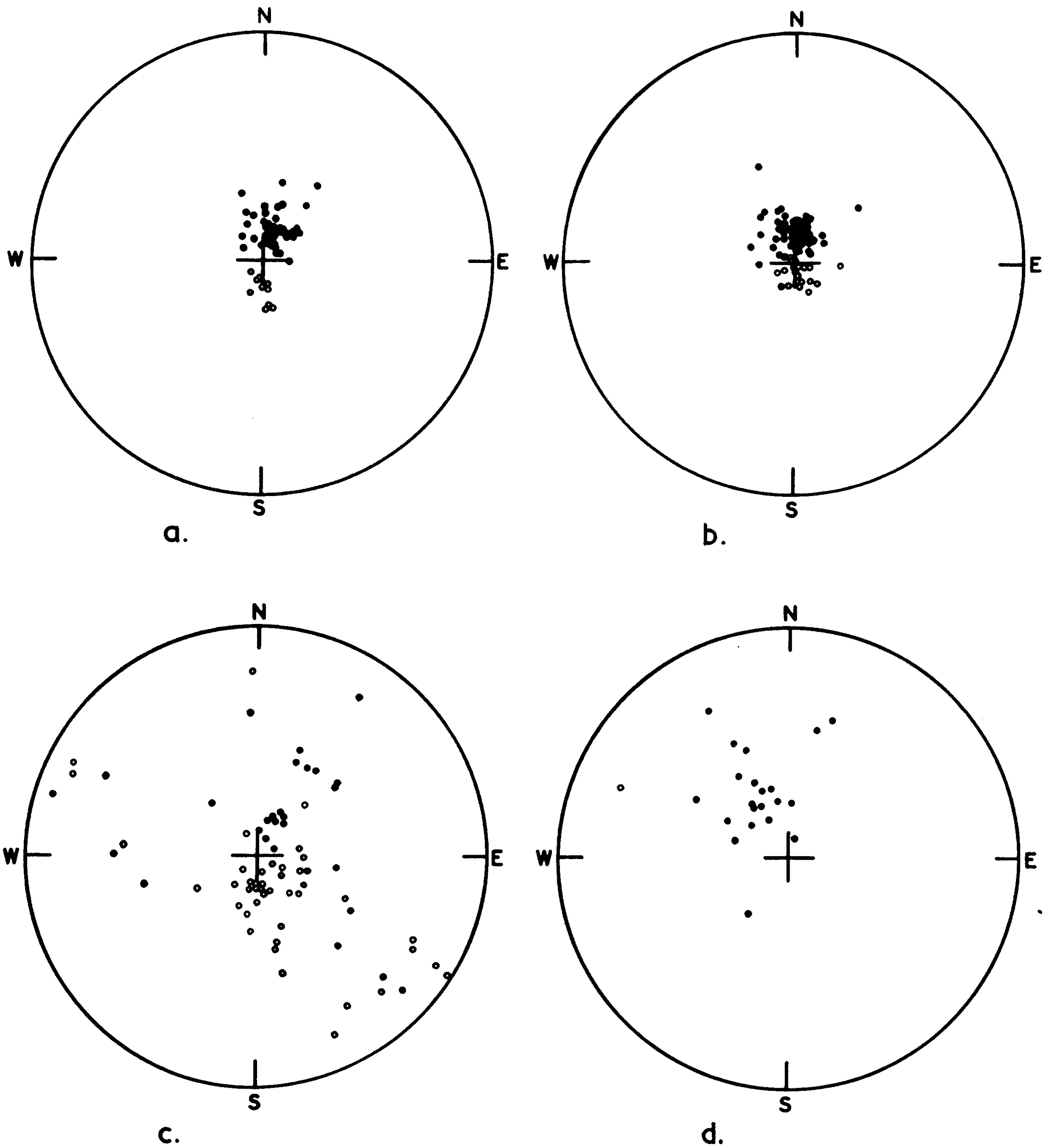

FIGURE 3

Stereograms showing the directions of the N.R.M. of:
a. Samples of the Tertiary volcanic rocks.
b. Samples of the Andean Intrusive Suite.
c. Specimens of the Upper Jurassic Volcanic Group.
d. Samples of the older intrusive rocks.
● Inclination **UP**
○ Inclination **DOWN**

case of site O.923, is divided evenly between the "within" and "between" specimen dispersions. The dispersions are greater than could result from experimental errors in orientating either the specimens or the samples and must be due to local variations within the rock. The small dispersion between sites and the agreement of magnetic directions between localities indicate little or no relative movement of

TABLE III

N.R.M. OF THE TERTIARY VOLCANIC ROCKS

Locality	*Site*	*Volcanic Group*	*Rock Type*	*Number of Samples N*	*R*	*k*	*α*	Mean Direction of N.R.M. *φ*	Mean Direction of N.R.M. *I*
Deception Island (see Fig. 3)	π.82	Pendulum Cove Group lava	andesite	3	2·936	31	23°	25°	72° **UP**
	π.83	Pendulum Cove Group lava	olivine-basalt	4	3·985	200	7°	20°	69° **UP**
	π.85	Pendulum Cove Group lava	oligoclase-andesite	4	3·994	500	4°	32°	79° **UP**
	π.86-87	Pendulum Cove Group lava	oligoclase- and hyalo-andesite	4	3·970	100	9°	15°	75° **UP**
	π.104	Pendulum Cove Group lava	andesite	4	3·928	42	14°	25°	74° **UP**
	π.88	Neptunes Bellows Group lava	olivine-basalt	4	3·970	100	9°	19°	77° **UP**
	π.84	Fumarole Bay Volcanics lava	andesine-basalt	4	3·882	25	19°	341°	75° **UP**
Point Thomas, King George Island	Gπ.3	? lava	hypersthene-augite-andesite	5	4·912	45	9°	28°	71° **UP**
Danco Island	O.923	post-Upper Jurassic dyke	dolerite	5	4·971	138	7°	35°	77° **UP**
Beak Island	D.3322	James Ross Island Volcanic Group lava	olivine-basalt	5	4·987	308	4°	185°	80° **DOWN**
Corrie Island	D.3323	James Ross Island Volcanic Group lava	olivine-basalt	4	3·951	61	12°	3°	63° **UP**
Buttress Hill, Tabarin Peninsula	D.3326	James Ross Island Volcanic Group lava	olivine-basalt	5	4·976	167	6°	177°	71° **DOWN**
TERTIARY	TOTAL			12 (sites)	11·932	162	3·4°	15°	74° **UP**

the formations. Some of the lava flows on Deception Island at present dip at angles up to 40° from the horizontal, and clearly these dips must be the original slopes down which the lavas poured. The "between site" dispersion is considered as most likely due to the effect of secular variation. The circle of confidence about the mean direction of magnetism for all the Tertiary rocks (Table III) has been calculated according to equation (4) to be of 3·4° radius, using the mean site direction as the statistical unit. The mean direction of the N.R.M. for all the Tertiary rocks is 4·6° from the axial dipole field in the area, which is directed towards geographic north with an upward inclination of 76°, and this difference, though small, is just significant.

TABLE IV

ANALYSIS OF DISPERSION OF THE DIRECTIONS OF N.R.M. OF THE TERTIARY VOLCANIC ROCKS

	N	R	ΣR_i	B	$\overline{W}$	*Dispersion*	*Precision Parameter*
Danco Island (O.923)	26 (specimens)	25·700	25·860	5 (samples)	5·13	Within sample	150
						Between samples	154
All Tertiary sites (Table III)	51 (samples)	50·170	50·462	12 (sites)	4·24	Within site	72
						Between sites	333
						Total	1920

The stability of the N.R.M. of all the specimens has been tested by storage and remeasurement so that all the results in Table III are based on specimens showing no gross instability. A representative selection of specimens has been demagnetized in alternating fields as described on p. 7. Nine specimens, each from a separate site, were investigated in some detail and Fig. 4 shows the relative changes in their magnetic intensity produced by demagnetization in successively higher fields. No significant changes in the N.R.M. directions were brought about, but demagnetization from a peak field of 150 oersted reduced the intensity of most of the specimens by half. The test was extended to include two specimens from each of ten sites, all of which were demagnetized in a peak field of 200 oersted. Changes in the magnetic directions of these specimens, brought about by the demagnetization, are shown in Table V and are seen to be insignificant. The average relative intensity after demagnetization, J/J_0, was $0{\cdot}46 \pm 0{\cdot}04$ for the 20 specimens. The conclusion from this test must be that the N.R.M. of the Tertiary rocks is stable against demagnetizing fields at least up to 200 oersted and that the direction of the N.R.M. is a fair record of the field direction prevailing when the magnetism was acquired. No evidence of hydrothermal alteration or weathering has been observed in thin sections of the rocks concerned so it is most likely that the magnetism was acquired when the rocks first formed.

Six samples were hastily collected by P. Kennett from recent lava flows on the South Sandwich Islands. The N.R.M. directions have been measured and analysed but, because the accuracy of the orientations of the samples is doubtful, the results have not been included in Table III. The mean direction of the N.R.M. of the six samples has a declination of 19° E. and an inclination of 69° **UP**. The precision parameter is 123 and the circle of confidence has a 6° radius. The axial dipole field in the area has an inclination of 69° **UP**.

TABLE V

A.C. DEMAGNETIZATION OF THE TERTIARY VOLCANIC ROCKS

	Number of Specimens N	R	k	α	*Mean Direction of N.R.M.* ϕ	I
Before demagnetization	20	19·726	69	4·0°	13°	75° **UP**
After demagnetization in 200 oersted field	20	19·636	52	4·6°	14°	78° **UP**

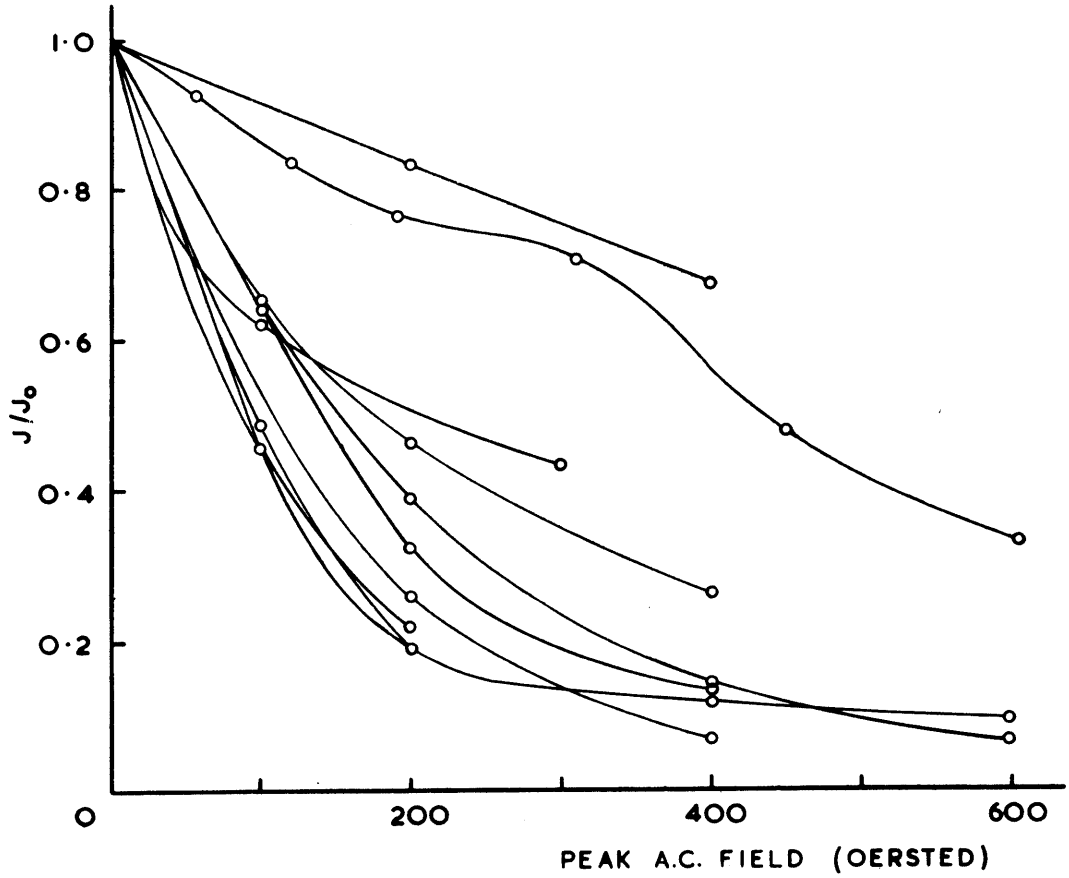

FIGURE 4

Relative intensities (J/J_0) of the N.R.M. of specimens of the Tertiary volcanic rocks after a.c. demagnetization.

B. Andean Intrusive Suite

The directions of the N.R.M. have been measured on 99 samples collected from 20 exposures along the west coast of Graham Land and covering a range of about 500 miles. Storage tests have been made on all the specimens, together with a.c. demagnetization on 30 of them. Largely as a result of the storage tests 22 of these have been rejected as possessing gross instability. The results of the measurements on the remainder are shown in Fig. 3b and Table VI, in which the total mean magnetic direction of the suite has been calculated giving equal weight to each of the first 11 sites listed and combining the results from the last five sites, which were less extensively sampled, to be equivalent to one of the others. The N.R.M. of the two samples from site W.538 is reverse so that in combining this result with the others the directions were normalized. Likewise, the magnetism of sites π.201 and π.39, which is reverse, was also normalized in the computation of the total mean direction. Since the samples were collected from a wide area it was necessary in combining the results to account for the different latitudes of the sampling sites. The axial dipole field direction at the Argentine Islands is 77° **UP**, on Tabarin Peninsula it is 76° **UP**, whilst in Marguerite Bay, the southernmost area sampled, it is 79° **UP**. Thus, in the calculation of the total mean direction and the precision of the distribution of mean site directions about it, 1° was added to the mean site inclination of sites π.11–16 (Tabarin Peninsula) and 2° was subtracted from the mean site inclinations of sites π.90, π.102, W.538, E.1515 and E.1543 (Marguerite Bay). Calculation of the total mean direction of the N.R.M., giving each sample equal weight, gave the same result. An analysis of the dispersion of the N.R.M. directions as described on p. 9 was carried out on the samples from the first 11 sites listed in Table VI, due account having been taken of latitude differences between the sites, and the result is given in Table VII. A comparison with the analysis of the N.R.M. directions of the Tertiary rocks

(Table IV) indicates an almost identical dispersion. Also, the total mean direction of magnetism is not significantly different from the axial dipole field (77° **UP** inclination) even though the circle of confidence has only a 3° radius.

TABLE VI

N.R.M. OF THE ANDEAN INTRUSIVE SUITE

Locality	*Site*	*Rock Type*	*Number of Samples N*	*R*	*k*	α	*Mean Direction of N.R.M.*	
							ϕ	*I*
Goudier Island, Port Lockroy	π.201*	quartz-diorite	6	5·952	104	7°	183°	87° **DOWN**
Nobby Nunatak, Tabarin Peninsula	π.11	diorite	4	3·957	70	11°	340°	73° **UP**
Summit Ridge, Tabarin Peninsula	π.12	diorite	5	4·991	476	4°	6°	75° **UP**
Last Hill, Tabarin Peninsula	π.13	gabbro	4	3·985	213	6°	8°	72° **UP**
Mineral Hill, Tabarin Peninsula	π.16	diorite	4	3·990	326	5°	0°	76° **UP**
The Barchans, Argentine Islands	π.39	quartz-diorite	12	11·891	109	4°	144°	82° **DOWN**
Cape Tuxen	π.46	gabbro	8	7·909	77	6°	9°	77° **UP**
Berthelot Islands	π.49	gabbro	8	7·965	205	4°	358°	72° **UP**
Somerville Island	π.52	gabbro	4	3·990	300	5°	355°	78° **UP**
Birdsend Bluff, Danco Coast	π.103	gabbro	5	4·866	30	14°	343°	70° **UP**
Horseshoe Island	π.90	diorite	5	4·935	62	10°	350°	85° **UP**
Chavez Island	π.23	diorite	2					
Liard Island, Hanusse Bay	W.538†	gabbro	2					
Red Rock Ridge, Neny Fjord	E.1515*	gabbro	3 } 12	11·324	16	11°	336°	74° **UP**
Lystad Bay, Horseshoe Island	E.1543*	gabbro	3					
Pyrox Island, Neny Fjord	π.102	diorite	2					
TOTAL (normalizing π.201 and π.39)			12 (sites)	11·939	180	3·2°	351°	77° **UP**

* Collected by A. K. Hoskins.
† Collected by D. C. Goldring.

The stability of the N.R.M. of a selection of 30 specimens was tested by a.c. demagnetization and a graph of the relative changes in intensity of some of the specimens investigated is shown in Fig. 5. The directions of magnetism in each case were substantially unaltered. An examination of the samples both in the hand specimen and under the microscope showed that all the rocks were fresh and unweathered, so it is most likely that their N.R.M. was formed during emplacement.

TABLE VII

ANALYSIS OF DISPERSION OF THE DIRECTIONS OF N.R.M. OF THE ANDEAN INTRUSIVE SUITE

(for first 11 sites given in Table VI)

N	*R*	ΣR_i	*B*	$\overline{W}$	*Dispersion*	*Precision Parameter*
					Within site	96
65 (samples)	64·094	64·435	11 (sites)	5·99	Between sites	253
					Total	1920

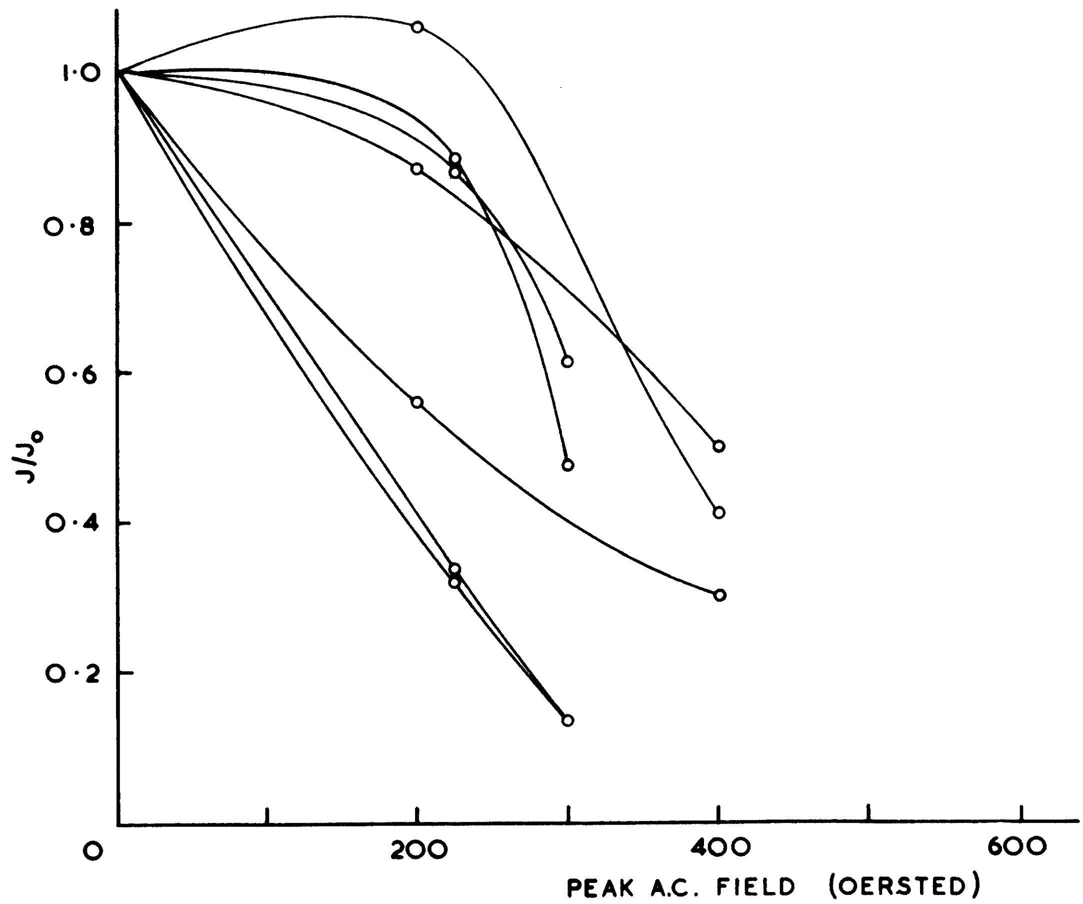

FIGURE 5

Relative intensities (J/J_0) of the N.R.M. of specimens of the Andean Intrusive Suite after a.c. demagnetization.

The magnetism of the specimens from sites π.15 (Ridge Peak, Tabarin Peninsula) and π.201 (Goudier Island, Port Lockroy) was investigated more fully, because, as can be seen in Table VIII, the distributions of both groups of N.R.M. directions were poor (with low precision). After demagnetization in a peak field of 160 oersted the distribution for site π.201 was much improved, whilst that for site π.15 was not. Furthermore, the mean direction of the N.R.M. for site π.201 was altered significantly, coming more into line with other mean directions of groups with large precision parameters. The improved precision of site π.201 appeared to indicate that an unstable component of magnetization had been removed and that the magnetism remaining after partial demagnetization gave a better estimate of the original direction of magnetism of the rock. This latter result was therefore included in Table VI and used in the calculations concerning the direction of magnetism of the Andean Intrusive Suite. The very low precision of site π.15 even after partial demagnetization indicated that the N.R.M. direction was of little significance and this result was rejected.

TABLE VIII

A.C. DEMAGNETIZATION OF ANDEAN INTRUSIVE ROCKS FROM TWO SITES

Site		*Number of Specimens* *N*	*R*	*k*	α	*Mean Direction of N.R.M.* *φ*	*I*
Ridge Peak, Tabarin Peninsula (π.15)	Before demagnetization	8	4·326	2	57°	324°	45° **UP**
	After demagnetization in 160 oersted field	8	4·546	2	54°	18°	53° **UP**
Goudier Island, Port Lockroy (π.201)	Before demagnetization	6	5·732	19	16°	347°	82° **DOWN**
	After demagnetization in 160 oersted field	6	5·952	104	7°	183°	87° **DOWN**

C. UPPER JURASSIC VOLCANIC GROUP

Magnetic measurements have been made on 43 samples collected from outcrops of Upper Jurassic lavas at King George Island, the Argentine Islands and Lallemand Fjord. The directions of the N.R.M. of these Jurassic volcanic rocks are widely scattered, as can be seen in Table IX and Fig. 3c, and, with the exception of the rock from site π.8, the precision parameter is lower than would be expected for rocks with a stable N.R.M. of thermo-remanent origin. The variation of the N.R.M. directions between specimens within a sample is large so that the statistical analysis shown in Table IX was made using the specimen N.R.M. directions as statistical units instead of the mean sample directions which have been used in the previous tables.

As a result of storage tests, about one-third of the specimens showed gross instability. Most of the specimens were demagnetized in alternating fields in the manner already described. The first few were demagnetized in fields up to 600 oersted and it was found that more than half the original N.R.M. was removed by demagnetization in a 200 oersted peak field, so this was used subsequently. The partial demagnetization resulted in very little improvement in precision and in some cases made it worse. The improvement is significant only for site π.45 and there the mean magnetic direction is little altered and appears to be similar to that of the Andean intrusive rocks of The Barchans (Table VI).

G. J. Roe (personal communication) has reported that the lavas of Indicator Island, the Three Little Pigs and Winter Island have steep dips, varying from one island to another, and this could possibly account for differences between the mean N.R.M. directions. Since the precision of N.R.M. directions within individual sites is so low, it is of little value to attempt to combine mean site directions. The N.R.M. directions, measured either before or after demagnetization, are too widely scattered to be of any palaeomagnetic value. A feature of every one of the samples collected was the altered appearance of the rock and microscopic investigation of thin sections revealed considerable hydrothermal alteration of the primary minerals, together with the formation of secondary minerals, principally chlorite, calcite, pyrite and iron ore. Titanomagnetite was generally altered to leucoxene. In all three areas the volcanic rocks outcrop close to Andean intrusions and it must be presumed that the intrusion of the Andean suite heated all the surrounding country rocks and caused the alteration observed in the Jurassic volcanic rocks. It must also be presumed that the heating destroyed the original magnetism to such an extent that partial demagnetization in a.c. fields could not reveal it. The only two results of any significance, from sites π.8 and π.45 (after demagnetization), are consistent with the field prevailing when the Andean suite was intruded. It may be argued that either the local field in the Upper Jurassic was the same as the axial dipole field (and reversed) or the N.R.M.s of sites π.8 and π.45 were acquired during the intrusion of the

TABLE IX

N.R.M. OF THE JURASSIC VOLCANIC ROCKS AND DYKES OF POSSIBLE JURASSIC AGE

Locality	*Site*	*Rock Type*	*Number of Samples*	*Number of Specimens N*	*R*	*k*	α	*Mean Direction of N.R.M.* ϕ	*Mean Direction of N.R.M.* *I*
			JURASSIC LAVAS						
Ullmann Range, Admiralty Bay	π.6	porphyritic andesite	3	3	2·892	20	29°	37°	31° **UP**
Keller Peninsula, Admiralty Bay	π.8	porphyritic andesite	3	3	2·999	5000	2°	32°	70° **UP**
Galindez Island, Argentine Islands	π.21	porphyritic andesite	3	5	1·676	1	>90°	124°	19° **DOWN**
Indicator Island, Argentine Islands	π.26	microdiorite	3	6	5·500 *5·263*	10 *7*	22° *28°*	150° *182°*	59° **DOWN** *73° DOWN*
Three Little Pigs, Argentine Islands	π.27	porphyritic andesite	3	3	1·904	2	>90°	158°	40° **DOWN**
Three Little Pigs, Argentine Islands	π.28	andesite	5	10	9·264 *9·355*	12 *14*	14° *13°*	176° *179°*	72° **DOWN** *69° DOWN*
Winter Island, Argentine Islands	π.35	porphyritic andesite	5	10	8·086 *9·296*	5 *13*	25° *14°*	132° *116°*	29° **DOWN** *24° DOWN*
Grotto Island, Argentine Islands	π.45	porphyritic andesite	3	6	4·466 *5·772*	3 *22*	44° *15°*	190° *174°*	67° **DOWN** *76° DOWN*
Irizar Island, Argentine Islands	π.55	trachyte	3	5	4·747 *2·946*	16 *2*	20° *77°*	96° *68°*	71° **DOWN** *34° DOWN*
Detaille Island, Lallemand Fjord	π.69		4	8	5·689 *4·686*	3 *2*	38° *52°*	308° *309°*	44° **UP** *39° UP*
Detaille Island, Lallemand Fjord	π.71		4	8	4·467 *4·200*	2 *2*	55° *59°*	53° *42°*	75° **UP** *67° UP*
Detaille Island, Lallemand Fjord	π.74		4	4	3·260	4	52°	7°	34° **UP**
			? JURASSIC DYKES						
Keller Peninsula, Admiralty Bay	π.7		3	3	2·991	233	8°	29°	77° **UP**
Detaille Island, Lallemand Fjord	π.70		4	7	6·950 *6·965*	122 *172*	6° *5°*	45° *39°*	67° **UP** *74° UP*
Detaille Island, Lallemand Fjord	π.72		5	9	7·048 *8·956*	4 *184*	29° *4°*	11° *6°*	50° **UP** *74° UP*
Black Thumb, Marguerite Bay	E.1502		3	9	8·773 *8·761*	35 *34*	9° *9°*	32° *44°*	70° **UP** *74° UP*
Lagotellerie Island, Marguerite Bay	Y.723		3	6	5·213 *3·614*	6 *2*	29° *63°*	38° *26°*	70° **UP** *76° UP*

The figures in italics give the results after a.c. demagnetization in a 200 oersted field.

Andean suite. In view of the alteration of the minerals in the Upper Jurassic volcanic rocks the latter explanation seems to be the more plausible.

Several dykes cutting Jurassic volcanic rocks were sampled in case they were of similar age but the geological evidence indicates only that they are younger than the volcanics. The result of measuring N.R.M. directions of samples taken from these dykes is given in Table IX. Storage tests indicate no gross instability, but the scatter of directions is large in some cases. A.c. demagnetization in a peak field of 200 oersted improved the precision of the data for sites π.70 and π.72 but it was useless for site Y.723. The precision of these distributions was much nearer to that of the Andean and Tertiary rocks investigated and the mean directions were also similar to the axial dipole field. No firm conclusions can be made from this, although the inference must be that the dykes are probably Tertiary in age.

D. Older Intrusive Rocks

In Marguerite Bay there are several large intrusive bodies which are generally regarded as being Lower Palaeozoic in age, but for which the only evidence of age is that they are pre-Upper Jurassic. Two of these intrusions were sampled at Horseshoe Island and Stonington Island. A basic dyke cutting the Stonington Island diorite, which is thought to be closely associated with it, and therefore contemporaneous, was also sampled. The results of the magnetic measurements carried out on all the samples are given in Table X and Fig. 3d. There is no geological reason for correlating the diorites on Horseshoe Island and Stonington Island but, because the mean directions of the N.R.M. are similar, they have been analysed together. However, this agreement of the mean directions of the N.R.M. of the two diorites and the dyke was found to be superficial as a result of a.c. demagnetization tests, details of which are also shown in Table X. The demagnetization brought about large changes in the directions of the N.R.M. of individual specimens and a reduction of the precision of the dispersion. Both before and after these demagnetization tests nearly half the samples exhibited gross instability as a result of storage tests. A field of 200 oersted was used for demagnetization because initial tests with three specimens indicated a 50 per cent reduction of intensity with this field. The demagnetization appeared to affect the N.R.M. directions of the Stonington Island diorite specimens in a systematic way, so a further demagnetization was made with a field of 350 oersted, but this produced no significant change. The precision of the dispersions of directions of the N.R.M. of the diorites and the dyke is so low, both before and after demagnetization, as to make the mean directions have little significance. It seems, therefore, that the magnetism of these rocks from Stonington Island and Horseshoe Island is too unstable to be of palaeomagnetic value. The remanent magnetism of the Stonington Island diorite and, perhaps, also that of the dyke and the Horseshoe Island diorite, was probably once in a reversed direction but, because of its instability, it has since turned towards the present field direction in Marguerite Bay, which has a 20° E. declination and a 61° **UP** inclination.

Table X

N.R.M. OF THE OLDER INTRUSIVE ROCKS OF MARGUERITE BAY

Locality	*Rock Type*	*Number of Samples N*	*Number of Specimens*	*R*	*k*	*α*	*Mean Direction of N.R.M.*	
							φ	*I*
Horseshoe Island (π.93 and π.98)	diorite	11 *11*	22 *11*	9·812 *7·898*	8 *3*	17° *30°*	327° *356°*	54° **UP** *40° UP*
Stonington Island (π.99)	diorite	8 *8* *8**	16 *8* *8*	6·709 *4·159* *5·653*	5 *2* *3*	26° *60°* *39°*	338° *255°* *331°*	52° **UP** *67° DOWN* *81° DOWN*
Stonington Island (π.100)	basic dyke	3 *3*	6† *6†*	5·761 *2·812*	21 *2*	15° *86°*	327° *297°*	53° **UP** *9° DOWN*

The figures in italics give the results after a.c. demagnetization in a 200 oersted field.

* Second demagnetization in 350 oersted field.

† Specimen used as statistical unit instead of sample.

TABLE XI

GEOMAGNETIC POLE POSITIONS FOR ALL SAMPLES COLLECTED FROM ANTARCTICA

Formation	*Locality*		*Present Field Direction*		*Axial Dipole Field Inclination*	*Number of Samples*	*Number of Sites*				*Mean Direction of N.R.M.*		*Geomagnetic Pole Position*		*Oval of Confidence Semi-axes*		*Reference*
	Lat.	*Long.*	ϕ	*I*	*I*		*N*	*R*	*k*	α	ϕ	*I*	*Lat.*	*Long.*	δp	δm	
Tertiary lavas, South Shetland Islands	63° S.	61° W.	13°	56° **UP**	76° **UP**	51	12	11·932	162	3°	15°	74° **UP**	82° S.	129° W.	6°	6°	Table III, p. 13
Andean Intrusive Suite, Graham Land	65° S.	64° W.	18°	58° **UP**	77° **UP**	77	12	11·939	180	3°	351°	77° **UP**	86° S.	2° W.	6°	6°	Table VI, p. 16
Cenozoic volcanics, Cape Hallett	72° S.	171° E.	—	—	81° **UP**	23	—	22·542*	48*	4°*	28°	80° **UP**	81° S.	94° E.	8°*	8°*	Turnbull (1959)
? Jurassic dolerite intrusions, Theron Mountains and Whichaway Nunataks	80° S.	30° W.	due N.	—	85° **UP**	8	7	6·691	21	14°	64°	68° **UP**	54° S.	136° W.	18°	18°	Blundell and Stephenson (1959)
? Jurassic dolerite intrusions, Wright Valley	78° S.	162° E.	155°	83° **UP**	84° **UP**	11	8	7·889	64	7°	262°	70° **UP**	51° S.	132° W.	10°	12°	Bull and Irving (1960)
? Jurassic dolerite intrusions, Ferrar Glacier	78° S.	161° E.	—	—	84° **UP**	57	5	4·994	714	3°	255°	76° **UP**	58° S.	142° W.	5°	5°	Turnbull (1959)
Precambrian gneiss, Ongul Islands	69° S.	40° E.	317°	66° **UP**	79° **UP**	18	3	2·967	60	16°	38°	35° **DOWN**	2° S.	104° W.	11°	18°	Nagata and Shimizu (1959)

* Calculated using each sample as a statistical unit.

IV. SUMMARY AND DISCUSSION

It has been argued that all the Tertiary and Recent lavas detailed in Table III have a stable N.R.M. in the direction of the magnetic field which existed when they were extruded. The average direction of the N.R.M. is 4·6° from the axial dipole field, which is a barely significant difference, and it is 18° from the Earth's present field. The "between site" dispersion can be ascribed to the effect of secular variation, so the steep dips of some of the Deception Island lavas are unlikely to be due to post-formational tilting. The James Ross Island Volcanic Group lavas are all flat-lying. None of the Deception Island lavas have a reversed magnetism and this may mean that they are all Pleistocene in age. The reversed magnetism of two of the three lavas of the James Ross Island Volcanic Group is in accordance with Miocene volcanics elsewhere (Cox and Doell, 1960, p. 680).

The magnetism of the Andean Intrusive Suite is very similar to that of the Tertiary and Recent volcanic rocks. There is evidence to suggest the N.R.M. is in the direction of the Earth's magnetic field prevailing when the rocks were intruded. The average direction of the N.R.M. is coincident with that of the axial dipole field. The N.R.M. of the rocks from three sites is reversed, but there is no evidence to suggest whether this is due to a reversal of the polarity of the Earth's field during their emplacement. The "between site" dispersion can also be ascribed to the effect of secular variation of present-day magnitude. It can therefore be inferred that there has been no major folding in the region covered by the sampling since the intrusion of the Andean suite.

The mean directions of the N.R.M. of the Andean and the Tertiary and Recent rocks both lie close to that of the axial dipole field. They are therefore consistent with the hypothesis that the Earth's magnetic field has remained constant, apart from the secular variation, in Graham Land since the beginning of the Tertiary and is equivalent to that of an axial geocentric dipole. The analysis of the dispersion of the N.R.M. directions accounts for random variations such as those due to errors of measurement, the effect of secular variation and the partial demagnetization of the N.R.M. from natural causes. It takes no account of any systematic errors that may have arisen as a result of inadequate sampling or a long-term partial instability of the N.R.M. that is undetected by laboratory tests, and this must be remembered whenever palaeomagnetic data are examined.

The magnetism of the Upper Jurassic Volcanic Group and the older intrusive rocks is so variable in direction from one specimen to another, even when tests indicate some stability, that no clear pattern can be seen. Examination of the rocks in thin section has indicated clear evidence of hydrothermal alteration of the primary minerals, in contrast with the Andean and younger rocks which are all relatively unaltered. Therefore, it seems that the original magnetism of the Upper Jurassic and older rocks has been destroyed, probably during the emplacement of the large batholithic Andean intrusions. Attempts to remove any secondary magnetism in the laboratory, in order to regain the direction of the primary magnetism, have failed, probably because the primary magnetism has been completely destroyed or was more easily demagnetized in alternating fields than the secondary magnetism. Thus, no information can be gained concerning the Earth's past field in Graham Land from the Upper Jurassic and older rocks.

The results of the magnetic measurements made on the Tertiary and Recent lavas and the Andean intrusive rocks are summarized in Table XI along with all published results of similar studies on other rocks from Antarctica. In order to assist comparison of these results the N.R.M. directions have been transformed, according to the procedure described on p. 9, using equations (9), (10) and (11), to provide positions of the geomagnetic pole in the Southern Hemisphere. The semi-axes of the oval of confidence about each pole position have been calculated using equations (12) and (13) (p. 10). The pole positions and their respective ovals of confidence are shown on an equal area projection of the Southern Hemisphere in Fig. 6.

It should be noted that the results of various authors are in agreement both for the Tertiary and the Jurassic rocks, though there are no data from the Jurassic rocks from Graham Land. The coincidence of pole positions calculated from the N.R.M. directions of rocks of the same age but from widely separated localities is evidence in support of the hypothesis that the Earth's magnetic field had a dipole character in the past. Thus, the difference between the Tertiary and the Jurassic pole positions appears to be due to a relative movement between the axis of the dipole field and Antarctica. The Jurassic pole position relative to Antarctica differs significantly from pole positions similarly calculated from Jurassic rocks from Australia, Africa, South America and India. The significance of these results has already

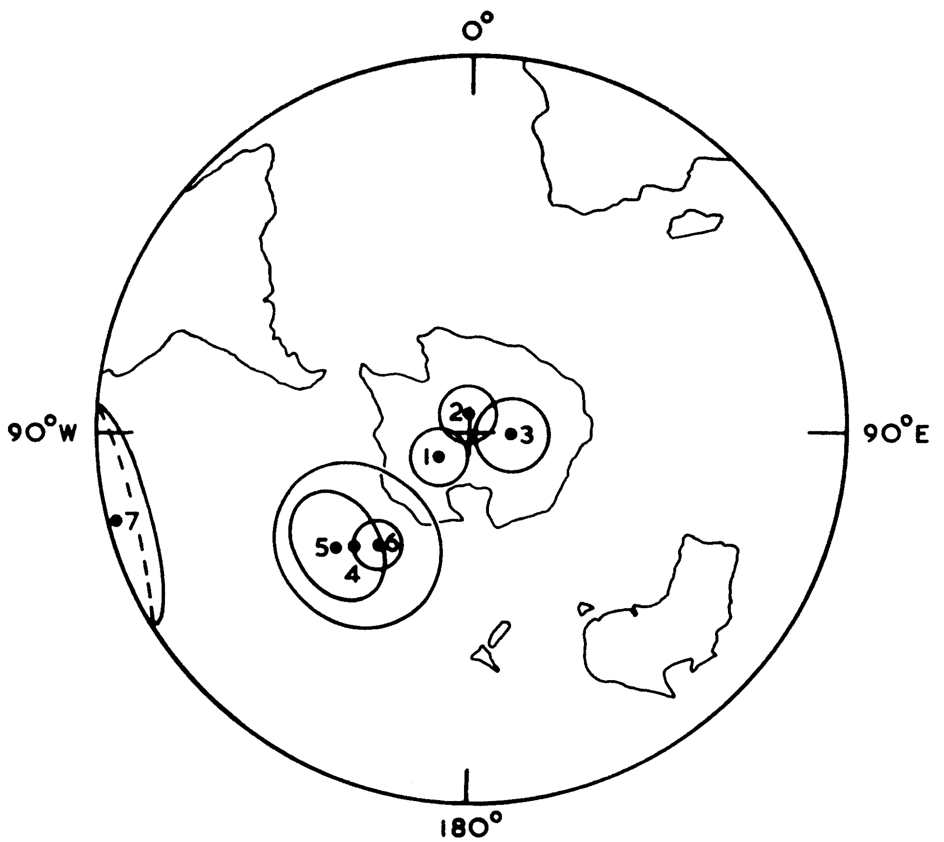

FIGURE 6

Geomagnetic pole positions and ovals of 95 per cent confidence calculated from the N.R.M. directions of:

1. Tertiary lavas, South Shetland Islands.
2. Andean Intrusive Suite, Graham Land.
3. Cenozoic volcanics, Cape Hallett (Turnbull, 1959).
4. ? Jurassic dolerite intrusions, Theron Mountains and Whichaway Nunataks (Blundell and Stephenson, 1959).
5. ? Jurassic dolerite intrusions, Wright Valley (Bull and Irving, 1960).
6. ? Jurassic dolerite intrusions, Ferrar Glacier (Turnbull, 1959).
7. Precambrian gneiss, Ongul Islands (Nagata and Shimizu, 1959).

(Schmidt equal area projection)

been discussed (Blundell, 1961, in press) and it has been inferred that the wide distribution of the pole positions indicates relative movement of these continents since the Jurassic. If the geomagnetic poles were on average situated at the geographical poles, as is the case for all late Tertiary and younger rocks, then the latitudinal position of Antarctica must have changed during the Cretaceous and Jurassic but has remained constant since the early Tertiary. Assuming that there was no movement between Graham Land and the main continent of Antarctica, the average latitude of Graham Land would have changed from 53° S. in the Jurassic to 65° S. by the beginning of the Tertiary and then remained constant to the present day.

It is of interest to compare this deduction with information relating to the climate of Graham Land since the Jurassic, which has been described by Adie (1953). Mid-Jurassic sediments were laid down in some parts of Graham Land under fresh-water lacustrine conditions and in other parts under marine conditions. The fresh-water sediments contain an abundant flora which must have "flourished under optimum temperate to sub-tropical climatic conditions" (Adie, 1953, p. 245). The marine sediments also contain an abundant invertebrate fauna including many ammonites, although no corals have been found in these or any other Jurassic sediments in Antarctica. Marine sediments of similar type continued to be deposited in Alexander Island through the Upper Jurassic and, after a short break in deposition, into the Lower Cretaceous. Upper Cretaceous marine sediments from north-east Graham Land also have a similar character and contain a fauna which includes ammonites, lamellibranchs, gastropods, belemnites and solitary corals. In parts of north-east Graham Land marine sedimentation continued through to the Lower Miocene. In other parts, such as King George Island, mid-Miocene deposits were laid down containing a rich flora including *Stercularia*, *Araucaria* and *Nothofagus* which indicate a temperate climate warm enough to support the growth of large deciduous trees (personal communication from C. M. Barton). The presence of the remains of fossil penguins in the Lower Miocene sediments of Seymour Island may be an indication of a cooler climate, although it must be remembered that penguins are not good climatic indicators. The climate certainly changed to polar conditions during the Plio-Pleistocene and has remained so ever since. Nowadays only a few lichens and mosses can grow and the greater part of the region is permanently ice-bound. The climate of Graham Land appears to have been warm temperate to sub-tropical from the Jurassic to the Oligocene and to have deteriorated to the present-day polar conditions partly during the Miocene and mainly during the Pliocene. If the climatic conditions were related to latitude as at present, then this evidence suggests that the latitude of Graham Land was fairly constant from the Jurassic to the Oligocene, possibly somewhere between lat. 30° and 50°, and altered during the Pliocene to a polar level, probably around lat. 70°. This is clearly at odds with the deductions made from the palaeomagnetic data. Geological evidence from many other parts of the world has clearly established a period of general glaciation during the Pleistocene, so the climatic change noted in Graham Land is better explained as part of a world-wide climatic change than as the result of a change of latitude. In this way the palaeomagnetic and palaeoclimatic deductions can be reconciled.

Recently Blackett (1961), Irving (1956*b*), Runcorn (1959) and others have tried to check the reality of the movements of the continents relative to the geographical poles, as deduced from palaeomagnetic evidence, with the past climates of the continents, as deduced from geological evidence, by equating climate with latitude. The evidence from Graham Land serves to illustrate the dangers inherent in such comparisons. It is an uncertain procedure to test an hypothesis with another set of inferences, and the only justification for this would be to build up a consistent explanation for a mass of data. Since a vast amount of geological evidence is required anyway, it would seem more appropriate to test the continental drift hypothesis as deduced from the palaeomagnetic evidence both for internal consistency, by obtaining more magnetic data, and for consistency with the stratigraphic and structural relations of the rocks on neighbouring continents.

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