PALAEOMAGNETIC STUDIES ON SOME SOUTH AFRICAN ROCKS.

by

KENNETH WILLIAM TURNER GRAHAM

A THESIS
PRESENTED TO THE
DEPARTMENT OF MINERALOGY AND GEOLOGY
UNIVERSITY OF CAPE TOWN

IN FULFILMENT OF THE REQUIREMENTS
FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

October, 1961.

Certificate.

I certify that I approve of the inclusion within this thesis of certain work already published by the candidate and that all such work is clearly identified in the thesis.

A.L. Hales

Supervisor

I, the undersigned, declare that, with the exception of many of the routine magnetic measurements, the work forming the basis of this thesis is my own and has not been incorporated in another thesis for a degree by me.

Signed by candidate

K.W.T. Graham.

17th October, 1961.

C O N T E N T S.

LIST OF ILLUSTRATIONS.

S U M M A R Y .

A brief review of the subject of palaeomagnetism as it affects the study of the behaviour of the earth's magnetic field and the problems of Continental Drift and Polar Wander is presented, giving the reasons why a systematic palaeomagnetic study of the Cape and Karroo Systems of South Africa would be of outstanding significance. This task was vigorously tackled by sampling the Karroo System at vertical intervals of approximately 50 ft. in two separate areas, using the techniques that were then available. The results, although negative, provide material for a discussion of the possible reasons for the scattered directions of magnetization of the samples.

A palaeomagnetic study of the Karroo dolerites was undertaken in an attempt to (i) determine the position of the geomagnetic pole at the time of the intrusions, and (ii) possibly assess the importance of the remagnetization of Karroo sediments by the thermal effects of the younger intrusions. Samples from surface exposures in the eastern half of South Africa, from the shafts of a gold mine and from a railway tunnel were collected and studied, giving a reliable mean direction of magnetization of the Karroo dolerites of Declination = 341°, Inclination = -60°. At the commencement of the Jurassic period the geomagnetic pole relative to Southern Africa had the present day

co-ordinates of Longitude $74\frac{1}{2}^{\circ}$E, Latitude 70°S. Both normally and reversely magnetized dolerites were found and evidence in favour of a true reversal of the earth's magnetic field is advanced. It is also suggested that in the area studied, the dolerite was intruded in two distinct phases.

Because the direction of magnetization of the Karroo dolerites is very close to that of the present magnetic field, it is difficult to separate samples remagnetized at the time of the intrusions from those remagnetized in the present field. However, some light is thrown on the problem of the scattered directions of magnetization of the Karroo sediments by the fact that dolerite samples collected from surface exposures are much less consistently magnetized than those from underground workings.

A reconnaissance collection of samples from the Cape System was made but the directions of magnetization were again scattered. In order to test the theory that this scattering is related to the daily thermal or thermo-stress cycling of the uppermost few inches of an outcrop, new and improved drilling and orienting equipment was designed and constructed, and the Lower Shales of the Table Mountain Series were sampled and studied in great detail. It is shown that the "surface effect" is operative to greater depths than had been thought and that the rock exposed on the natural mountain-side has been remagnetized in various directions by some local agency. In contrast, the rock exposed in a deep road cutting has not been similarly affected and a bed of red siltstone about two feet thick is consistently magnetized over the 100 ft. sampled and probably reflects the direction of the field at, or soon after, deposition. The mean direction of magnetization is $D = 161.8^{o}$, $I = -3.5^{o}$ and the geomagnetic pole at this time (probably Silurian) would have the present day co-ordinates of Longitude 10.9^{o}W, Latitude 50.3^{o}N.

The problem of scattered directions of magnetization of surface samples bars the progress of palaeomagnetic investigation in South Africa. Accordingly, a detailed study of a certain outcrop that was known to be randomly magnetized was undertaken. Twenty cores, three or six feet long, were drilled from this outcrop by means of the above mentioned rig. The pattern of magnetization that emerged suggested qualitatively that a large electrical current could have been responsible for the remagnetization of this outcrop. Apparatus was specially designed or developed by the author in order to perform certain laboratory experiments which lead to a quantitative proof that two horizontal lightning currents, one of 5,000 amps. and one of 50,000 amps. were responsible for the peculiar observations.

It is shown that the remagnetization of surface outcrops by currents associated with lightning discharges is probably common. The significance of this hazard in palaeomagnetic studies is discussed and ways of avoiding or eliminating its effects are suggested. On this basis a programme for palaeomagnetic research in South Africa is suggested and the preliminary results of new attempts to study the remanent magnetism of the Karroo System are presented to show that at least some of the major problems of palaeomagnetic research in South Africa have been solved.

The following papers based on the above work have been published:-

1) Graham, K.W.T. and Hales, A.L., 1957. "Palaeomagnetic measurements on Karroo dolerites." Phil. Mag. Suppl., Vol.6, pt.22, pp. 149.

2) Graham, K.W.T. and Keiller, J.A., 1960. "A portable drill rig for producing short oriented cores." Trans. Geol. Soc. S.A.

In press:

1) Graham, K.W.T. and Hales, A.L. "Preliminary palaeomagnetic measurements on Silurian sediments from South Africa." (Geophys. Journ.)

2) Graham, K.W.T. The remagnetization of a surface outcrop by lightning currents." (Geophys. Journ.)

CHAPTER 1.

INTRODUCTION.

1. The purposo of palaeomagnetic studies.

Since the first magnets to be recognised as such were pieces of highly magnetic natural rock, it may be said that the study of rock magnetism is as old as the study of magnetism itself. Although the discovery and production of iron and steel magnets largely diverted attention away from natural materials, by the beginning of the 20th century a fair amount was known about the magnetic properties of rocks. This study of "Rock Magnetism" was further extended by various workers and particularly by Königsberger in the 1930's. Shortly after World War II the development of apparatus sufficiently sensitive to measure the direction and intensity of magnetization of common, weakly magnetized rocks resulted in the birth of "Palaeomagnetism", a branch of the study of rock magnetism dealing primarily with the Natural Remanent Magnetism (N.R.M.) of rocks.

It is considered unnecessary to present a comprehensive review of the subject of palaeomagnetism prior to 1955 in view of the fact that in April of that year Runcorn (1955) published a most extensive review of the subject. However, it might be of interest to mention some of the major points which prescribed the course of our investigations.

Palaeomagnetism can and has been viewed from different angles by people with different interests. The problems on which palaeomagnetism may possibly throw some light include:-

1) The history of the earth's magnetic field.
2) The extent to which "Continental Drift" has taken place.
3) The extent of "Polar Wander".
4) The origin of the earth's magnetic field.
5) Geological structure problems, such as the original attitude of igneous bodies.
6) Geological correlation of unfossiliferous formations.
7) The orientation of bore cores.

The work described in this thesis is almost entirely connected with attempts to obtain information relevent to problems 1), 2) and 3). The usefulness of palaeomagnetism for these purposes depends upon two fundamental hypotheses:

(i) Many rocks become magnetized at the time of their formation by, and in the direction of, the geomagnetic field at that time.

(ii) The geomagnetic pole, averaged over any period of several thousand years is co-incident with the axis of rotation of the earth during that period.

These hypotheses will be discussed in slightly greater detail.

Hypothesis (i)

Nagata (1953) and others have shown experimentally that igneous rocks cooling through their Curie Point may acquire a relatively strong and stable T.R.M. (thermo-remanent magnetization) in the direction of the applied field. Néel (1955) explained on theoretical grounds why a magnetic mineral passes from a state of low coercive force to one of higher coercive force at the Curie Point. Most rocks contain more than one magnetic mineral, each with its own characteristic Curie Point. The most common magnetic minerals are magnetite (Fe_3O_4, Curie Point : 575°C), the titano magnetites and hematite (Fe_2O_3, Curie Point : 675°C).

Johnson, Murphy and Torreson (1948), King (1955) and lately Griffiths, King and Wright (1957) have shown that during the process of sedimentation the magnetic particles can statistically orient themselves parallel to the applied field. Dateable varved clays from New England and from Sweden are magnetized in directions consistent with historic records of the secular variation of the earth's magnetic field. Some small systematic errors in inclination may result from the rolling of magnetic grains to fit into the nearest valley in the depositional surface. (Griffiths, 1957). Clegg, Almond and Stubbs (1954) have shown that in uncompacted sediment containing more than about 50% water, the magnetic grains are still free enough to align themselves with the applied field. Irving (1954) demonstrated that in the case of certain Torridonian Sandstones, the magnetization was acquired after some mud-slumps had occurred.

Unfortunately many rocks do not retain the magnetism acquired at their birth. Nagata (1953), Runcorn (1955), Néel (1955) and others discuss the growth of Isothermal Remanent Magnetization (I.R.M.) in rocks at ordinary temperatures in fields which may be different from the geomagnetic field at the time of the formation of the rocks. Néel (1955) showed that grains of diameter less than the critical value D_T at temperature T will be unstable. Those whose diameters are larger will be stable.

Creer (1954) developed the concept of a time constant associated with the growth and decay of I.R.M. and showed that rocks with a short time constant will appear either to be randomly magnetized or to be magnetized in the direction of the present field of the earth. Those with a longer time constant will be magnetized in the direction of the dipole field.

Cox (1957), Creer (1959) and especially As and Zijderveld (1958) have shown that in many cases I.R.M. can be removed by magnetic cleaning using heat and/or A.C. fields.

Néel (1955) provides some theoretical basis for these "cleaning" techniques by showing that the coercive force of I.R.M. should be much lower than that of T.R.M.

Other factors which are thought to be capable of altering or destroying the original magnetization of a rock include lightning (see Chapter 6), chemical processes including weathering (Doell, 1957), and possibly stress resulting in a magnetostrictive effect. (Graham, Buddington and Balsley, 1957).

Obviously one of the greatest problems in practical palaeomagnetism is to distinguish between magnetically stable and unstable rocks. Once this has been done, the unstable samples may simply be discarded or an attempt may be made to identify the cause of the instability and remove or avoid it if possible. Numerous laboratory tests have been designed and used in an attempt to establish the stability or otherwise of specimens. Determinations of Curie Point, Königsberger ratio, coercive force and the effects of D.C. and A.C. fields have all been used with varying degrees of success (Nagata and others - see Nagata, 1953, and Nagata et. al., 1957a and b, Graham, 1953, Kawai 1954, Creer 1954, Gough 1956, Graham and Hales 1957). However, very rarely can positive proof of stability be obtained by these methods.

Consistency of magnetization over large areas of contemporaneous rock, particularly if the direction of magnetization is far from that of the present geomagnetic field or the dipole field, is strongly indicative of stability (Runcorn 1955, Gough 1956).

J.W. Graham (1949) showed that positive proof of stability over long periods of time can be obtained by comparing the directions of magnetization of a folded sediment referred to the vertical, with those referred to the bedding planes. Considerable improvement in grouping should be obtained by "unfolding" the bed. The "Conglomerate" test proposed by J.W. Graham may be less reliable in view of the possible effects of lightning currents (see Chapter 6).

Hypothesis (ii)

The magnetic field of the earth approximates to that of a geocentric magnetic dipole with secular variation superimposed upon it. In either the "Dynamo theory" or the "Thermo-electric theory" (discussed by Runcorn, 1955) these fields appear to be controlled largely by the Coriolis force and are therefore related to the axis of rotation of the earth. Averaged over a period of several thousand years, the magnetic pole should be coincident with the geographic pole. Important work in verifying this hypothesis for the Quarternary has been done by Johnson, Murphy and Torreson (1948), Griffith (1955) and Hospers (1954b). However Hospers in particular observed rocks magnetized in a direction very close to that of the present field, except that the sense of the magnetic field is reversed.

2. The problem of reversals.

Throughout the Geological column both igneous and sedimentary rocks have been found with polarisations of a sense opposite to that of the present field. (Hospers 1953, 1954; Hospers and Charlesworth, 1954; Campbell and Runcorn, 1955; Irving, 1954; Graham, 1953; Clegg, Almond and Stubbs, 1954; Creer, 1954; Graham and Hales, 1957; and many others). Frequently, as in the case of the Icelandic lavas, the Columbia River basalts and the Torridonian Sandstones, these reversals occur in zones alternating with zones of normally magnetized rocks. This phenomenon may be interpreted in two different ways. The sense of the earth's magnetic field may have reversed on numerous occasions in the past and these rocks have been magnetized during such periods of reversal. Alternatively, the rock itself is capable of becoming magnetized in a sense opposite to that of the applied field.

The latter possibility was suggested by J.W. Graham in a letter to Néel who then showed, on theoretical grounds, that such "Reversals" could be produced by four different mechanisms (Néel, 1955).

(I) a) Due to exsolution, a magnetic mineral may form two interleaved sub-lattices A and B. In the case of magnetite ($Fe_{3-m}Ti_m O_4$) the A lattice contains Fe^{+++}

only while B contains Fe^{+++} and Fe^{++}. The spin exchange forces between the lattices are much stronger than within either lattice, and are of opposite sign in the two lattices. In the case of magnetite the Fe^{+++} of A balances out the Fe^{+++} of the B lattice leaving only the effect of the Fe^{++} of the B lattice. However, since substitutions by other cations may occur, either lattice may predominate. The spontaneous magnetization of the two lattices may vary differently with temperature so that just below the Curie Point say B may predominate and will be parallel to the applied field. At a lower temperature A may predominate and will therefore be reversed.

b) The spontaneous magnetization of A may be greater than that of B at all temperatures, so that no reversal will occur on cooling. However, should physical or chemical changes weaken A more than B, a reversal may occur in time.

(II) a) In an intimate mixture of two ferromagnetic substances A and B, A may have a higher Curie Point but a lower intensity of magnetization than B. A would be magnetized first and would be parallel to the field. At the Curie Point of B the field as seen by B would be the sum of the applied field and the field due to A. Under certain circumstances the field of A could be greater than the applied field and B would be magnetized in the reverse sense. Since the intensity of magnetization of B is greater than that of A, the rock as a whole would show reversed magnetization.

b) Should the grains of type B of the above example (IIa) not, in fact, have the greater intensity of magnetization then there would be no reversal on cooling. However, physical or chemical processes could destroy A in preference to B, causing a reversal of the sense of magnetization. This could occur in sediments as well as in igneous rocks.

Nagata has found a rock which, when cooled through its Curie Point, complies with the requirements of (II a), causing a reversal. Asami (1956) has found blocks of normally and reversely magnetized basalt occurring side by side in the same flow and electron microscopic studies have revealed just the kind of intergrowths in the magnetic material of some basalts necessary for the Néel mechanisms (Nagata et.al., 1954).

There can be no doubt that under certain circumstances rocks can become polarised in a sense opposite to that of the applied field. The only debatable point is whether or not these circumstances are very special ones that occur only rarely. Unfortunately it is not possible to gain positive evidence from routine heating experiments because of the possible alteration of the intimate exsolution relationships in the magnetic minerals (Runcorn, 1955).

Balsley and Buddington (1954) have shown that a close correlation exists between the sense of magnetization and the chemical composition of the magnetic minerals of the metamorphic rocks of the Adriondacks. Runcorn (1955) suggests that these rocks acquired a T.R.M. when the earth's field was reversed. Those containing only the highly stable but weakly magnetic hematite preserved the reversed magnetization. In those containing a large proportion of the less stable but more strongly magnetic magnetite this direction may have been swamped by I.R.M. acquired in recent times. However, Uyeda (1958) shows that for the ilmenite-hematite solid solution series $xFeTiO_3 (1-x) Fe_2O_3$ reversed T.R.M. due to a type of exchange interaction between co-existing ferrimagnetic and parasitically ferromagnetic phases is characteristic of the composition range $0.45 < x < 0.6$. Another type of "imperfect reversed T.R.M." in the range $x \approx 0.1$ may explain the features described by Balsley and Buddington.

Theoretically there seems to be no connection between the sense of the geomagnetic field and the direction of rotation of the earth. Should the field die down it could be revived in either sense (Runcorn, 1954).

The widespread occurrence of reversals, sometimes in zones which appear to be continuous over large horizontal distances, is strongly suggestive of reversals of the geomagnetic field. Both Hospers and Roche (see Runcorn, 1955) have found instances where intrusions or extrusions of reversely magnetized rocks have baked adjacent normally magnetized sediments or lavas. In the contact zones the rock has become reversely magnetized. Similar but somewhat more vague observations are presented in Chapter 3. It is extremely difficult to see how any of Neel's self reversal mechanisms could apply equally on both sides of the contact, especially if the other rock is a sediment.

On these grounds it seems highly probable that at least some of the observed reversals are due to reversals of the earth's field. Runcorn (1955 p.281) suggests three conclusive tests between the two hypotheses:-

(1) Between zones of reversals one ought to find a zone in which the direction actually turns round.

(2) Zones that are sufficiently large should be identifiable over large areas and should be consistently magnetized.

(3) There should be no systematic difference in the chemical or physical properties of the magnetic materials of reversely and normally magnetized rocks.

The virtually continuous sedimentary succession of the Cape and Karroo Systems (which are briefly described below) seems to provide the ideal testing ground for these criteria, since it represents apparently continuous deposition from the Silurian to the Jurassic. It would be most interesting to be able to compare the pattern of the zones of reversals from several widely separated traverse lines, each covering the whole succession but each, due to facies changes, slightly different petrographically. One should be able to demonstrate conclusively which of the two mechanisms operates most commonly in nature.

3. Continental Drift versus Polar Wander.

By the beginning of 1955 abundant data showed that the mean magnetic pole and, accepting Hypothesis (ii), the geographic pole had not always occupied the same position relative to Europe or America as it does today. Creer (1954) had already published a map showing the various positions occupied by the pole during the geological past, joined by a relatively simple curve. The differences between contemporaneous pole positions as determined in America and Europe were thought to be insignificant and Runcorn (1955) regarded them as being due either to experimental error or to inaccurate dating. If the latter were true then the curve described by the pole would have to be extremely complicated.

With the exception of Irving's work (Irving, 1954) on the Torridonian sandstones the geological column had only been sampled in small, isolated patches. No attempt had been made to follow the pole in detail during the Mesozoic or Palaeozoic. If one is not to be confused by rapid excursions (much slower than secular variation) of the pole from a mean path then it becomes imperative that the path of the pole be traced out in detail. Only then would one be able to say with any certainty whether Continental Drift had or had not taken place.

If, in fact, Continental Drift has taken place (together with considerable Polar Wander) then it would be extremely interesting to attempt to trace the relative movements of continents by means of Palaeomagnetism. From any single palaeomagnetic determination one can calculate the latitude of the point of observation at the time of magnetization from the formula

$$\text{Cot } p = \tfrac{1}{2} \text{ Tan } I$$

where p is the co-latitude of the point of observation at the time of magnetization and I is the observed palaeomagnetic inclination. The direction of the pole relative to the present N-S line on a continent at any one time is given by D, the observed palaeomagnetic Declination. However, the longitude of the continent is indeterminate.

Thus the relative positions of two continents during any geological period cannot be deduced from a single observation on each continent, even if the samples used are of exactly the same age.

One might be able to trace out in detail the apparent pole path as seen by the two continents for a period of time sufficiently short to exclude appreciable Continental Drift. By moving a model of one continent relative to the other until the two patterns coincided one could determine their exact relative positions. This is in fact the basis of Irving's (1958) method of "palaeographic reconstructions".

Because the Cape and Karroo Systems were continuously deposited over a vast length of time they appear to provide an outstanding opportunity for such detailed studies.

4. The geology of the Cape and Karroo Systems.

The distribution of the Cape and Karroo Systems is shown in fig. 1/1, a map of South Africa, and sections through lines A-B and C-D, are intended to show the broad structural relationships of these two Systems. The ages of the various sub-divisions, based on du Toit (1954), are given in table 1/1 together with the maximum thicknesses and a brief and generalised description of the lithology of the southern portion of the Cape and Karroo Systems.

5. The course of the research programme.

In view of the considerations set out above, it was decided to sample the Cape and Karroo Systems systematically from bottom to top. The Karroo System was tackled first, largely because outcrops of this System are more easily accessible from Johannesburg than are those of the Cape System. Most of the Karroo succession, excluding the lavas, was sampled at regular intervals in two separate areas, as described in Chapter 3. The apparatus and techniques used are described in Chapter 2. The directions of magnetization of the Karroo samples proved to be highly inconsistent and unreliable as palaeomagnetic data. One of the possible causes of the scatter of results from the Karroo System is that many of the samples could have been heated to temperatures above the Curie Point of some or all of the magnetic minerals at the time of the intrusion of the Karroo dolerites which probably represent a hyper-byssal phase of the Stormberg igneous activity. By determining the direction of the earth's field at this time one might be able to assess the relative importance of this factor in the remagnetization of the older sediments. In addition, such a study would be of value in establishing the position of the geomagnetic pole relative to Africa for the early Jurassic. The direction of magnetization of the Karroo dolerites was successfully determined, giving a reliable palaeomagnetic datum for this period. In view of the fact that the direction of magnetization of the Karroo dolerites is close to that of the present field, it is difficult to estimate the relative importance of remagnetization of the sediments due to heating by the dolerites and chemical or viscous magnetization in the present field.

A reconnaissance collection of samples from the Cape System was made before work on the Karroo dolerites had been completed. The results, though perhaps a little less scattered than those from the Karroo sediments, were thought to be unreliable. For reasons presented in Chapter 4, it became evident that new drilling and orienting equipment, capable of producing oriented cores from a depth of 3 ft., was necessary. Accordingly, the equipment described in the latter part of Chapter 2 was designed and constructed.

Using this improved sampling technique, the Lower Shales of the Table Mountain Series were studied in great detail. It became clear that the rock exposed in a deep road cutting was consistently magnetized and was reliable from the point of view of palaeomagnetism while that on the open mountain side owed its magnetism to some local agency. This fact, together with similar observations described in Chapter 3 clearly showed that palaeomagnetism in South Africa would not be able to progress satisfactorily until the cause of this "surface effect" - the inconsistency of magnetization of surface samples - had been established.

An outcrop that was known to be randomly magnetized at the surface but consistently magnetized at depth was investigated in great detail. The cause of the "surface effect" was proved to be electrical currents associated with lightning. Ways of avoiding or eliminating the effects of this hazard are presented and these techniques

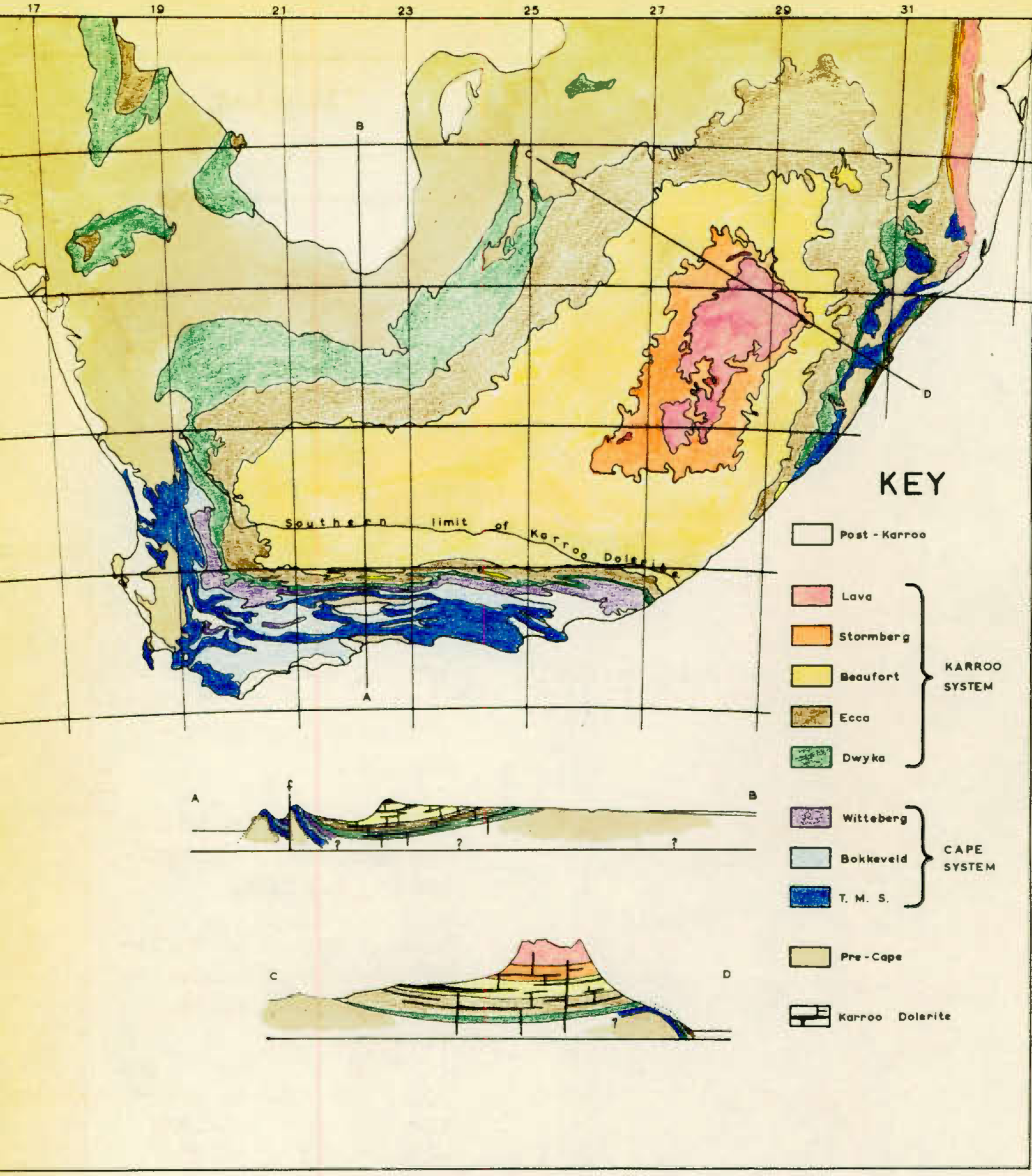


Figure 1-1.

...e Cape and Karroo Systems of South Africa.

Table 1/1.

KARROO SYSTEM

Series	Stage	Maximum thickness (ft.)	Lithology	Period
Stormberg	Drakonsberg Lavas	4500	Amygdaloidal basalts	Jurassic
	Cave Sandstone	1000	Fine grained aeolian sand	Triassic
	Red Beds	1600	Red shales and mudstones with yellow sandstones	
	Molteno Beds	2000	Grey-blue shales and sparkling sandstones	
Beaufort	Upper (Burghersdorp Beds)	2000	Green, Blue and red shales and mudstones with yellow sandstones.	
	Middle	1000	Pale, massive sandstones with subordinate shales.	Permian
	Lower	8000	Blue, green & sometimes red shales interbedded with sandstones.	
Ecca	Upper	3000	Blue or green mudstones and shales alternating with sandstones.	
	Middle	4000	Mainly blue to black mudstones and shales.	
	Lower	3000	Green or blue shales with sandstones or quartzites.	
Dwyka	Upper Shales	500	Green, blue, dark brown or black shales.	Upper Carboniferous
	Tillite	4000	Hard green-blue matrix with inclusions of all sizes.	

Table 1/1 (Contd.)

System	Series	Stage	Maximum thickness (ft.)	Lithology	Period
CAPE SYSTEM	Witteberg	Upper Shales	1000	Mainly greenish Shales	Lower Carboniferous
		Sandstones	2000	Fine grained white quartzite with minor shale horizons	
	Bokkeveld	5 Shale horizons alternating with	2500	Black, blue or green shales.	Devonian
		4 Sandstone horizons		White quartzites.	
	Table Mountain	Upper Sandstone	2000	White quartzites.	Upper Silurian or Lower Devonian
		Upper Shales	300	Variable, green, red or sometimes dark grey shales and mudstones with tillite.	
		Lower Sandstones	2000	White quartzites.	
		Lower Shales	200	Red sandstones.	

CHAPTER 2.

INSTRUMENTATION.

1. Magnetometers.

The standard magnetic variometers used in geophysical prospecting cannot measure the direction and intensity of the Natural Remanent Magnetization (N.R.M.) of a rock directly; they can only measure the distortion of the earth's magnetic field by nearby magnetic rocks. Since the majority of rocks are very weakly magnetized the magnetic "anomalies" they produce are so small as to be undetectable. It is possible to determine the approximate direction of polarization of strongly magnetized rocks by matching the observed anomaly with a theoretically derived "type curve". Besides being crude this method can be misleading because of the possible effect of induced magnetism.

Magnetometers of two different basic designs are commonly used in palaeomagnetic research. These are the "Astatic Magnetometer" and the "Spinner Magnetometer" or "Rock Generator".

A. The Astatic Magnetometer.

The development of the Astatic Magnetometer is largely due to Blackett (1952). Basically the instrument consists of a pair of identical, small bar magnets, rigidly mounted in anti-parallel some few inches apart and suspended by a fine quartz or phosphor bronze thread. The specimen is moved quickly from a distance (theoretically infinity) to within a centimeter or two of one of the magnets in a variety of ways. The deflection of the magnet system, as amplified by a long optical lever, is proportional to the intensity of magnetization of the specimen in a particular plane relative to the magnet system. By varying the orientation of the specimen and its mode of approach to the magnet system, the intensity of magnetization of the specimen in any plane may be obtained. From these readings the direction in space and the intensity of magnetization of the specimen may be calculated.

In order to obtain the required sensitivity, however, the external magnetic field must be cancelled and all magnetic and thermal gradients avoided. The earth's field may be nullified by means of Helmholtz and/or Fanselau coil systems. To a first approximation this is quite easy, but to obtain the highest degree of sensitivity the current in the coils must be continuously adjusted to follow the daily variation of the earth's field. To avoid magnetic gradients the instrument must be housed in a special non-magnetic hut far from the influence of electrical power lines, trolley-bus and train lines.

The only advantage of the Astatic Magnetometer over the Spinner type lies in its greater adaptability to laboratory experiments of the kind commonly carried out for the determination of the magnetic properties (Curie Point, coercive force, etc.) of rock specimens.

B. The Spinner Magnetometer.

In principle, the Spinner type magnetometer is simple. If a magnetic specimen is rotated about an axis perpendicular to the axis of a surrounding coil, it will generate an alternating voltage in the coil. A maximum in the e.m.f. occurs each time the north pole of the specimen passes limb A of the coil and a minimum each time the north pole passes limb B. If, knowing the frequency of rotation, one could measure the interval of time between the occurrence of the maximum in the e.m.f. and the instant at which a mark on the specimen passes limb A of the coil one would have a measure of the angle between the mark and the direction of the north pole projected onto the plane of rotation.

In the original spinner magnetometer devised in 1938 by McNish and Johnson the specimen was rotated at the end of a long, mechanically driven shaft. Mounted on the shaft in a fixed position relative to the zero mark on the specimen was a device which mechanically closed a pair of electrical contacts at each revolution. By moving the pair of contacts about an axis parallel to the spinning shaft, the instant at which the contacts closed could be made to coincide with the maximum of the voltage in the coil, so that the angle through which the contacts had to be rotated was a measure of the angle between the zero mark and the magnetic axis of the specimen.

The modern spinner magnetometer is a result of developments and improvements mainly by Johnson, Murphy and Michelsen (1949) and J.W. Graham (1955). The magnetometer used at the Bernard Price Institute of Geophysical Research is based on the latter design and was built by Dr. A.L. Hales, Director of the Institute.

In this instrument an oriented specimen in the form of a cylinder one inch in diameter and one inch long is held in a plastic (perspex) cube which fits into a perspex top. The top is driven by compressed air in the manner of a Beam's air turbine, at a fixed speed depending on the electronic filters. The spinning specimen generates an A.C. signal in a pick-up coil surrounding it, while a photo-electric cell receives a second signal from a sinusoidal pattern painted on the top. The angular phase difference between the two signals is a measure of the angle between the fixed zero of the paint pattern and the projection of the South magnetic pole of the specimen onto the plane of rotation. The specimen is rotated through 180^{o} about an axis through the zero of the paint pattern and a second measurement is made. If there were no zero error in the instrument these two readings would add up to 360^{o}. In general the two readings do not add up to 360^{o} and an arithmetical correction is applied to cancel out the zero error.

By spinning the specimen about three mutually

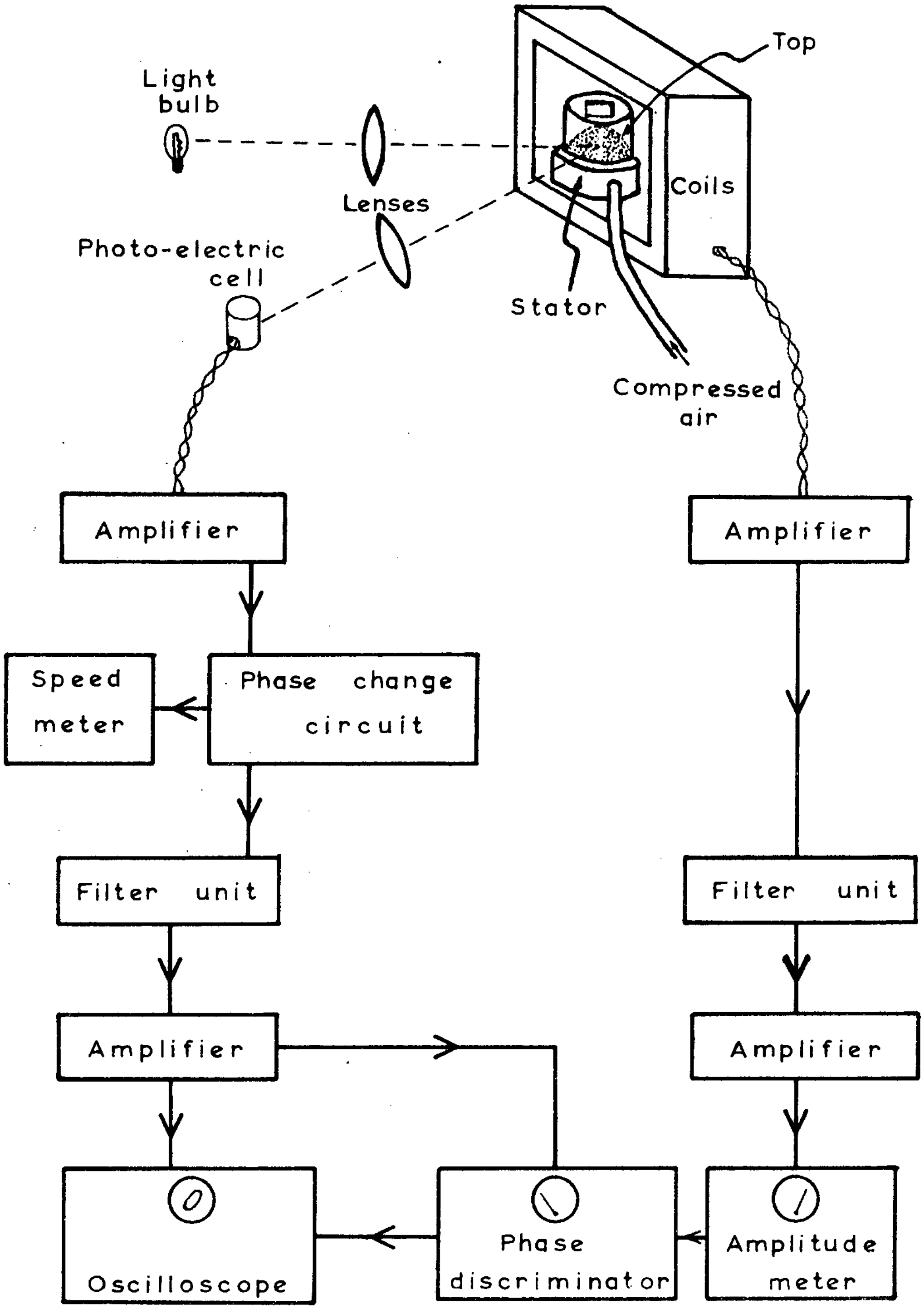


Figure 2-1.

A schematic diagram illustrating the arrangement of the spinner magnetometer.

perpendicular axes the direction of magnetization in three planes may be determined. These directions are plotted on a Wulff Stereographic net, as described in the Appendix, and should intersect at a point representing the direction of magnetization in space, relative to the orientation marks on the specimen.

In the system as devised by J.W. Graham the signals from the coils and the photoelectric unit are fed through carefully matched narrow band pass filters before they are compared in a phase discriminating circuit. Originally our magnetometer operated on a system involving only one filter the signals from the coils and photoelectric unit being mixed before filtering. If the signal from the photoelectric unit be adjusted until it is equal in amplitude but opposite in phase to that from the coils, then the resultant signal will be a minimum. The filter thus acts as a null detector. This method works very well down to intensities of magnetization of the order of 10^{-6} gauss giving an accuracy at this level of better than two or three degrees. However, as the signal approached noise level the accuracy with which it is possible to set to a minimum falls rapidly so that the system containing two separate filters, as used by Graham, is very much more convenient for measuring weakly magnetised specimens. The Department of Terrestrial Magnetism, Carnegie Institution of Washington, has very kindly lent us a pair of their matched filter units and the instrument was modified in 1956 to operate in the Graham

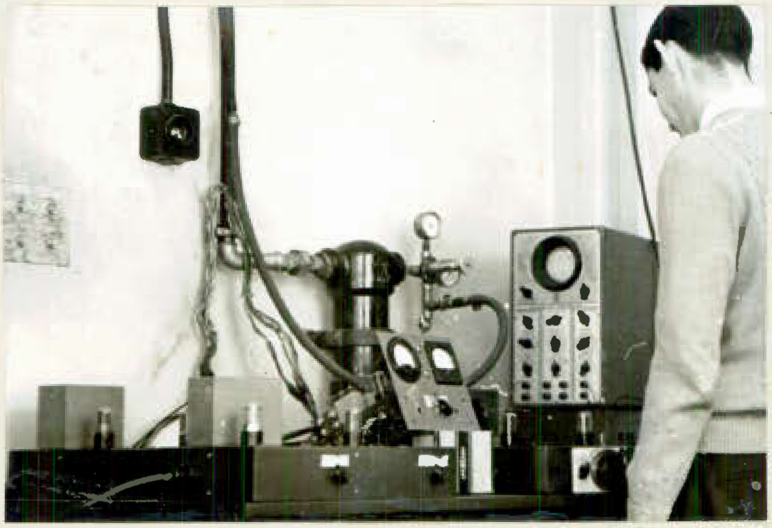


Figure 2/2. Part of the magnetometer showing the air filter and air pressure controls (top centre), the matched filter units (left), the phase change circuit (right) and the phase discriminator (centre).

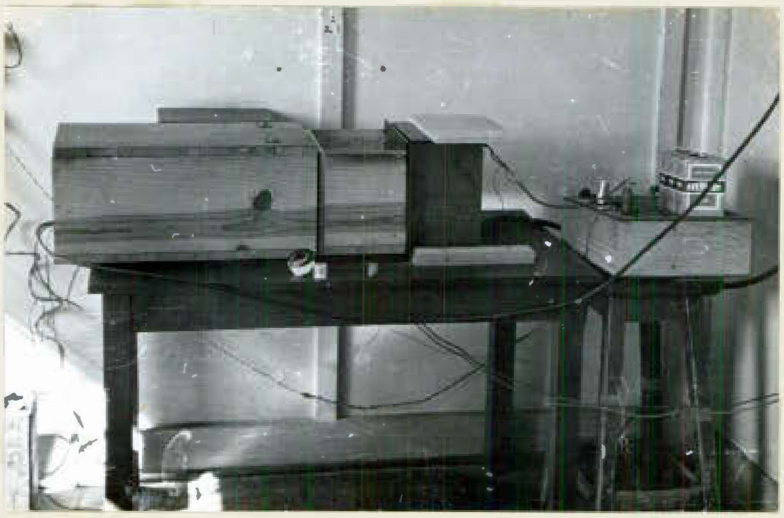


Figure 2/3. Part of the magnetometer, showing the photo-electric cell housing (left), the stator housing and coils (centre) and the pre-amplifier (right). A top, cube and specimen are on the table.

manner. Figure 2/1 is a schematic diagram of the lay-out of the magnetometer as used at present and figures 2/2 to 2/4 are photographs of various parts of the equipment.

2. Methods of Collecting Oriented Samples.

Because of the balance requirements of the top, a spinner magnetometer requires specimens of some regular geometric shape. The specimens must, of course, be accurately oriented in space and their angular relationship to the bedding planes of the rock must be known. The simplest way of fulfilling these requirements is by drilling short cores either out of the rock in situ or from oriented hand samples in the laboratory. In the latter case some care is necessary to transfer the orientation marks on the sample to the core. Having produced a core by either process, it may be cut into accurate, parallel ended specimens on a diamond impregnated circular saw equipped with a suitable holder and properly positioned stops. Each core may be cut into a number of specimens.

A. The hand-sample technique.

Orienting hand-samples by scratching on them lines of known bearing and inclination was found to be tedious and inaccurate and a much better method was devised. Two lines, A and B, at right angles to each other were engraved on the top of a circular brass plate (figure 2/5). Three

Figure 2/4. The top in its stator. The cube containing the specimen may be seen inside the top.

Figure 2/5. A hand-sample orienting plate and a sample oriented by this means.

triangular brass bars were soldered onto the bottom of the plate to form three asymetrically distributed ridges. When the hand-sample has been loosened from its surroundings without altering its orientation, a quantity of quick-setting plaster of paris is placed onto it and the orienting plate pressed into the plaster. The direction and inclination of lines A and B is measured and the hand-sample removed from its surroundings. After a few minutes the brass plate can be removed, leaving an impression of its under surface in the plaster. In the laboratory the plate may be replaced and the orientation of the hand-sample restored. This method of orienting hand-samples works very well provided a little care is exercised in the handling of the sample so that the plaster cast does not become detached or unduly damaged.

In spite of this improved technique for orienting hand-samples, the method as a whole, i.e. the collection of oriented hand-samples from which cores are later drilled, is not ideal for the following reasons:

(i) Although more hand-samples than cores drilled in situ can be collected per day in the field, it takes longer to produce a core from a hand-sample in the laboratory than it does to produce the core from the rock in situ, and the complete hand-sampling process becomes extremely tedious.

(ii) It often happens that the hand-sample collapses either in transit or in the clamps of the drill press in the

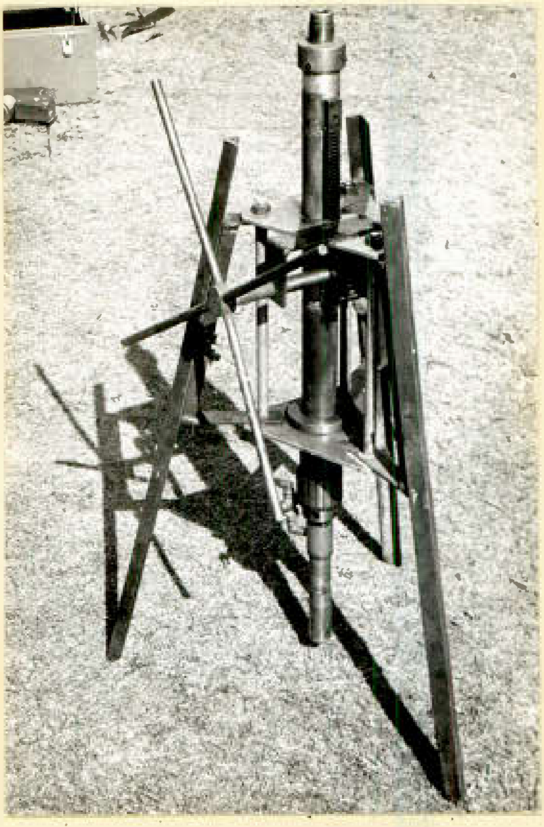


Figure 2/6. The original drill rig.

laboratory and the sample is lost. Also, it is sometimes impossible to produce a sufficiently long core from a particular sample because the core breaks at bedding planes or other discontinuities. Although this might well occur when drilling in the field, one can simply try again elsewhere.

(iii) The transportation of bulky, often fragile hand-samples is far more difficult than that of the cores.

(iv) Probably the most important objection to the hand-sampling technique involves the question of the quality of the sample. Very often the only way of obtaining a suitably sized block of rock from an outcrop without destroying its orientation, is to select a block that is partially bounded by joints. This inevitably means that the sample is more weathered than one that could be obtained by drilling into a solid slab of rock.

B. <u>The early drilling equipment.</u>

The drill rig devised by Mr. J.A. Keiller (figure 2/6) consists of a triangular frame supported by three adjustable legs. A barrel containing the main spindle slides through bushes in the frame and can be raised or lowered by means of a capstan-operated rack-and-pinion connection. A Jacob's chuck is fitted to the lower end of the spindle which is driven by a one horse-power petrol motor through a flexible shaft. A brass core barrel with a

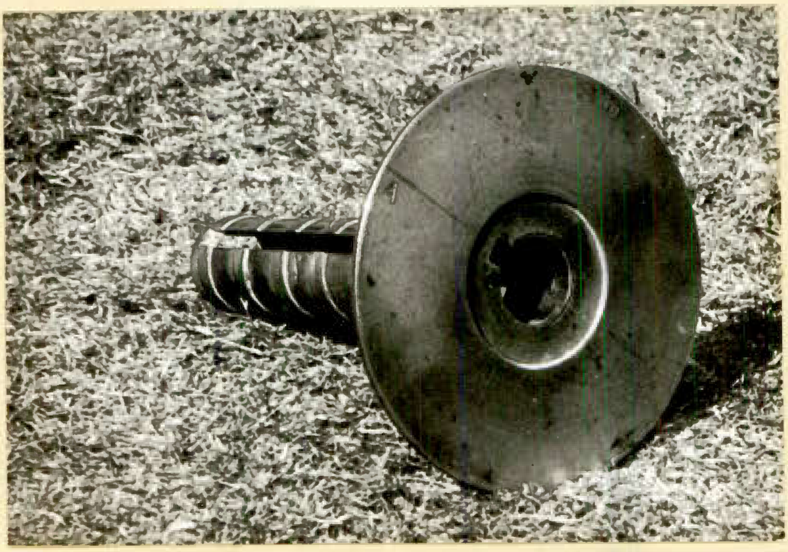


Figure 2/7. The original orienting device.

special brass diamond-impregnated coring crown is gripped in the chuck. Water is fed through a "water jacket" above the core barrel and flows through the core barrel to the coring bit.

In order to obtain sufficient pressure on the bit, at least two people, besides an operator, are required to hold the rig down. In addition, a number of sacks full of stones attached to the rig may be necessary to provide extra weight. Nevertheless, the drilling of hard rock is extremely slow, particularly when the diamonds become polished due to insufficient pressure on the bit. The soft, well bedded, horizontal strata of the Ecca in Natal are equally difficult to sample because, although the cutting speed is tolerable, the vertical cores break off at horizontal bedding planes before they can be oriented. Since the maximum depth of penetration of this drill is six inches, one can not merely persevere until a suitable length of unbroken core is obtained; it is often necessary to move and set-up the rig several times before being successful.

The orienting instrument (figure 2/7) consists of a brass tube which can slide into the hole and over the core. A circular brass plate, soldered onto the top of the tube and perpendicular to it, is inscribed with two mutually perpendicular lines A and B, as in the case of the plate used for orienting hand-samples. The direction and inclination of these two lines can be measured by means of a

In order to correct for the inclination of the axis of the core, given the inclination of line A (parallel to the scratch) = S_1 and the inclination of line B = S_2, one must calculate the angle X between the direction of line A and the direction of the true inclination of the axis. It can be shown that

$$\operatorname{Tan} X = \frac{\operatorname{Sin} S_2}{\operatorname{Sin} S_1} = \frac{S_1}{S_2} \quad \text{for small angles, and}$$

$$S = \frac{S_1}{\operatorname{Cos} X} \quad \text{where S is the true inclination of}$$

the axis of the core. Although this correction for the inclination of the axis of the core is a little simpler if the angles involved are small, it can be applied in the rigorous form for any angles. However, if the inclination of the axis of the core is large then the plate on the top of the orienting instrument will not be nearly horizontal and, in the general case, it is not meaningful to talk in terms of the horizontal angle between north and line A which may be inclined at a large angle to the horizontal. If line A is accurately brought into the vertical plane through the axis of the core then it is correct to describe the horizontal angle between true north and this vertical plane. However, with the instrument in its original form it is very difficult to measure this horizontal angle accurately. It is clear that, in order to keep these routine operations tolerable, the core has to be drilled as nearly vertical as possible. Because of this severe limitation many of the best exposures, viz. the vertical walls of cuttings and quarries, cannot be sampled.

C. The new drill rig and orienting devices.

(a) Requirements.

Although the old drilling equipment has many faults, it can be used to drill and orient cores up to about six inches long. It was the need for cores about three feet long which made new equipment essential (see Chapter 5). Clearly, the new design should not only satisfy the new requirement but should also eliminate the faults of the old system.

An important requirement is that the rig should be portable. At the same time it must be capable of exerting at least 600 lbs. pressure on its diamond coring drill bit. These conflicting requirements are overcome by strapping a light rig firmly onto the outcrop. This is conveniently done by drilling a small hole into the rock, using a hand-held power tool and inserting an expanding bolt. A turn buckle is attached to the expanding bolt and to the rig. On tightening the turn buckle a force of about a ton may be exerted on the bit without lifting the rig. This procedure also enables the rig to drill into non-horizontal surfaces of an outcrop.

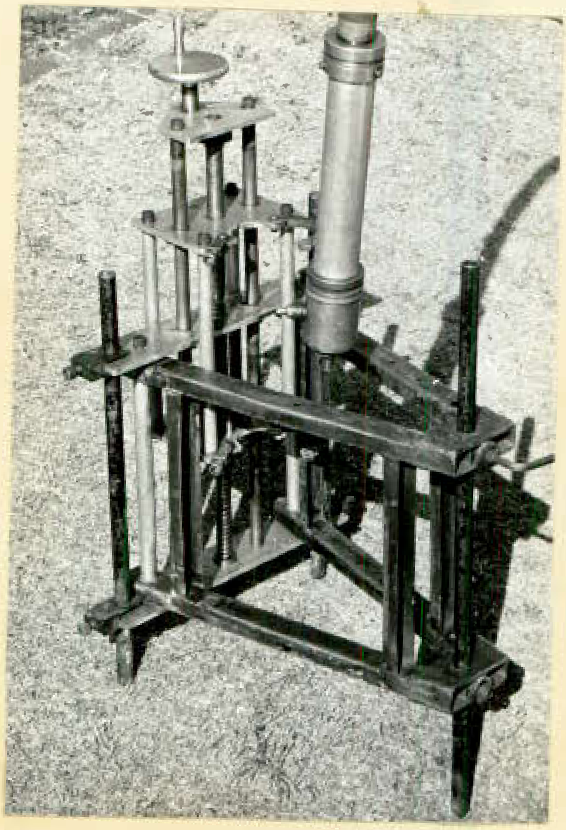


Figure 2/8. The new drill rig.

It is convenient to use the same drill spindle to hold the small bit for drilling the bolt hole or the larger bit or drill rods for drilling the actual core. The spindle is most simply driven by a small petrol motor through a flexible shaft, as in the old rig.

The rig must be provided with a means of orienting the unbroken core without having to remove the rig from its position over the hole.

(b) The Rig.

The basic rig (Figure 2/8) consists of a triangular frame fabricated from light square steel tube and rod and sheet "Dural". Legs of adjustable length, made from $\frac{3}{4}$ inch electrical conduit, are held by clamps in the frame. The travelling carriage slides on two guide rods bolted into the frame and is driven by a lead screw. The carriage is equipped with two clamps for holding the spindle housing and a key-way for locating the orienting instrument.

The spindle (Figure 2/8) is carried by two radial ball-bearings and a thrust bearing in the "Dural" spindle housing. A "water jacket", equipped with sealed ball-bearings and synthetic rubber water seals enables water to be introduced into the drill bit through a hole up the centre of the lower portion of the spindle. The end of the spindle is threaded to take the core barrel or drill rods and can be held by a spanner on a hexagon while tightening or loosening the rods or barrel.

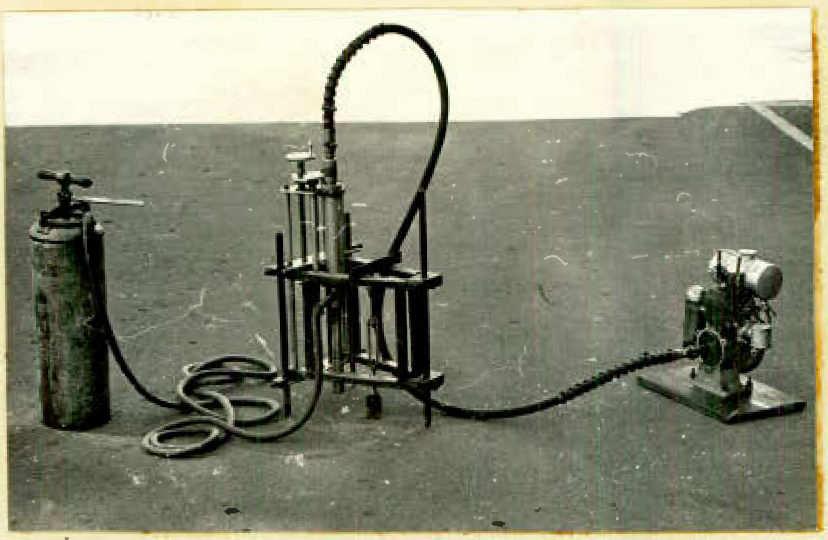


Figure 2/9. The new drilling equipment ready for operation.

The top end of the spindle and the spindle housing are both threaded to take the inner rotating cable and the outer stationary housing respectively of the flexible shaft. In addition, the spindle housing is provided with grooves for locating it in the clamps of the drill carriage.

The carriage has a travel of eight in. and the core barrel normally used is seven in. long. Having drilled six or seven in., the barrel and spindle are removed and the core is oriented and removed. A six in. long extension rod is fitted between the barrel and the spindle to permit the drilling of a further six in. of core. This process is repeated until the desired depth is reached.

The rig is 2 ft. 6 in. high and, with the spindle, weighs 30 lbs.

Water under pressure is supplied to the water jacket from a simple "pump can" commonly used for spraying fruit trees.

Figure 2/9 shows the rig ready for operation.

(c) The Orienting Device.

The direction of magnetization of a cylindrical specimen cut from the core is measured relative to a scratch down its side (the X axis) and to the axis of the cylinder (the Z axis). In order to define the direction of magnetization in space, corrections must be applied for any difference between the X axis and true North (the "bearing correction") and between the Z axis and the vertical (the

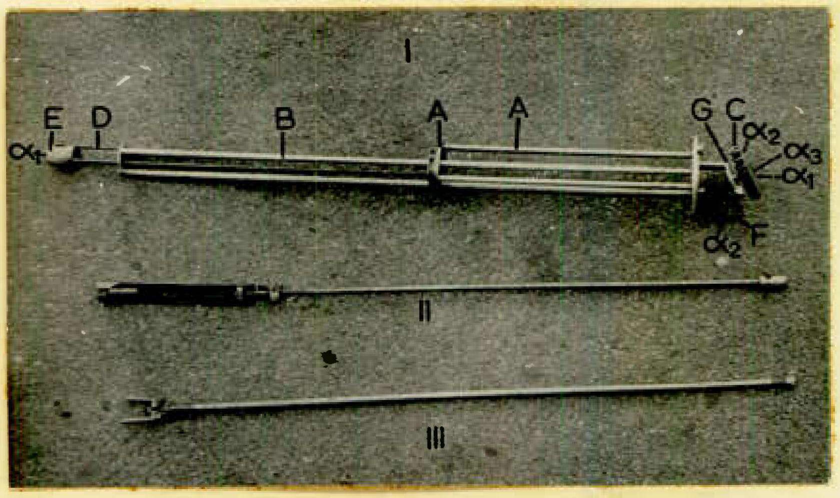


Figure 2/10. I. The new orienting instrument.

II. The core detacher.

III. The "fishing tool".

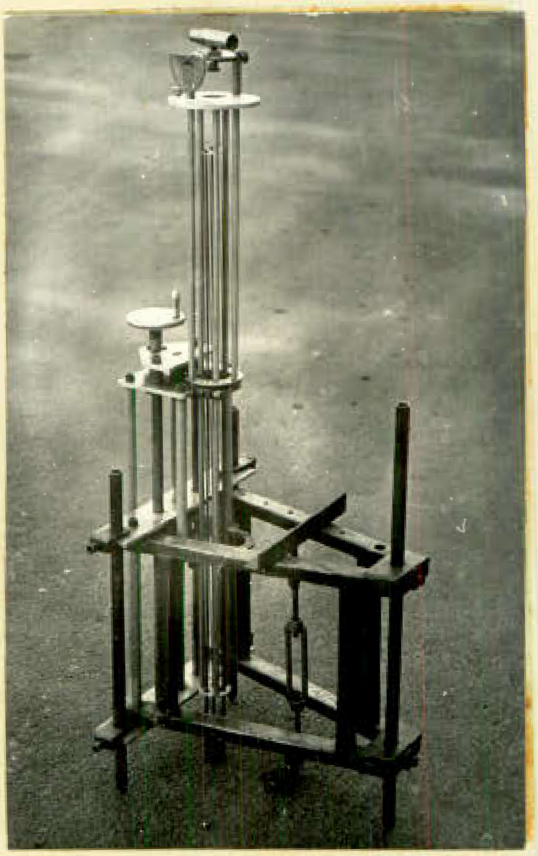
"slope correction"). As pointed out by Dr. John W. Graham (private communication) these corrections are greatly simplified if the X axis is chosen in the vertical plane through the Z axis, i.e. if the scratch is drawn along the uppermost surface of the sloping core. The inclination of the third axis Y, at right angles to X and Z, will then always be zero. The conditions to be satisfied by the orienting instrument are:-

i) The scratching tool (a small diamond) must be accurately adjustable so as to draw the line down the uppermost surface of the core, i.e. the Y axis must be horizontal.

ii) The angle between true North and the vertical plane through the Z axis must be measured.

iii) The angle between the vertical and the axis of the core (the Z axis) must be measured.

The Orienting instrument (Figure 2/10,I) consists of a light "dural" frame (A), the lower end of which is provided with a groove and a key to fit uniquely into, and be held by the upper clamp of the drill rig (Figure 2/11). The centre of the upper surface of the frame is recessed and acts as a bearing surface for the rotating base plate to which the guide rods (B), and the "theodolite" (C), are attached. Sliding on and guided by the guide rods, is a third frame (D), the lower end of which consists of a brass tube (E) carrying on its inside a small diamond mounted on



igure 2/11. The orienting instrument clamped in the rig.

a beryllium-copper leaf spring. Besides the rotation of the whole base plate about axis α_1, carrying with it the theodolite and the guide rods, the "theodolite" itself is capable of rotation about a further two axes. The first axis, α_2, is perpendicular to the plane P_1 which includes the diamond scratcher and the axis of rotation of the base plate α_1. The angle of rotation about α_2 can be read on scale F. The second axis α_3 is perpendicular to α_2; the rotation about α_3 being read on scale G. Attached to scale G is a "T" level and a small telescope.

The instrument is located and clamped in the rig (figure 2/11) and automatically the axis α_1 will coincide with the axis of the core (the Z axis of the specimen) since the rig remains firmly bolted to the outcrop until the last section of core has been oriented. By rotating about axes α_1 and α_2 until the T bubble is horizontal, axis α_3 is made vertical. The clamping screws are tightened. Axis α_2 which, when the orienting instrument is correctly located in the drill rig, will coincide with the Y axis of the specimen, will of course be horizontal so that the plane P_1 which includes the X and Z axes of the specimen will be vertical. Care must be taken to avoid the 180° ambiguity in the position of the diamond and the above adjustments should be made so that the diamond occupies the upper position.

Since axis α_3 is vertical, the horizontal angle between a known direction (as determined by a compass, sundial, theodolite, etc.) and the plane P_1 may be measured by means of the telescope and scale G. In fact, if the zero mark is suitably placed, this angle is automatically read when the telescope is pointing in the known direction. The direction or "Bearing" of plane P_1, relative to North is then easily calculated.

Scale F automatically gives the true angle between the vertical and the axis of the core (α_1).

The inner frame is then pushed downwards so that the cylinder at its end slides over the core. The spring loaded diamond scratches a mark down the core. The instrument is removed and the core extracted to permit further drilling. If all clamping screws are tight and the rig firmly bolted down, the orienting instrument may be replaced in the rig to mark the subsequent lengths of core without further adjustments or readings being necessary. All pieces of core from the same hole will be marked in an identical manner.

(d) Accessory Equipment.

Having removed the orienting instrument, the core may be broken off at the bottom of the hole by means of the instrument shown as II in figure 2/10.

This "core detacher" is basically a cut-away section of brass tube sliding on a rod of suitable length.

Attached to the rod is a piece of brass cut to form a wedge at one side and a flat at the other. The tube is pushed over the core by means of the flat. The rod is raised slightly and rotated through 180° to position the wedge behind the tube. Forcing the rod downwards will wedge the tube to one side of the hole and will break the core near the bottom. The core is held in the tube by a pair of springs and may be removed from the hole in the tube.

If during the drilling operation, the core breaks at a joint or other discontinuity in the rock, it generally slips out of the core barrel when the latter is removed from the hole and lies against the wall of the hole. The tube carrying the diamond marker will not be able to slide over the core so that there is little danger of marking the core after it has been broken. However, the tubular core detacher will similarly not be able to slide over the core so the core cannot be removed from the hole. In such cases a "fishing tool" (figure 2/10 III) may be used. This tool consists of two "fingers" pivoted on pins set into a small brass plate which is attached to a long thin tube. The fingers can be made to pinch together by pulling on a rod sliding through the centre of the tube.

(e) Performance.

The rig was designed to drill to a depth of 3 ft. This it does equally satisfactorily whether drilling into horizontal, vertical or even overhanging surfaces of an outcrop. It has been used to drill a number of 6 ft. holes. The last 3 ft. of core were oriented by matching the pieces up to the core above and extending the orienting scratch. This is only possible for certain massive rocks.

3. The Magnetizing and Demagnetizing Apparatus.

In attempting to determine the cause of the peculiar pattern of magnetization of a certain outcrop of rock (see Chapter 6) it became necessary to determine some of the magnetic properties of this particular rock. The design of the apparatus used in the magnetizing and demagnetizing experiments described in Chapter 6 was adapted by the author from ideas from various sources.

(A) The magnetizing apparatus.

Basically, apparatus for magnetizing rock samples is very simple and has been used many times in the past. The specimen is commonly placed near the centre of a solenoid through which a D.C. electric current is passed. The magnetic field to which the specimen is subjected should be slowly and smoothly increased to the desired level and then slowly decreased to zero. This may be done either by carefully varying the current in the solenoid or by slowly drawing the solenoid up to, and away from, the specimen. Initially the magnetic field was controlled by the first

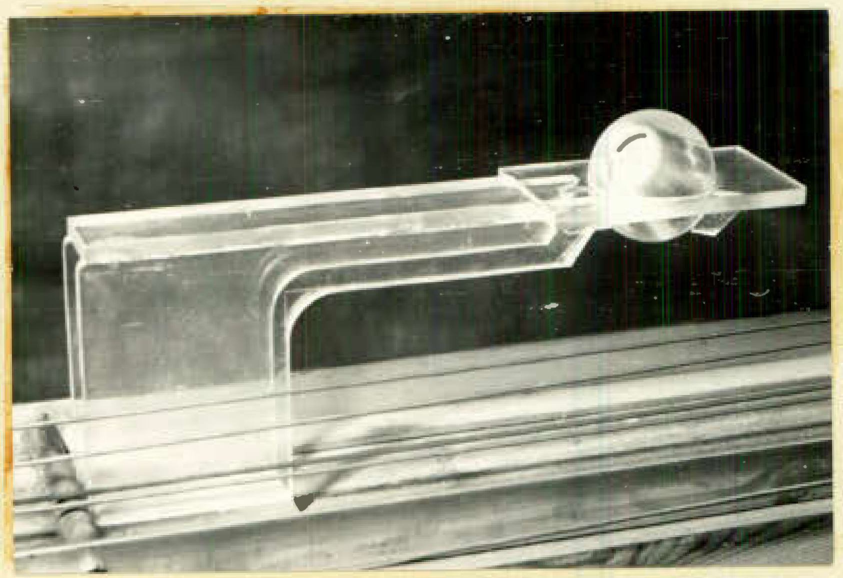


Figure 2/12. The magnetizing equipment, showing the sphere containing the specimen, resting in the jig.

technique but after the demagnetizing equipment had been constructed (see below) the coil, mounted on a winch driven trolley, was moved slowly and smoothly relative to the specimen. The two methods work equally well, the latter technique being preferred only because the coil and trolley are common to both the magnetizing and demagnetizing apparatus.

As will be seen in Chapter 6, it was important to be able to accurately control the angle between the N.R.M. of the specimen and the direction of the applied magnetic field. The apparatus used was based on a type of "universal stage" designed by Vincent (1954) for studying mineral grains under the microscope.

After measuring its direction of magnetization, the specimen is placed into a cylindrical hole in a small perspex sphere and its direction of magnetization is plotted in ink on the surface of the sphere. This is done by measuring the "declination" along the equator from a zero mark (which is made to coincide with the scratch on the specimen) and the "inclination" from the equator towards the pole of the sphere (which coincides with the Z axis of the specimen). These measurements are made easy and accurate by resting the sphere in a jig so that a scale marked in degrees exactly forms a great circle round the sphere. If the zero mark on the scale is made parallel to the axis of the solenoid then the angle between the N.R.M. of the specimen and the direction of the applied field is controlled

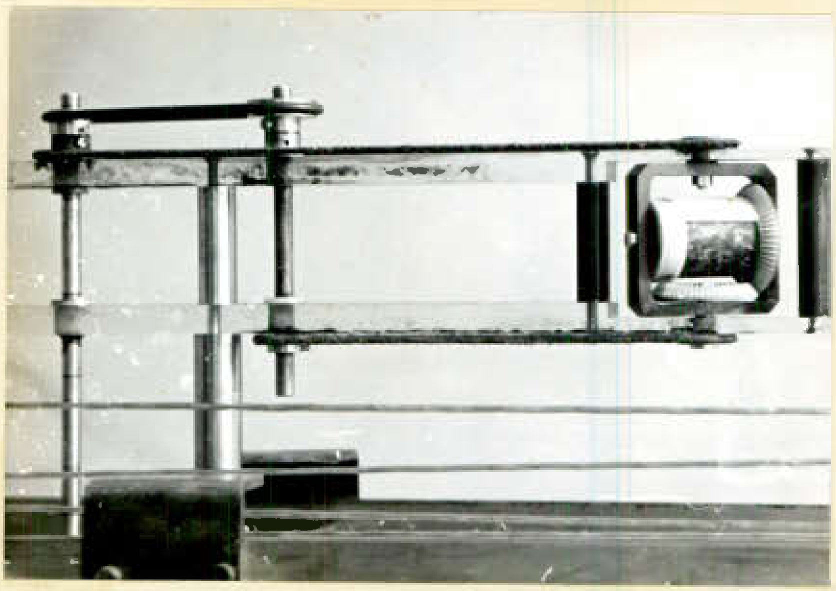


Figure 2/13. The equipment for rotating the specimen during A.C. demagnetization.

jig

by placing the sphere in the fig with the plotted direction of magnetization opposite the desired mark on the scale. Figure 2/12 is a photograph of the sphere resting in the jig.

For the experiments described in Chapter 6, the ambient magnetic field of the earth was neglected because it was always insignificant compared with the field generated by the solenoid.

(B) The alternating current demagnetizing apparatus.

As and Zijderveld (1958), Rimbert (1958) and others have shown the value of alternating current demagnetization. These workers generally applied the A.C. field to the specimen successively in three mutually perpendicular directions. Ideally, the A.C. field should be applied in all directions.

Equipment similar in principle to that described by Creer (1959) in which the specimen is simultaneously rotated about a horizontal and a vertical axis by means of a pair of bevel gears was constructed and tested. If the two bevel gears are identical then all directions lying on a certain plane cutting the specimen obliquely, never exactly coincide with the direction of the applied field. It was found empirically (by the author) that better results were obtained if the lower bevel gear is also rotated but at a speed different from that of the main cradle (see figure 2/13). This ensures a more random motion of the specimen which presents every possible direction in it to the A.C.

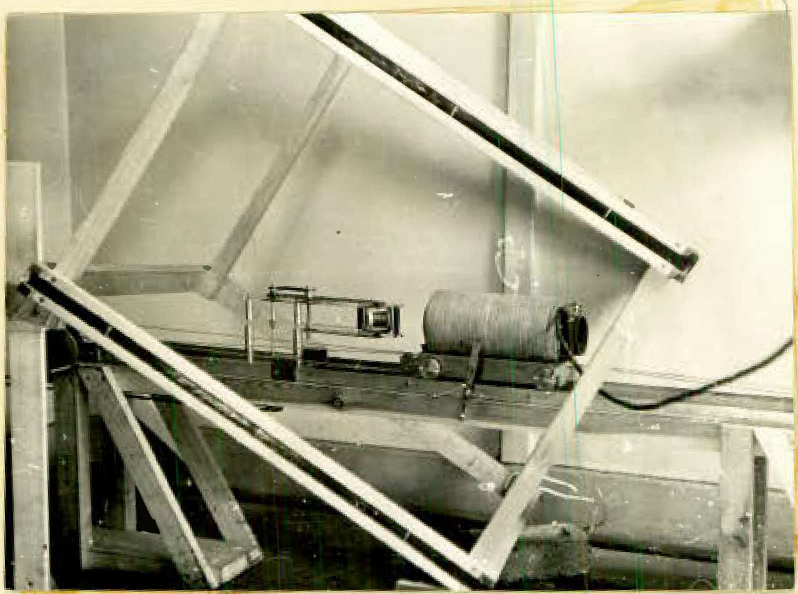


Figure 2/14. The complete A.C. demagnetizing equipment.

field. In our apparatus the peak field at the centre of the coil is set to the desired level by means of a variac. The coil, mounted on a trolley, is then slowly pulled up to and over the spinning specimen by means of a winch. After any desired length of time the field at the specimen may be reduced very nearly to zero by reversing the winch and removing the trolley to about 5 ft. from the specimen. The increase and decrease of the field is, of course, not linear with time but it can be made to vary very slowly and smoothly over a wide range.

It was found experimentally that better results were obtained using 500 c.p.s. alternating current from a generator than by using 50 cycles from the "mains". There appears to be no fundamental reason why one frequency should be better than another, provided that (i) the increase and decrease of the A.C. field is slow enough to submit the specimen to a very large number of cycles per oersted change in the peak A.C. field, and (ii) the rate at which the specimen spins is slow compared with the frequency of the current but fast compared with the change in the peak A.C. field. However, the current from the 500 cycle generator is probably "cleaner" than that from the mains which frequently has large switching surges. Series tuning the circuit at 500 cycles was accomplished with condensers of about 6 micro farads, and this further reduces the distortion in the wave form of the current. To tune the circuit at

50 cycles would require about 600 μF.

A large pair of Helmholtz coils was arranged so as to cancel the D.C. field of the earth at the specimen. It was found that cancelling the earth's field or doubling it made no difference to the A.C. "washing" experiments and the use of the Helmholtz coils has been discontinued.

CHAPTER 3.

MEASUREMENTS ON KARROO SEDIMENTS.

As concluded in Chapter 1, the Cape and Karroo Systems appear to be ideal for palaeomagnetic purposes. It was decided to tackle the Karroo System first. It was thought desirable that the samples should be as representative as possible of the whole of the geological column covered by the Karroo System and it was therefore decided to collect samples at more or less regular intervals throughout the whole, or as much as possible, of the succession. Subsequent trips could be planned to fill in the detail, if necessary, or to study points of special interest.

1. Collection of Samples.

(A) Natal.

In January 1955 a reconnaissance trip to Natal was undertaken to collect well oriented samples systematically covering as much of the Karroo System as possible, excluding the lavas. From an inspection of the Geological Map the best section line appeared to be along the road from Highflats through Ixopo, Donnybrook and Underberg to the Drakensberg Garden Hotel (see figure 3/1).

In practice it was found that the sediments are not well exposed along this road, and where they do outcrop

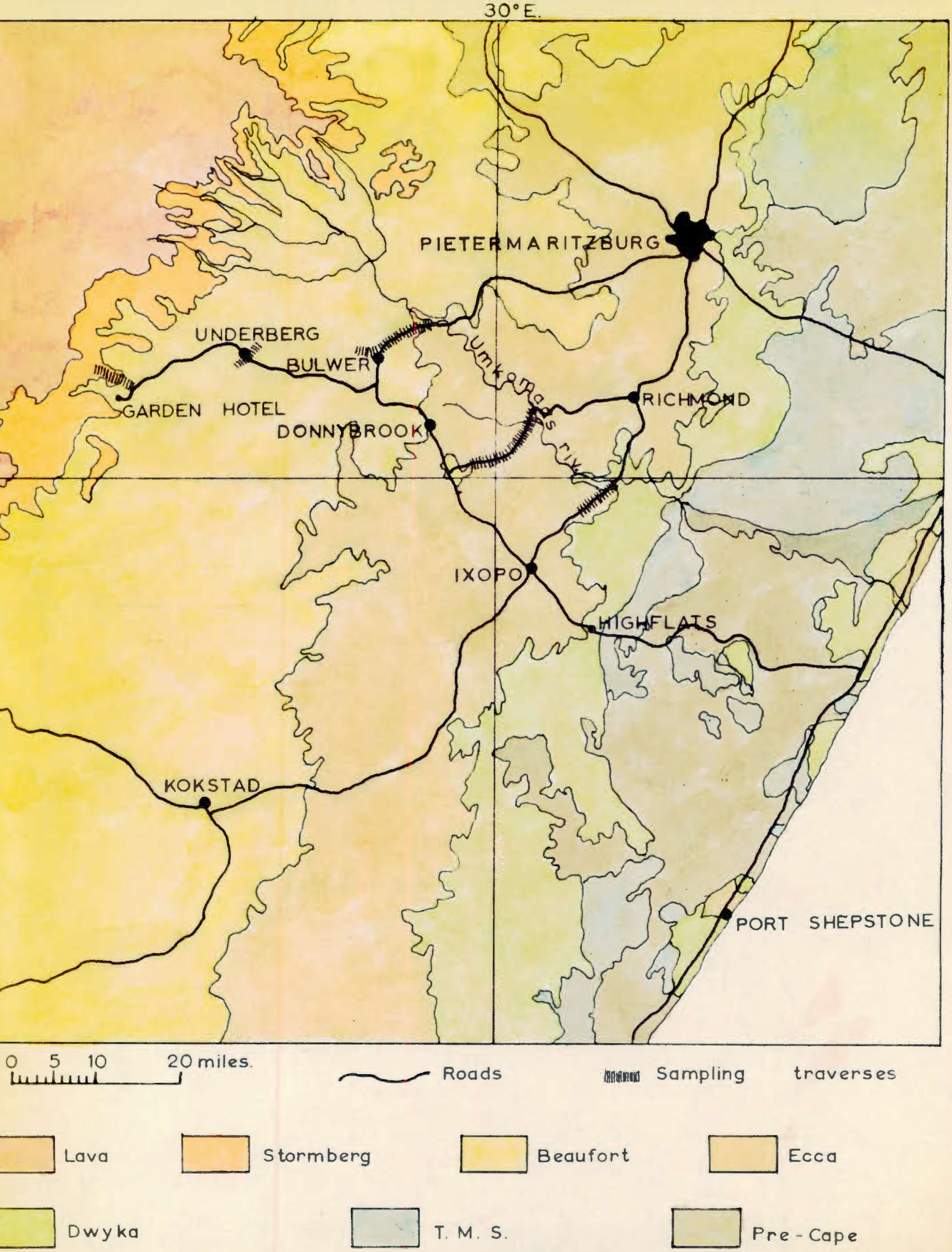


Figure 3-1.

A geological map of part of Natal.

they are generally weathered. Instead, sampling was carried out along a number of traverses indicated in figure 3/1, each covering a large thickness of strata and each correlated as accurately as possible with the next. Even along these sections the outcrops were not as fresh as they might have been. Dolerite intrusions were avoided as far as possible, but in the absence of any detailed map of the area the distance from dolerite intrusions, particularly those that may have been removed by erosion, was not easily estimated.

Table 3/1

Geological Formation	Locality	No. of Samples	
		Drilled	Hand-Samples
Cave Sandstone	Bamboo Mountain, Underberg.		3
Red Beds to U.Beaufort	Bamboo Mountain		17
Middle Beaufort	Underberg		17
Middle Beaufort	Bulwer Mountain		11
Lower Beaufort	Umkomaas Valley, Bulwer		14
Upper Ecca	Umkomaas Valley, Bulwer	10	1
Upper Ecca	Umkomaas, Donnybrook		4
Middle Ecca	Umkomaas, Donnybrook		5
Lower Ecca	Umkomaas, Donnybrook		2
Lower Ecca	Umkomaas, Ixopo	18	
Dwyka Tillite	Umkomaas, Ixopo	5	

Most of the Middle and Upper Ecca in the section near Donnybrook was considered to be unsuitable because it is intruded by an enormous dolerite sill whose thermal effects appear to be widespread.

Table 3/1 shows the locality and number of samples obtained from each formation. The thickness of strata covered by these 107 samples was slightly in excess of 7,000 feet.

(B) The Eastern Cape Province.

A second field trip was undertaken in March, 1955, with the object of obtaining a second representative collection of samples of the Karroo System but in a different locality - the Eastern Cape. Detailed maps covering this area were available. These included Geological Survey publications by Du Toit (Lady Grey), Mountain (Grahamstown) and copies of field maps very kindly supplied by Mr. P.J. Rossouw of the Geological Survey ("Rosendal" and "Doornhoek", Molteno, and an area near Naauwpoort covered by Middle Beaufort). These localities are shown in figure 3/2, a map of the Eastern Cape.

After having difficulty in avoiding the enormous number of dolerite intrusions at Doornhoek, it was decided to abandon the area near Naauwpoort where a similar number of intrusions had been mapped.

Table 3/2 summarizes the results of this trip.

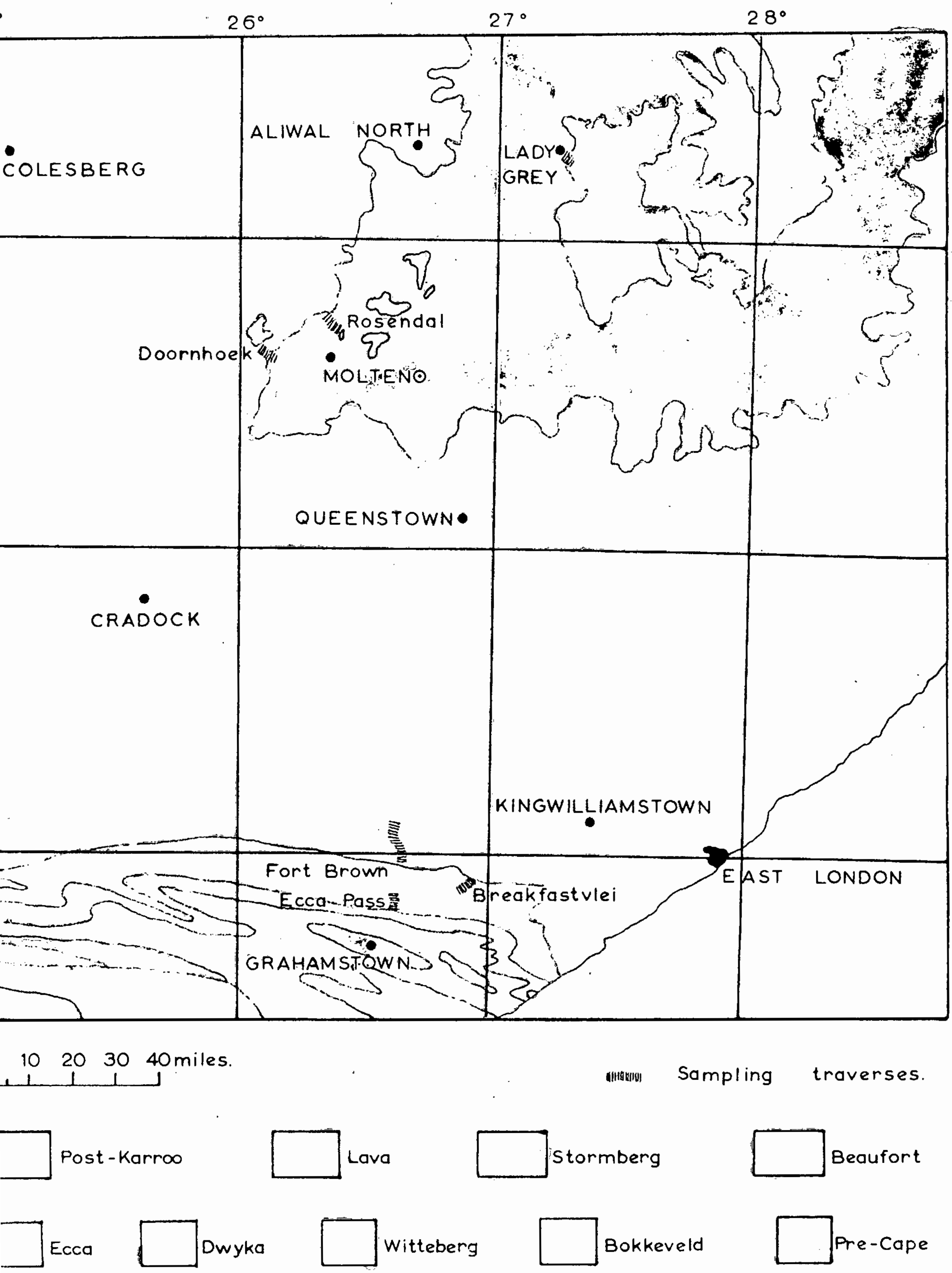


Figure 3 - 2.

A geological map of part of the Eastern Cape.

Table 3/2.

Geological Formation	Locality	No. of Samples Drilled	No. of Samples Hand-Samples	Approx. Thickness Sampled Ft.
Cave Sandstone	Joubert's Pass, Lady Grey	6		200
Red Beds	Joubert's Pass	9		450
Molteno Beds	Joubert's Pass	5		500
Cave Sandstone	"Rosendal", Molteno		2	50
Red Beds	"Rosendal"		7	450
Molteno Beds	"Rosendal"		6	500
Lower Molteno Beds	Doornhoek, Molteno		5	200
Upper Beaufort	Doornhoek	7	1	300
Lower Beaufort	Fort Brown	11		?
Upper Ecca	Breakfast Vlei	27		6,000
Middle Ecca	Ecca Pass, Grahamstown	2		?
Lower Ecca	Ecca Pass	26		3,500
U. Dwyka Shales	Ecca Pass	1		

2. The Magnetic Measurements.

Specimens suitable for magnetic measurement in the spinner magnetometer were prepared in the laboratory from

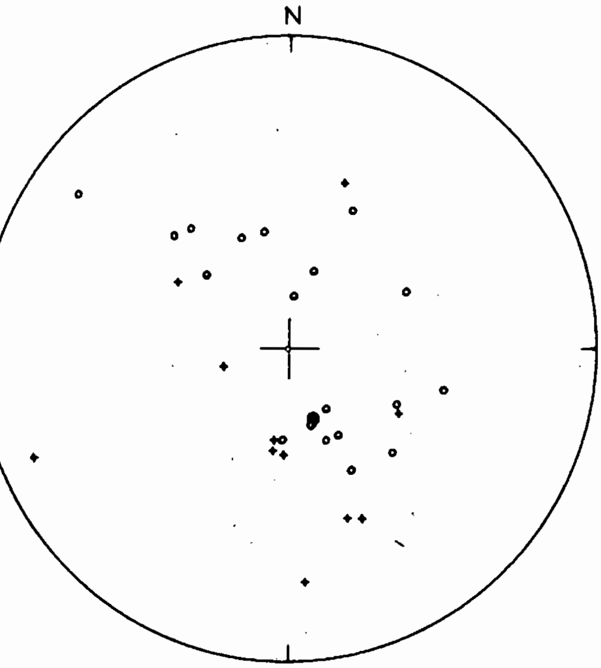


Figure 3-3.

The directions of magnetization of the individual specimens from the Lower Ecca, Ixopo.

∘ = South pole downwards (normal).

+ = North pole downwards (reversed).

● = The present field.

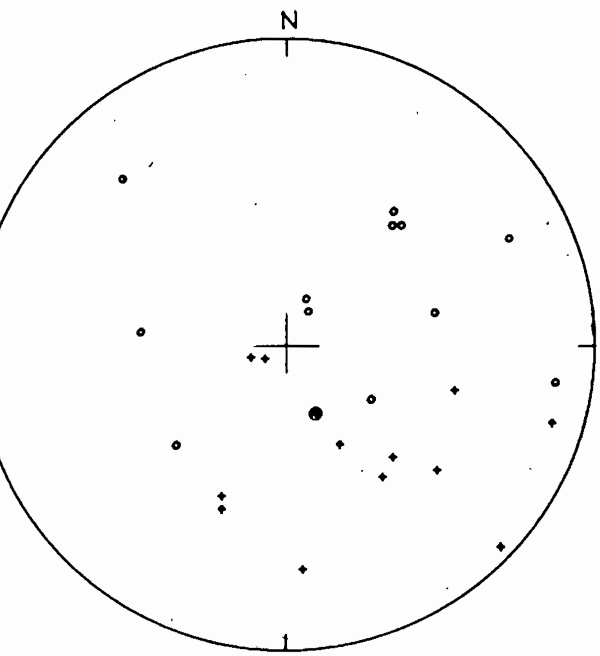


Figure 3 - 4.

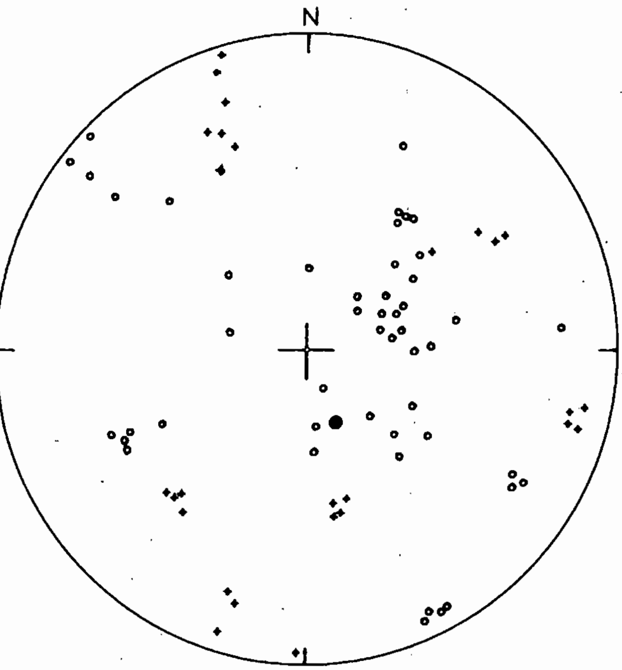
The directions of magnetization of the individual specimens from the Lower Ecca, Ecca Pass, Grahamstown.

the samples collected. At least two specimens each 1 inch long were cut from each drilled core. Hand-samples had first to be cored in a drill press in the laboratory, the cores then being cut to the correct length.

Measurements of the direction and intensity of magnetization of the Karroo specimens were made by means of the spinner magnetometer in its original form, i.e. operating as a null detector (see Chapter 2). Only about 30% of the specimens collected were magnetized sufficiently strongly to be measured by this method.

The directions of magnetization of these specimens are so scattered as to be virtually unintelligible. Figures 3/3 to 3/6 are lower hemisphere stereographic plots of the directions of magnetization of some groups of samples. In the case of the Lower and Upper Ecca from Ecca Pass and Breakfast Vlei respectively corrections for the present dip of the strata have been applied. In all other cases the dip was less than 2^{o} and has been disregarded.

In general, specimens from the same sample agree fairly well with one another but differ widely from those from neighbouring samples. However, in the case of the Upper Ecca from Breakfast Vlei and to some extent in the case of the Stormberg from Rosendal the direction of magnetization of a sample is often nearer to that of the sample immediately above or below it than to that of samples further removed. By joining the plot of the directions of



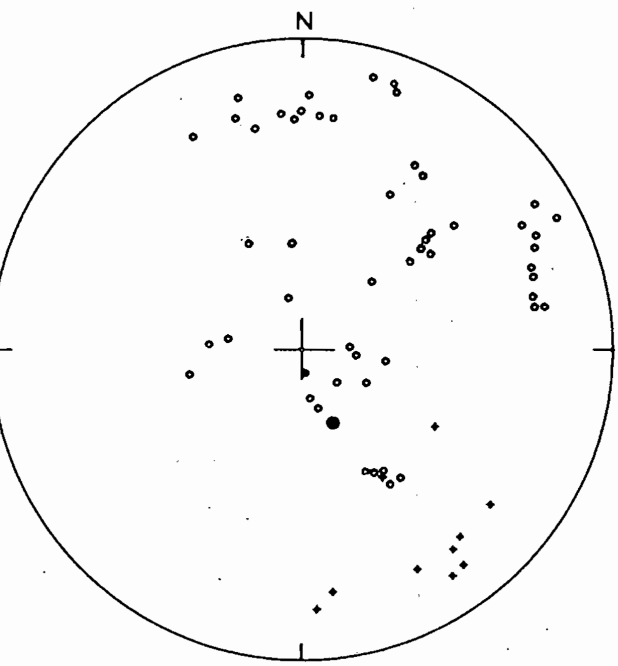
<u>Figure 3 - 5.</u>

The directions of magnetization of the individual specimens from the Upper Ecca, Breakfastvlei.

∘ = South pole downwards (normal).

+ = North pole downwards (reversed).

● = The present field.



<u>Figure 3 - 6.</u>

The directions of magnetization of the individual specimens from the Stormberg sediments, Molteno.

magnetization of samples in stratigraphic order some sort of a "path" may be obtained, but the path appears to wander randomly over the entire plot and is often discontinuous.

3. Discussion of the Results.

In the problem of determining the direction of the earth's magnetic field during Karroo times no significance can be attached to these virtually random directions of magnetization. It seems unlikely that the magnetic field could have varied quite as rapidly as would be required to keep pace with the variations of the observed directions of magnetization. Some other factor capable of magnetizing or re-magnetizing these samples in virtually any direction must exist. The possible explanations include the following:-

a) Original random magnetization.

Such factors as strong wind or water currents at the time of deposition of the sediment could cause the direction of magnetization to deviate considerably from that of the applied field. If the direction and/or velocity varied from time to time and from place to place one would expect the observable direction of magnetization of the specimens from one sample to be more consistent with each other than with those of another sample collected from younger or older rock. As mentioned above, this effect is commonly observed in samples from the Karroo System.

The frequent occurrence of currents at the time of deposition of the Karroo System, particularly during Ecca times is abundantly demonstrated by ripple marks and it is possible that the conditions of deposition of a large proportion of the Karroo System were unfavourable for the accurate preservation of the direction of the earth's field at that time.

b) Unstable magnetization.

The presence in the rock of magnetically "soft" minerals may permit the acquisition of an I.R.M. of varying "viscosity". Cases in which the magnetic viscosity is very high (long decay constant) would result in an I.R.M. in the direction of the present dipole field (see Chapter 1), while a slightly shorter time constant would permit magnetization parallel to the present field. With the exception of the Dwyka tillite from Natal, relatively few specimens are magnetized in the direction of either the present field or the dipole field so that it is improbable that this mechanism is of major importance in the magnetization of the samples studied.

The fact that, in general, specimens from the same sample agree fairly well, seems to indicate that I.R.M. of very short time constant is not very common because, after the individual specimens were prepared, they were stored in random orientation for several weeks or months before measurement.

c) The geological history of the rock.

The actual consolidation of a sediment without shear cannot alter the direction of magnetization of the sediment since no rotation of the magnetic grains in a preferred direction occurs. However, certain factors related to the history of the sediment after deposition and consolidation may change its direction of magnetization. These include the following:

(i) Heating to above the Curie Point of some of the magnetic minerals, due to either deep burial or the intrusion of igneous material, will cause partial or complete remagnetization of the rock in a field that may or may not be the same as that at the time of deposition. It is possible that some of the Ecca may have been affected by deep burial while many of the other samples from the Karroo could have been affected by intrusions.

(ii) Deformation of the sediment can change its direction of magnetization (J.W. Graham, 1949). Graham (private communication) points out certain features in the Lower Ecca of Ecca Pass which may be associated with shear.

(iii) Some magnetostrictive effect, due to non-hydrostatic pressure of any kind might be operative (Graham, 1956).

d) "Surface effects".

Gough (1956) found that while samples of certain Pilanesberg dykes collected at the surface were randomly magnetized, those from the same dykes exposed in underground workings were extremely consistently magnetized. Possible explanations include:-

(i) Weathering. Chemical destruction of some of the original magnetic minerals and the growth of new ones in a field different from the original field could cause a large variation in the direction of magnetization which will be the vectatorial sum of a variable amount of the original magnetization and a variable amount of the new chemical magnetization. Some of the Karroo samples may have been partially weathered.

(ii) Thermal cycling. The daily temperature variations (below the Curie Point) of a rock exposed at the surface might cause it to be more easily magnetized by the present field. Magnetization acquired in this way could possibly appear to be more stable than normal I.R.M.

(iii) Magnetostriction. Particularly in the case of an igneous rock, the weathering of the outermost few millimeters results in a tendency for the crust to expand. The stresses so generated may reach the breaking stress of the rock, as in exfoliation. Stresses below the breaking stress of the rock may cause some magnetostrictive effect on the magnetic minerals. A magnetostrictive cycling process due to the daily thermal expansion and contraction of the surface rock, may have some effect. The role of this type of magnetostriction in palaeomagnetism is uncertain, although Stott and Stacey (1960) and Stacey (1960) show that ordinary magnetostrictive effects are negligible in rocks with less than 10% magnetic anisotropy.

(iv) Lightning. The importance of the remagnetization of surface outcrops by electrical currents associated with lightning is demonstrated in Chapter 6.

4. Conclusions.

The results of the reconnaissance survey of the Karroo sediments are disappointing and it is clear that there are a large number of factors which could have produced the discordant results. There are two possible courses. The first is to conclude with J.W. Graham (1957) that "the prospect is hardly encouraging" and abandon further studies on South African sediments. The second course is to attempt to discover which of the factors are, in fact, important in practice and devise methods of avoiding or eliminating the disturbing factors. In the succeeding chapters an account is given of the efforts which were made to follow the latter course.

CHAPTER 4.

MEASUREMENTS ON KARROO DOLERITES.

It is well known that there are extensive dolerite intrusions in the Karroo System north and east of the line marked on the Geological Map of South Africa prepared by the S.A. Geological Survey in 1955, as the southern limit of the Karroo dolerites. This line also approximates to the northern limit of folding during the Triassic. Dolerites of possible Karroo age do occur south of this line but comparatively infrequently. However, in this southern region the Karroo sediments have been affected by the Cape foldings and in some cases show evidence of shear. Both heating of nearby intrusions and high stresses with or without shear could possibly affect the direction of magnetization of the sediments. Exactly how potent these factors are, is not known.

If the direction of the field at the time of the intrusion of the Karroo dolerites were known, it might be possible to assess the relative importance of heating by these intrusions, simply by comparing this direction with the directions obtained from the sediments. The determination of the direction of magnetization of the dolerites would be of value in its own right, since it would provide a datum for the position of the pole, relative to Africa, at the time of the intrusions.

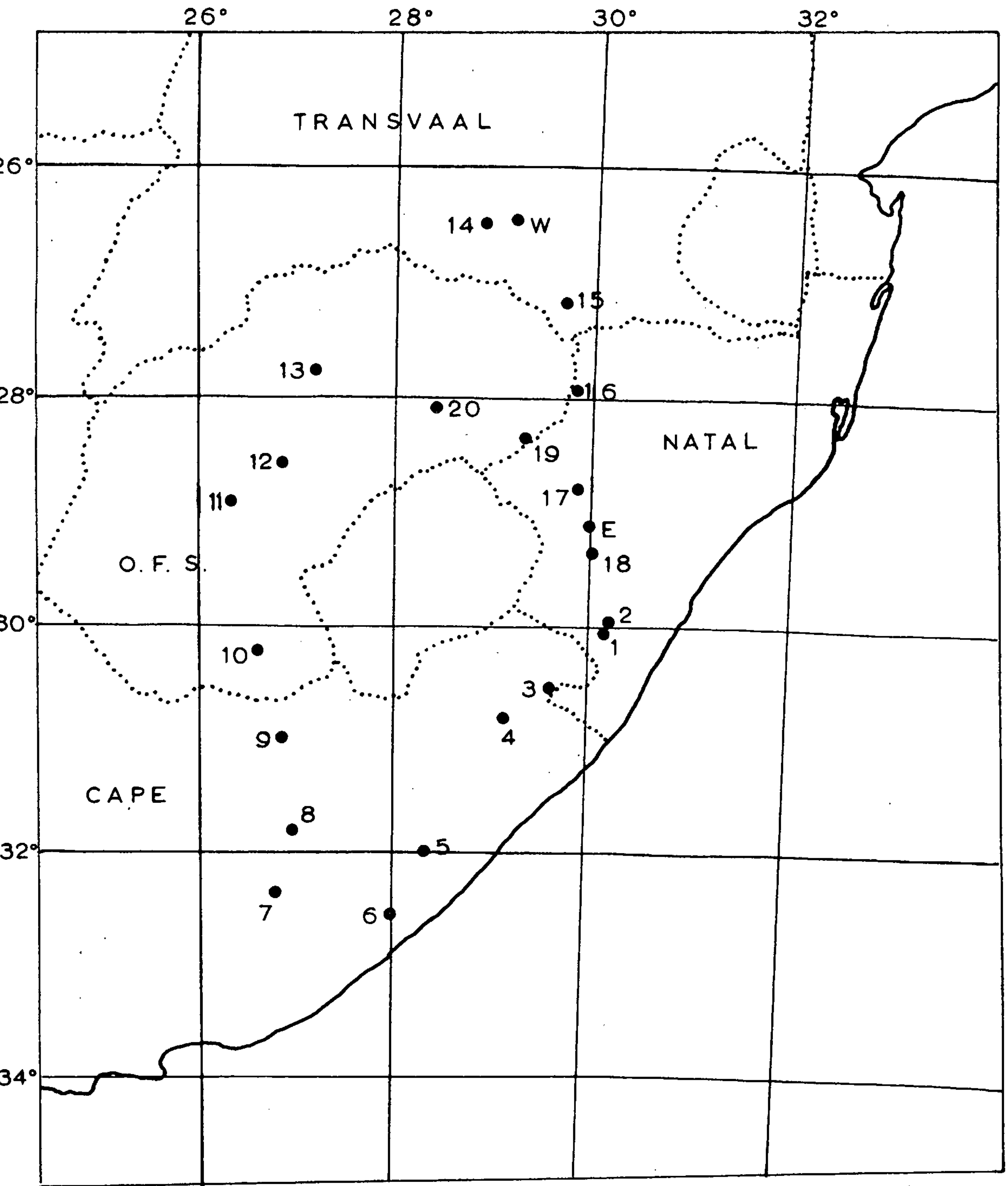


Figure 4 - 1.

The Eastern half of South Africa. The numbered points indicate the localities at which surface dolerite samples were collected. E and W represent Estcourt and Winkelhaak respectively.

The Karroo dolerites have been extensively studied by Walker and Poldervaart (1949). They consider that the Stormberg lavas were poured out towards the close of Triassic time and that the dolerites were more or less contemporaneous with the lavas. Du Toit (1954) remarks also that there is an intimate connection between the Stormberg basalts and the dolerites and concludes that the dolerites appear to have been intruded at the commencement of the Jurassic epoch.

1. The Surface Samples.

The first collection of 30 dolerite samples from 13 sills and dykes exposed in road cuttings and quarries was made in December, 1955, during a visit of Dr. John W. Graham, then of the Department of Terrestrial Magnetism, Carnegie Institution of Washington. On a later trip a further 17 samples from 7 similar fresh exposures and 6 additional samples from a sill sampled during the first trip were collected. The localities from which the samples were collected are indicated by numbers on a map in figure 4/1.

Roughly half of the samples collected were in the form of hand-samples. The remainder were collected as 5 or 6 inch cores. Four or five specimens were usually obtainable from each sample whether it was drilled in situ or in the laboratory. The magnetic measurements were made with the magnetometer in its original form, operating as a null detector.

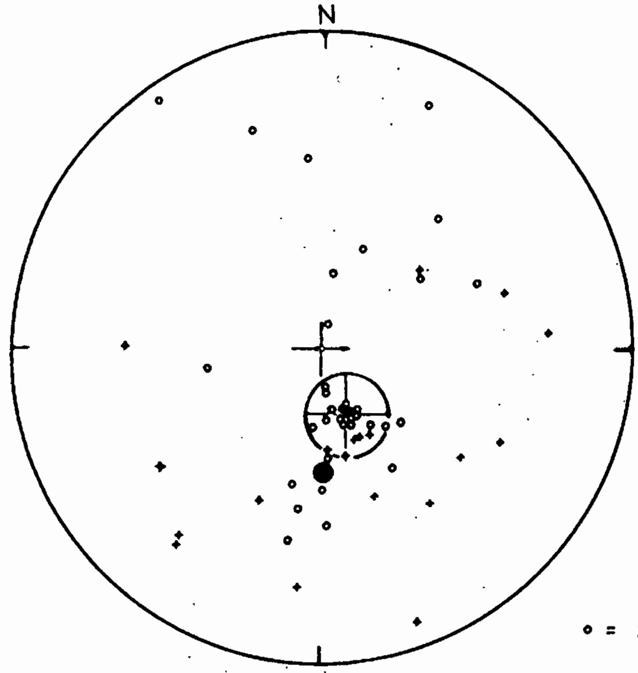


Figure 4 - 2.

○ = South pole downwards.

+ = North pole downwards.

⊕ = Direction of present field.

● = Direction of axial dipole field.

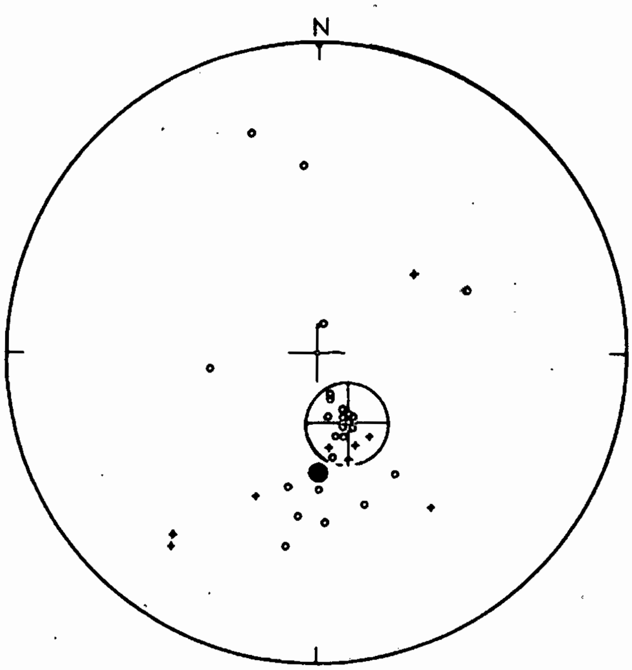


Figure 4 - 3.

The directions of magnetization of the surface dolerites before and after eliminating those found to be unstable.

A "sample mean" was calculated from the observed direction of magnetization of the individual specimens from the same sample. A lower-hemisphere stereographic plot of these sample means is shown as figure 4/2. These directions can be seen to be rather scattered except for a concentration of both North and South poles near the direction of the present field. The presence of a large number of North poles in this vicinity suggests that this concentration is not entirely due to instability. However, it is felt that no reasonably reliable idea of the direction of the field during Jurassic times can be obtained from these data.

Three or four months after the above measurements were made one specimen from each sample was re-measured, and another specimen from each sample was re-measured seven or eight months after the first measurements. It was found that some specimens showed a considerable change from the direction of magnetization first measured and it seems reasonable to conclude that those specimens for which the change was large are unstable. It was decided to exclude all samples from a locality if any one of the specimens re-measured had shown a change in the direction of magnetization of more than 10 degrees. The sample means for the remaining samples are shown in figure 4/3.

The mean for the surface collection was calculated disregarding sign and giving unit weight to each sample and is given in table 4/1. As will be seen from a plot of this mean and its circle of 95% confidence (figure 4/8) the surface samples are not inconsistent with those obtained later from Estcourt or Winkelhaak.

It will be noted that there are still a number of scattered measurements but in most cases the two samples from the same locality do not agree. The two samples from sill No.11, near Brandfort collected during the first trip, were magnetized in widely differing directions. On a later trip six more samples were collected from the same outcrop covering an area of some 1,000 sq. yards. The directions of magnetization of these were also found to be scattered and although some showed signs of instability, they were similar to the randomly magnetized samples collected by Gough from surface outcrops of the Pilanesberg dykes. One of these Pilanesberg outcrops was sampled in detail and, as will be shown in Chapter 6, the effects of lightning provide an explanation for the scattered, yet apparently stable, observations.

2. Samples from the Shafts of Winkelhaak Mines.

Before the measurements of the surface samples had been completed the sinking of the shafts of Winkelhaak Mine offered an opportunity to test the growing feeling that samples obtained from the surface gave more scattered results than those obtained at depth.

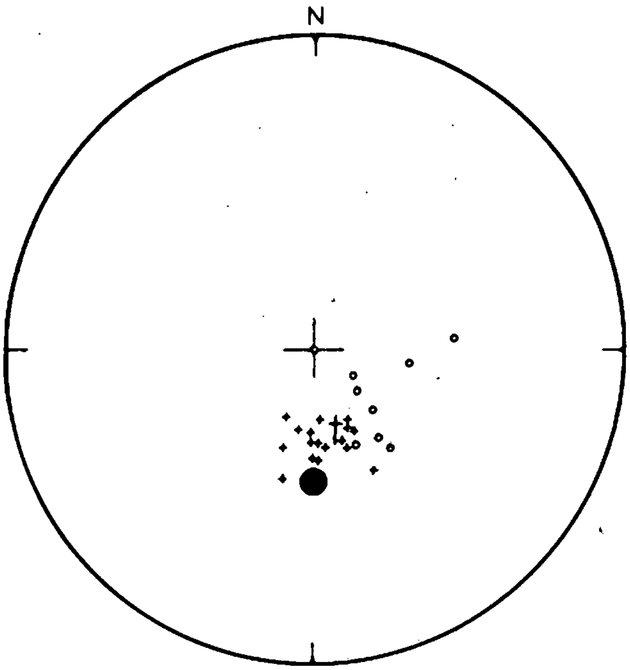


Figure 4 - 4.

The directions of magnetization of the dolerite samples from Winkelhaak. The lower sill is normally magnetized while the upper sill is reversed.

∘ = South pole downwards (normal).

+ = North pole downwards (reversed).

† = Present field.

● = Axial dipole field.

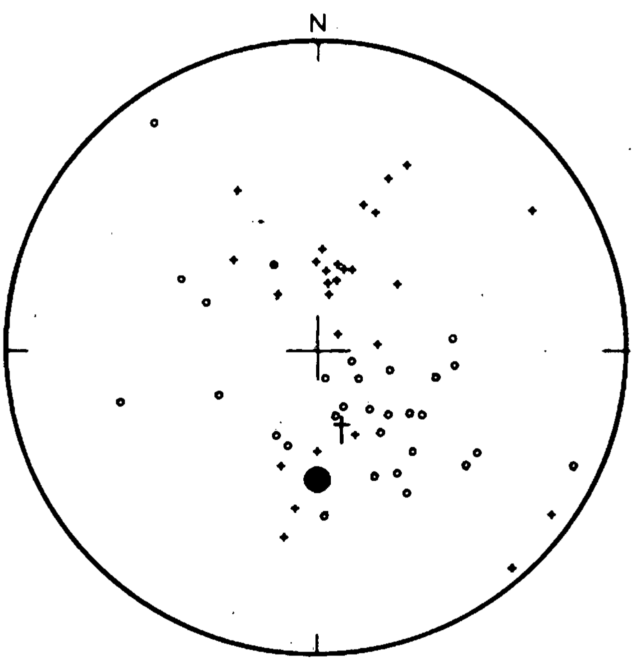


Figure 4 - 5.

The directions of magnetization of the Ecca sediments from Winkelhaak.

Oriented samples were very kindly collected for us by geologists of Union Corporation during the course of shaft sinking operations at Winkelhaak Mines Ltd. on the Far East Rand. The position of the mine is marked as 'W' on the map of the eastern half of South Africa shown in fig. 4/1. Two pairs of vertical shafts were sunk, the members of a pair being approximately 750 feet apart and the distance between the pairs about one mile.

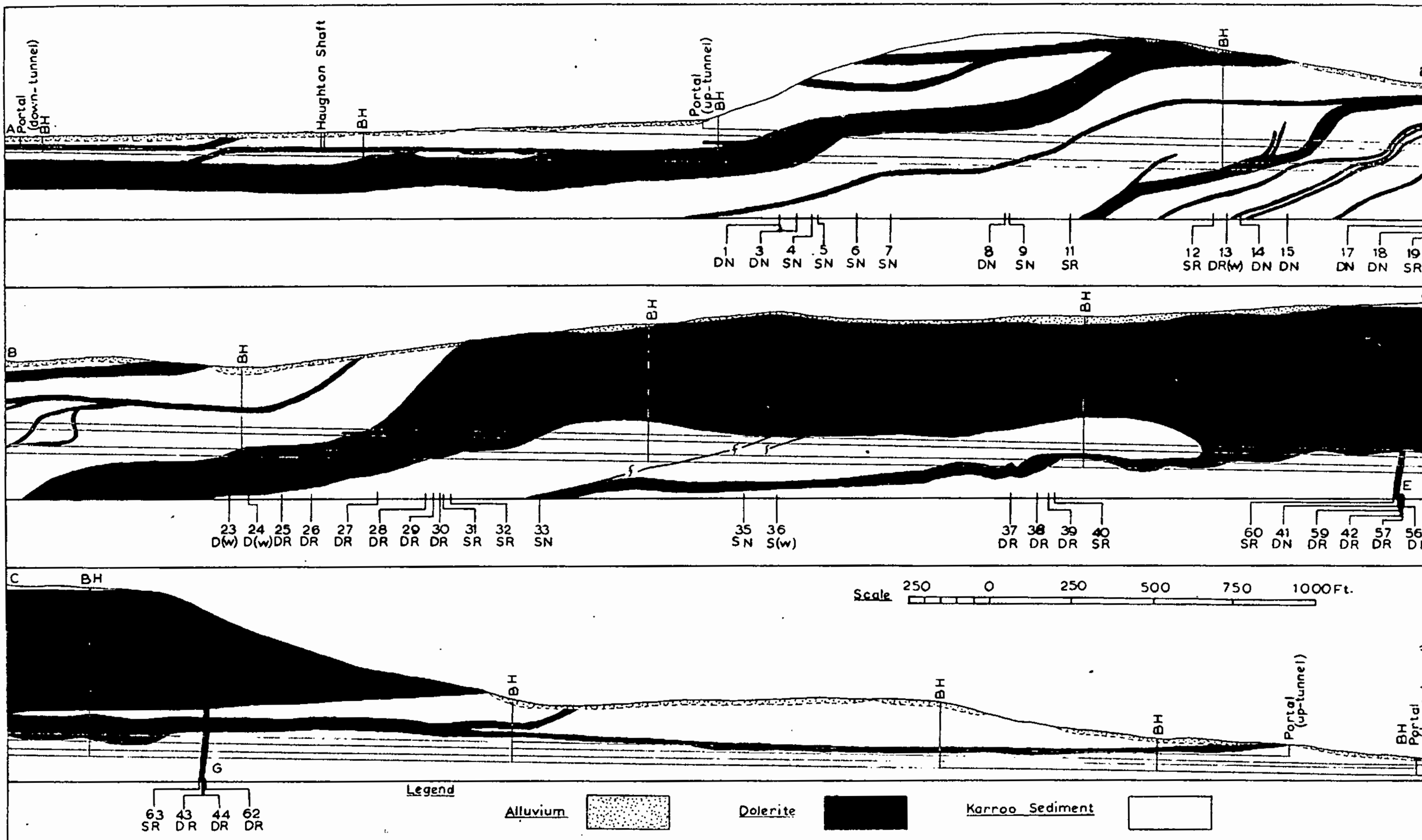
Two dolerite sills intruded into Lower Karroo (Ecca) sediments, were intersected in the shafts. The upper sill extends from the surface to a depth of between 70 and 80 feet. The lower sill, occurring at a depth of about 630 feet, is about 50 feet thick. Seventeen samples, subsequently cut into 57 specimens, were collected from the upper sill, while 8 samples, cut into 33 specimens came from the lower sill.

All specimens from the upper sill were magnetized with the north seeking poles downwards, i.e. in the reverse direction to the present field, whereas all specimens from the lower sill had the south seeking pole downwards, i.e. are magnetized in the normal sense. The results of these measurements are shown in figure 4/4, a stereographic plot of the lower hemisphere. It should be noted that the directions found for the upper and lower sills are not exactly reversed relative to each other. The directions of magnetization of the samples from the lower sill have steeper dips and lie farther east than those of the upper sill.

The statistics for these samples are given in table 4/1. In calculating the mean directions, sample means were first calculated from the directions of the individual specimens. These sample means were then used to calculate the mean for the group, giving each unit weight. If the measurements on each specimen had been given unit weight the circle of 95% confidence would have been much smaller but it is doubtful whether directions found from several specimens cut from the same sample can be regarded as independent measurements in terms of sampling the dyke or sill as a whole.

Samples of sedimentary rocks covering most of the Ecca Series were also collected for us from the shafts of Winkelhaak Mines. All these samples were very weakly magnetized and many could not be measured. The directions of magnetization of those that could be measured are shown in figure 4/5. The great scatter of these directions renders them of negligible value though the group of north poles with D about 10°, I about 60°, could possibly be significant. There was no obvious correlation between the distance of the sedimentary sample from the sills and its direction of magnetization. However, since the samples were collected at intervals of about 20 ft. the narrow "baked zone" was generally missed.

Figure 4-6.



A geological section of the environs of the tunnels near Estcourt. The samples were taken from the lower tunnel vertically above the points indicated by numbers.

D = Dolerites. S = Baked sediments. N = Normally magnetized. R = Reversely magnetized. W = Scattered.

It would seem as though the scatter in the directions of magnetization of these sediments is due largely to unfavourable conditions of deposition such that the magnetic grains were unable to align themselves in the direction of the field. Such a sediment would be much more weakly magnetized than one deposited under more favourable conditions. This very weak remanent magnetism would be easily swamped by a small amount of I.R.M. or other secondary magnetism.

3. Underground Samples from a Railway Tunnel near Estcourt.

A geological section of the tunnel environs, prepared by Mr. P.J. Smit of the Geological Survey, is shown as figure 4/6. The samples were taken from the lower tunnel vertically above the points indicated by numbers on the diagram. Dolerite and baked sediment samples are distinguished by "D" and "S" respectively, while "N" indicates that they are magnetized in the normal sense and "R" in the reversed sense. In the case of four samples (13, 23, 24 and 36) the individual specimens from a single sample form a streak instead of a fairly tight group. These are indicated by "W". The directions of magnetization are plotted on the lower hemisphere of a stereographic net in figure 4/7. For the four samples showing the streaking, the directions of magnetization of the individual specimens have been plotted, those from the same sample being linked by a line. The rest

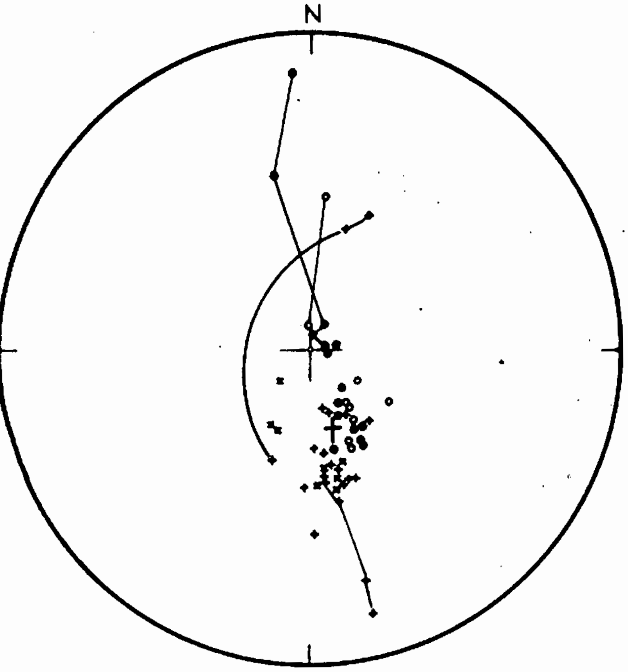


Figure 4 - 7.

The directions of magnetization of the samples from the Estcourt tunnel. Individual specimens from a single sample showing a streak are joined by a line. Otherwise sample means are plotted.

• = Normally magnetized dolerites.

+ = Reversely magnetized dolerites.

o = Normally magnetized baked sediment.

x = Reversely magnetized baked sediment.

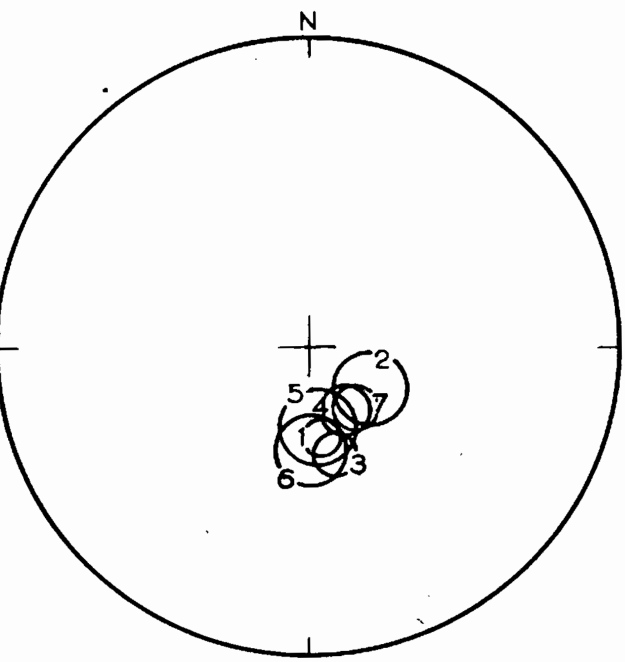


Figure 4 - 8.

The circles of 95% confidence of the mean values for :-

(1) Winkelhaak reversed dolerites,

(2) Winkelhaak normal dolerites,

(3) Estcourt reversed dolerites,

(4) Estcourt normal dolerites,

(5) Surface dolerites,

(6) Estcourt reversed baked sediments,

(7) Estcourt normal baked sediments.

are shown as the mean for the sample, calculated from several specimens.

Examination of the data in figure 4/7 shows that in general the baked sediments are magnetized in the same sense as the adjacent dolerites. There are however some anomalies.

When the first collection was made two samples (41, 42) were taken from the dyke at point E. One of these (41) was found to be magnetized in the normal sense, the other in the reversed sense. It was decided to return to the tunnel to collect additional samples from this dyke. (The other anomalous regions had already been cemented up).

These samples served to show that the chill zones were normally magnetized, whereas the interior of the dyke and the only sample of baked sediment that was measurable, were magnetized in the reversed sense. Possible explanations of this are:

(i) that the chill zones are unstable

(ii) that a self reversal mechanism operates in the chill zones

(iii) that a self reversal mechanism operates in both the interior of the dyke and in the adjacent sediments but not in the chill zones

(iv) that a reversal of the earth's field occurred while the dyke was cooling

(v) that there is, in fact, more than one intrusion with a reversal of the earth's field between the intrusions.

The possibilities of (iii), (iv) and (v) seem unlikely. On the information available at present it is impossible to decide between (i) and (ii), though the possibility of instability in some samples is supported by the streaking noted in samples 13, 23 and 24.

Considering the results from this tunnel as a whole, mean directions calculated from the reversely magnetized dolerites, the reversely magnetized sediments, the normally magnetized dolerites and the normally magnetized sediments are given in table 4/1. Samples 13, 23, 24 and 36 have been omitted from these calculations. The difference between the sediments and the dolerites is in all cases within the limits of error of the means, whereas the mean for the normally magnetized samples is significantly different from that of the reversely magnetized group. This point is clearly shown in figure 4/8, a lower hemisphere stereographic plot showing the 95% confidence circles for the four groups of samples from Estcourt and the two groups from Winkelhaak. It will be noted also that the Winkelhaak reversed samples do not differ significantly from the Estcourt reversed samples nor do the Winkelhaak normal samples differ significantly from the normal Estcourt samples. All the normally magnetized samples do, however, differ significantly from the reversed ones. It may be

Table 4/1.

	1	2	3	4	5	6	7
Latitude of collection point	26.5°S	26.5°S	29.1°S	29.1°S	29.1°S	29.1°S	30.3°S
Longitude of collection point	29.1°E	29.1°E	29.9°E	29.9°E	29.9°E	29.9°E	28.5°E
Number of samples	17	8	15	8	9	7	33
Number of specimens	57	33	53	25	34	24	149
Mean declination, D †	173°E	127°E	167°E	180°E	151°E	144°E	172°E
Mean inclination, I †	58°	63°	51°	55°	64°	62°	62°
Semi-vertical angle of 95% confidence, α*	5°	12°	6°	11°	8°	7°	12°
Latitude of pole	77°S	44°S	79°S	-	62°S	-	76°S
Longitude of pole	53°E	82°E	101°E	-	76°E	-	52°E
δp	6°	14°	6°	-	10°	-	14°
δm	7°	18°	8°	-	12°	-	19°

(1) Winkelhaak Upper Sill; (2) Winkelhaak Lower Sill; (3) Estcourt reversed dolerites; (4) Estcourt reversed sediments; (5) Estcourt normal dolerites; (6) Estcourt normal sediments; (7) Surface collection.

† To facilitate comparisons, the directions are measured disregarding the sign of the pole.

* Calculated by Fisher's Method (1953)

expected that, in view of the possible instability of some of the normally magnetized samples, the mean for these samples might not be as satisfactory a datum as that found from the reversely magnetized ones. In the case of the latter it is considered that the fact that they have retained a direction of magnetization in the opposite sense to the present field is in itself an assurance of their stability.

Inspection of figure 4/7 reveals that, although the normally magnetized samples give directions closer to the present field of the earth than do the reversed ones, they all lie off to the east and it seems unlikely that they are all unstable. Similarly, it seems unlikely that a self reversal mechanism should affect dolerites and their baked sediments in some areas while those in other areas should be unchanged.

The explanation of these observations would seem to be complex. It seems probable that these intrusions are not strictly contemporaneous and the possibility of a reversal of the earth's field during the time of intrusion of this swarm of sills and dykes must be considered. Perhaps samples 13, 23 and 24 happened to be cooling through their Curie Points at the time of the reversal of the field. If we assume that such a reversal did take place, we would have a picture of normally magnetized sills and dykes with normally magnetized adjacent sediments and reversely magnetized dolerites with their reversed baked sediments.

Secondary effects, due to self reversal under special circumstances or to instability, might be superimposed on the simple picture.

4. Discussion.

The above results may be of value in two different ways. They add to the information available regarding the mechanisms whereby rocks may become magnetized and they provide information about the direction of the earth's field at the time of the intrusion.

As regards the underground samples, the mechanism causing the almost complete reversal of the direction of magnetization is still uncertain. The most reasonable explanation seems to be that over a large area including Natal and the South Eastern Transvaal , Karroo dolerite was intruded in at least two distinct events separated by sufficient time to allow the earlier intrusions to cool to below the Curie Point of their magnetic minerals. During this time the earth's field reversed. The second family would then cool and become magnetized in a field of the opposite direction.

According to Jaeger's curves (Jaeger, 1959) for the cooling of an intrusion from about 1000°C to the Curie Point of magnetite (about 575°C), the centre of the upper sill at Winkelhaak with a thickness of 80 ft. would only take about 9½ years to cool to its Curie Point. At its thickest point the main sill at Estcourt would take about 300 years to cool to the same temperature. Thus, no single intrusion sampled underground, cooled and became magnetized over a sufficiently long period of time for secular variation to be averaged out completely. The close agreement of the normally magnetized intrusions from Winkelhaak and Estcourt and of the reversely magnetized intrusions from both places suggests that the intrusion of each family took place over a very short period of time allowing cooling and magnetization of all members of the family before much secular variation had taken place. It is possible that the difference between the direction of magnetization of the "normal" and the "reversed" families, neglecting the sign, represents secular variation. If this is so, the best estimate of the position of the pole relative to South Africa during early Jurassic times may be obtained from the mean of the direction of magnetization of (1) the Winkelhaak reversed dolerites, (2) the Winkelhaak normal dolerites, (3) the Estcourt reversed dolerites, (4) the Estcourt normal dolerites, (5) the surface dolerites, (6) the Estcourt reversed baked sediments, and (7) the Estcourt normal baked sediments. Giving each unit weight and neglecting the sign the mean direction of magnetization is $D=161^{\circ}$, $I=60^{\circ}$ (or $D=341^{\circ}$, $I=-60^{\circ}$). Assuming an axial dipole, the corresponding position of the pole is: Longitude $74\frac{1}{2}^{\circ}$E , Latitude 70°S.

As mentioned earlier, this simple picture of the intrusion of the dolerite in at least two distinct events with a reversal of the field in between, plus rare cases of instability and/or self reversal completely explains the observations on the underground samples. There are undoubtedly other explanations, particularly with regard to the mechanism of reversal but these appear to be much more cumbersome (see section 3 above). However, there is absolutely no evidence for, and strong evidence against any suggestion that, disregarding the sign, these rocks owe their magnetization to anything other than thermoremanent magnetization in the earth's field at the time of their intrusion. In particular, it is improbable that the stresses were the same at the Winkelhaak and Estcourt areas thus producing equal magnetostrictive effects in the intrusions at both places. When the surface samples are included the suggestion becomes even more unreasonable.

It is clear from this and other work (e.g. Gough, 1956) that in general samples obtained underground are more consistent than those collected from surface outcrops. In the case of the Karroo dolerites, the incidence of instability is much higher among the surface samples than among the underground samples. This may be due to a number of reasons including slight weathering and thermal or thermo-stress cycling. However, even after the elimination of the obviously unstable surface samples, the grouping of the directions of magnetization is much poorer than that of the underground samples. Also there are a number of samples which, although apparently stable, are not magnetized in or near the mean direction of magnetization.

The poorer grouping is partially due to the fact that both the normally and the reversely magnetized samples are included in the plot, figure 4/3. Due to the greater spread of the sample localities it may well be that some dolerites that were emplaced during other intrusive events have been included in the "Surface" collection. This would allow secular variation to play a greater part than it does in the picture presented above for the underground samples.

As demonstrated in Chapter 6, the effects of lightning provides an adequate explanation of the apparently stable, yet widely scattered, observations.

One of the objects in determining the direction of the field at the time of the intrusion of the Karroo dolerites was that it may be of assistance in the interpretation of the results obtained from the Karroo sediments. Unfortunately the mean field during early Jurassic times was very nearly co-incident with the present field. This fact makes it difficult, if not impossible, to assess the relative importance of baking of sediments by Karroo dolerites and magnetization in the present field either by simple I.R.M. or by chemical processes. The presence on the plots of the sediments of a number of North seeking poles more or less in the direction of the present field may, in fact, be due to baking by dolerite when the field was reversed.

CHAPTER 5.

MEASUREMENTS ON SEDIMENTS OF THE CAPE SYSTEM.

1. Reconnaissance.

After the complete failure of the palaeomagnetic programme on the Karroo sediments, the Cape System was investigated in a preliminary manner. By comparison with the Karroo System, dolerite intrusions are comparatively rare, but the rocks of the Cape System generally have suffered much more deformation than has much of the Karroo System.

Isolated samples of the highly deformed Table Mountain Series, Bokkeveld and Witteberg Series from the Port Elizabeth - Grahamstown area showed that the white, glassy quartzites were invariably too weakly magnetized to be measurable. The directions of magnetization of the few samples that were obtained from the Bokkeveld shales were measurable though they did not appear to be entirely systematic.

A trip to the Cape was undertaken in November, 1955, with the object of collecting a few reconnaissance samples from each of the argillite or greywacke horizons in the Cape System. Samples were collected from the T.M.S. Lower "Shales" at Chapman's Peak, near Cape Town and from the Bokkeveld Series at Gydo Pass, near Ceres and along the

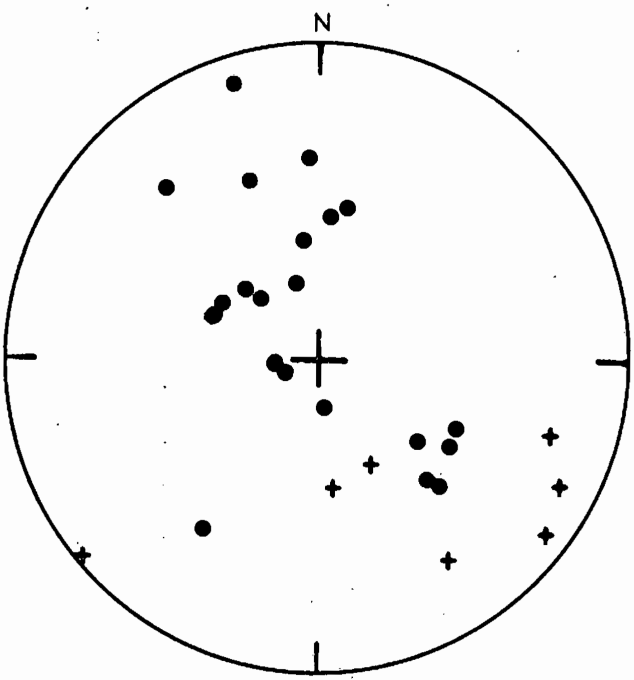


Figure 5 - 1.

A lower hemisphere stereographic plot of the directions of magnetization of the first collection of samples from the T.M.S. Lower Shales at Chapman's Peak.

● = South pole downwards.

+ = North pole downwards.

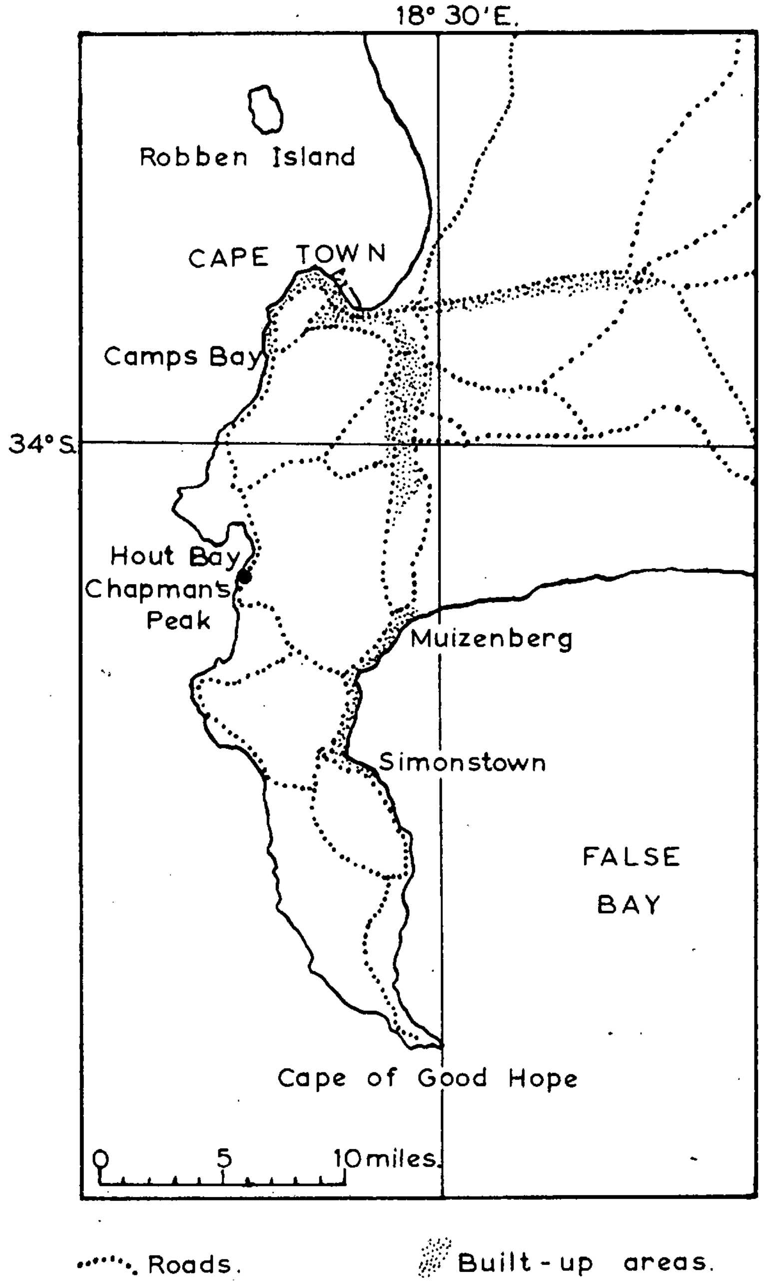
Wupperthal valley, near Clanwilliam. The Upper T.M.S. Shales exposed in Mitchell's Pass, near Ceres, were found to be too weathered.

A total of 40 samples were obtained from the Bokkeveld Series. The directions of magnetization, when plotted, form a complicated pattern with a large number of points falling close to the direction of the present field. Further work on the Bokkeveld as exposed at Wupperthal and in the Botterkop Pass, between Clanwilliam and Calvinia, is currently under way.

Eleven samples, made up of both hand-samples and short cores, were collected from the T.M.S. Lower Shales at Chapman's Peak. These were cut into a total of 29 specimens. The measured directions of magnetization are plotted on the lower hemisphere of a stereograph as figure 5/1. This shows a broad streak of South poles from North-West, almost horizontal, to South-East, inclination about 30°. There is what could be the beginning of a group of North poles of low inclination towards the South-East.

2. The Need for New Techniques.

Once again the question of possible "surface effects" arises and it becomes abundantly clear that, if palaeomagnetism is to make any headway in South Africa, the cause of the scattering of surface samples would have to be

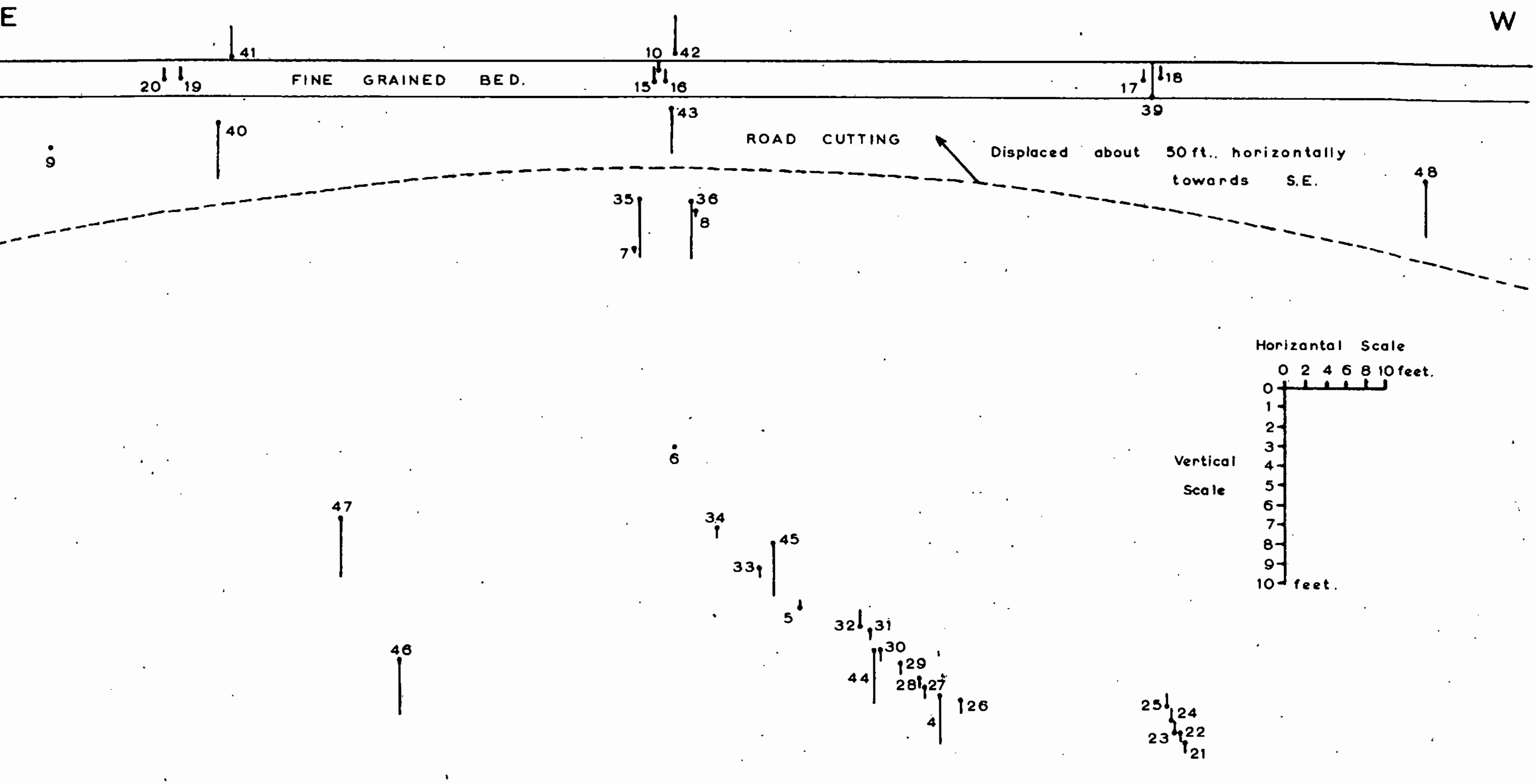


<u>Figure 5 - A.</u>

A map of the Cape Peninsula showing the sample site at Chapman's Peak.

investigated. From the work on the Karroo dolerites (Chapter 4) it is clear that samples from a depth of about 100 ft. showed much less scatter than do surface samples. In the Estcourt tunnel several samples were taken from within two feet of wet, open, weathered joints and showed very little scatter. For this reason it is thought that provided the sample is not obviously weathered, its proximity to a weathering surface is relatively unimportant. A surface outcrop differs from an open joint exposed in a tunnel in that the former is regularly exposed to the sun. The consequent thermal or thermo-stress cycling (see Chapter 3, section 3) could possibly have some effect on the magnetic properties of the rock. Because of the low thermal conductivity of rock, the thermal effect cannot penetrate more than a few inches below the surface; the range of the thermo-stress cycling is somewhat more difficult to estimate. Any experiment designed to directly observe the effect on a rock of artificially produced thermal cycling would probably have to be carried out over a long period of time. If such an experiment showed a positive correlation between thermal cycling and scattered directions of magnetization, a way of avoiding these "surface effects" would have to be found. It was thought that the construction of a drill rig capable of drilling to about three feet could both be used to demonstrate the reality or otherwise of the thermal cycling effect, as well as provide a way of avoiding it.

Figure 5-2.



A diagramatic representation of the vertical and horizontal distances between the sample sites at Chapman's Peak and the length of geological column covered by each bore core.

The drill would have to satisfy the other requirements mentioned in Chapter 2 and some provision for orienting the core would have to be made. No commercially available drill rig satisfies all the requirements. The rig developed at the Bernard Price Institute of Geophysical Research (Graham and Keiller, 1960) and described in Chapter 2 has proved entirely satisfactory.

3. Work on the Lower Shales of the T.M.S.

At Chapman's Peak in the Cape Peninsula (see figure 5/A) the Lower Shales of the Table Mountain Series rest on the peneplained surface of the Cape Granite. The bedding planes are often irregular, as is the thickness of many beds, but the overall dip in this area is negligible. The structure is broken by several near vertical faults, the most significant of which has a throw of about 100 ft. A dolerite dyke some 14 ft. thick occupies the plane of the latter fault. Broadly speaking, the sediments vary from almost white, glassy quartzite near the bottom to softer, finer-grained, red, argillaceous sandstones in the middle, while near the top of the succession pale, glassy, quartzites reappear. Particularly near the bottom and the top of the succession irregular beds, up to 4 ft. thick, or lenses of maroon siltstone occur interbedded with the coarser material. With the exception of these siltstones, strong current bedding, and often ripple marks, are conspicuous features

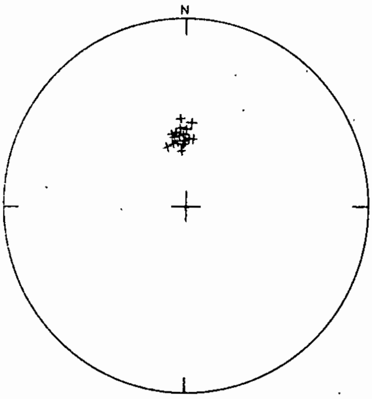


Fig. 5-32, P7.

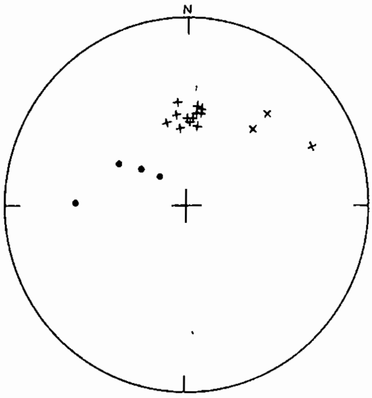


Fig. 5-33, P35.

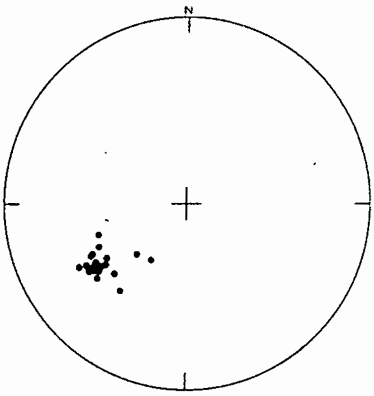


Fig. 5-34, P8.

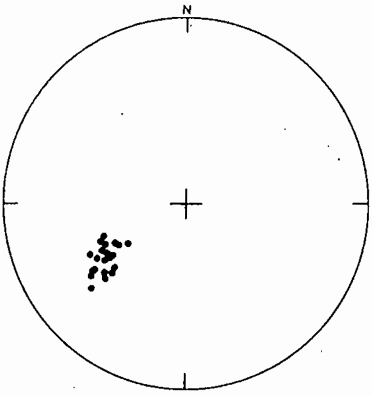


Fig. 5-35, P36.

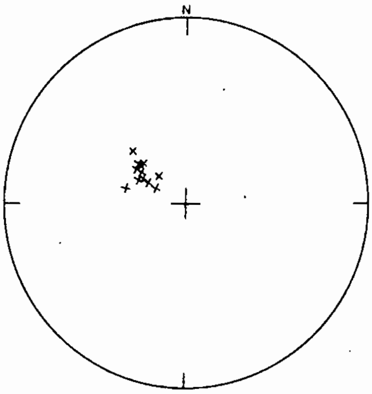


Fig. 5-36, P47.

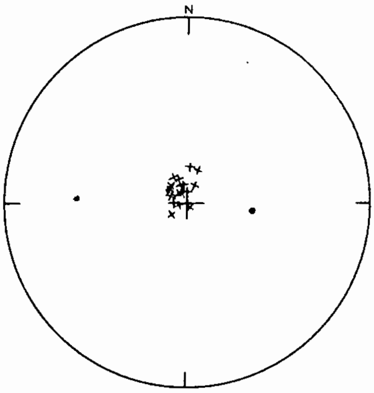


Fig. 5-37, P45.

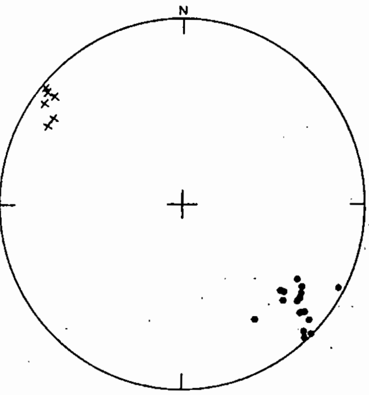


Fig. 5-38, P46.

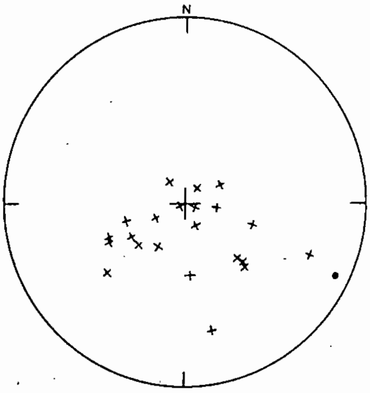


Fig. 5-39, P44.

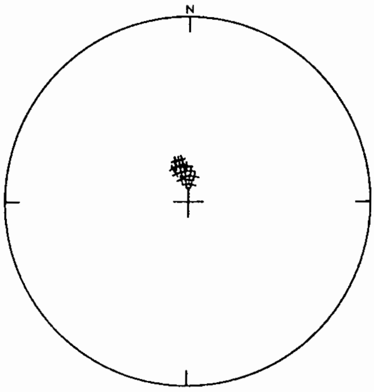


Fig. 5-40, P34.

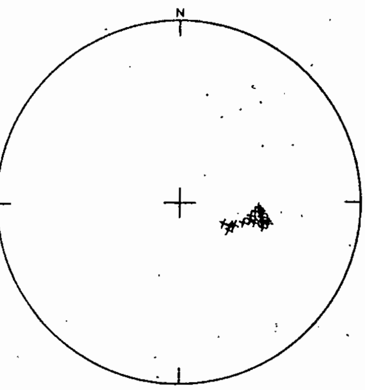


Fig. 5-41, P 6.

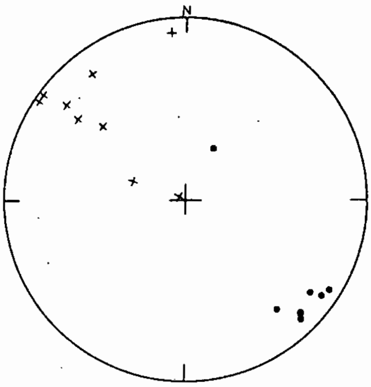


Fig. 5-42, P38.

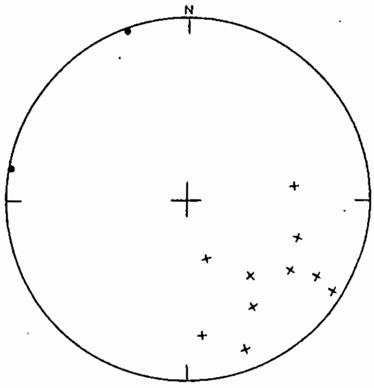


Fig. 5-43, P37.

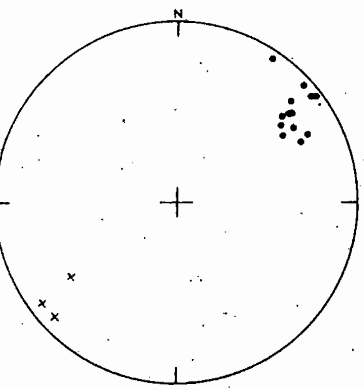


Fig. 5-44, P 3.

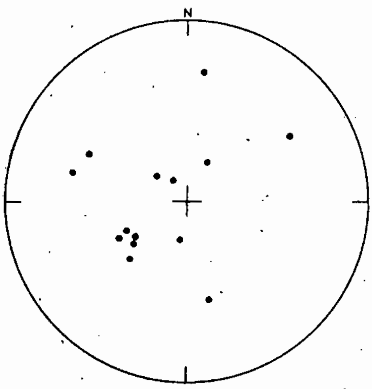


Fig. 5-45, P11.

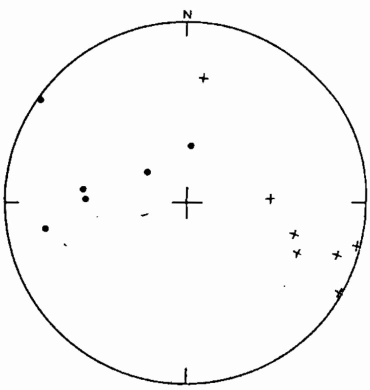


Fig. 5-46, P12.

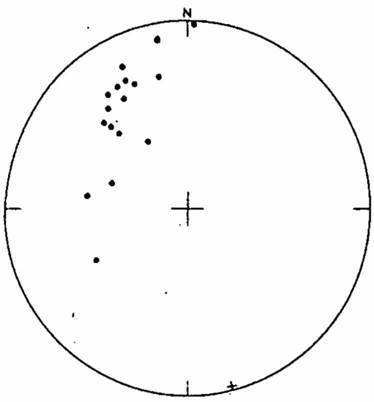


Fig. 5-17, P21.

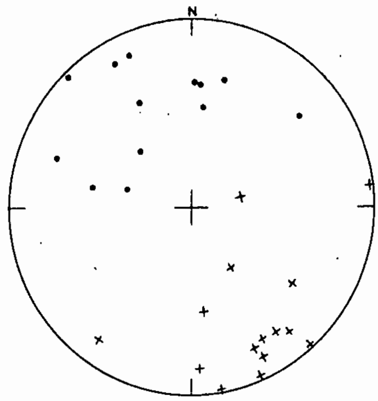


Fig. 5-18, P22.

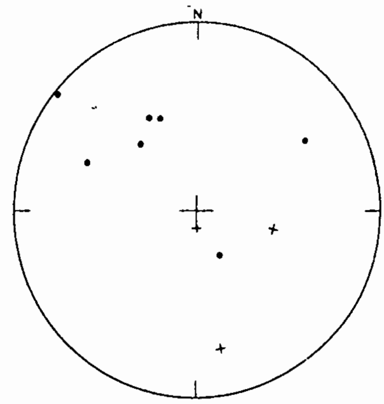


Fig. 5-19, P23.

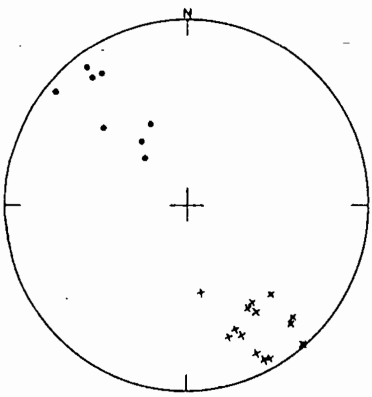


Fig. 5-20, P24.

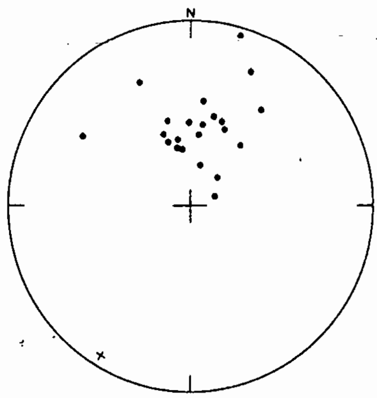


Fig. 5-21, P25.

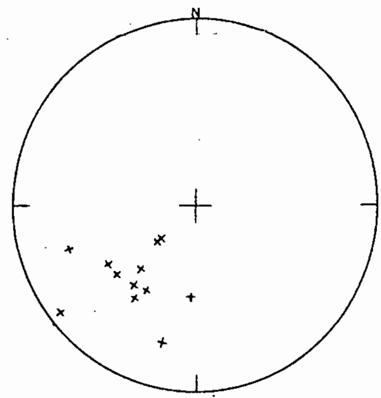


Fig. 5-22, P26.

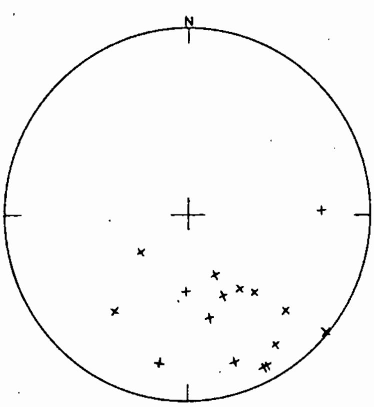


Fig. 5-23, P4.

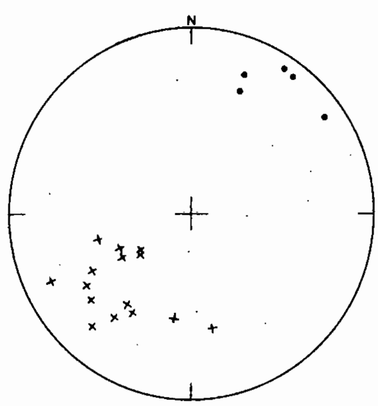


Fig. 5-24, P27.

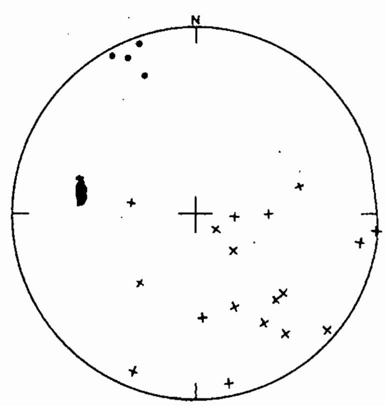


Fig. 5-25, P28.

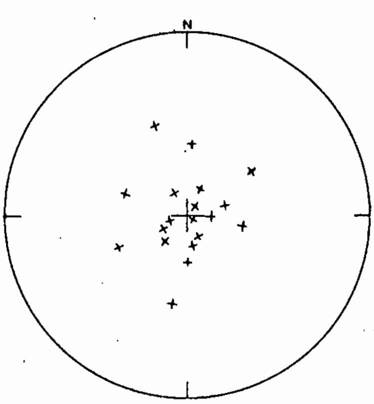


Fig. 5-26, P29.

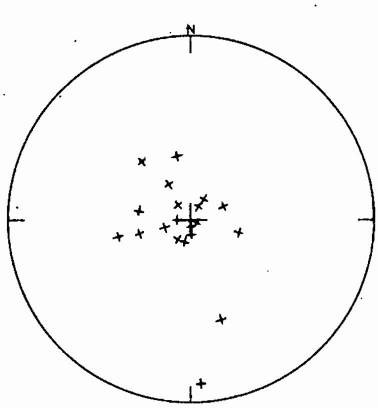


Fig. 5-27, P30.

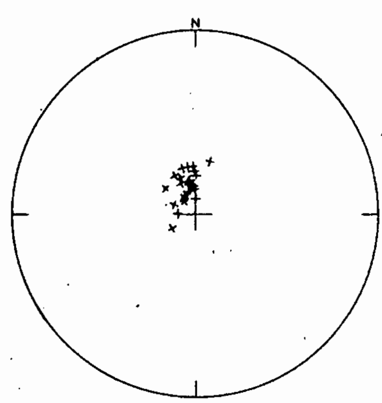


Fig. 5-28, P31.

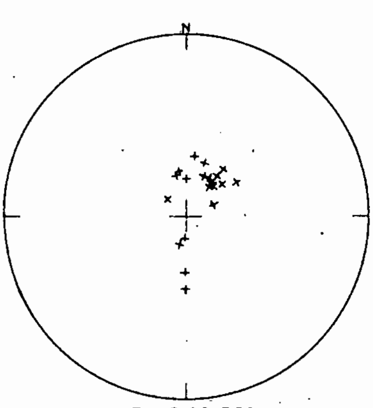


Fig. 5-29, P32.

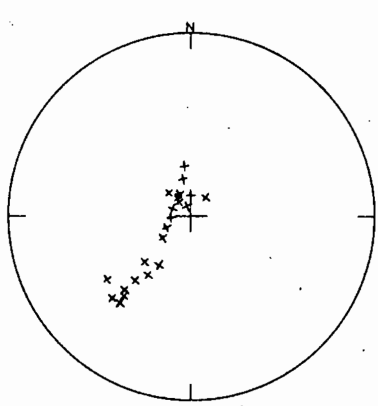


Fig. 5-30, P5.

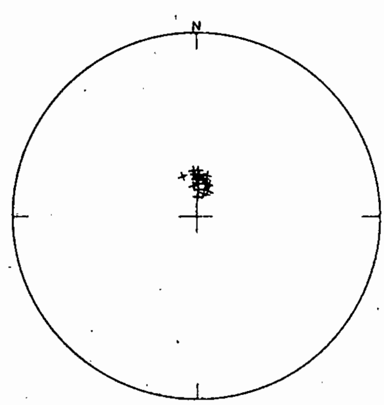


Fig. 5-31, P33.

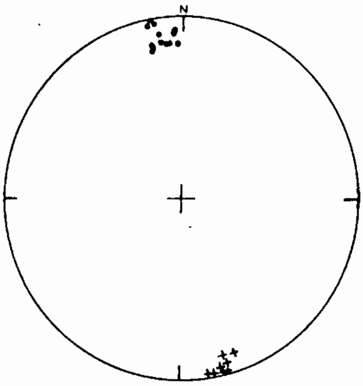


Fig. 5-3, P20.

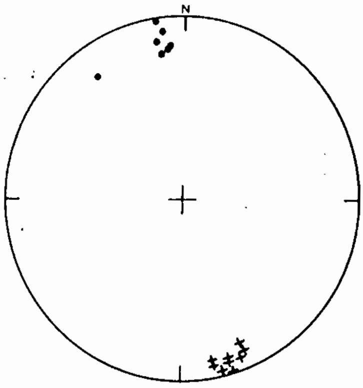


Fig. 5-4, P19.

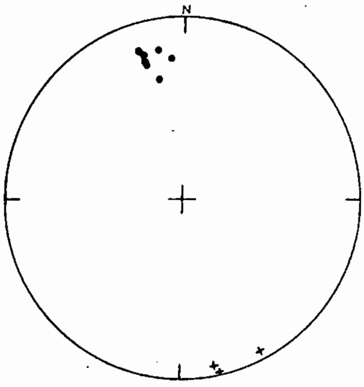


Fig. 5-5, P15.

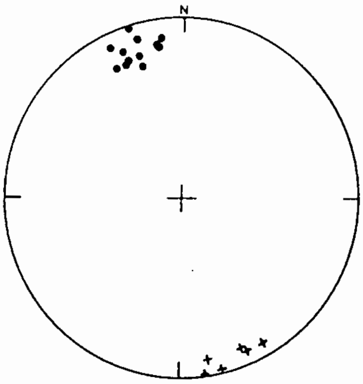


Fig. 5-6, P10.

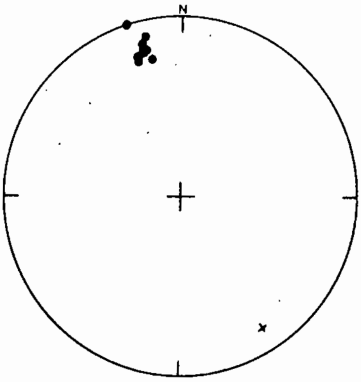


Fig. 5-7, P16.

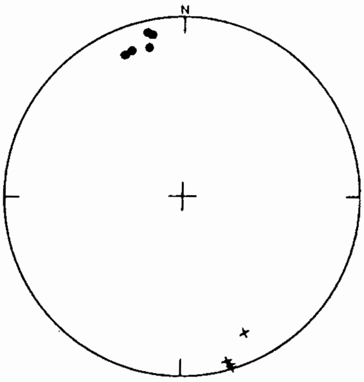


Fig. 5-8, P17.

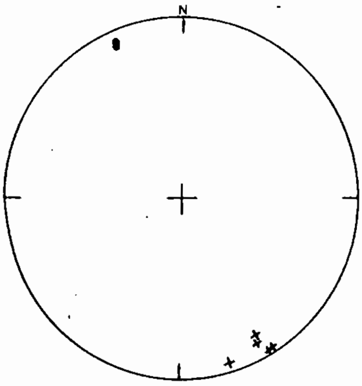


Fig. 5-9, P18.

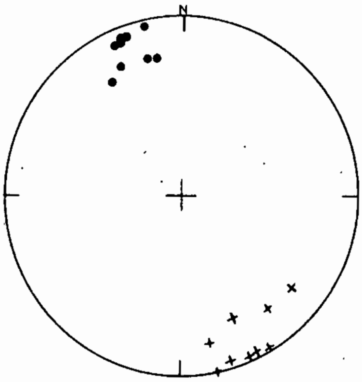


Fig. 5-10, P39.

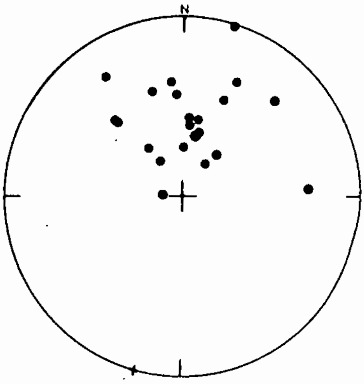


Fig. 5-11, P9.

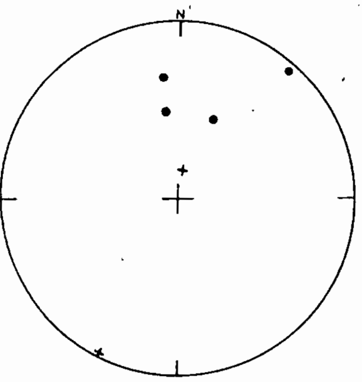


Fig. 5-12, P40.

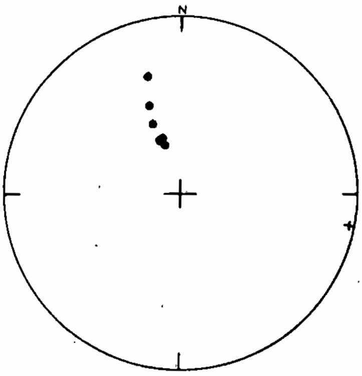


Fig. 5-13, P41.

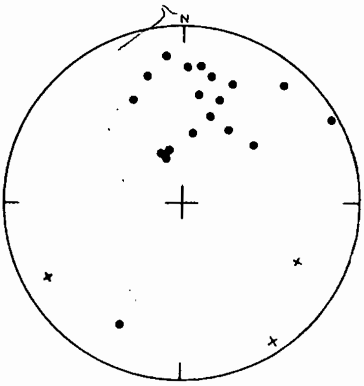


Fig. 5-14, P43.

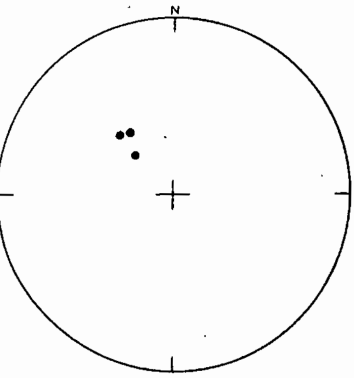


Fig. 5-15, P42.

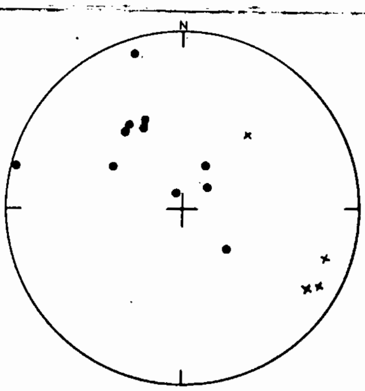


Fig. 5-16, P48.

CAPE SYSTEM

LOWER T. M. S. "SHALES"

Lower Hemisphere Stereographic Plots of the directions of magnetization of the 3 ft. cores from Chapman's Peak.

Those collected on the first trip are underlined.

• = SOUTH POLE DOWNWARDS.

x = NORTH POLE DOWNWARDS.

of these rocks.

Using the new drill rig, thirteen three foot cores were drilled from various horizons in the T.M.S. Lower Shales at Chapman's Peak, Cape Town. Some of the cores were drilled horizontally so as to sample the same horizon over the length of the core. Others were drilled nearly vertically so as to cut two feet or more of the untilted sedimentary series (see figure 5/2).

Cores number P.1 and 2 came from the more quartzitic beds at the base of the formation and were too weakly magnetized to be measured. The directions of magnetization of ten of the remaining eleven samples are shown in the underlined figures 5/44 (core no. P.3), 5/23 (P.4), 5/30 (P.5), 5/41 (P.6), 5/32 (P.7), 5/34 (P.8), 5/11 (P.9), 5/6 (P.10), 5/45 (P.11) and 5/46 (P.12). Sample P.13 is not plotted here but like P.11 and P.12, shows wide scatter.

Samples P.11, 12 and 13 were drilled from a highly jointed area which, on closer examination, appears to be a fault zone of small throw. In order to avoid the ambiguities involved in the possible effects of shear and/or magnetostriction in this once highly stressed zone, these samples will be excluded from further discussion.

Of the remaining samples, numbers P.4 and 9 show considerable scatter, and numbers 5 and 6 form peculiar "tadpole" patterns with a "tail" of specimens in consecutive order leading to a "head" of well grouped specimens. The specimens from each of cores number 10, 7 and 8 are fairly tightly grouped but the cores differ from one another.

Quite clearly, drilling to 3 ft. in this case did not solve the problem of the scattering of surface samples. In a determined effort to find a satisfactory solution, a further 25 long (3 ft.) cores were drilled (numbers 15 to 39 inclusive).

Cores number P.15, 16, 17, 18, 19 and 20 were drilled in pairs so as to pass very slowly through exactly the same few inches of a well defined, red siltstone bed about two feet thick exposed in a deep road cutting. The members of a pair were about six inches apart horizontally while each pair was about 50 ft. from the next. This bed had already been sampled by core no.10. Core no. P.39 was drilled in such a way as to cut almost the entire bed.

The direction of magnetization of these cores (figures 5/3 to 5/10 inclusive) are extremely consistent. The mean and the semi-angle of the cone of 95% confidence (α) for each core is given in table 5/1. This direction of magnetization, with almost horizontal south poles to the N.N.W. which is consistent over about 100 ft. horizontally and about 2 ft. vertically must, surely, be meaningful. But this amounts to 1 site only.

Cores number P.21 to 34 inclusive were drilled either upwards or downwards at small angles to the horizontal so as to cover in great detail the geological column

Table 5/1.

The mean direction of magnetization
of each core from the red, fine grained bed.

Core No.	No. of Specimens	D. (degrees)	I* (degrees)	(degrees)
10	18	161.7	- 5.2	4.5
15	10	165.6	- 9.2	6.4
16	10	162.3	- 7.9	5.5
17	8	161.8	- 2.0	5.7
18	7	152.7	+ 1.5	5.7
19	15	164.6	- 1.6	5.4
20	22	169.7	- 2.9	2.8
39	17	155.8	- 0.2	6.2

* a positive inclination indicates a North pole downwards.

represented by cores number P.4, 5 and 6 (see figure 5/2). The sediments here sampled are more arenaceous, coarser grained and less brightly coloured than the siltstone bed sampled by cores number P.15 to 20, 10 and 39, but microscopic examination did not reveal any major difference in the nature of the magnetite in the two groups of samples. The rocks comprising this second group of samples are well exposed on the open mountain side and they do not appear to be weathered. Strong current bedding is an almost universal feature of the coarser grained T.M.S. Lower "Shales".

The directions of magnetization of cores number P.21 to 34, together with cores P.4, 5 and 6 are plotted as figures 5/17 to 5/31 inclusive and figures 5/40 and 41. In broad and general terms, these stereograms show a gradual but not altogether systematic shift in the direction from one similar to that measured in the fine grained bed (almost horizontal South poles to the N.N.W. or North poles to the S.S.E.) to one with nearly vertical North poles downwards. The scatter is generally less in the latter direction, though there is a tendency to the "tadpole" distribution mentioned earlier and well displayed in Chapter 6.

In attempting to analyse these results it was felt that, because of the consistency of the fine grained bed in the cutting, the almost horizontal South poles to the North could represent the direction of the field at or soon after the time of deposition of the sediments. According to King (1955) currents during deposition cause the angle of inclination of the resulting magnetization of the sediment to be less than that of the applied field. It is difficult to picture a process which operates in the reverse direction.

The possibility of extremely wide secular variation at the time of deposition of these sediments was considered. However, it is unlikely that this should have occurred while the coarser grained sediments were being deposited and cease for the deposition of the finer grained material.

Core 7 had been drilled about two feet above core number 8 and about five feet from it horizontally. The directions of magnetization of these two cores are entirely different.(see figures 5/32 and 5/34). Cores number P.35 and 36 were drilled vertically above numbers 7 and 8 respectively, in such a way that each would cover the material sampled by both 7 and 8 as well as the vertical interval between them (see figure 5/2). Number 35 agreed in its direction of magnetization with number 7 and number 36 with number 8 (see figures 5/33 and 5/35). Thus samples representing exactly the same horizon and only five feet apart horizontally are magnetized in very different directions.

This phenomenon occurs less spectacularly over much of the section of coarser grained material sampled. For example, figure 5/2 shows the way in which many of cores number P.21 to 34 and P.4 and 5 overlap one another in their coverage of a small piece of the geological column. P.22, 23, 24, 25 and 26 cover exactly the same horizon as number 4, and core P.25 covers the same horizon as number 26. These cores are, at the most, 20 ft. apart and yet their directions of magnetization differ widely (see figures 5/18 to 5/23).

It is clear that some local cause is responsible for the magnetization of the rocks in this section. It seems unlikely that rapid secular variation is an adequate explanation nor, in spite of the marked current bedding of the coarser rocks, does it seem likely that currents at the time of deposition would produce the pattern of magnetization observed.

Cores number 37 and 38 were drilled from a bed of fine grained, red siltstone very similar to that sampled by cores number 15 to 20 etc. but lower down in the succession. This bed is exposed in a second but much shallower road cutting in which the original exposed surface of the rock was not more than about 10 ft. from our sample sites. These two cores are magnetized in almost opposite directions (see figures 5/42 and 43). Both show considerable scatter which in the case of number 38 forms a "streak". It seems as though consistency of the direction of magnetization is not purely a function of grain size, colour or any other obvious lithological feature of the rock.

With the realization of the importance of lightning in the remagnetization of near-surface rocks this possible answer to the peculiar pattern of magnetization of the Chapman's Peak samples was considered. Could it be that many of the samples drilled at, or near, the natural surface of the outcrop had been remagnetized by lightning currents whereas those taken from the deep road cutting might not have been affected?

The rock exposed in the cutting above and below the red siltstone bed consists of a coarse, pinkish, often glassy quartzite. It shows particularly strong current bedding and in many places is highly jointed. Such material would normally be considered unsuitable for palaeomagnetic purposes. In view of its coarseness alone it would be expected to show considerable scatter. However, since no other material was available in the cutting it was decided to drill a number of cores above and below the fine grained bed in an attempt to get qualitative confirmation of the supposition that the material in the cutting had not been affected by lightning. Cores P.40, 41, 42, 43 and 48 were drilled in the positions indicated in figure 5/2.

The directions of magnetization of these cores together with that of number 9 are shown in figures 5/11 to 5/16. The scatter is very considerable but the directions of magnetization of these samples are not inconsistent with that of the fine grained bed. Particularly, there is no trace of the direction consisting of almost vertical North poles downwards so prominently displayed by samples 29 to 33 (figures 5/26 to 5/31).

If, in fact, many of the samples collected from outside the cutting have been remagnetized by the magnetic fields due to lightning currents, then a single geological horizon would not be consistently magnetized over the length of its outcrop. It has been shown above that this is the case for certain sections of the outcrop but the phenomenon should be confirmed for other areas.

Cores number 44 and 46 were drilled from the same horizon but about 50 ft. apart. Cores 45 and 47 were about the same distance apart in a different horizon (see figure 5/2). The directions of magnetization of these samples are plotted as figures 5/36 to 5/39. Cores number 47 and 45 show very tight grouping of the directions of magnetization of the specimens from each core but the cores are significantly different from each other.* Cores number 46 and 44 show less tight grouping and are magnetized in vastly different directions.

* Yes, but no more differently than many sites from 'consistently' magnetised formations.

4. Conclusions.

Samples distributed both horizontally along the same sedimentary layer and vertically up the geological column show that the surface outcrops are inconsistently magnetized. This may be due to partial or complete remagnetization of the near surface material by lightning currents. It was not thought worthwhile to make a detailed study of the kind described in Chapter 6 once it had been established that the directions of magnetization in the same horizontal stratum varied so widely.

Allowing for the scatter of the directions of magnetization of the very coarse material, samples from the deep road cutting are consistently magnetized. The directions

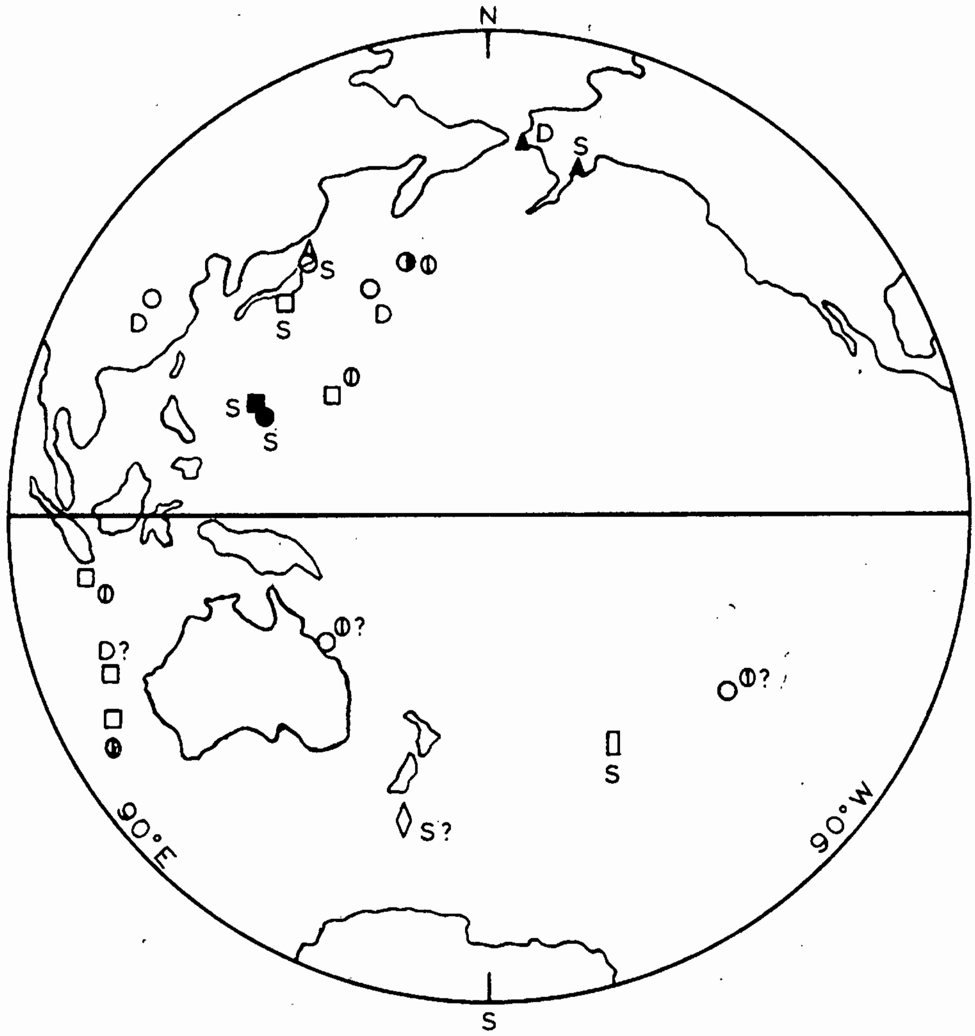


Figure 5 - 47.

Early Palaeozoic Virtual Geomagnetic Poles.

(After Cox & Doell, 1960; fig. 23.)

O	European	D	= Devonian
□	North-American	S	= Silurian
Δ	Australian	Φ	= Ordovician
▯	Asian	●	= South magnetic poles
◊	African	O	= North magnetic poles

of magnetization of the red siltstone bed are particularly consistent both laterally over the 100 ft. sampled as well as over its width and it is thought that this bed has preserved its original direction of magnetization. The mean for the 8 samples from this bed is Declination = 161.8°, Inclination =-3.5° (the South pole is downwards) The semi-angle of the cone of 95% confidence (α) is 4½°. Although the time taken for the deposition of this two foot thick bed may not have been long enough for secular variation to have been meaned out completely, it seems probable that the mean direction of magnetization of this bed represents a reasonable approximation to the field during Silurian times.

Assuming an axial dipole field, the South pole relative to Africa would have the present day co-ordinates of Longitude 10.9°W, Latitude 50.3°N (or the North pole 169.1°E, 50.3°S). The co-latitude of the Cape Peninsula relative to the Silurian pole would be 88°, which places South Africa very nearly on the equator at the time. The presence of a tillite in the Upper T.M.S. Shales is puzzling and demands further work on the Cape System.

It is interesting to compare this pole position with those found for other continents. Figure 5/47 is based on Cox and Doell's figure 23 (Cox and Doell, 1960) and shows clearly that the pole position found from the Lower

Shales of the Table Mountain Series is not in agreement with those of Ordovician, Silurian or Devonian age from any of the other continents.

CHAPTER 6.

A STUDY OF THE "SURFACE EFFECTS".

Almost invariably magnetically stable samples from surface outcrops in South Africa have shown scattered directions of magnetization while those from deep quarries, cuttings or underground workings have often proved to be consistently magnetized (see the preceding chapters as well as Gough, 1956, and Gough and van Niekerk, 1959). Various workers have suggested a number of possible explanations for these "surface effects" including weathering, thermal cycling, magnetostriction, thermo-stress cycling and lightning.

As mentioned in Chapter 3, section 3, weathering is generally detectable and avoidable and the daily thermal cycling of an outcrop can be shown to be limited to a very few inches below the exposed surface. However, the weathering of the uppermost half inch of rock can produce very high stresses which might be felt several feet down in the rock. Similarly the daily thermal expansion and contraction of the surface of an outcrop could possibly result in a kind of stress cycling. Whether or not these forces could have any permanent magnetostrictive effect on the rock is not known.

Hallimond and Herroun (1933) issue a warning that lightning can remagnetize rocks and advise that samples used in laboratory experiments should be taken from the considerable depth of about 50 ft. If vertical lightning strokes were responsible for the remagnetization of rocks, one might expect to find the remanent magnetic directions forming a pattern of concentric rings round the point at which the current reached the ground. Random sampling over a wide area would be expected to yield samples magnetized almost horizontally but with random declinations. The directions of magnetization of the numerous samples collected by the author (see Chapters 3, 4 and 5) are not concentrated in the horizontal plane. This was taken as an indication that lightning was not of major importance in the remagnetization of surface samples.

The success of the above mentioned palaeomagnetic collections in which the samples came from some depth below the surface provides an obvious answer to the problem and clearly, deep quarries, road cuttings and underground workings should be used wherever possible. However, in South Africa such workings very often do not exist in the rock formations of most interest in palaeomagnetic investigations. Drilling to depths of 50 to 100 ft. would no doubt provide an alternative solution but securing accurately oriented samples from such depths is a formidable task for the research worker with a limited budget. A third alternative solution is to acquire an understanding of the exact nature and cause

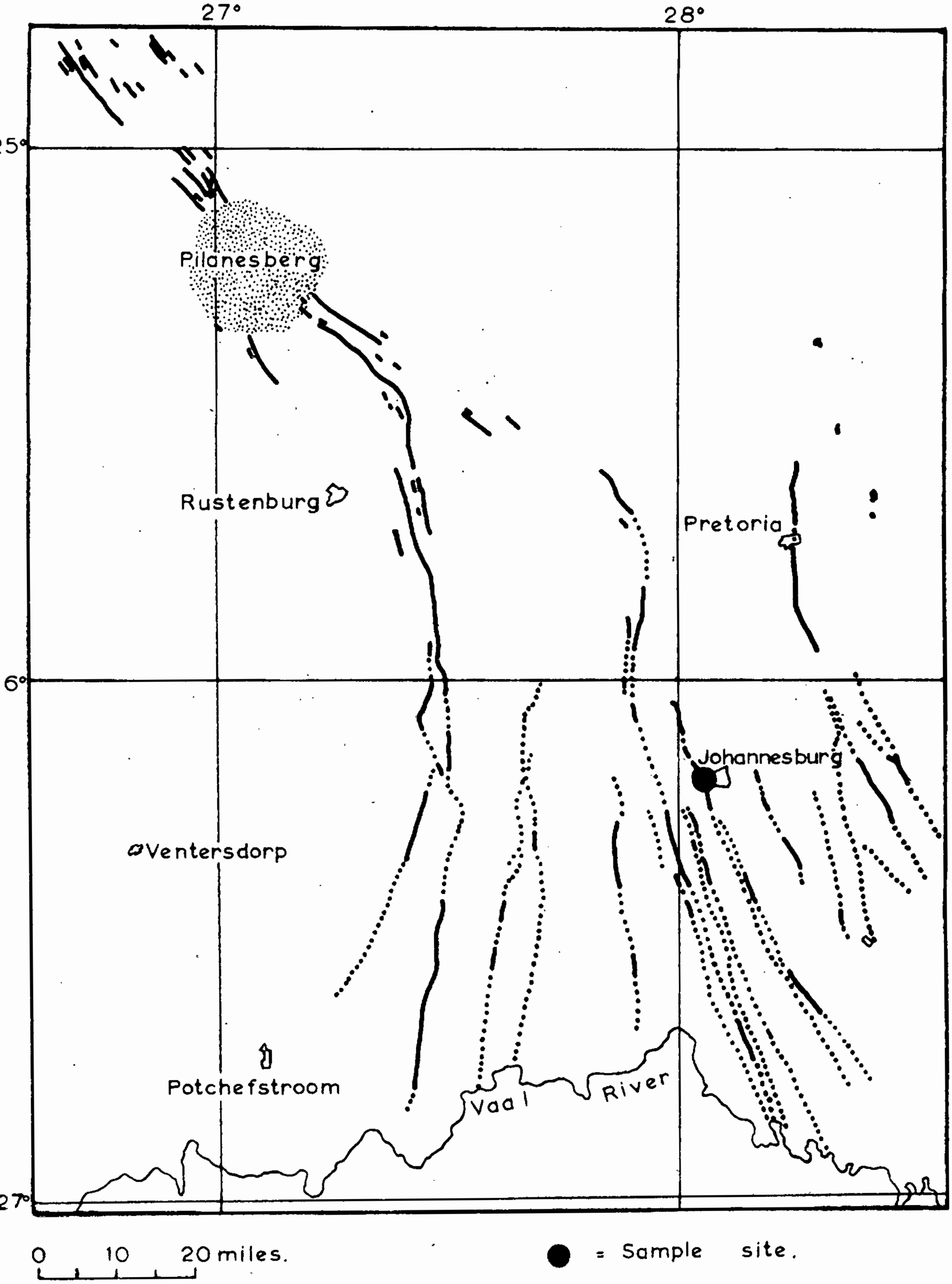


Figure 6 - 1.

A map of part of the Transvaal showing the distribution of the Pilanesberg dykes (Gelletich, 1937).

of these "surface effects" so that they may be avoided or eliminated. With this object in mind a detailed study of one outcrop that was known to be randomly magnetized was undertaken.

1. Work on an Outcrop of the Robinson Dyke.

The Robinson dyke is a member of the family of basic Pilanesberg (or Pilansberg) dykes which fan out to the north-west and south-east of the Pilanesberg alkaline intrusive body (see figure 6/1). Gelletich (1937) described these dykes in some detail, identifying them by their characteristic negative magnetic anomaly. Some of the dykes are of a composite nature consisting of basic or mafic borders with a central felsic part. A summary of the work done on the Pilanesberg dykes is given by van Niekerk (1959) who also describes the petrology of some of these dykes in great detail.

Gough (1956) showed that the Robinson dyke, as well as five others, was randomly magnetized at the surface but consistently magnetized at depth. His figures for the basic part of this dyke exposed underground are:-

Number of samples:		42
Direction of mean North seeking pole:	Azimuth	14.1°
	Inclination	71.8°
Radius of cone of 99% confidence (α)		4.9°

One of the outcrops of the Robinson dyke that had been sampled by Gough was chosen for a study of the "surface effects". The exposure, marked on figure 6/1, is about 50 ft. square, fairly flat and weathered to not more than about half an inch below the surface.

By means of the special drill rig described in Chapter 2, section 2C, a total of 20 oriented cores were drilled from this outcrop. Some of the cores were 3 ft. long and others 6 ft. long. All were drilled vertically. The cores, one inch in diameter, were cut into specimens one inch long, the specimens being numbered from the top of the core downwards. Generally 10 specimens could be cut from 12 inches of core. The direction and intensity of each of the 784 specimens was measured by means of the spinner type magnetometer.

2. Laboratory Experiments.

In attempting to understand the peculiar pattern of remanent magnetization of part of this outcrop (described in section 3 below) it became obvious that certain laboratory experiments were necessary. Although these experiments were carried out after it became evident that lightning could possibly cause such a pattern, an account of the experiments is given here so as not to interrupt the description and explanation of the remanent magnetic observations.

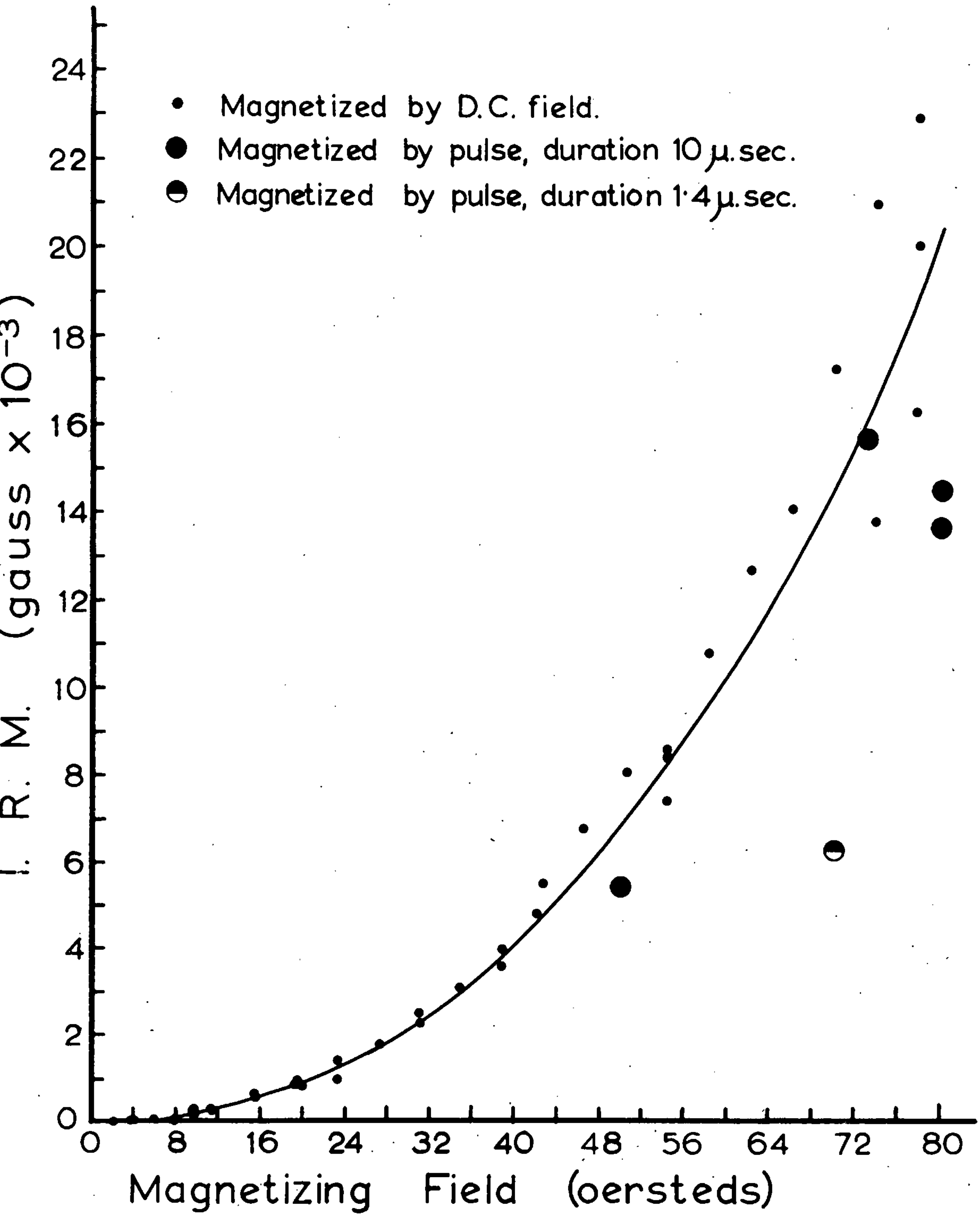


FIGURE 6-2.

The I.R.M. caused by various magnetic fields.

A. Magnetization experiments.

Some six specimens from the deepest bore cores were initially selected for experiments using a D.C. magnetic field. These specimens had intensities close to 2.8 x 10^{-3} gauss which was calculated from Gough's (1956) figures as the mean for the underground samples from the basic part of this dyke.

The direction and intensity of magnetization of the specimen was measured and a D.C. magnetic field of known intensity was applied at a known angle (usually at right angles) to the N.R.M. for a predetermined length of time (usually one minute) before slowly decreasing the field to zero. The apparatus is described in Chapter 2, section 3A. After measurement of the direction and intensity of remanent magnetism of the specimen the procedure may be repeated with a larger field if desired.

Knowing the direction and intensity of magnetization before and after the experiment one can, by completing the parallelogram, estimate the remanent magnetic vector produced by the applied field. The angle between the original magnetic remanence and the applied field need not be used in this calculation so that if the angle between the applied field and the calculated vector is small, it would imply that one can legitimately picture the I.R.M. as adding vectatorially to the N.R.M. In all cases this angle was found to be within the experimental error, never exceeding

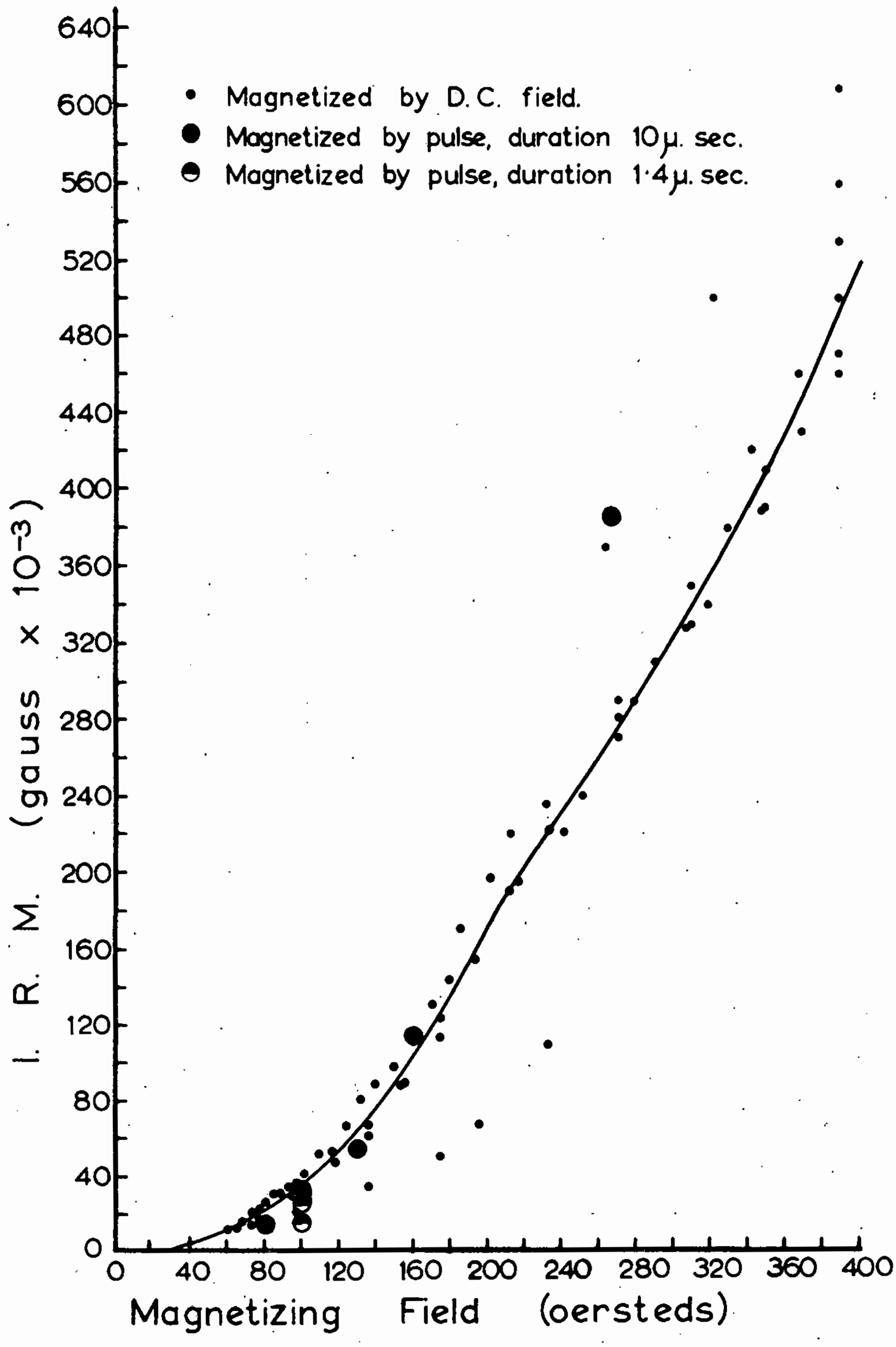


FIGURE 6-3.

The I.R.M. caused by various magnetic fields.

5 degrees.

This vector of remanent magnetism has been plotted on the vertical axis in figures 6/2 and 6/3. It will be seen that the curve starts to depart from the horizontal axis at about 8 oersteds and that 12 oe. is sufficient to produce a small but significant magnetic vector. The curve shows no signs of approaching saturation at 380 oe. It would appear as though the best curve through the points has a slight "kink" at about 210 oe.

No magnetic anisotropy was observed in these experiments.

Subsequent experiments showed that the remanent magnetism produced by the application of the D.C. field for periods ranging from 15 seconds to 28 hours was consistent with the curves. The random storage of the specimens in the earth's field for periods of several months showed no significant effect.

In spite of the fact that for this rock the remanent magnetism is independent of the duration of the applied D.C. field for periods ranging from 15 seconds upwards, it could not be said that the field due to a lightning discharge would behave similarly. A lightning discharge consists of one or more consecutive strokes, usually four in South Africa (Schonland, 1956). Each stroke consists essentially of a leader (stepped or otherwise), carrying a fairly low current, followed by the main flash. It should be noted that although the electrical breakdown for the leader proceeds from cloud to ground while that for the main flash is from ground to cloud, nevertheless, the actual current or flow of electrons is in the same direction throughout any particular discharge. (Generally the cloud is negatively charged and electrons move from cloud to ground.) There can therefore be no alternating field as suggested by Rimbert (1958). Instead the field is made up of a number of D.C. pulses, all of the same sign.

The current in the main flash varies from 10,000 amps. to more than 160,000 amps. In 50% of the discharges recorded in Rhodesia, the current exceeded 40,000 amps. (Anderson and Jenner, 1954). The time taken for the current to reach its peak varies from 1 to 19 μsecs., with an average of 6 secs. while the time taken for the current to fall from its peak value to half its peak value varies from 7 to 115 secs. with an average of 24 μsecs. (Chalmers, 1957, p.252).

Thanks to the generous co-operation of Mr. J.J. Kritzinger of the Department of Electrical Engineering of the University of the Witwatersrand, it was possible to evaluate the effect of very short pulse fields on the magnetic remanence of specimens from the Robinson dyke. The rock specimens were placed at fixed distances from a long straight conductor connected via a spark gap to a high voltage impulse generator and were subjected to the pulse fields resulting from high current discharges along the conductor. Photographs of the trace of a calibrated oscillograph were taken so that estimates of the current, pulse shape and duration of the discharge could be made (for further details see Kritzinger, 1961). The direction and intensity of magnetization was measured before and after each experiment and the vector produced by the field was estimated in the manner described above. The results of these experiments are presented in table 6/1 and the magnetic vector is plotted against the field as large circles in figures 6/2 and 6/3.

Table 6/1

Specimen No.	Peak Current Amps.	Distance cms.	Field Oe.	Duration* μsecs.	No. of shots	Magnetic vector Gauss $\times 10^{-3}$
6/48	4000	16	50	10	1	5.4
6/48	4000	8	100	10	1	29
6/48	4000	3	267	10	1	386
6/49	4000	11	73	10	1	15.7
6/49	4000	5	160	10	1	114
11/48	3900	6	130	10	1	53
11/51	4000	10	80	10	1	14.5
11/50	4000	10	80	10	5	13.7
11/47	3200	9	70	1.4	1	6.3
11/46	3000	6	100	1.4	1	15.8
6/47	3000	6	100	1.4	1	27.5
6/46	3000	6	100	1.4	5	33.5

* From start, through the peak, to ½ peak current.

The accuracy of this experiment is not as high as that obtainable when using a D.C. field generated by a solenoid. The calibration and reading errors involved in the estimation of the current should not have exceeded 10%. The error in measuring the distance between the centre of the specimen and the conductor should not have exceeded 5% but when the specimen is very close to the conductor the curvature of the field and the field gradient across the specimen is appreciable. Although the specimens were oriented relative to the conductor by eye, the angle between the direction in which it was intended to direct the field and the calculated magnetic vector reached 9° in one case but otherwise did not exceed 5°.

In spite of these difficulties it is clear that the effect of D.C. pulses of 10 μsecs. duration from start, through the peak to half current is very similar to that of a D.C. field applied for a much longer time. The effect of the shorter pulses of 1.4 μsecs. duration may be a little lower. However, with such short pulses the circuit showed some tendency to oscillation and an overshoot of the current of some 10% was observed. It is therefore not known whether the lower I.R.M. observed for pulses of very short duration is meaningful or not.

As shown in table 6/1, the effect of several pulses of the same size is not significantly different from that of a single pulse. It is, therefore, highly likely that the

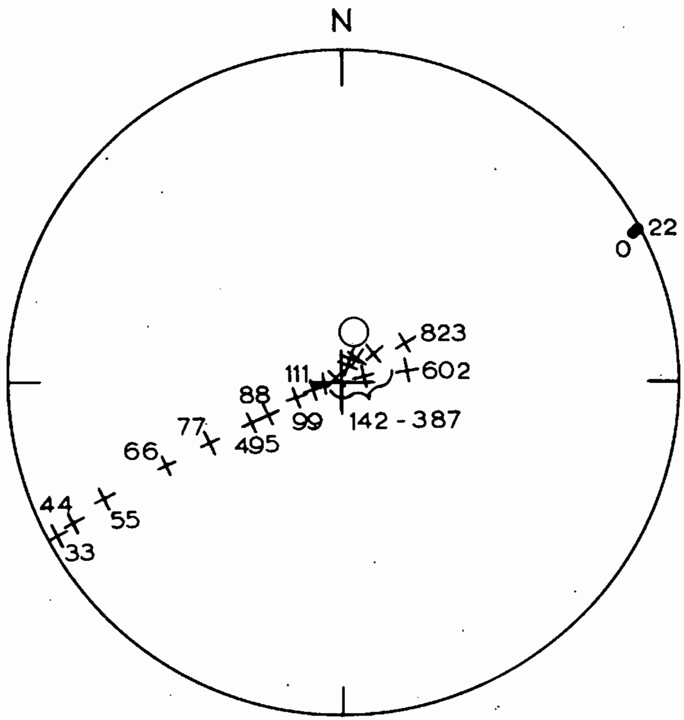


Figure 6-4.

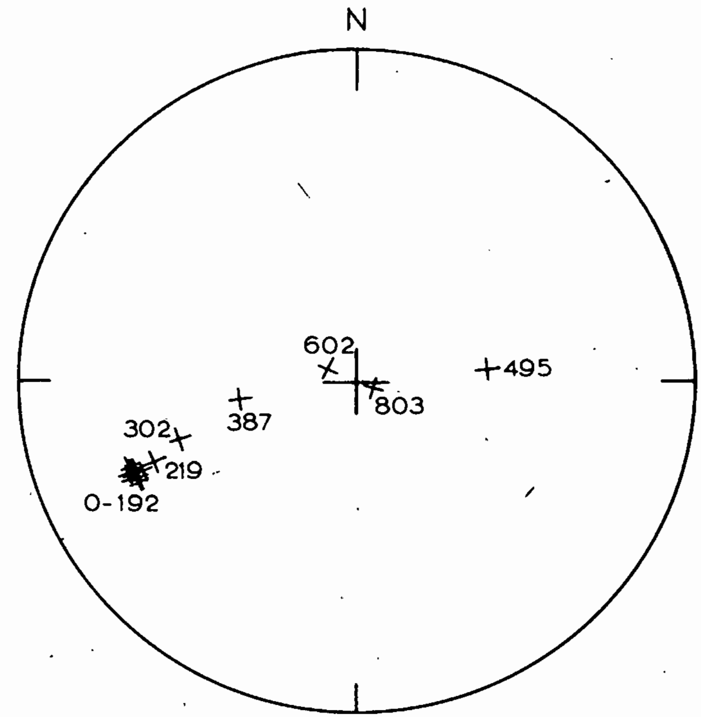


Figure 6-5.

Lower Hemisphere Stereographic Projections of the Directions of Remanent Magnetization of Specimens 1/26 and 12/13 after each stage of A.C. Demagnetization.

× = North pole downwards. ● = South pole downwards.

○ = Cone of 99% confidence for mean direction of magntization (Gough, 1956).

Figures denote peak A.C. field in oersteds.

magnetic effect on this rock of one or more main strokes of a lightning discharge will follow the curves shown as figures 6/2 and 6/3, and these curves will be used to estimate the field and thence the current responsible for the remagnetization of part of this outcrop.

B. Demagnetization by alternating current.

Alternating current demagnetization experiments were performed on specimens from this outcrop primarily in order to determine to what extent, if any, it is possible to remove the secondary magnetization without affecting the original T.R.M. By this means it might be possible to make an estimate of the direction and intensity of the T.R.M. of the rock in spite of the fact that the original magnetization had been swamped by magnetizations acquired subsequently.

The apparatus used is described in Chapter 2, section 3B. The direction and intensity of magnetization of the specimen is measured after each of the successively larger applications of A.C. field. Figure 6/4, a lower hemisphere stereographic plot, shows the way in which the direction of remanent magnetization of specimen 1/26 changes with increasing A.C. field. After being subjected to a peak field of 165 oe. its direction of magnetization is very close to that determined by Gough (1956) for the basic part of this dyke in Robinson Deep Gold Mine. Further increases in the field do not alter the direction appreciably until the intensity of magnetization is less than about one tenth of Gough's mean intensity of magnetization of this dyke of 2.8×10^{-3} gauss. Beyond this stage the directions of magnetization start to scatter.

The initial intensity of magnetization of specimen 1/26 was 17.9×10^{-3} gauss (see also figure 6/6) i.e. about six times more strongly magnetized than unaffected rock at depth. Similar results are obtainable from specimens with initial magnetizations up to about 30×10^{-3} gauss, i.e. about ten times that of the original T.R.M. In each case the direction of magnetization moves towards and finally pauses at a point very close to Gough's mean direction. Some scatter may occur with fields exceeding about 600 oe.

In specimens whose secondary magnetization is more than about 10 times stronger than the T.R.M., A.C. washing does not effectively restore the original direction of magnetization. Figure 6/5 shows the progress towards the original direction of magnetization of specimen 12/13 whose initial intensity was 2.1×10^{-1} gauss. No clear "end point" is reached. After treatment in the A.C. field of 387 oe. the intensity of magnetization was down to 1.1×10^{-4} gauss and it is clear that the effective coersive force of such strong magnetization is very close to that of the T.R.M.

Rimbert (1958) drew attention to the difference in the intensity vs. A.C. demagnetizing field - curve for magnetization probably due to lightning and that due to a

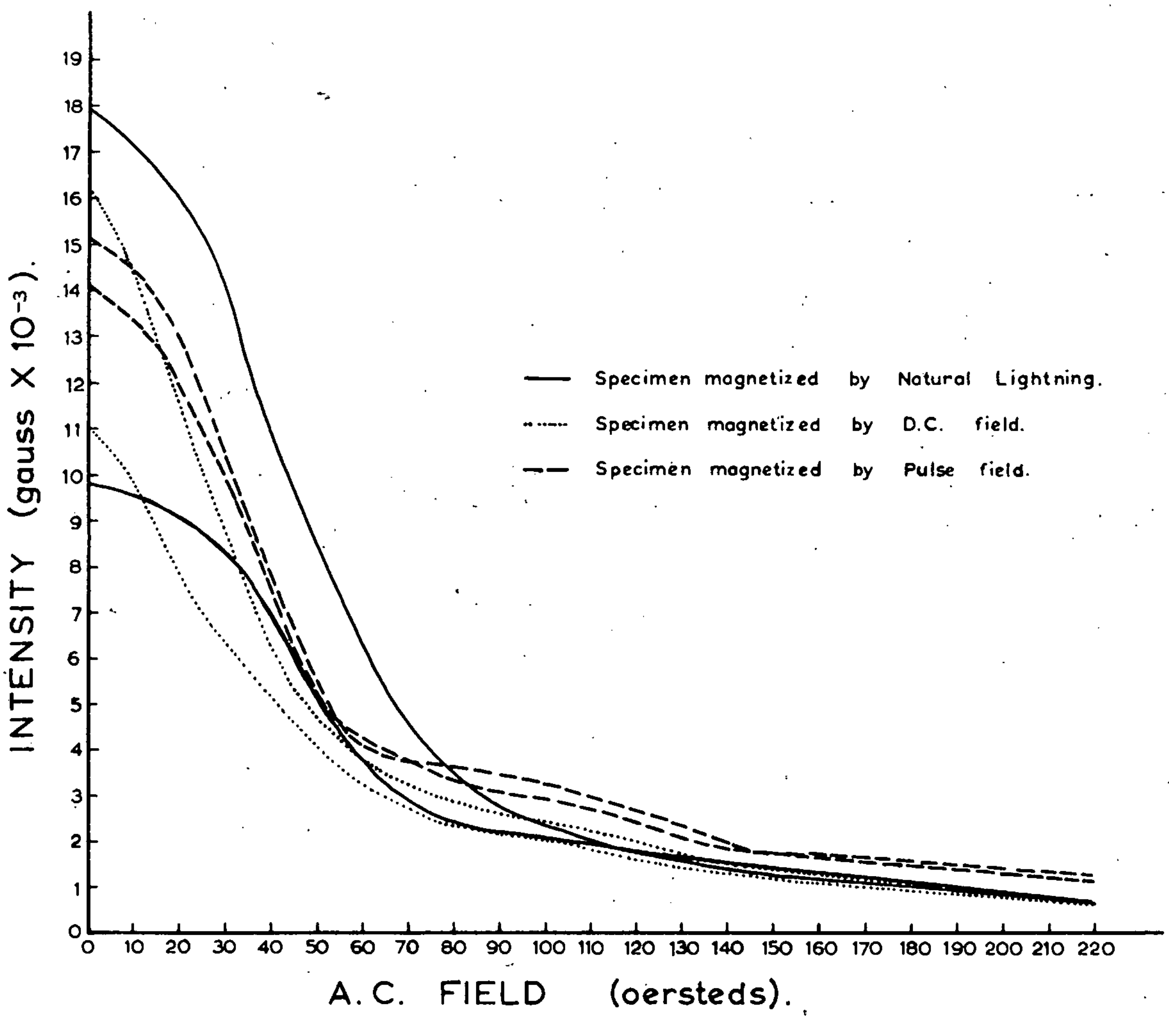


FIGURE 6-6.

A.C. demagnetization curves.

D.C. field. Figure 6/6 confirms this observation. The demagnetization curves for the specimens probably magnetized by natural lightning begin with a gentle slope which increases to a point where the curve becomes nearly linear. The curves for the specimens magnetized by a D.C. field do not show this initial gentle slope. Specimens 11/50 and 11/51 were magnetized by the field due to an artificial spark discharge (see section 2A). Specimen 11/50 was subjected to one such discharge while 11/51 was magnetized by five equal discharges at short intervals. The demagnetization curves for these two specimens do not appear to be significantly different from each other and they resemble the curves for the specimens magnetized by natural lightning more closely than they do those magnetized by a D.C. field.

The slight plateau formed by each demagnetization curve at intensities ranging from 2 to 4 x 10^{-3} gauss probably represents the stage at which the I.R.M. becomes comparable with the T.R.M. This supports the assumption that the average T.R.M. of this outcrop of the Robinson dyke has much the same intensity of magnetization as the underground exposures studied by Gough (1956). The mean for the underground exposures (calculated from Gough's figures) of 2.8 x 10^{-3} gauss is consistent with these and other demagnetization curves.

Since the addition of magnetic vectors (see sections 2A and 3B) appears to be entirely satisfactory,

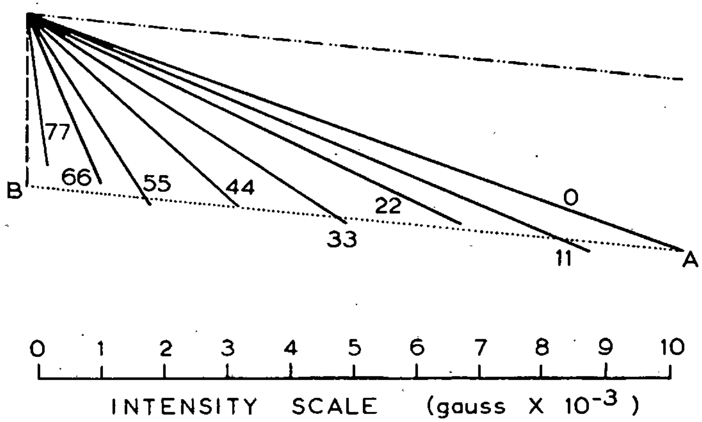


Figure 6-7.

A specimen magnetized by a D.C. field.

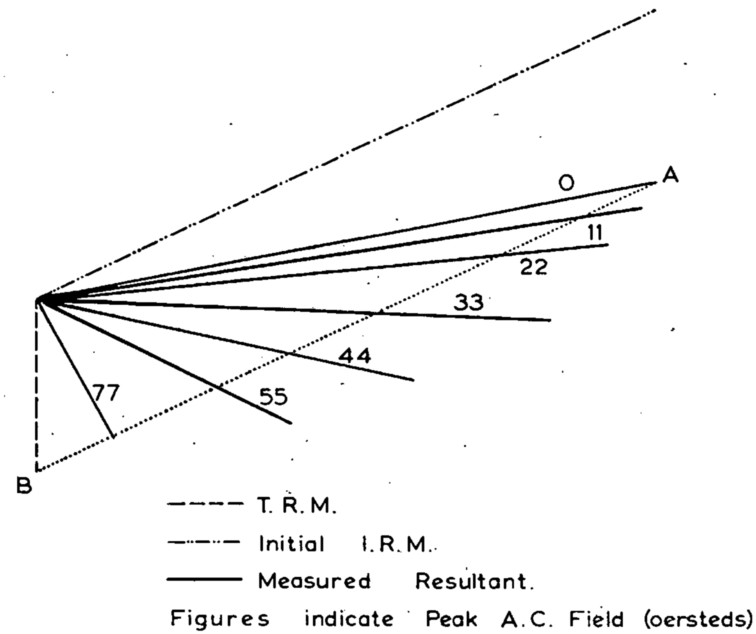


Figure 6-8.

A specimen magnetized by lightning.

The direction and intensity of remanent magnetism at various stages of demagnetization.

one would expect that with the removal of one or more vectors during demagnetization a similar sort of vector subtraction would be possible. In fact this does occur for specimens magnetized by a D.C. field. Figure 6/7 shows that at least during the first stages of demagnetization one can picture the T.R.M. remaining constant while the I.R.M. is progressively removed without changing its direction. The vector resultant decreases in length and changes in direction in accord with the parallelogram and moves along line AB. However, figure 6/8 shows that in the case of a specimen with I.R.M. due to lightning no such simple model is possible. This peculiarity is probably directly related to the initial gentle slope of the demagnetization curve for specimens with I.R.M. due to lightning but the phenomenon is not yet clearly understood.

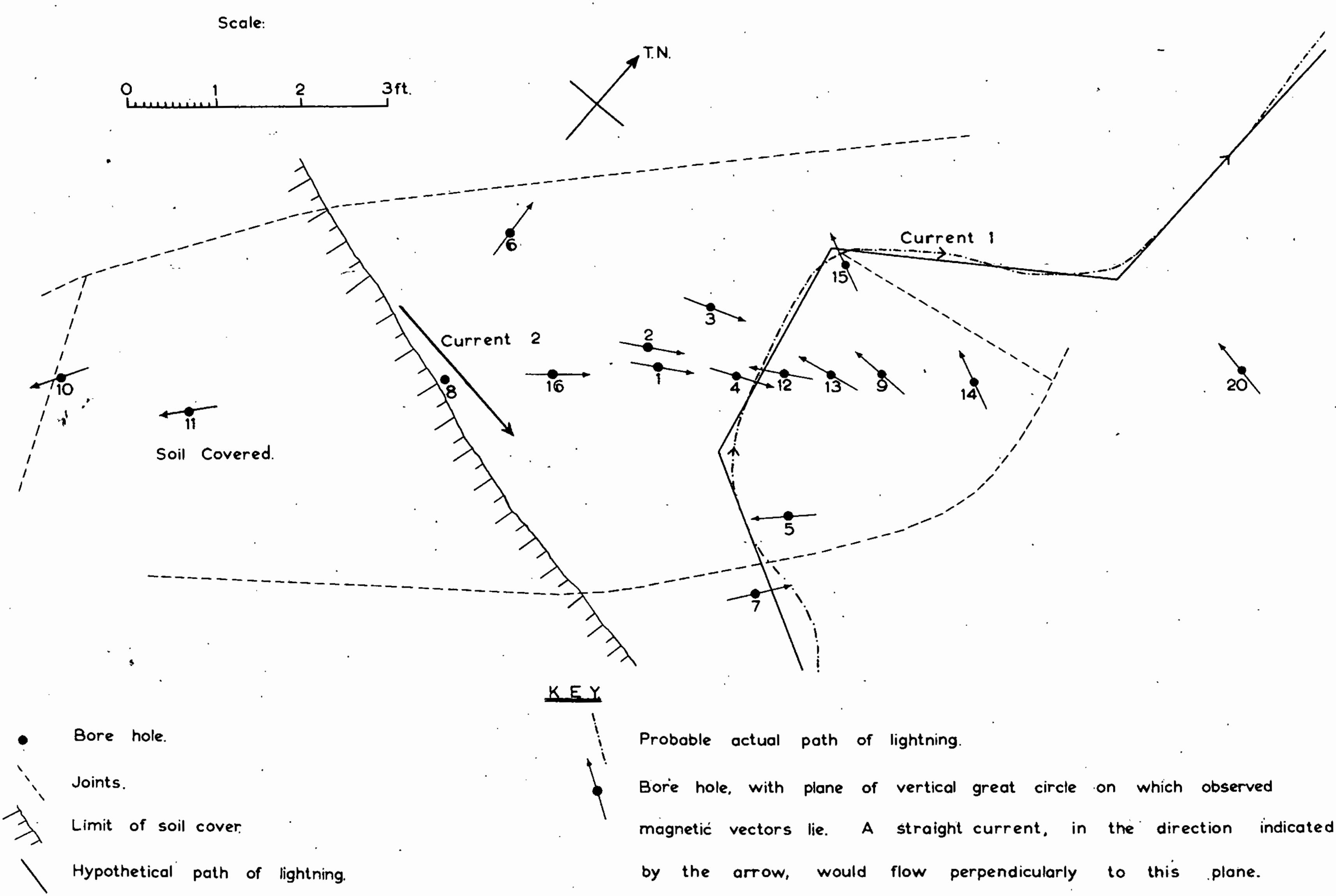
3. The Natural Remanent Magnetism.

A. The main pattern.

Seventeen of the twenty cores drilled from the outcrop described above came from the area about 14 ft. by 5 ft. depicted in plan as figure 6/9.

Lower hemisphere stereographic plots of the directions of magnetization of the specimens from each of cores 1, 4, 12, 14, 20 and 8 are shown as figures 6/11 to 6/16 respectively. On the whole the specimens from these

Figure 6-9.



A PLAN OF THE PART OF THE PILANESBERG DYKE SAMPLED.

cores as well as those from most of the other cores, are magnetized in directions which fall on nearly vertical, approximately NE-SW great circles. The "strike" of each of these planes of magnetization is shown as the line through each of the "bore holes" in figure 6/9. As will be seen from the plan, these vertical NE-SW planes nearly coincide with the approximate plane from which the specimens of cores numbers 8, 16, 1, 4, 12, 13, 9, 14 and 20 were drilled.

It is therefore fairly accurate to represent the direction and intensity of magnetization of the specimens as vectors in the plane of a section approximately through these cores. Every fourth specimen from each of the above cores is represented in such a section which is presented as figure 6/10. The magnetic vectors for core number 8, shown as dashed lines, are not direct observations but have been calculated as described in section 3B below.

Except for core number 8, the pattern of the direct remanent magnetic observations represented in figure 6/10 is qualitatively highly consistent with one that would be produced by an electrical current flowing along a single straight conductor passing perpendicularly into the plane of the section at the point marked C 1. However, it is equally clear that this simple picture is not quantitatively accurate. For example, specimen 16/9 is about 2 ft. 4 in. from C 1 and has an intensity of magnetization of 2.2×10^{-2} gauss while specimen 9/17 is very nearly the same distance from

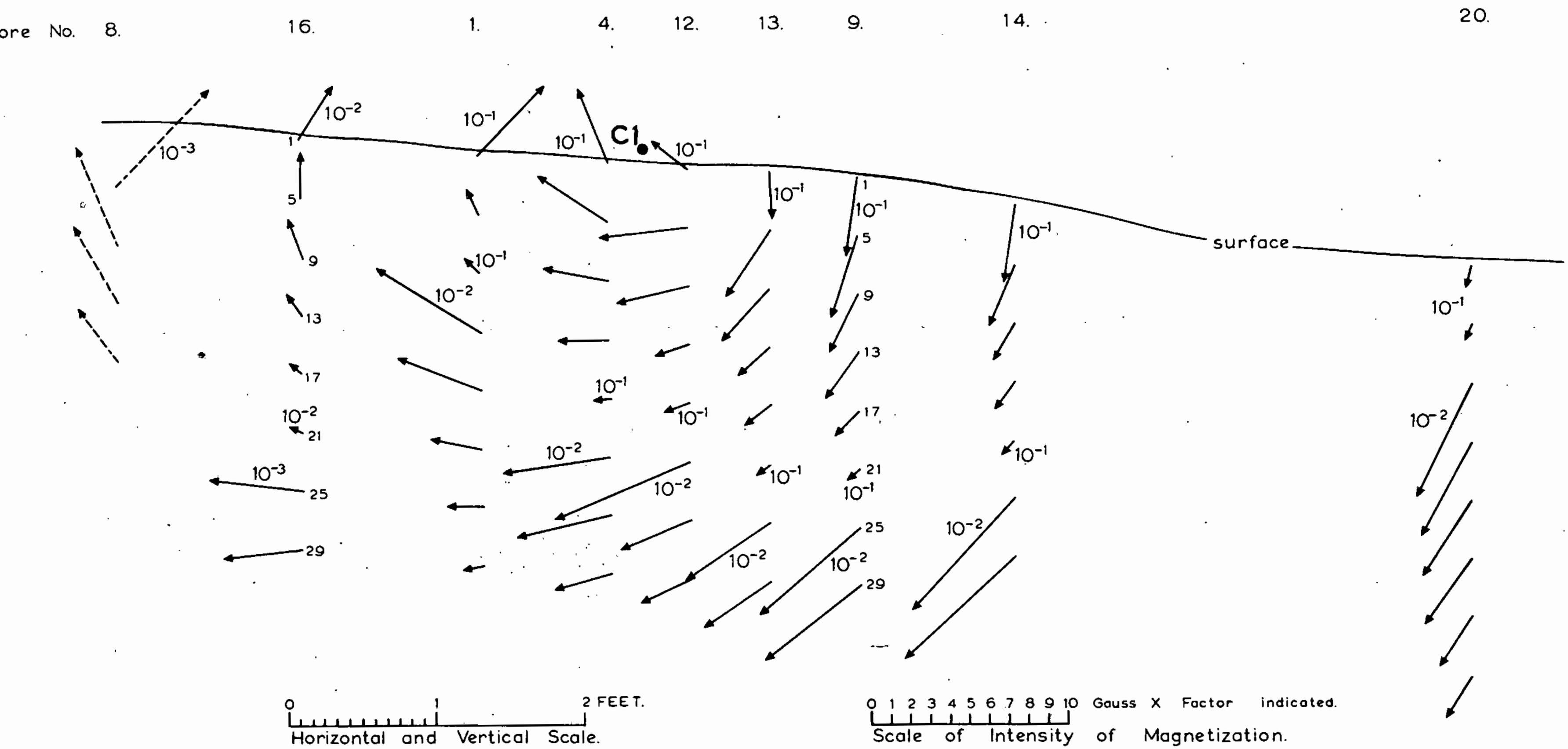


Figure 6-10.

A section through part of the outcrop showing the variations in the direction and intensity of magnetization. The North-seeking poles have been plotted.

C 1 but has an intensity of 1.9 x 10^{-1} gauss. Many other examples of specimens to the left (S.W.) of C 1 being much less strongly magnetized than specimens equidistant to the right (N.E.) of C 1 are to be found.

The simplest explanation for this phenomenon is that there is a gradual increase towards the N.E. in the intensity to which a specimen could be magnetized by a given field. This could occur by a progressive change in the quantity or nature of the magnetic minerals in the rock. This possibility was investigated by subjecting specimens 14/29 and 16/30 to D.C. fields of various strengths. Within the limits of experimental error the two specimens behaved identically and in complete harmony with the field vs. remanent magnetism curves described earlier.

Two other possible explanations were investigated. One, involving the vectatorial sum of the field due to the current at C 1 and another large current in the opposite direction but some distance to the right (N.E.) of C 1, was abandoned when a test core (No.20) failed to fit the predicted pattern. The possibility that the current at C 1 instead of following a thin, wire-like path, spread out in the form of a sheet was considered mathematically. It became clear that in any sheet-like model, the field at any point below the sheet would be predominantly horizontal even if the point is very close to a sheet in which the current distribution is highly non-uniform. Such specimens as 4/5 and 13/5 show

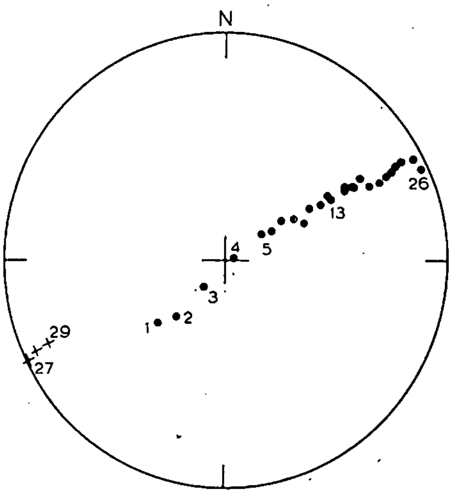


Figure 11, Core 1.

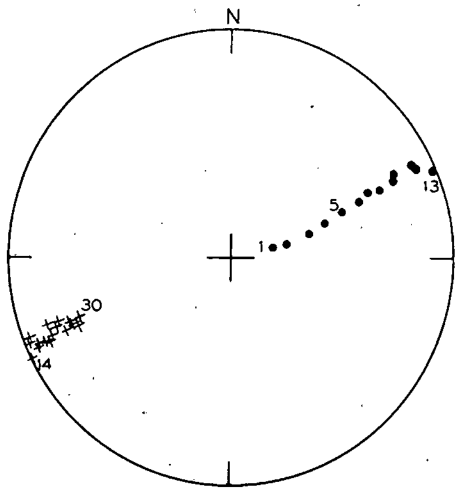


Figure 12, Core 4.

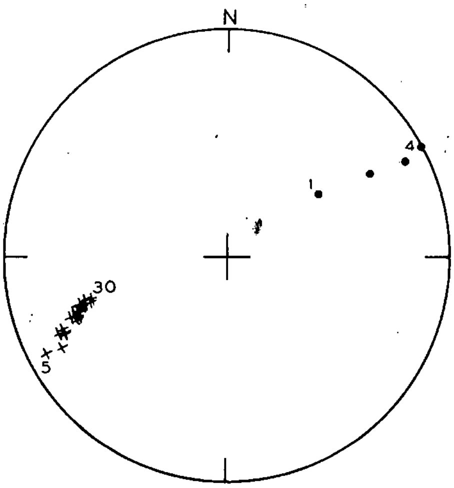


Figure 13, Core 12.

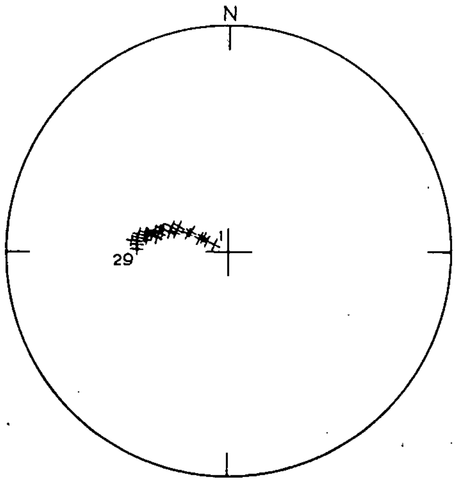


Figure 14, Core 14.

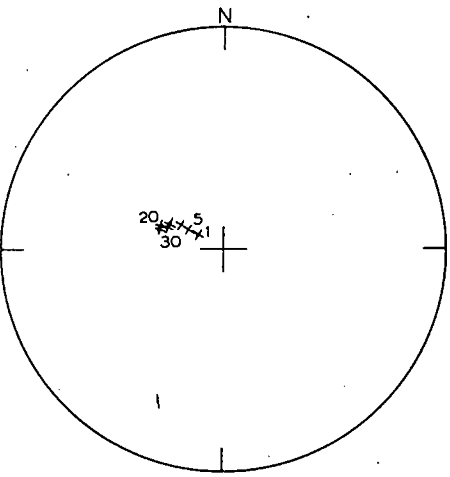


Figure 15, Core 20.

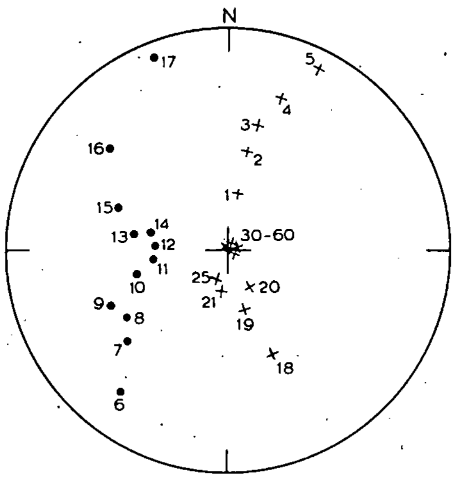


Figure 16, Core 8.

× North pole downwards. • South pole downwards.

The specimens are numbered from the top to the bottom of each core.

that the current path could not have been more than one foot wide.

As pointed out above, the directions of magnetization of the specimens from any one core lie on a great circle. The planes of these vertical great circles are represented by the lines through the "bore holes" on figure 6/9. For any particular core the direction of the perpendicular to the current will lie in this plane and its sense can be determined by noting the way in which the magnetic vectors rotate as one proceeds from the top of the core downwards. This direction for each core is indicated in figure 6/9 by the arrow heads. It is clear from the non-parallelism of these directions that the current did not follow a straight path and a path similar to that indicated in the figure seems possible.

A good approximation to such a curved current path may be made by dividing the curve up into a number of straight segments whereupon the problem may be tackled quantitatively in a simple manner. Guided by the intensity of magnetization of some of the specimens nearest to it, a guess may be made at the magnitude of the current. The direction and strength of the field due to each of the straight current-path segments may be calculated for a point occupied by any specimen. The angle between any two of these magnetic fields, A and B, may be determined with the aid of a stereographic net and their vectatorial sum (A+B) may be calculated. The direction of (A+B) may now be plotted by using the angle between A or B and (A+B). This process may be repeated until all the vectors representing the magnetic field due to segments of the current-path have been added. The resultant field can then be converted to I.R.M. by means of the curves shown as figures 6/2 and 6/3. The calculated direction of the field and intensity of I.R.M. may be compared with the values observed for the particular specimen. The current magnitude may be adjusted if necessary.

By trial and error, the current path consisting of the four straight segments shown in figure 6/9 was found to fit the observations fairly well. The best value of the current was found to be 5.0 x 10^4 Amps.

Table 6/2 compares the observed direction and intensity of magnetization of fourteen specimens with those calculated on the basis of this model.

Specimens 5 and 25 of core number 7 show that the model is not accurate at its extremities. Clearly this is due to the assumed semi-infinite straight segments at either end of the current path. However, the overall agreement between the observed and calculated values of Declination, Inclination and Intensity of magnetization is good enough to indicate to a high degree of probability that the pattern of magnetization of this part of the outcrop is due to an electrical current of about 50,000 Amps flowing along an approximately horizontal, narrow but curved path.

Table 6/2.

Specimen No.	OBSERVED. D deg.	I deg.	Intensity gauss x 10^{-3}	CALCULATED. D deg.	I deg.	Field oe.	Intensity gauss x 10^{-3}
1/21	243	-12	29	245	-18	103	37
2/9	244	-55	99	250	-45	137	72
3/25	256	+ 5	23.6	261	-10	106	39
4/13	244	+ 1	270	253	+ 1	224	210
5/13	224	+36	280	223	+32	261	260
7/5	215	- 1	480	210	-19	662	500
7/25	226	+18	34	224	+ 7	124	56
9/13	265	+54	310	275	+52	260	260
12/17	251	+20	146	257	+21	195	160
13/9	256	+48	380	263	+60	377	470
14/17	282	+50	116	282	+41	166	110
15/17	286	+ 9	135	283	+ 7	178	130
16/13	233	-55	15.2	235	-56	81	21
20/21	288	+56	41	280	+51	120	53

Note: D (declination) is measured clockwise from true North to the North-seeking pole.

I (inclination) is positive if the North-seeking pole is down.

The reason for the peculiar directions of magnetization of the uppermost three or four specimens from cores

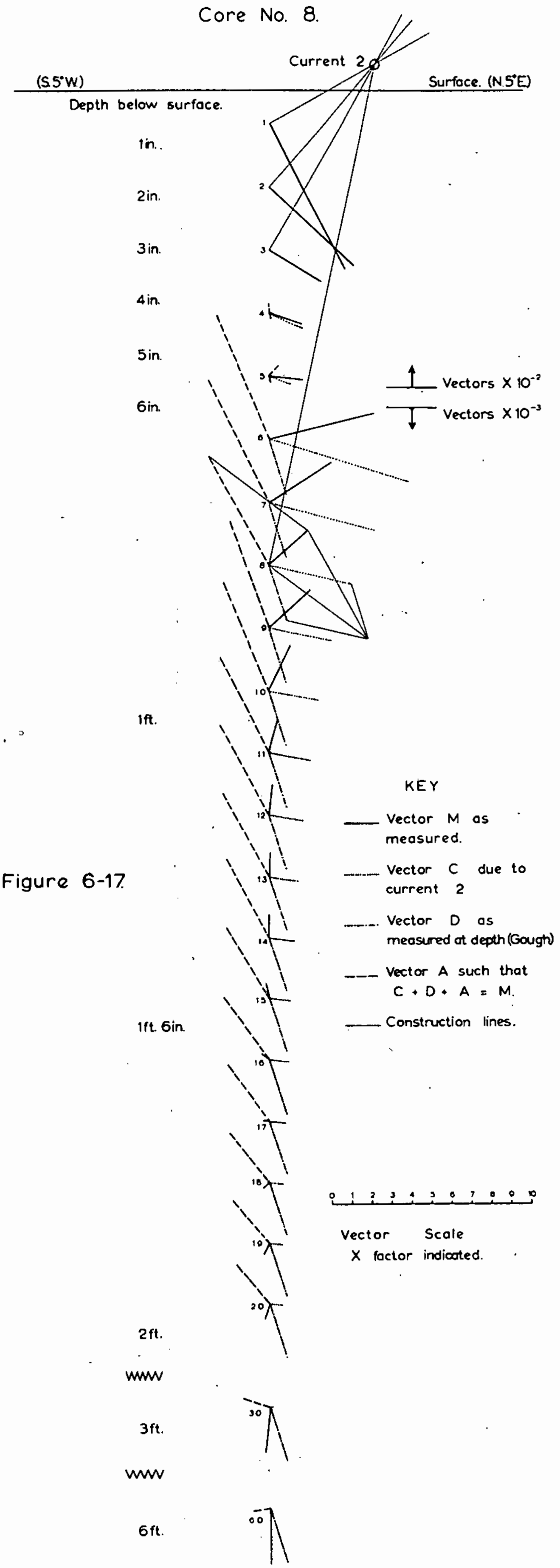

Core No. 8.
Current 2
(S.5°W.)
Surface. (N.5°E.)
Depth below surface.
1in.
2in.
3in.
4in.
5in.
6in.
1ft.
1ft. 6in.
2ft.
3ft.
6ft.
Vectors X 10⁻²
Vectors X 10⁻³
KEY
Vector M as measured.
Vector C due to current 2
Vector D as measured at depth (Gough)
Vector A such that C + D + A = M.
Construction lines.
0 1 2 3 4 5 6 7 8 9 10
Vector Scale
X factor indicated.

Figure 6-17

16, 1, 4 and 2 (see figure 6/10) is not known. They may be due to very small branch currents which feed the main current.

B. Core number 8.

The solid lines in figures 6/17 represent the observed directions and intensities of magnetization of core number 8. These directions are also plotted stereographically in figure 6/16. Note the way in which the direction rotates through nearly 360° between the surface and about 3 ft. and also the initial decrease in the intensity of magnetization to a minimum at about 1 ft. 9 in. (specimen number 17) followed by an increase.

If perpendiculars are drawn from the observed directions of magnetization of the first three specimens, they happen to intersect at the point marked "Current 2". The remanent magnetism of these three specimens could be due to a long straight horizontal current flowing perpendicularly into the plane of the paper through this point. Knowing the intensity of magnetization, the field and thence the magnitude of the current may be found. Specimen 1 gives a value of 4.3×10^{3} Amps. while specimens 2 and 3 give 5.0×10^{3} Amps. Specimen 1 may be slightly weathered so that 5000 Amps. is probably the better figure. The field and thence the intensity to which each of the remaining specimens of core number 8 would be magnetized, may now be found. The direction of this vector is given by the perpendicular to the line joining the centre of the specimen to the point marked "Current 2" and the vector C is shown accordingly in figure 6/17 for each specimen.

On the basis of the demagnetization experiments described above, the thermoremanent magnetization of this core is assumed to be the same as that determined by Gough (1956) underground, viz. D = 14.1°, I = 71.8°, mean Intensity = 2.8×10^{-3} gauss and is represented by vector D in the figure. It will be noted that for specimens 1, 2 and 3 this vector is negligible compared with the observed vector so that the estimation of the current will not be affected by it.

For any particular specimen, the vectatorial sum of C and D does not produce the observed vector M, and a further vector A is required to account for the observations. This vector, drawn as the dashed lines in figure 6/17 may be found by completing the parallelogram as shown for specimen number 8.

The behaviour of vector A is rather more systematic than that of the observed vector M. Its direction remains more or less constant and its intensity falls off smoothly with depth. Figure 6/10, in which this calculated vector A is shown as dashed lines, shows clearly that it fits in with the rest of the "Main Pattern". It is undoubtedly due to current 1 described above.

4. Discussion.

Both the electrical currents responsible for the remagnetization of part of this outcrop followed predominantly horizontal paths close to the surface of the rock. The magnitude of the currents, their behaviour and the characteristic A.C. demagnetization curves leave very little doubt that they were associated with lightning discharges.

From figure 6/9 it will be seen that current 2 could possibly curve towards the North to join up with the main current. Another small current may have joined the main current near core number 15. This could possibly explain the magnetism of core number 6. It seems probable that cores number 10 and 11 were magnetized by another large current to the West of them. This current may or may not have been associated with the main current described above.

In the area of the outcrop studied, the effect of a vertical lightning current is not seen at all. It seems probable that the horizontal currents could remagnetize a greater area of rock than would the vertical current with which they are associated. It is clearly fallaceous to argue that if the pattern of magnetization of a surface outcrop is not one of concentric horizontal vectors then it could not have been caused by lightning.

For this rock the minimum field required to produce a significant change in the remanent magnetism is about

12 oe. (see figure 6/2). From the equation:

$$H = \frac{2i}{10\ a}$$

where H = the magnetic field, in oersteds, due to an infinitely long straight conductor,

i = the current, in Amps., and

a = the perpendicular distance, in cms.

it can be shown that to entirely avoid such fields due to lightning one should not use samples from depths of less than 50 ft. In view of the difficulty of drilling and orienting samples from a depth of over 50 ft., deep quarries, road cuttings and mines should be used wherever possible.

The next best technique at present available is that of drilling to 3 or 6 ft. Although the directions of magnetization at these depths can be very significantly different from that of the original N.R.M., A.C. "washing" would in most cases remove the unwanted effect.

Clearly, if either vertical or horizontal lightning currents have affected the remanent magnetism of an outcrop, systematic sampling over an area of, say, 50 ft. by 50 ft. cannot yield a consistent but wrong impression of the original magnetic direction. The results will merely be negative in that they will be scattered.

Having shown that the overall random magnetization of one outcrop is due to lightning currents, one is left to wonder whether this kind of remagnetization is common or not. Gough (1956) sampled ten outcrops of five Pilanesberg dykes, including the outcrop sampled by the present author. All ten were found to have scattered directions of magnetization. There is no reason to believe that the cause of the scatter was anything other than lightning currents. The marked decrease in scatter of the underground Karroo dolerites when compared with the surface samples (Chapter 4) has already been mentioned. Similarly, samples of the Lower "Shales" of the Table Mountain Series taken from a deep road cutting (Chapter 5) were found to be consistently magnetized whereas those from the mountain side were inconsistently magnetized. In both these cases it is felt that lightning currents could have been the cause of the scattering.

Workers in other countries have frequently encountered surface outcrops with scattered magnetization. These negative results are generally only mentioned in passing, or are not reported at all, so that it is impossible to form an opinion as to the frequency or cause of such phenomena. However, the "minor deviations" in the magnetic directions of certain outcrops of a family of Tertiary tholeiitic dykes of North England reported by Bruckshaw and Robertson (1949) are probably attributable to lightning currents. The patterns of magnetization of some outcrops studied by Bruckshaw and Robertson are very similar in nature to that described above.

The possibility of the remagnetization of many surface outcrops by lightning currents puts an obstacle in the way of the "conglomerate stability test". J.W. Graham (1949) argued that if each boulder or rock slab in a conglomerate is consistently magnetized but the remanent magnetic directions for the various boulders is different to the point of randomness, then the rock from which the boulders are derived is probably magnetically stable. However, it is obvious that, particularly where horizontal lightning currents are involved, the direction of magnetization of a surface outcrop may vary rapidly over a small area. Thus, this test is only valid if either (a) the samples came from a considerable depth below the surface, or (b) it can be shown that the separation of the specimens from each boulder is of the same order as the distance between the various boulders sampled.

5. Conclusions.

The magnetic fields generated by large electrical currents associated with lightning discharges have remagnetized the portion of the outcrop studied and probably are the cause of many of the "scattered" directions of magnetization encountered in the palaeomagnetic study of surface samples. The only completely satisfactory way of avoiding this hazard is to restrict measurements to samples collected from depths of greater than about 50 ft. However, systematic sampling over even a fairly small area cannot yield consistent but "wrong" directions of magnetization resulting from lightning currents. If scattering is found, A.C. washing may prove useful, particularly if the specimens have come from moderate depths such as 3 to 6 ft.

J.W. Graham's (1949) "conglomerate test" for magnetic stability should be used only with extreme caution.

Post Script.

After the initial preparation of this chapter, as well as that of a paper describing this work (Graham, in press), a paper by Cox (1961) dealing with an identical problem in a somewhat similar manner was published. The two works are mutually confirmatory. Cox's paper further serves to demonstrate beyond doubt that the remagnetization of rocks by lightning currents running close to the surface of the outcrop, is widespread.

CHAPTER 7.

GENERAL DISCUSSION.

1. A Programme for the Future.

The palaeomagnetic work relevant to the establishment of a pole path for Southern Africa is summarized in table 7/1 below. Many of these results are based on too few observations and can only be regarded as tentative.

One of the most significant and interesting problems that may be solved by palaeomagnetism is that of "Continental Drift". It is not the purpose of this chapter to review the available palaeomagnetic evidence for Continental Drift since this has been done by numerous writers (Cox and Doell, 1960; Collinson and Runcorn, 1960, etc.). Because of the lack of sufficient data these writers have been forced to present their conclusions in broad terms and, although it is amusing to move models of continents on a globe so that appropriate palaeomagnetic poles coincide, a description of the possible combinations, particularly with reference to Africa, only serves to emphasize the lack of data. Let us therefore, consider how much and what sort of data is required in order to solve this intriguing problem.

As mentioned in Chapter 1, the ancient co-latitude of the sample site can be determined for any period of time long enough to allow secular variation to be eliminated.

Table 7/1.

Palaeomagnetic results from Southern Africa.

Age	Formation	D	I	α^{o}	Ancient Pole		Sampling	Reference
Jurassic	Karroo Dolerites (mean disregarding sign)	341	-60	-	70S	74½E	82 Dolerite samples and 16 baked sediments from area 400 x 250 miles	Present thesis Chapter 4
Jurassic	Karroo Basalts, Rhodesia	328	-40	4½	60S	103E	12 samples	Nairn 1960
Triassic	Cave Sandstone, Bechuanaland.	325	-13	8½	53S	136E	10 samples	Nairn 1960
Triassic	(Mean ?)	352	-31	7	84S	172E	21 samples (6 sites)	Nairn 1960
Permian	Maji Ya Chumvi, Kenya.	267	+38	11	4N	150E	5 samples	Nairn 1960
Permian	Taru Grit, Kenya	87	+61	16½	0	87E	8 samples	Nairn 1960
Carboniferous	Dwyka Varved Clays	-	-	-	15S	23E	4 samples	Nairn 1960
lurian (?)	Table Mountain Series	162	-3.5	4½	50.3N	10.9W	8 samples from a single bed covering 100 ft. horizontally	Present thesis Chapter 5
50 m.y.	Pilanesberg Dykes	24	+69½	6	7½N	42½E	5 dykes covering 54 miles 5 to 28 samples per dyke	Gough 1956
50 m.y.	Bushveld Gabbro			12	23N	36E	5 sites covering 154 miles, 12 to 29 samples per site.	Gough and van Niekerk, 1959.

Also, declination, the angle between the present North-South line on a continent and the direction of the ancient pole, may be found thus establishing the orientation of the continent relative to the pole. However, the longitude of the continent cannot be found from one palaeomagnetic determination so that the exact ancient relationship of continents, one to the other, cannot be found from one palaeomagnetic determination from each continent, even if these determinations are made on exactly contemporaneous rocks.

"Polar Wander" further complicates the picture. It is convenient to confine the term "Continental Drift" to the movement of the continents relative to one another. Any movement of the continents relative to the pole while remaining fixed relative to one another should be called "Polar Wander", regardless of any possible similarity in mechanism.

It is clear that in order to determine the extent of Continental Drift one must also determine the amount of Polar Wander and vice-versa. Theoretically, the ancient relative positions of the continents can be found from two palaeomagnetic determinations from each continent, separated by sufficient time to allow some Polar Wander but insufficient to allow appreciable Continental Drift (Irving, 1958). Each of these two determinations should be made on rocks of exactly the same age from each of the continents; and herein lies the major obstacle in the way of this method. Intercontinental correlation of strata cannot be relied upon to this extent. Further, although it is clear that for most of the Palaeozoic and Mesozoic, relative movement between Europe and North America has been slow compared with Polar Wander, it cannot be assumed that this is true for all continents at all times. Therefore, the necessary condition that there should be appreciable Polar Wander but no Continental Drift in the interval between the formation of the rocks on which the two determinations are made, may not always be fulfilled.

The only satisfactory approach is to determine the entire pole path relative to each continent in as much detail as is possible. Kinks, reversals of the field and other idiosyncrasies of these curves could provide the necessary intercontinental correlation, and by matching the curves from the various continents where they fit neatly, the roles of Continental Drift and Polar Wander can be separated and completely defined.

This is a long job !

The task should be tackled step by step. The first object in South Africa should be to determine an approximate pole path for the Palaeozoic and Mesozoic by making about a dozen palaeomagnetic determinations scattered throughout as much of this period as possible. The reasons for giving this project priority are :-

1) This appears to be the period of most active Polar Wander.
2) Although Africa is probably a key piece in the Gondwanaland puzzle, palaeomagnetic data from this continent are particularly sparse.
3) Rocks covering most of this period are available in South Africa, although they are seldom of the igneous or bright red clay types which have so far yielded the bulk of the data from other continents.
4) As has been seen from previous chapters, there are many problems associated with palaeomagnetic work in South Africa; some have been solved, but several remain. In particular a technique for dealing with the very weakly magnetized rocks which make up the bulk of the Cape and Karroo Systems is, as yet, lacking. Until such techniques are available one is more or less confined to the isolated horizons made up of the more magnetic sediments.

It is quite probable that during the course of these studies, ideas and instruments will emerge which will enable the use of the very weakly magnetized (below say, 2×10^{-8} gauss) sediments. Should this be the case, the Cape and Karroo Systems should be studied virtually foot by foot. The effects of lightning make deep drilling advisable. If one is going to drill 20 ft. why not drill

1,000 ft. and so solve what can become a very difficult problem, viz. very accurate correlation? Orienting the very deep cores is only a problem of instrumentation and is commonly practiced by at least one South African prospecting group. By means of an improved design (Sacks and Graham, unpublished) it may be possible to orient deep cores without unduly interrupting the drilling routine.

Deep drilling seems to be the only way of adequately sampling the softer shaly horizons which characteristically form the gentle talus slopes in the Karroo and Cape Systems.

The Pre-Cape rocks of South Africa should not be forgotten. Particularly, the Dominion Reef, Witwatersrand, Ventersdorp and Transvaal Systems represent a more or less continuous record of Geological time and could provide extremely interesting data on the history of the Earth's magnetic field and possibly, in conjunction with work in other continents, on the history of the Earth's crust and the continents as far back as about 2,400 million years ago. Between the Transvaal System (about 2,000 million years old) and the Cape System (about 400 m.y.) large gaps exist in the Geological record. The Bushveld Gabbro (about 1950 m.y.) and the Pilanesberg dykes (about 1350 m.y.) have already been studied, but between these two intrusive events are the Loskop System and particularly the Waterberg System which warrant attention. The Malmesbury System may be too metamorphosed in most areas to yield much of significance but the Nama System could be of great interest.

And the Cape Granite? It would be interesting to study the remanent magnetism of a granite, simply because this has never been done before.

The possibility of using palaeomagnetism as a tool in the correlation of sedimentary and volcanic systems makes a study of the older rocks doubly worth-while.

2. Steps in the Right Direction.

Having realized the importance of lightning currents in the remagnetization of surface outcrops, new attempts to study the palaeomagnetism of the Cape and Karroo Systems have been undertaken at the Bernard Price Institute of Geophysical Research. At present only preliminary results are available but these show clearly that enormous advances in technique have been made since the first palaeomagnetic attempts in South Africa in 1954.

A. Measurements on Stormberg Lavas.

Using the new drilling and orienting equipment described in Chapter 2, section 2C, Mr. J.S.V. van Zijl has systematically sampled some 4000 ft. of the Stormberg Lavas at Sani Pass and about 3000 ft. near Maseru, both in Basutoland. Wherever possible the samples were taken from road cuttings and other places less likely to have been affected by lightning but in these areas deep road cuttings are not common and many samples had to be taken from natural exposures. In spite of many scattered directions of magnetization, van Zijl's results yielded a highly reliable mean direction of magnetization of the lavas and showed that reversely magnetized lavas at the bottom of the succession are followed by a "transition zone" of variable direction of magnetization. The upper lavas are magnetized in the normal sense. Subsequent A.C. demagnetizing experiments performed by van Zijl, using the apparatus developed by the author (Chapter 2, section 3B), has reduced the scatter in the directions and intensities of magnetization of the samples so much that it is possible to describe the detailed behaviour of the magnetic field at the time of the extrusion of the lavas. Mr. van Zijl hopes to submit a thesis for the degree of Ph.D. (University of the Witwatersrand) based on this work in the very near future.

B. Measurements on Upper Beaufort Sediments.

Twenty-one three foot cores have been drilled by the author from deep road cuttings in the Upper Beaufort (Burghersdorp Beds) near Queenstown, Cape Province. Most of the cores are from reddish shales or mudstones. Preliminary results obtained by measuring five or more specimens from each core are given in table 7/2.

All the cores are normally magnetized. The 19 highly consistent cores give a mean direction of magnetization for the Upper Beaufort of $D = 333.7^{\circ}$, $I = -59.6^{\circ}$.

Table 7/2.

The mean directions of magnetization of the 3 ft. cores from the Upper Beaufort.

No.	D	I	N	α	k
106	324.7	-48.8	5	3.2	570
107	323.8	-57.4	5	3.8	400
108	328.0	-47.0	5	5.9	133
109	338.4	-55.9	6	3.1	500
110	340.0	-55.8	7	3.0	400
111	343.8	-55.3	6	3.9	390
112	348.9	-56.0	5	2.2	1330
113	324.4	-59.2	7	4.7	162
114	346.4	-67.9	5	5.8	174
115	334.6	-70.3	7	2.0	1000
116	315.4	-70.7	5	3.6	444
117	352.2	-63.1	5	8.2	89
118	328.5	-64.9	6	3.9	294
119	322.9	-57.9	6	2.8	556
120	333.5	-69.5	5	4.4	308
121	314.4	-54.5	6	1.7	1670
122	Scattered				
123	Scattered				
127	327.5	-63.8	7	4.8	154
128	340.4	-49.3	5	6.5	138
129	350.2	-56.6	8	3.7	226

α = Radius of cone of 95% confidence

k = Fisher's (1953) estimate of the dispersion.

Giving each core unit weight, $\alpha = 3.9^\circ$, $k = 76$. At the 95% confidence level this direction is not significantly different from the mean direction of magnetization of all the dolerites (Chapter 4) of D = 341 , I = -60 (or D = 161 , I = 60). Although the direction of magnetization of the Upper Beaufort is very close to that of the present field (D = 338½, I = -65), it is significantly different at the 95% confidence level.

Preliminary demagnetization up to 550 oe. peak A.C. field indicates that, with the exception of samples 122 and 123, these sediments are extremely stably magnetized. Assuming therefore, that the mean direction represents the direction of the axial dipole field at the time of deposition of the sediments (Lower Triassic), the geographic pole would have the present co-ordinates of 67.1°S, 87.1°E. The semi-axes of the oval of 95% confidence for the position of the pole are $\delta p = 4.4^\circ$, $\delta m = 5.9^\circ$.

C. Measurements on "Red Beds" of the Stormberg Series.

Eight reconnaissance samples were drilled by the author from road cuttings in the Red Beds near Jamestown, Cape Province. Preliminary results show that two of the samples are normally magnetized in a direction close to that of the Upper Beaufort. However, the specimens from the other six cores which probably come from a slightly higher horizon are scattered, some even being reversely magnetized.

Could this be another "transition zone" dividing the normally magnetized Lower Stormberg and Upper Beaufort from the reversely magnetized Lower Lavas ?

3. Conclusions.

Although it may not be possible to construct a continuous and detailed pole path curve for Southern Africa until new apparatus and techniques are evolved for dealing with the very weakly magnetized sediments, the techniques developed by the author will make it possible to obtain reliable palaeomagnetic data from the more strongly magnetized horizons of the Cape and Karroo Systems. Joining the pole positions calculated from these isolated determinations will produce an approximate pole path for Southern Africa, similar to those already available for some other continents.

APPENDIX.

1. The Plotting Technique.

A method of graphically representing the measured direction of magnetization and of correcting this for the slope of the hole and for any dip the strata may have had, has been given by J.W. Graham (1949). The system used here is identical in principle to that used by Graham but it is thought to be a little simpler and more suitable for routine use.

The direction of magnetization of a specimen is measured relative to a right-handed system of axes. Plus X is in the direction of the scratch, Z is parallel to the axis of the cylindrical specimen and is positive downwards. Y is perpendicular to these two axes and is positive in the direction 90° clockwise from +X. In the convention used here the direction of magnetization is defined as the direction of the South-seeking pole.

In a spinner-type magnetometer the direction of magnetization projected onto the plane perpendicular to the axis of rotation (hereafter called the plane of rotation) of the specimen is measured. It follows that more than one measurement is required to define the true direction of magnetization in space. In practice three independent measurements are made per specimen.* When rotating about the X axis, the angle A is measured, representing the angle between +Y and the half-plane terminated by the X axis and perpendicular to the plane of rotation. Similarly, B is measured by rotating the specimen about the Y axis, and represents the angle between +Z and the half-plane terminated by the Y axis and cutting the plane of rotation perpendicularly. When rotating about the Z axis, C is measured, corresponding to the angle between +X and the vertical half-plane terminated by the Z axis. The direction of the south magnetic pole is represented by the line formed by the intersection of these three half-planes. The problem now is to determine the direction of this line from the readings A, B and C. This is most easily done graphically, with the aid of a Stereographic or Equal Areas net.

For reasons which are discussed in section 3 below, we have chosen to use the stereographic net and to plot only on the lower hemisphere, distinguishing South-seeking poles downwards by a circle (o) and North poles downwards by

---

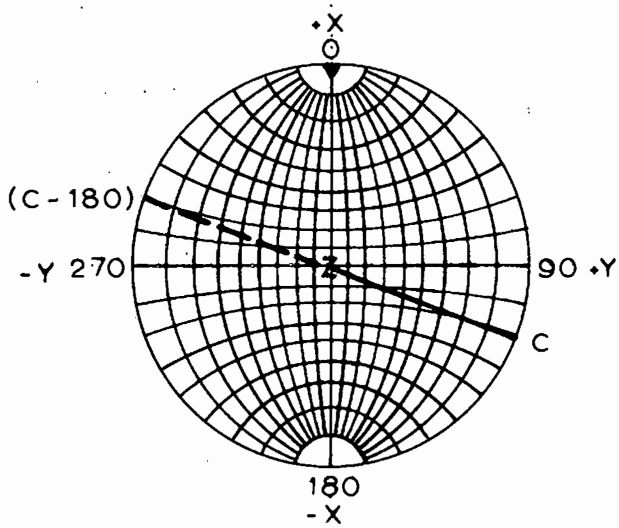
* Actually six readings are made because of the necessity to eliminate the zero error discussed in Chapter 2. These six readings are combined in pairs to give three independent measurements.

a cross (x). A Wulff stereographic net of about ten inches in diameter is used in routine plotting. The net is pasted onto a suitable board. A double pointed straight pin is pushed into the board at the centre of the net so that it projects about $\frac{1}{4}$ inch above the surface of the net. The actual plotting is done on a piece of tracing paper laid over the net, being pierced by the pin.

The X, Y and Z axes may be plotted on the tracing paper as follows:- Plus X will be on the circumference of the net at the zero mark, +Y at the 90° (clockwise) mark, -X at the 180° mark and -Y at 270°. Plus Z will be at the centre of the projection but -Z is not plotted since it falls on the upper hemisphere. (See figure A.1)

It is most convenient to plot the three measurements in the order C, A, B. With the +X mark on the tracing paper coinciding with the zero mark on the net, C is measured clockwise from +X along the circumference of the net where an appropriate mark is made on the plotting paper. If one were plotting on both hemispheres, a solid line joining this mark C with Z (the centre of the projection) would represent the half-plane on which the direction of the south magnetic pole must lie. However, since we have chosen to plot only on the lower hemisphere, this line represents only the lower half of our half-plane. If the south pole is below the horizon it will fall on this solid line but if the south pole is above the horizon we

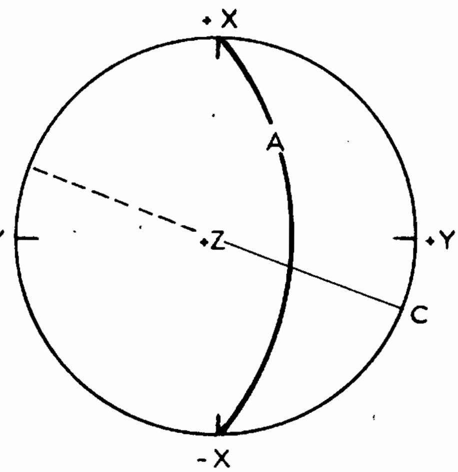
PLOTTING C



C = 110°

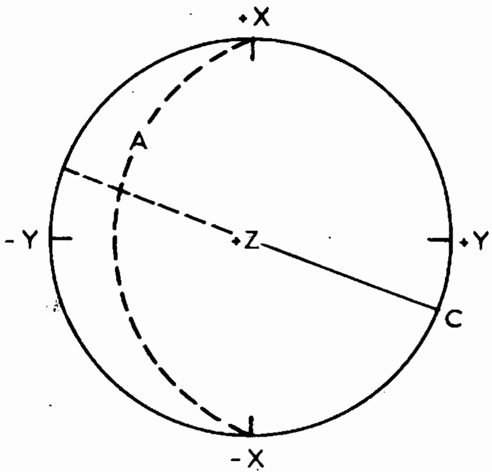
Figure A.1.

PLOTTING A



A = 50°

Figure A. 2a.



A = 340°

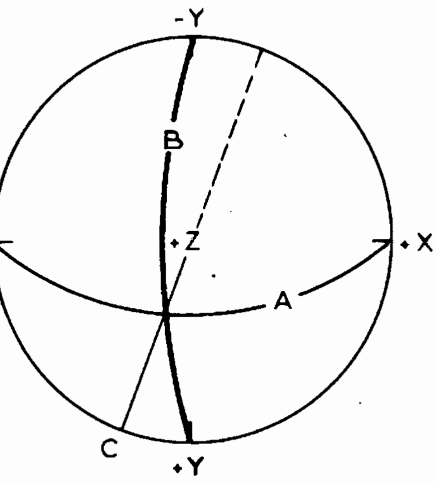
Figure A. 2b.

must plot the north pole which must be below the horizon and which will fall on a dotted line Z(C-180°) which is simply an extension of the solid line CZ, as shown in figure A.1.

A is plotted as half a great circle perpendicular to the line YZ on the stereograph. With the +X mark on the plotting paper coinciding with the zero mark on the net, the angle A is measured along the line YZ from +Y towards or through +Z. If A is between 0° and 180°, the south pole will be in the lower hemisphere and the great circle is drawn as a full line (figure A.2a). As A increases beyond 180°, the south pole comes above the horizon at -Y and the north pole comes into the lower hemisphere at +Y. Therefore, at 180° one again starts counting from +Y towards +Z, the great circle for A = 180° to 360° being drawn dotted, as in figure A.2b.

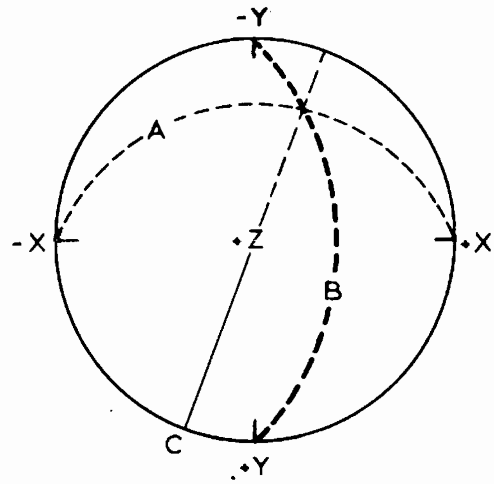
The third measurement, B is represented by a great circle perpendicular to the line XZ. In order to cause the great circles of the stereographic net to lie perpendicularly to the line XZ on the plot, the tracing paper must be rotated about the pin at its centre until the +X mark on the paper coincides with the 90° mark on the net, as in figure A.3. The angle B may now be counted off from +Z towards or through +X. If B = 0° to 90° the south magnetic pole of the specimen will be in the lower hemisphere and the great circle is drawn as a solid line.

PLOTTING B.



B = 342°

Figure A. 3a.



B = 225°

Figure A. 3b.

THE SLOPE h OF A CORE.

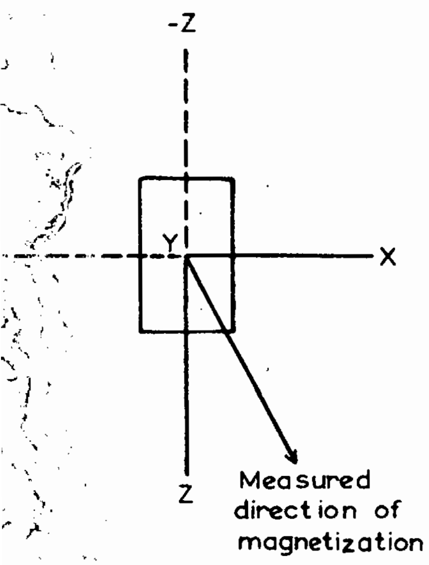


Figure A. 4a.

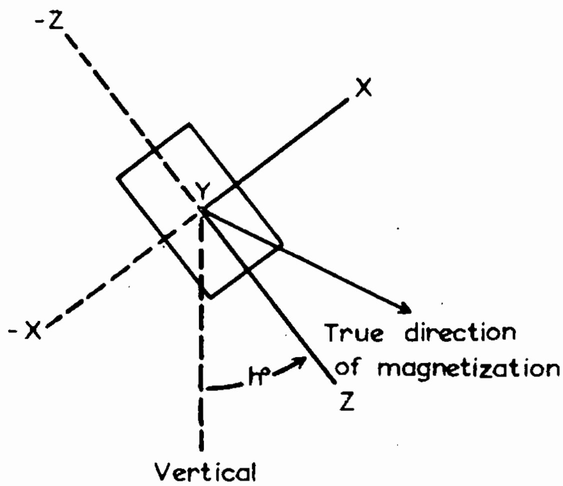


Figure A. 4b.

From 90° to 270° the north pole will be in the lower hemisphere, moving from -X through + Z to + X and the great circle should be drawn dotted. Between 270° and 360° the south pole will again fall in the lower hemisphere and the great circle is again drawn as a solid line. Figures 3a and 3b are examples of two possible cases.

The direction of magnetization of the specimen is represented by the point P at the intersection of the three planes. P will be the direction of the south pole in the lower hemisphere if it marks the intersection of three solid lines and will represent a north pole downwards if the lines are dotted (figures A.3a. and A.3b. respectively).

In general the three lines on the plot should intersect at a point. Any small error in one or more of the measurements will cause the lines to form a small triangle, in which case the most probable position of P is at the centre of the triangle. Occasionally the three lines form a very large triangle. This usually indicates that a mistake has been made in the measurement or in the associated arithmetic. In the case of very weakly magnetized specimens, a small amount of magnetic dust on the top can generate a signal in the coils of the same order as that due to the specimen. Since the specimen (in the cube) is placed into the top in various different positions (see Chapter 2) the magnetism due to the top adds vectatorially to that due to the specimen in different ways. This has the effect of introducing a different error into each of the three readings and the plotted triangle becomes large. A similar effect occurs if the top picks up an electrostatic charge. The size of the plotted triangle thus generally provides a very useful check on the accuracy of the measurement. However, it occasionally happens that two lines are parallel (e.g. $C = 180^{\circ}$ and $A = 90^{\circ}$) so that the third measurement cannot be checked.

2. Corrections.

A Correcting for the orientation of the specimen.

The exact technique for correcting for the orientation of the specimen depends very largely on the way in which its orientation is measured in the field and therefore, on the orienting instrument used. The procedure for correcting specimens oriented by means of the old device is mentioned briefly in Chapter 2. Here only the procedure for correcting the direction of magnetization of specimens oriented by means of the newer instrument will be described.

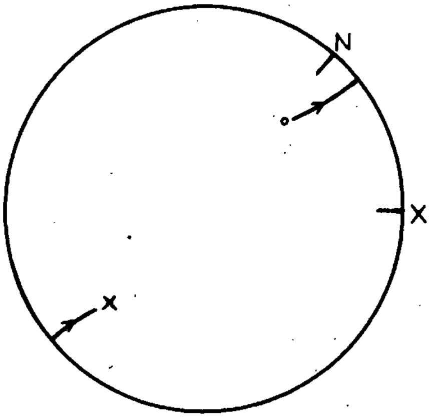
The angle between the X axis of the specimen (the scratch) and True North, as measured and recorded in the field is called the "Bearing". The angle between the Z axis (the axis of the core) and the vertical is called the "Slope". As described in Chapter 2, the new orienting device is designed so that the Y axis of the specimen is always made horizontal.

"Bearing = k^{o} " simply means that the X axis of the specimen is k^{o} clockwise from True North. To apply the correction the plotting paper is merely rotated about the pin through its centre until +X coincides with a point on the circumference of the net k^{o} clockwise from the zero mark on the net. "North" is then marked on the plotting paper so as to coincide with the zero mark on the net.

With regard to the "Slope" correction, one can imagine that the direction of magnetization is measured and originally plotted as if the specimen had been drilled vertically (figure A.4a). In fact the Z axis of the specimen may have been inclined at an angle h^{o} from the vertical, as in figure A.4b. Thus to correct the original plot to take account of the inclination of the Z axis one must, so to speak, rotate the specimen and with it its direction of magnetization, about the Y axis. The study of a model will show that, in the general case, such a rotation will cause the direction of magnetization to describe portion of a <u>small circle</u> about the Y axis. Because the scratch (the +X axis) is always made on the uppermost surface of the core, the direction of this rotation is always the same, viz. anti-clockwise about the +Y axis.

In order to cause the small circles on the

APPLYING THE SLOPE CORRECTION.



Slope = 70°

o = South pole downwards.

x = North pole downwards.

Figure A. 5.

PPLYING THE BEARING CORRECTION
AND PLOTTING STRIKE.

Bearing = 50°

Strike = 120° (or 300°)

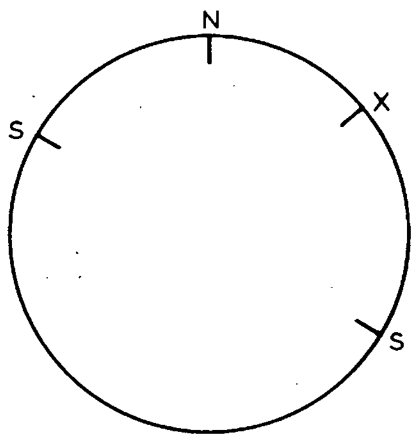


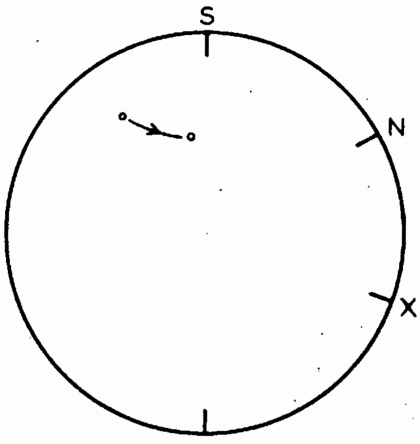
Figure A. 6.

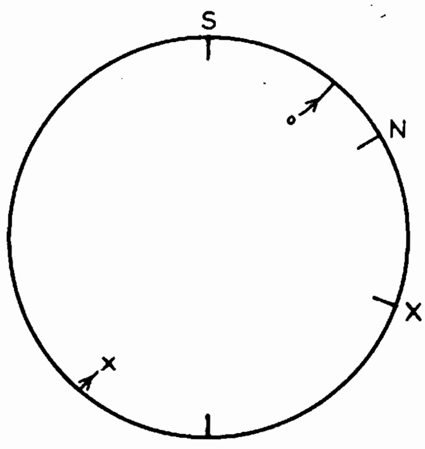
stereographic net to be perpendicular to the Y axis of the plot, the tracing paper must be rotated about the pin at its centre until +X coincides with the 90° mark on the net. Now the plotted direction of magnetization is corrected for slope h by moving h° along the small circle, always from left to right. If, during such a rotation, a south pole becomes horizontal, further rotation will cause a north pole to appear below the horizon diagonally opposite the point at which the south pole disappeared. The north pole then moves along the new small circle, again from left to right, as in figure A.5.

B Correction for the dip of the strata.

The Dip r and Strike s are recorded in the field. Having corrected the measured direction of magnetization for the orientation of the core, a correction for the dip of the strata may be applied in much the same way. In this case the rotation is about an axis parallel to the strike, in such a way that the direction of magnetization moves towards the direction of (down) dip. The direction of strike is plotted on the tracing paper, relative to the "True North" mark previously made, as in figure A.6. The plotting paper is then rotated until the direction of strike coincides with the zero or 180° mark on the net. The direction of magnetization is moved r degrees along the small circle towards the direction of dip (figure A.7a.). Again,

THE DIP CORRECTION





o = South pole downwards.

x = North pole downwards.

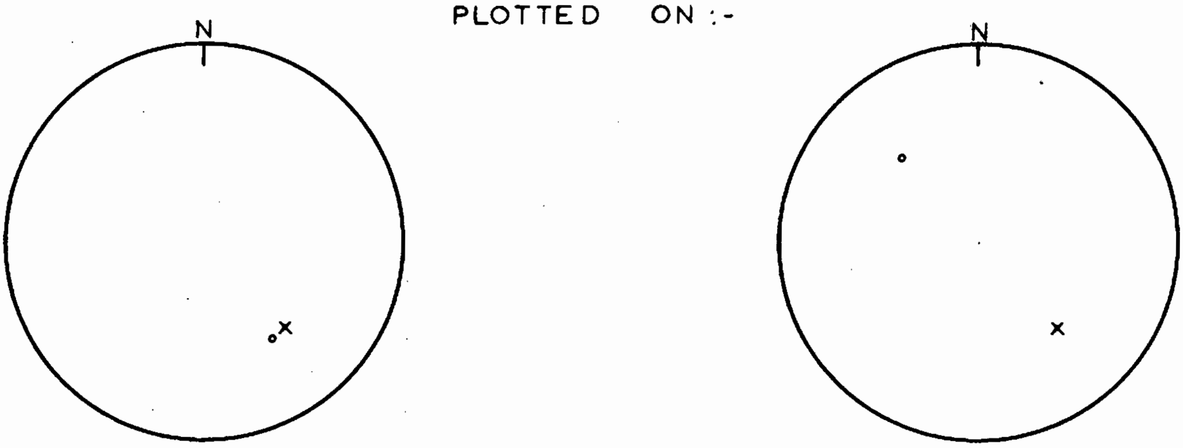
Dip = 50° (E.N.E.)

Figure A. 7a.

Dip = 50° (E.N.E.)

Figure A. 7b.

POLES OF DIFFERENT SIGN BUT THE SAME DIRECTION PLOTTED ON :-



(a) THE LOWER HEMISPHERE

x = North pole downwards

o = South pole downwards

(b) BOTH HEMISPHERES.

x = North pole downwards

o = North pole upwards.

Figure A. 8.

in solving structural problems shows the way in which to approach the more complex palaeomagnetic corrections.

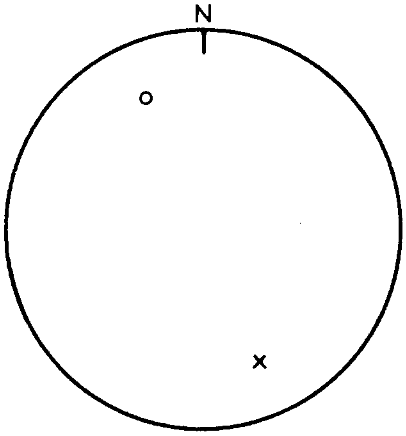
implies, the area will be the same, no matter where the circle is plotted. Consequently, palaeomagnetic directions randomly distributed about a mean will appear randomly distributed about the mean on a stereographic plot but they will appear to be more tightly grouped if they happen to fall near the centre of the projection than if they fall near the circumference. On the equal areas net the same directions will appear to be equally well grouped whether plotted near the centre or near the circumference of the net but generally, they will appear to form a streak instead of being randomly distributed about the mean.

In the opinion of the author, the stereographic net is to be preferred because (i) it is important to be able to recognise true "streaking" when it occurs since this is a characteristic feature of partially unstable magnetic specimens (Creer, 1957) and (ii) a precise mathematical method of evaluating the grouping of palaeomagnetic observations exists (Fisher, 1953) and should be used wherever possible.

B. Lower, upper or both hemispheres ?

In a choice between using only the lower hemisphere or only the upper hemisphere, the former is slightly preferred for palaeomagnetic work because the declination of a point on the lower hemisphere immediately indicates the direction of the nearer ancient geomagnetic pole.

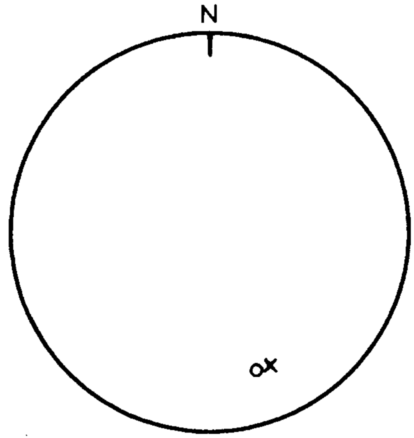
OLES OF THE SAME SIGN AND EQUAL BUT OPPOSITE INCLINATION PLOTTED ON :-



(a) THE LOWER HEMISPHERE

o = South pole downwards

x = North pole downwards



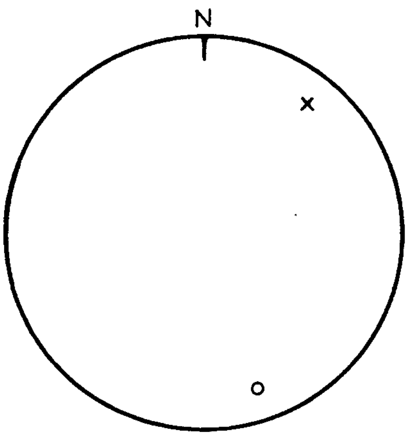
(b) BOTH HEMISPHERES

x = North pole downwards

o = North pole upwards

Figure A. 9.

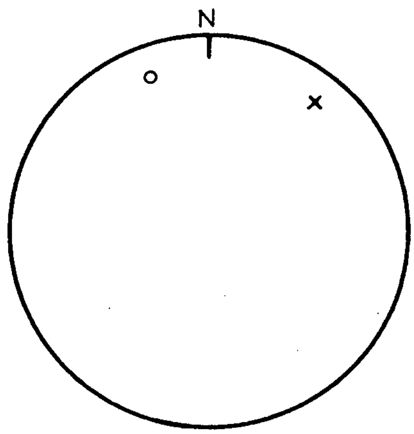
THE DECLINATION OF DIRECTIONS PLOTTED ON :-



(a) THE LOWER HEMISPHERE

x = North pole downwards, D = 40°

o = South pole downwards, D = 340°



(b) BOTH HEMISPHERES

x = North pole downwards, D = 40°

o = North pole upwards, D = 340°

Figure A. 10.

In one respect, plotting only on the lower hemisphere is preferred to the use of both hemispheres. Figures 8a and 8b illustrate the fact that poles of different sign but the same direction are more easily recognised as such if plotted only on the lower hemisphere. Also, poles of the same sign and with equal but opposite inclination are more easily recognised as having different directions on the lower hemisphere projection (figure A.9a) than when both hemispheres are used, as in figure A.9b.

The main disadvantage of using only the lower hemisphere results from the confusion which arises when palaeomagnetic plots are compared with tables in which the directions of magnetization are listed in terms of Declination and Inclination. This is because, strictly, declination is the horizontal angle between true north and the <u>north</u> seeking palaeomagnetic direction. If both hemispheres are used, then only the north seeking pole is plotted and its declination and inclination are readily associated with the plot, as illustrated by figure A.10b. When using only the lower hemisphere, all is well if the north seeking pole falls on the lower hemisphere but if it happens to be above the horizon, the south pole must be plotted, as in figure A.10a. In the author's opinion, it is extremely confusing to say that the direction represented by such a point is $D = 340^{\circ}$, $I = +10^{\circ}$. Because of this difficulty it may be preferable to quote the horizontal angle between true north and which ever pole falls in the lower hemisphere, specifying whether the north or south pole is downwards. Because this procedure is unconventional it is not entirely satisfactory but, bearing in mind the ambiguity with regard to the sign of palaeomagnetic directions introduced by the possibility of self-reversal (Chapter 1, section 2), it may be the lesser of the two evils.

ACKNOWLEDGEMENTS.

It is a great pleasure to acknowledge my indebtedness to the vast number of people who have materially contributed towards the success of this project. These include Mr. P.J. Rossouw, Dr. L.E. Kent and Mr. P.J. Smit of the Geological Survey of the Republic of South Africa, Professor E. Mountain of Rhodes University, Professor D.L. Scholtz of the University of Stellenbosch and Professor E.S.W. Simpson of the University of Cape Town for invaluable geological information and maps, Mr. A. Frost, Mr. E.F. Marland and the staff of Union Corporation for the samples from Winkelhaak Mines Ltd., Carnegie Institution of Washington, Dr. F.J. Hewitt, Director of the National Institute of Telecommunications Research and Professor W. Cormack of the Department of Electrical Engineering, University of the Witwatersrand for the loan of certain electrical equipment, Professor G.R. Bozzoli and Mr. J.J. Kritzinger of the Department of Electrical Engineering, University of the Witwatersrand for their assistance in the experiments involving the high voltage impulse generator, the South African Council for Scientific and Industrial Research for financial support for the palaeomagnetic programme, Dr. A. Fuller of the University of Cape Town for very helpful advice and criticism related to the work on the T.M.S. Lower Shales and Professor E.S.W. Simpson for invaluable advice regarding the presentation of this thesis.

Mention has already been made of the loan of the matched filters by the Carnegie Institution of Washington, but I would like to thank Dr. M.A. Tuve, Director of the Department of Terrestrial Magnetism of this Institution who arranged this loan. Particularly, may I express my appreciation of the experience and special knowledge in this field passed on to us by Dr. John W. Graham during his visit to us in 1955. His help in the early stages of this programme was of inestimable value.

I am grateful to my colleagues at the Bernard Price Institute of Geophysical Research for helping create the kind of atmosphere conducive to scientific research and for the continuous flow of helpful and other ideas. In particular, I would like to thank Mr. J.A. Keiller for his technical advice and skill in the design and construction of the apparatus used in this project. Above all, I am deeply indebted to Dr. A.L. Hales, Director of the Bernard Price Institute for his practical assistance, encouragement, advice and criticism throughout this work.

Thank you all !

REFERENCES.

Anderson, R.B. and Jenner, R.D., 1954.
A summary of eight years lightning research in Southern Rhodesia.
Trans. S.A. Inst. Elect. Eng., v.45, p.215.

As, J.A. and Zijderveld, J.D.A., 1958.
Magnetic cleaning of rocks in palaeomagnetic research.
Geophys. Jour., v.1, p.308.

Asami, E., 1956.
A palaeomagnetic consideration of the remänent magnetism of the basalt lavas at Kawajiri-misaki, Japan.
Jour. Geomag. and Geoelec., v.8, p.147.

Balsley, J.R. and Buddington, A.F., 1954.
Correlation of reverse remanent magnetism and negative anomalies with certain minerals.
Jour. Geomag. and Geoelec., v.6, p.176.

Blackett, P.M.S., 1952.
A negative experiment relating to magnetism and the earth's rotation.
Roy. Soc. Lond. Phil. Trans., ser.A, v.245, p.303.

Brukshaw, J.McG. and Robertson, E.I., 1949.
The magnetic properties of the tholeiite dykes of North England.
Mon. Not. Roy. Astr. Soc., Geophys. Suppl., v.5, p.308.

Campbell, C.D. and Runcorn, S.K., 1956.
Magnetization of the Columbia River basalts in Washington and Northern Oregon.
Jour. Geophys. Res., v.61, p.449.

Chalmers, J.A., 1957.
Atmospheric electricity.
Pergamon Press.

Clegg, J.A., Almond, M. and Stubbs, P.H.S., 1954.
The remanent magnetism of some sedimentary rocks in Britain.
Phil. Mag., ser.7, v.45, p.583.

Collinson, D.W. and Runcorn, S.K., 1960.
Polar wandering and continental drift: evidence from palaeomagnetic observations in the United States.
Bull. Geol. Soc. Amer., v.71, p.915.

Cox, A., 1957.
Remanent magnetization of lower to middle Eocene basalt flows from Oregon.
Nature, v.179, p.685.

Cox, A., 1961.
Anomalous remanent magnetism of basalt.
U.S. Geological Survey Bull. 1083 - E, p.131.

Cox, A. and Doell, R.R., 1960.
Review of palaeomagnetism.
Bull. Geol. Soc. Amer., v.71, p.645.

Creer, K.M., 1954.
Private communication, published as Creer 1957.

Creer, K.M., 1957.
Palaeomagnetic investigations in Great Britain, V.The remanent magnetization of unstable Keuper marls.
Phil. Trans. Roy. Soc. Lond., ser.A, v.250, p.130.

Creer, K.M., 1959.
A.C. Demagnetization of unstable Triassic Keuper Marls from S.W. England.
Geophys. Jour., v.2, p.261.

Doell, R.R., 1957.
Crystallization magnetization.
Phil. Mag. Suppl. - Adv. in Phys., v.6, p.327.

Du Toit, A.L., 1954.
Geology of South Africa.
2nd Edit., Edinburgh; Oliver and Boyd.

Fisher, R.A., 1953.
Dispersion on a sphere.
Proc. Roy. Astr. Soc. Lond., ser.A, v.217, p.295.

Gelletich, H., 1937.
Über magnetitführende eruptive Gänge and Gangsysteme im mittleren Teil des süidlichen Transvaals.
Beitr. Ang. Geophys., v.6, p.337.

Gough, D.I., 1956.
A study of the palaeomagnetism of the Pilansberg dykes.
Mon. Not. Roy. Astr. Soc., Geophys. Suppl., v.7, p.196.

Gough, D.I. and van Niekerk, C.B., 1959.
A study of the palaeomagnetism of the Bushveld gabbro.
Phil. Mag., v.4, p.123.

Graham, J.W., 1949.
The stability and significance of magnetism in sedimentary rocks.
Jour. Geophys. Res., v.54, p.131.

Graham, J.W., 1953.
Changes of ferromagnetic minerals and their bearing on magnetic properties of rocks.
Jour. Geophys. Res., v.58, p.243.

Graham, J.W., 1955.
Evidence of polar shift since Triassic time.
Jour. Geophys. Res., v.60, p.329.

Graham, J.W., 1956.
Palaeomagnetism and magnetostriction.
Jour. Geophys. Res., v.61, p.735.

Graham, J.W., 1957.
Rock magnetism.
Carnegie Inst. of Washington Year Book, v.56, p.97.

Graham, J.W., Buddington, A.F. and Balsley, J.R., 1957.
Stress-induced magnetizations of some rocks with analyzed magnetic minerals.
Jour. Geophys. Res., v.62, p.465.

Graham, K.W.T., In press.
The remagnetization of a surface outcrop by lightning currents.
Geophys. Jour.

Graham, K.W.T. and Hales, A.L., 1957.
Palaeomagnetic measurements on Karroo dolerites.
Phil. Mag. Suppl. - Adv. in Phys., v.6, p.149.

Graham, K.W.T. and Hales, A.L., In press.
Preliminary palaeomagnetic measurements on Silurian sediments from South Africa.
Geophys. Jour.

Graham, K.W. and Keiller, J.A., 1960.
A portable drill rig for producing short oriented cores.
Trans. Geol. Soc. S.A., v.63, p.71.

Griffiths, D.H., 1955.
The remanent magnetism of varved clays from Sweden.
Mon. Not. Roy. Astr. Soc. - Geophys. Suppl., v.7, p.103.

Griffiths, D.H., King, R.F. and Wright, A.E., 1957.
Some field and laboratory studies of the depositional remanence of Recent sediments.
Phil. Mag. Suppl. - Adv. in Phys., v.6, p.306.

Hallimond, A.F. and Herroun, E.F., 1933.
Laboratory determinations of the magnetic properties of certain igneous rocks.
Proc. Roy. Soc. Lond., ser.A., v.141, p.302.

Hospers, J., 1953-1954.
Reversals of the main geomagnetic field.
Proc. Kon. Ned. Akad. Wet., ser.B. v.56, p.467; v.56, p.477; v.57, p.112.

Hospers, J., 1954b.
Summary of studies on rock magnetism.
Jour. Geomag. and Geoelec., v.6, p.172.

Hospers, J. and Charlesworth, H.A.K., 1954.
The natural permanent magnetization of the lower basalts of Northern Ireland.
Mon. Not. Roy. Astr. Soc. - Geophys. Suppl., v.7, p.32.

Irving, E., 1954.
Private communication, published as Irving 1957.

Irving, E., 1957.
Palaeomagnetic investigations in Great Britain, III. The origin of the palaeomagnetism of the Torridonian Sandstones of North-West Scotland.
Phil. Trans. Roy. Soc. Lond., ser.A., v.250, p.100.

Irving, E., 1958.
Palaeogeographic reconstructions from palaeomagnetism.
Geophys. Jour., v.1, p.224.

Johnson, E.A., Murphy, T. and Torreson, O.W., 1948.
Pre-history of the earth's magnetic field.
Terr. Mag. & Atm. Elect., v.53, p.349.

Johnson, E.A., Murphy, T. and Michelsen, P.F., 1949.
A new high sensitivity remanent magnetometer.
Rev. Sci. Instr., v.20, p.429.

Kawai, N., 1954.
Instability of natural remanent magnetism of rocks.
Jour. Geomag. and Geoelec., v.6, p.208.

King, R.F., 1955.
The remanent magnetism of artificially deposited sediments.
Mon. Not. Roy. Astr. Soc. - Geophys. Suppl., v.7, p.115.

Kritzinger, J.J., 1961.
High-current pulse testing.
Trans. S.A. Inst. Elec. Eng., v.52, p.67.

McNish, A.G. and Johnson, E.A., 1938.
Magnetization of unmetamorphosed varves and marine sediments.
Terr. Mag. and Atm. Elec., v.43, p.401.

Nagata, T., 1953.
Rock Magnetism.
Tokyo, Japan, Maruzen Co. Ltd.

Nagata, T., Akimoto, S., Uyeda, S., Momose, K. and Asami, E., 1954.
Reverse magnetization of rocks and its connection with the geomagnetic field.
Jour. Geomag. and Geoelec., v.6, p.182.

Nagata, T., Uyeda, S. and Ozima, M., 1957.
Magnetic interaction between ferromagnetic minerals contained in rocks.
Phil. Mag. Suppl. - Adv. in Phys., v.6, p.264.

Nagata, T., Akimoto, S., Uyeda, S., Shimizu, Y., Ozima, M. and Kobayashi, K., 1957.
Palaeomagnetic study on a Quarternary volcanic region in Japan.
Phil. Mag. Suppl. - Adv. in Phys., v.6, p.255.

Nairn, A.E.M., 1960.
A palaeomagnetic survey of the Karroo System.
Overseas Geology and Min. Resources, v.7, p.398.

Néel, L., 1955.
Some theoretical aspects of rock magnetism.
Phil. Mag. Suppl. - Adv. in Phys., v.4, p.191.

Rimbert, F., 1958.
Contribution à l'étude de l'action de champs alternatifs sur aimantations rémanentes des roches. Applications géophysiques.
Thesis, Faculty of Science, University of Paris.

Runcorn, S.K., 1950.
Rock magnetism - geophysical aspects.
Phil. Mag. Suppl. - Adv. in Phys., v.4, p.244.

Runcorn, S.K., 1954.
The earth's core.
Trans. Amer. Geophys. Un., v.35, p.49.

Schonland, B.F.J., 1956.
The lightning discharge.
Encyclopedia of physics, v.22, p.36.

Stacey, F.D., 1960.
Magnetic anisotropy of igneous rocks.
Journ. Geophys. Res., v.65, p.2429.

Stott, P.M. and Stacey, F.D., 1960.
Magnetostriction and palaeomagnetism of igneous rocks.
Jour. Geophys. Res., v.65, p.2419.

Uyeda, S., 1958.
Thermo-remanent magnetism as a medium of palaeomagnetism, with reference to reverse thermo-remanent magnetism.
Japanese Jour. Geophys., v.2, p.1.

Van Niekerk, C.B., 1959.
A petrographical study of certain dykes of Pilansberg age intrusive into the Witwatersrand System.
Unpublished thesis, Faculty of Science, University of Pretoria.

Vellet, V., 1957.
The application of the "Stereographic Projection" to problems of Structural Geology.
Annals of the University of Stellenbosch, v.33A, p.331.

Vincent, H.C.G., 1954.
An accessory to the polarizing microscope for the optical examination of crystals.
Mineral.Mag., v.30, p.513.

Walker, F. and Poldervaart, A., 1949.
Karroo dolerites of the Union of South Africa.
Bull. Geol. Soc. Amer., v.60, p.591.