A Thesis

entitled

A PALAEOMAGNETIC STUDY OF SOME EAST AFRICAN ROCKS

by

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ABSTRACT

This thesis presents the results of palaeomagnetic studies made on the Tertiary volcanics of Turkana (North-West Kenya) and of the Central Rift. The rocks studied span the period Miocene to Pleistocene and consists of different types such as basalts, phonolites, rhyolites and trachytes. Stability tests conducted on these samples have shown that rock samples with high Q_n values and low Curie points are best suited for palaeomagnetic studies. Measurement of initial susceptibilities of rock samples and low field hysteresis studies have revealed the phenomenon of "disaccommodation" in some of them. This has been found to be one of the causes of the erratic behaviour of these rocks during A.F. demagnetization.

In the Lokitaung gorge where extensive sampling was done, reverse polarities are found to be dominant over the period from the middle of the lower basalt to the beginning of the rhyolite extrusion suggesting a field reversal during this period. Evidence from two dykes and their baked contacts supports this hypothesis of field inversion.

Calculation of the pole from the mean direction obtained from 62 sites (30 normal and 32 reversed) from Turkana indicates a shift of approximately 5 degrees from the geographic pole. This is in agreement with a similar shift obtained by Mr. T.A. Reilly (1968) for the rift volcanics of the age group 10 - 14 m.y. from south of equator. However, at this stage it cannot be stated categorically whether this indicates a polar movement or a clockwise rotation of the continent of Africa.

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CHAPTER 1

INTRODUCTION

Palaeomagnetic studies carried out by various workers during the past twelve years have significantly contributed towards the understanding of several geological and geophysical phenomena. One of the basic assumptions made in interpreting the data is that the mean geomagnetic field has always been dipolar and geocentric and that rocks retain in them a record of the geomagnetic field prevailing at the time of their formation. On this assumption palaeomagnetic data have been used for studies such as continental drift and polar wandering (Blackett et al 1960, Athavale et al 1963, Irving 1964 and McElhinny et al 1968). Palaeo-climatological studies carried out by Blackett (1961) and by Opdyke (1962) have given evidence in support of the conclusions arrived at on the basis of palaeomagnetic data.

Palaeomagnetic data has also been used as a tool for stratigraphic correlation of lava flows across large distances and as an alternative method of determination of the ages of lava. Thus Radhakrishnamurty (1963) has arrived at the conclusion that dykes of Damodar Valley and Mahanadi Valley are contemporaneous in origin with Rajmahal traps. McElhinny and Opdyke (1964) have used palaeomagnetic evidence to conclude that the Pre-Cambrian dolerites of Eastern Southern Rhodesia were formed at two distinct periods.

The hypothesis of geomagnetic field inversions in the past depends on palaeomagnetic evidence. Radiometric dating combined with polarity determinations of stable rocks have enabled Cox et al (1963) and McDougall and Chamalaun (1966) to construct a geomagnetic polarity scale extending to 4 m.y.

Very little previous palaeomagnetic work has been done on the rift volcanics from Kenya, East Africa. Nairn (1964) has published results based on measurements made on a few samples collected from Nairobi, Naivasha, Nakuru and Kisumu. Patel (1968) carried out a study on the Kapiti phonolites and has shown the existance of both normal and reversed polarities in these lava.

During the years 1963-66 a large number of samples were collected from the rift volcanics. This thesis presents the results of palaeomagnetic study conducted on the extensive collections from Turkana (N.W. Kenya) and on the samples collected from the central rift on a reconnaissance basis.

In order to interpret the palaeomagnetic results correctly it is essential that the directions of magnetization obtained from rocks should be the same as those of the dipole field at the time the rocks were formed. Very often this direction will be masked by secondary magnetizations the rocks acquire subsequent to their formation. It is, therefore, necessary to "clean" the rocks so as to recover the primary directions. During the course of this process of cleaning by alternating field (A.F.) demagnetization, it was noticed that a few specimens behaved erratically. A study of the magnetic properties of the rocks showed that these rocks exhibited the phenomenon of "disaccommodation" which is described in Chapter 5.

The rocks sampled span the period Miocene to Pleistocene. Both normal and reversed flows were found in them suggesting geomagnetic field reversals in the past. Investigation of bulk magnetic properties such as Curie points, saturation remanence and low field susceptibility has not shown any significant difference in them for reversed and normal lavas. Self reversals though not completely ruled out cannot account for the reversed polarity of these lavas. Further, the identical directions obtained from two dykes and their baked contacts strongly support the hypothesis of field reversal during Miocene period.

The ages of rock samples collected from Turkana range from 12.5 - 33 m.y. (Reilly et al 1966). It can hardly be expected that during this short period, the continent of Africa has significantly drifted. The present study has, however, enabled to detect a small polar movement. It is significant that the same degree of shift of the pole compared to the geographic pole was also obtained by Reilly (1968) from the volcanics of 10 - 14 m.y. of age from the Southern rift. The new palaeomagnetic pole position for the Turkana lavas obtained from this work may be of importance as recording the last stage of the movement of Africa into its present position.

Thus, as can be seen from the chapters following, this study has enabled:

(a) to establish a palaeomagnetic pole for Turkana,
(b) to obtain useful information regarding stability criteria,
(c) to show that no significant differences exist between the bulk magnetic properties of normal and reversed lavas
(d) to produce evidence from two baked contacts in favour of field reversals as the origin of reversed magnetization in rocks, and
(e) to infer that field reversals must have occurred as frequently in the Pliocene period as in the last 3.6 m.y.

CHAPTER 2

GEOLOGY, SAMPLING AND MEASUREMENT

2.1 Introduction The East African rift system stretches from the Mediterranean Sea in the north to the Zambesi River in the south - a distance of over 6000 Km. It is now believed that this system is related to a major world wide tectonic feature, a good part of the evidence for which, such as the mid-ocean ridges and associated rift valleys, is concealed beneath the seas. Nowhere else is it so much exposed to the surface as in East Africa.

The Kenya rift system consists of a main rift called the Gregory Rift which runs from north to south and a branch rift called the Kavirondo Rift traversing east-west into Lake Victoria. Turkana (N.W. Kenya) where most of the sampling was done falls within the north zone of the Gregory Rift.

2.2 Geology of Turkana Geological survey and mapping of the above area was done in 1963 by J. Walsh and R.G. Dodson (1968) on the basis of a reconnaissance and they have suggested the following succession.

Rhyolites and andesites	Upper Miocene
Olivine basalts	
Phonolites and nephelinites	
Augite and analcime basalts	
Turkana Grits	Lower Miocene
Basement System	Pre-Cambrian

<u>Basement System</u> The metamorphosed sedimentary rocks constituting this system are the oldest in the area and are supposed to be of Pre-Cambrian age.

<u>Turkana Grits</u> It is believed, on the basis of Palaeontological evidence from vertebrate fossils and fossil wood of <u>Dryoxylon</u> series, that the Turkana Grits were laid down during early Miocene sedimentation which occurred over many parts of northern and western Kenya.

<u>Augite and analcime basalts</u> This succession referred to as lower basalts, is exposed in a continuous section from near the mouth of the Lokitaung gorge to west of Lokitaung township. It is tilted at about 15° to west, south-west and consists of about 6000 feet of lavas. The rock is of fine grained texture and is composed of augite and plagioclase, with analcime occurring in some of them. The lower basalts were extruded after the deposition of Turkana Grits. The contact between the two is usually unconformable.

<u>Olivine basalts</u> According to the above authors, olivine basalts (which will henceforth be mentioned as upper basalts) are only locally developed. Intercalations of thin rhyolite flows are seen in topmost part of the upper basalt sequence about four miles north-west of Lokitaung and east of Lokwanamur. Similar conformable intercalations between rhyolites and underlying lower basalts were also seen by Walsh and Dodson (1968) in an area where upper basalts are not seen. These suggest that both upper and lower basalts were extruded at the start of the rhyolite emplacement. Nowhere was augite basalt seen overlying olivine basalts.

Phonolites and nephelinites These rocks overlie the lower basalts in some places, but are nowhere found to be in contact with the upper basalts. They are considered to be younger than both types of basalts and of the same age as the Kapiti phonolites. Potassium-Argon dating has confirmed this. Neither basalts nor rhyolites were seen to overlie phonolites or nephelinites.

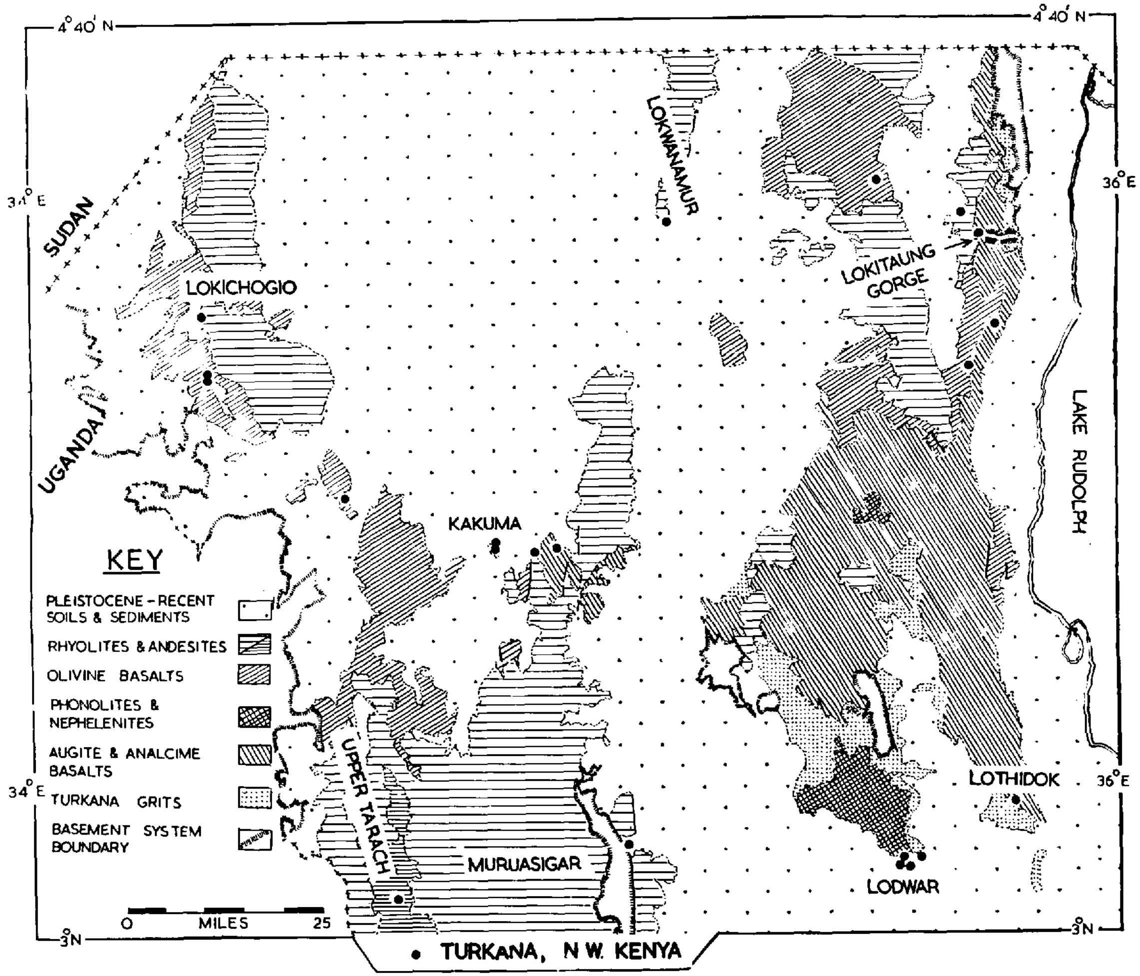
Rhyolites All the major mountain ranges in the area are capped by rhyolites. Fairburn and Matheson (1968) have subdivided the rhyolite succession into two groups, a lower Muruasigar series separated from the upper Puch Prasir series by an andesite group. It is, therefore, significant as will be shown in Chapter 7, that the rhyolites collected from the Lokitaung area were different in magnetic properties from those sampled from south west (Tarach). Whereas all the rhyolite samples from Lokitaung were magnetically weak and reversed in polarity, those from Tarach were of medium intensity and normal in polarity. It is, therefore, likely that these two types belong to two different age groups.

General Petrology Within each stratigraphic unit there is much variation in composition, grain size, vesicularity etc. Weathering and mechanical breakdown are common in the lower basalts and these occur to a lesser degree in other units. The occurrence of secondary minerals such as iron ores, quartz, calcite, uralite and chlorite is common and the glassy ground mass of many of the rhyolites is often devitrified. Intercalated pyroclastics and sediments are found to occur most commonly in the lower parts in the succession.

2.3 Sampling   Oriented samples were collected either as blocks or as cores using a portable drill similar to that of Graham and Keiller (1960). The areas where the various stratigraphic units of lava were sampled are broadly illustrated in Fig.2A. In block sampling a template with two Abney levels mounted in perpendicular directions was used. The positions of the three feet of the template could be marked with white ink on the block and with the help of the Abney levels the dips of the block in two perpendicular directions could be read. The orientation of a scratch made on the rock is read by means of a theodolite mounted about ten to fifteen feet away from the block. Whenever possible, the sun's azimuth was used as a check of the magnetic orientation. The difference between the bearings calculated by the two methods was in no case found to be more than 2°. With the above drill, cores of 7/8 inch in diameter and about 6 - 7 inches in length could be collected.

Samples were collected on two occasions. During the first trip in 1963, about 65 samples - many of them as cores - were collected. A second trip was made in 1965 and this time about 200 blocks were collected. The polarities of many of these were checked in the field using a portable astatic magnetometer, so that further detailed sampling could be done from areas of mixed polarity.

A comparison of the two methods of sampling rocks for palaeomagnetic purposes is given by Gough (1967). It should be mentioned that in areas like Turkana, where transport poses such a difficult problem, it is advantageous to resort to a drilling method. Further, by drilling cores, orientation errors could be minimised and surface effects reduced. On the other hand block collection is faster and several sites could be covered in a day, thereby saving a few days of work in the field.

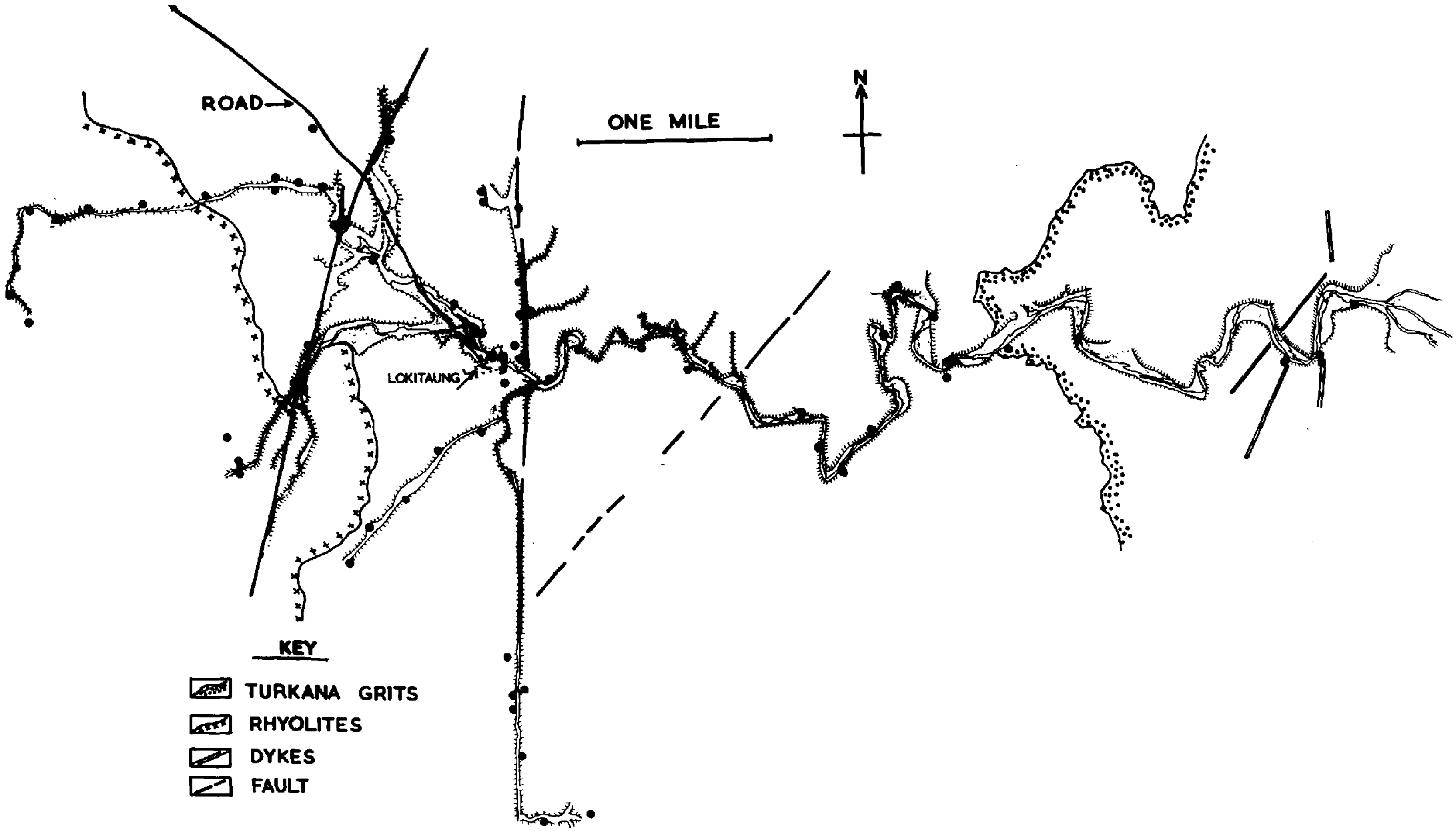


FIG·2A-GEOLOGICAL SKETCH MAP OF THE TURKANA AREA - STRATIGRAPHIC UNITS & SAMPLING SITES

As mentioned earlier, the lava succession is best seen in the Lokitaung gorge where about 6000 feet of lavas and pyroclastics and sediments are exposed. Extensive collection of samples was made from this area and the collecting sites are shown in Fig.2B. At least two samples from each site were collected. They were usually spaced at least six feet apart so that lightning effects, if any, will not be the same for both the samples.

Cores 7/8" diameter were taken from the block samples and specimens 1" in length were cut from them. This specimen size was found by Roy (1963) to be most suited for measurement under the astatic magnetometer. Cores from the same block or from the same site were marked with alphabets A, B, C etc. Thus 273 A, 273 D and 273 F denote cores cut from the same block 273. Specimens cut from the same cores were given numerical suffixes in the serial order starting from the top of the core. Thus 320 A_1 and 320 A_2 are two specimens cut from core A from sample 320, the first specimen being from the surface and the other one being immediately below the first.

2.4 <u>Measurement of direction and intensity</u> The directions of natural remanent magnetization (NRM) of the specimens and their intensities were measured under an astatic magnetometer. Initially, the X, Y and Z components of the magnetic vector were measured for all the orthogonal directions and then averaged. But later it was possible to perform the measurement quickly, by spinning the specimen under the astatic magnetometer as suggested by Dr. R.L. Wilson (1966, Pers. Communication). In this case only one measurement was necessary for each component.



FIG· 2B - LOKITAUNG GORGE - SAMPLING SITES

2.5 CENTRAL RIFT - GEOLOGY AND SAMPLING

Sampling of lavas from the central rift was done on a reconnaissance basis and in all except two areas, not more than two or three samples were collected from each stratigraphic unit. The areas sampled lie between Long.34.7°E - 37.5°E and Lat.0.7°S - 0.5°N with the exception of Loperot from where lavas were sampled from a locality 36°E and 2.3°N. The various stratigraphic units are divided into three groups based on stratigraphic grouping of Kenya volcanics done by Williams (1965).

Group I	
Loperot Pleistocene Lava	Plio-Pleistocene
Marsabit Lava	
Mbaruk Basalt	
Thiba Basalt	
Gilgil Volcanics	
Londiani Trachyte	
Kabernet Trachyte	
Naivasha Trachyte	

Group II	
Laikipian Basalt	Pliocene
Nyeri Tuff	
Thomsons Falls Phonolite	

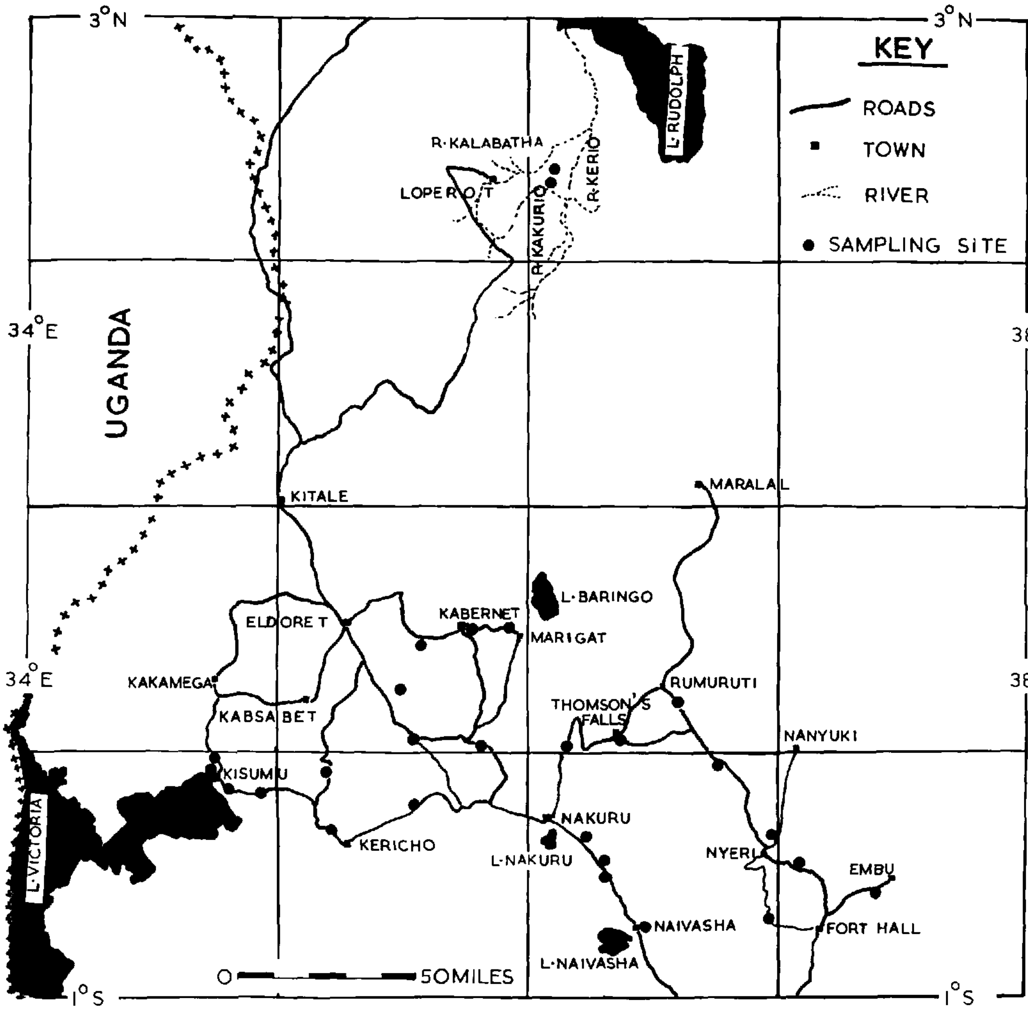
Group III

Kisumu Phonolite	Upper Miocene
Kericho Phonolite	
Loperot Miocene Lava	
Samburu Basalt	
Rumuruti Phonolite	
Uasin Gishu Phonolite	

As sampling was done in some detail in the Kisumu phonolites and the Loperot lava, a brief geology of both areas will be given below.

Kisumu phonolites   Kisumu falls within the zone of the Kavirondo Rift. Phonolitic lavas cover wide areas in this region. Saggerson (1952) has divided the phonolites into three petrographic groups, the Kenya type, the Losaguta type and the Kericho type. K-Ar datings done on the Kenya and Kericho type by J.A. Miller (1966?) gave an age of 12.3 $\pm$ 0.2 and 12.4 $\pm$ 0.2 m.y. respectively, a little younger than the Kapiti phonolites. Altogether, 12 samples were collected covering the three types.

Loperot lava   The Pleistocene lava samples collected were from a thin basaltic flow capping the Kanopoi Pleistocene sediments. The area was recently surveyed by Patterson (1966) and K-Ar dating done by Geochron Laboratories gave an age of 2.9 $\pm$ 0.3 m.y. Further dating was done by Geochron Laboratories and an age of 2.5 $\pm$ 0.2 m.y. was obtained (Patterson and Howells 1967). This age is considered by the authors as the more reliable one because of the much smaller atmospheric argon correction. A few samples of Miocene lava overlying the Turkana Grits were also collected from a nearby area. It is believed that this series is an extension of the Turkana basalts in the north. Fig.2C shows the collecting sites.



FIG· 2C - MAP OF CENTRAL RIFT SHOWING SAMPLING SITES.

CHAPTER 3

STABILITY TESTS

3.1 Introduction The direction and intensity of primary magnetization of rocks are very often altered by the addition of secondary components since the rocks were formed. The variations are caused from a number of sources of which the main ones are

a) Isothermal magnetization acquired in the geomagnetic field
b) Partial thermo-remanence due to heating of rocks
c) Isothermal remanent magnetization due to lightning discharges
d) Chemical magnetization due to weathering.

One of the basic assumptions on which interpretations of palaeomagnetic results are based is that igneous rocks take up the direction of the prevalent geomagnetic field when they cool through the Curie point. Therefore the success of palaeomagnetic studies depends upon the recovery of the remanent magnetization the rocks acquired at the time of their formation and on the stability of this remanent magnetism.

Two kinds of tests are usually employed to assess the magnetic stability of rocks. They are (1) Field Tests and (2) Laboratory Tests. The "Fold" and "Conglommerate" tests proposed by Graham (1949) come under the first category and since they could be applied only in special cases they have not been applied in the present study. The "Baked contact" test which is also a field test for stability has been applied in two cases and this will be described in a later chapter.

3.2 Laboratory tests   Progressive demagnetization of the rock specimen either by alternating field or by step-wise heating are the two routine methods employed in Palaeomagnetism to test the stability of rocks in the laboratory. The advantage of both these tests is that, in addition to indicating the magnetic stability in rocks, they also remove the unwanted secondary magnetization and thus permit the recovery of the primary magnetization.

3.3 A.F. demagnetization   Directions of natural remanent magnetizations and intensities of rocks measured under an astatic magnetometer showed high degree of scatter suggesting the presence of secondary components. It was, therefore, necessary to "clean" the specimens. Most of the specimens were cleaned by subjecting them to alternating fields in a manner similar to the one described by McElhinny and Gough (1963). The specimen was rotated at the centre of a solenoid which could produce a peak alternating field of 1200 Oersteds. The tumbling ratio used was 9:13 which is very nearly equal to the ratio of 11:16 recommended by McElhinny (1966) as having some advantage over ratios used by other workers. The cube holding the specimen was rotated about a vertical axis at approximately 100 revolutions per minute. The tumbling mechanism enables different parts of the specimen to be subjected successively to A.F. demagnetization and also assures that there is no preferential demagnetization in any one direction. Smooth reduction of the field from the peak value to zero was achieved by reducing the current in the solenoid slowly by means of a water potentiometer, the time taken for one complete run being about 3-4 minutes.

At least one specimen from each site was progressively demagnetized in steps in peak fields of 50, 100, 200, 300 .... 1000 Oe. and the directions and remanent intensity measured under the astatic magnetometer after each demagnetization. A majority of specimens showed initial changes in directions which remained stable even when the field was increased by a few hundred Oersteds. On further increasing the field the directions scattered in many cases. However, a number of specimens gave the same directions even after demagnetizing in fields of 800 or 900 Oe. A field slightly more than the minimum required to give the stable direction for the pilot specimen was then chosen as the field for cleaning and all the specimens from the site were then demagnetized in this field.

Table 1 explains this method of demagnetization.

In some cases it was noticed that specimens cut from the surface of the sample required a field of about 50-100 Oe. more than the specimens lower down. This is probably due to the fact that secondary magnetization affected specimens from the surface region more than the ones at the bottom.

Fig.3A illustrates the typical changes in direction of a few specimens during A.F. demagnetization. As can be seen, the initial directions were very different from the cleaned directions which showed little change even when the peak field required for cleaning was increased by a few hundred Oersteds.

TABLE 1

Specimen No.	NRM Directions		Direction after demagnetization in peak fields of													
			50 Oe.		100 Oe.		200 Oe.		300 Oe.		400 Oe.		500 Oe.		600 Oe.	
	D	I	D	I	D	I	D	I	D	I	D	I	D	I	D	I
192 A_2	249	-42	229	-34	203	-13	195	- 5	193	- 3	193	- 2	193	- 1	195	- 1
A_1	233	-36							192	- 3						
193 A_2	181	-60							177	- 2						
608 D_1	156	1	169	14	165	14	176	14	182	12	184	16			157	13
G_2	176	2							182	12						
H_1	171	12							184	11						
736 B_1	187	-14	187	-13	187	-14	186	-13	186	-13	185	-13	185	-13		
C_1	182	-17									180	-16				
738 A_2	162	- 6									182	-13				
D_2	170	- 5									173	- 9				
674 D_1	175	- 4	178	- 3	178	- 3	178	- 2	178	- 2	177	- 2	176	- 2	173	- 5
B_1	172	- 6					176	- 3								
A_1	175	- 6					175	- 4								
673 B_1	231	-58					186	-12								
B_2	202	-74					179	- 6								
C_2	102	-56					193	-16								
663 A_5	11	- 7	8	2	5	4	4	5	3	5	3	5	3	13		
A_4	6	- 9							0	7						
A_1	106	18							5	5						

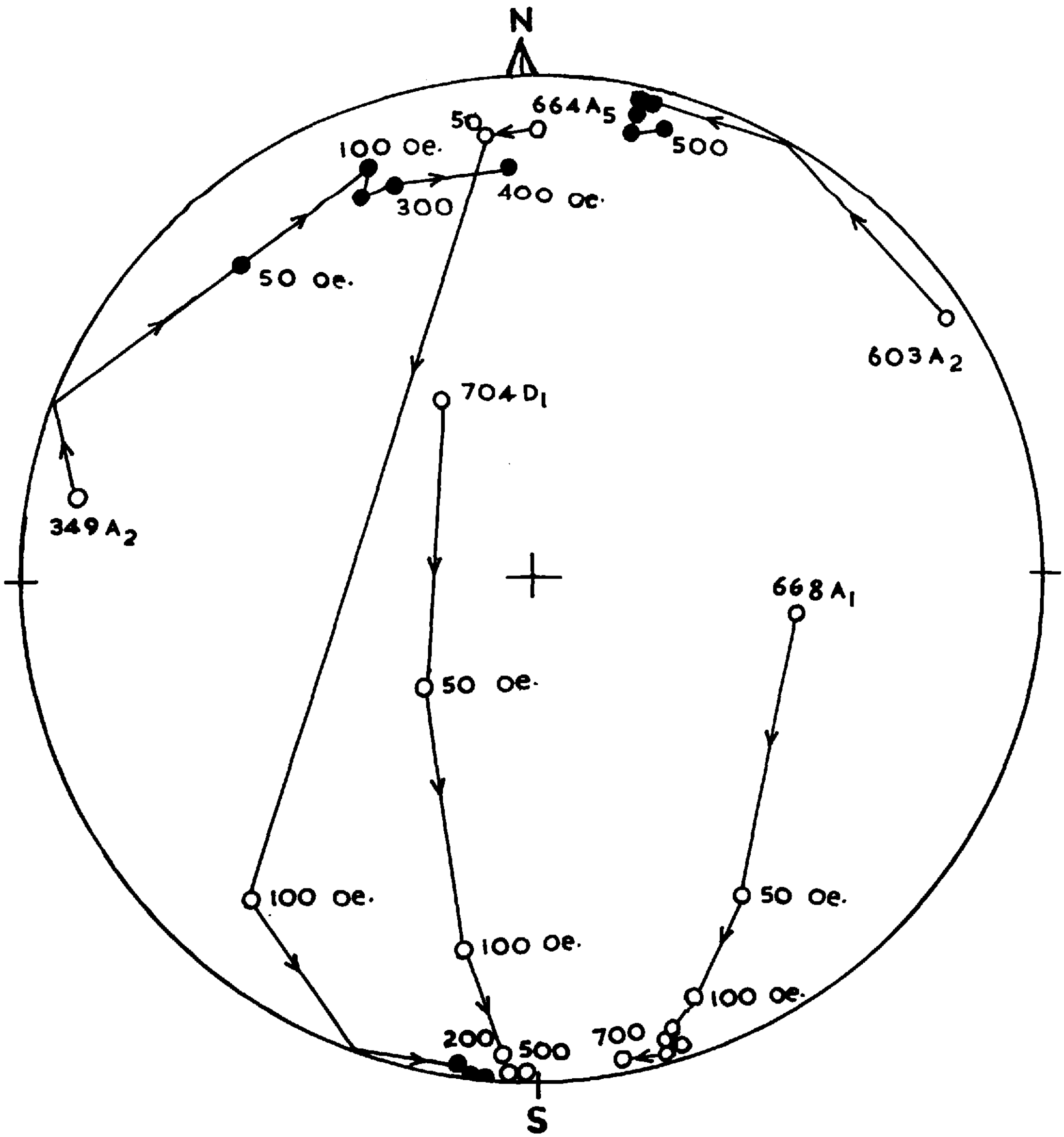


FIG. 3A – POLAR PROJECTION OF TYPICAL CHANGES OF DIRECTION DURING A.F. DEMAGNETIZATION.

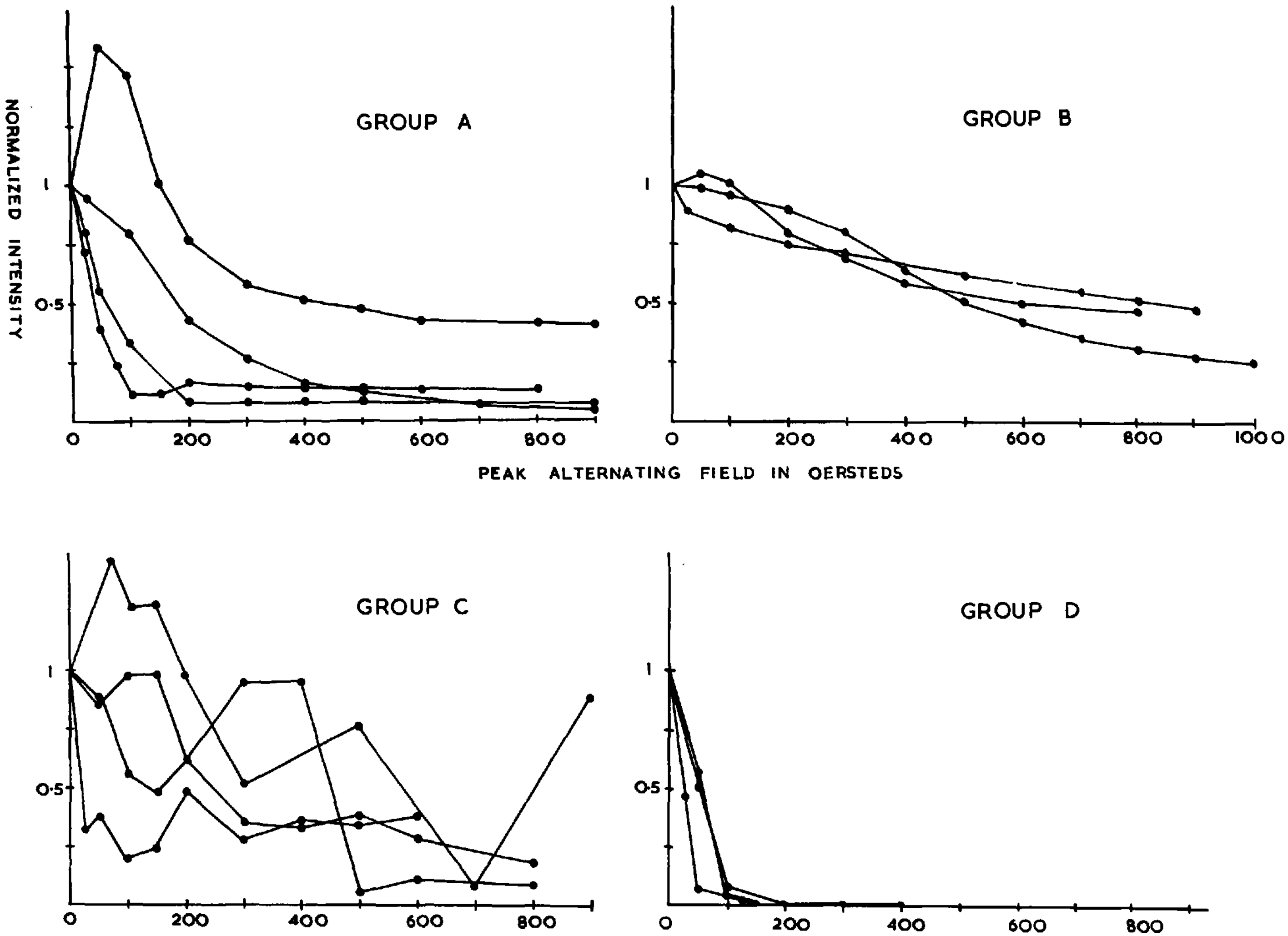
● DIPS DOWN; o DIPS UP

3.4 <u>Demagnetization curves</u> When the normalized intensities of the demagnetized specimens were plotted against the demagnetizing fields, the curves were found to fall roughly into four groups as in Fig.3B.

The curves of Group A show an initial rapid change of intensity in low fields, thereafter showing little change. This could be attributed to the removal of a soft secondary component making an arbitrary angle with the stable primary component. This group consists mainly of basalts and phonolites and nephelinites. Most of the specimens of this group required fields less than 300 Oe. for successful cleaning.

Rhyolites, trachytes, agglommerates and sediments, gave in general, the type of curve shown by Group B. The gradual decrease in intensity indicates that the ferromagnetic grains in these rocks possess a broader coercive force spectrum than in the basaltic rocks. The remanent intensity of these specimens was more than 25% of the initial intensity even after demagnetization in peak fields of 1000 Oe. A large number of the specimens in this group showed little change in direction on demagnetization. It should, therefore, be assumed that rocks giving such curves have little or no viscous component in them. This was also noticed by Uyeda (1958).

The Group C curves are characterised by fluctuations in intensity. Many of the specimens belonging to this group showed irregular changes in direction during demagnetization and it was not possible to obtain a stable direction. These specimens, therefore, had to be rejected as being unstable. Low field hysteresis behaviour of some of these specimens gave some indication as to the cause of the fluctuations in intensity. An account of these experiments is given in Chapter 5.



FIG·3B – TYPICAL ALTERNATING FIELD DEMAGNETIZATION CURVES

3.5 Effects of lightning The intensity of the specimens represented by Group D curves falls off rapidly to less than 1% of their initial intensity even in as low a field as 100 Oe. The following observations suggest that specimens of this group might have acquired strong isothermal magnetization from lightning currents.

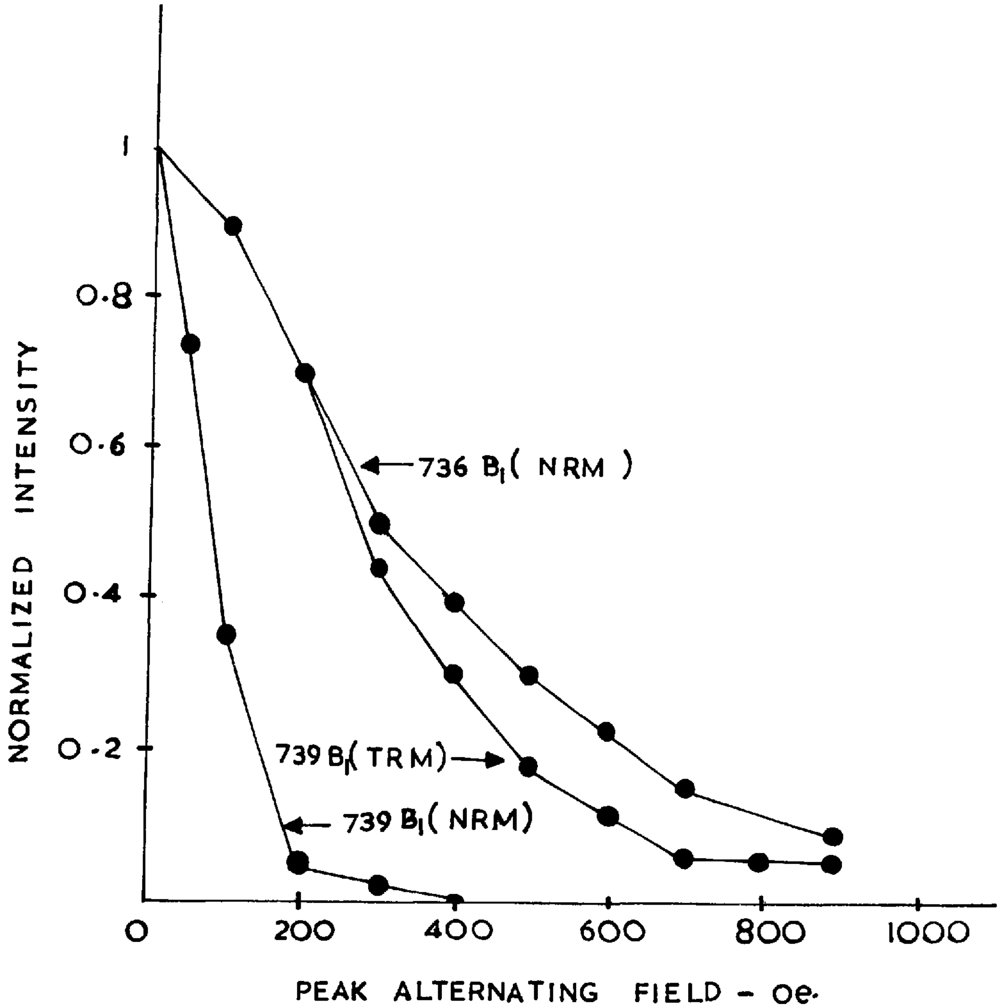
1 High intensities of the order of 200 x 10^{-4} emu/gm and more
2 Directions of magnetization very different from nearby samples of normal intensity
3 Steep dips
4 A majority of such specimens could not be cleaned even in fields of the order of 1000 Oe. whereas specimens from samples collected nearby, from distances of about 10 ft. could be cleaned in a few hundred Oersteds.

Similar effects of lightning were noticed by McElhinny and Gough (1963), McElhinny and Opdyke (1964) and Graham (1961).

Two typical examples are given in Table 2. Samples 607 and 736 were collected only a few (about 10) feet away from 606 and 739 respectively.

TABLE 2

Specimen No.	NRM Direction D°	NRM Direction I°	Intensity $\times 10^4$ (emu/gm)	Cleaned Direction D°	Cleaned Direction I°
606 A_1	150	-50	3000	Did not clean even in 1200 Oe.	
B_1	146	-22	5780	Did not clean even in 1200 Oe.	
607 A_2	20	-13	11.0	187	5 (100 Oe.)
B_1	12	- 4	14.6	181	5 (100 Oe.)
C_1	358	- 5	10.5	181	6 (100 Oe.)
739 A_1	224	-37	309.8	Did not clean	
B_1	218	-34	307.3	Did not clean	
736 B_1	187	-14	31.5	185	-13 (100 Oe.)
C_1	182	-17	31.8	180	-16 (100 Oe.)



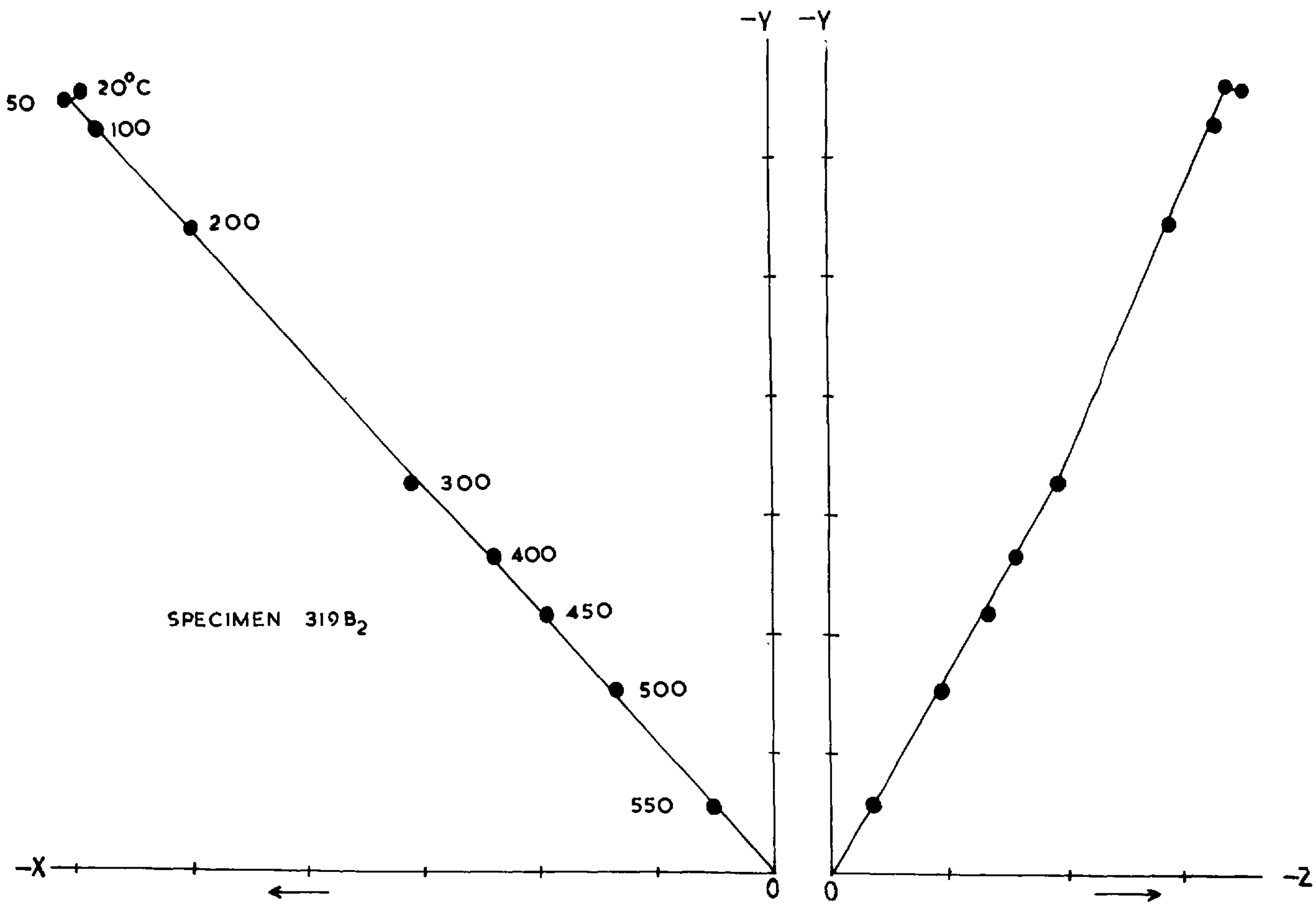
FIG·3C - A·F· DEMAGNETIZATION CURVES OF NRM AND TRM OF A SPECIMEN AFFECTED BY LIGHTNING·

Fig.3C shows A.F. demagnetization curves of NRM of a specimen from the sample 739 and of TRM given to it by heating it to above its Curie point and cooling in the earth's field. The TRM intensity was only about a twentieth of the natural intensity. Further, the shapes of the two curves are different, the one for NRM indicating a high IRM component. Compared to this, the demagnetization curve for NRM of 736 B_1 (specimen from sample a few feet away from 729) is almost identical to the TRM demagnetization curve. It must, therefore, be concluded that sample 739 must have acquired a large IRM probably from lightning currents.

3.6 Thermal demagnetization Progressive thermal demagnetization of about 50 carefully chosen specimens was carried out with a view to study their magnetic behaviour and also to check the directions of magnetization obtained by thermal cleaning with those of A.F. cleaning. This was done partly in India using the furnace built by Radhakrishnamurty and Sahasrabudhe (1965) and partly at Nairobi using the Vector tube furnace designed and built by Mussett and Reilly (1968, unpublished).

Measurements of the X, Y and Z components of the magnetic vector were made in steps at progressively higher temperatures whilst the specimen was being heated in the furnace mounted under the astatic magnetometer. The directions in specimens at high temperatures were deduced using vector diagrams as described by Wilson (1960).

Figs.3D and 3E show two such diagrams, one for a very stable specimen which hardly changed its direction and the other for a specimen which had a large secondary component. The direction in the latter changed considerably because of the disappearance of the secondary component.



FIG·3D – VECTOR HEATING DIAGRAM FOR A STABLE SPECIMEN

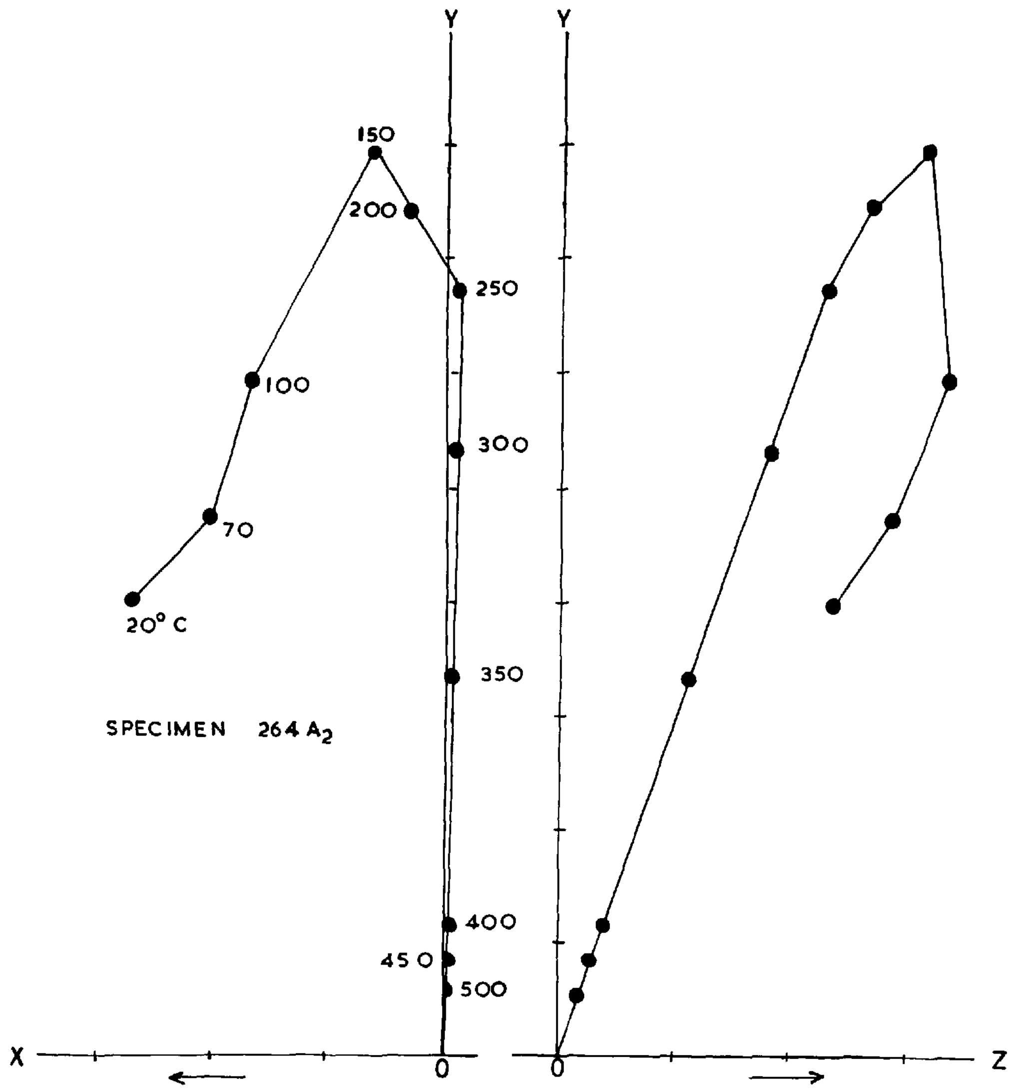


FIG. 3E - VECTOR HEATING DIAGRAM FOR A SPECIMEN WITH SECONDARY COMPONENT.

3.7 <u>A.F. and thermal demagnetization - a comparison</u> Fig.3F shows the stereographic projections of the directions of magnetization in 48 specimens from 24 samples cleaned either thermally or by A.F. demagnetization. One specimen from each sample was cleaned by both methods. The good agreement in the directions indicates that both methods are equally effective in removing unwanted secondary magnetizations. It is clear that thermal demagnetization may prove to be ineffective in removing secondary magnetization if the blocking temperature of the domains is near or at the Curie point. In such cases A.F. demagnetization alone will be effective. On the other hand, if a specimen is unstable and exhibits the phenomenon of "disaccommodation", thermal demagnetization will prove more effective in cleaning than the A.F. technique. It should also be mentioned that, whereas heating produces magnetic and chemical changes in some rocks, A.F. demagnetization does not produce such irreversible changes in rocks.

Wilson (1960) noticed that spurious magnetization was superimposed on the remanent one in specimens during A.F. cleaning and, therefore, found it difficult to obtain a final direction on A.F. demagnetization. As stated earlier, in many rocks the directions fluctuated on increasing the demagnetizing field by more than 200 - 300 Oe. of the peak field required to give the stable direction. In the case of stable and partially stable rocks it was always possible to obtain this stable direction before the onset of fluctuations. It was noticed that in the case of a number of stable rocks, it was possible to deduce the 'cleaned' directions from vector diagrams similar to the vector heating diagrams.

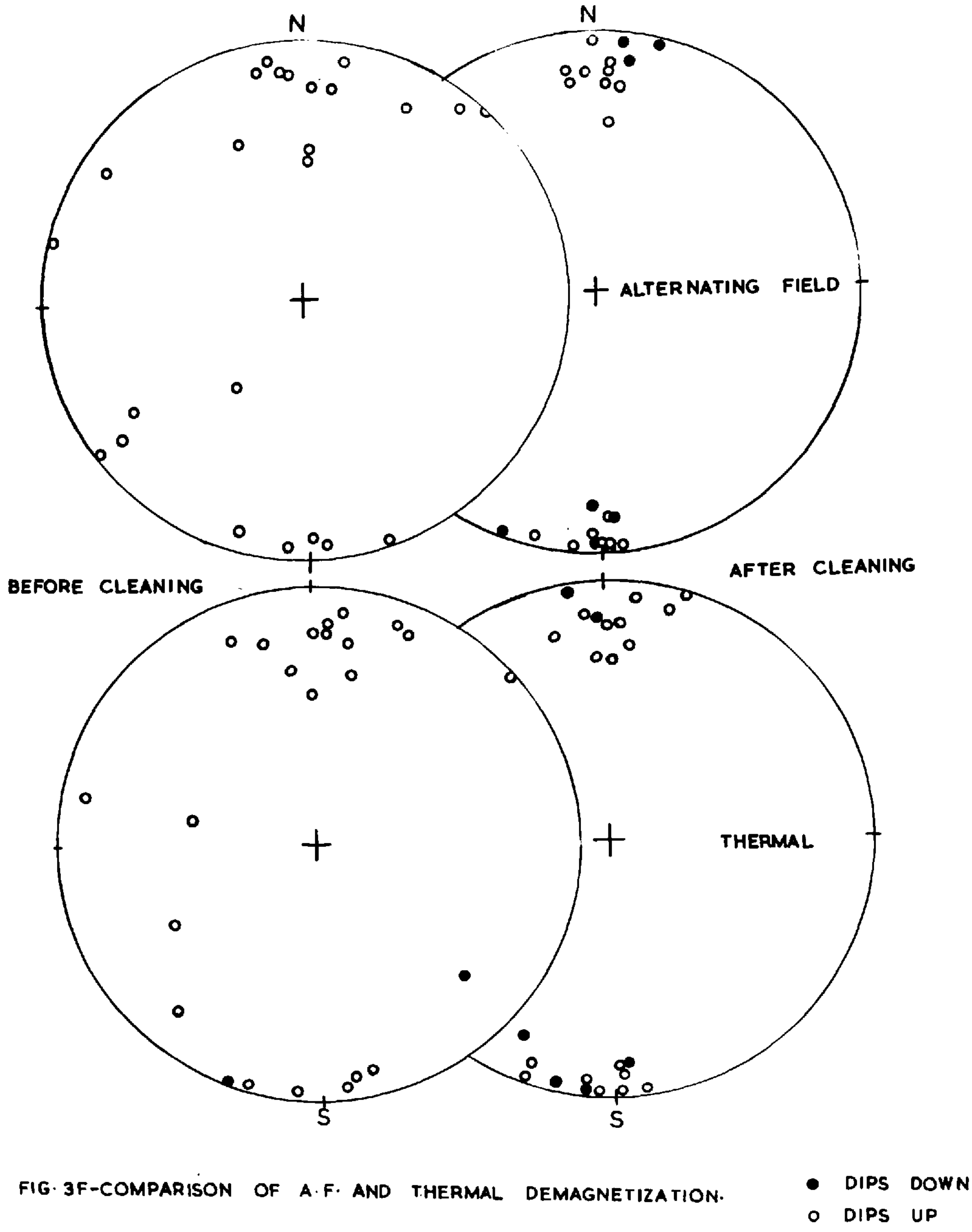


FIG. 3F—COMPARISON OF A.F. AND THERMAL DEMAGNETIZATION.

This is illustrated by Figs.3G, and 3H. Specimen 314 A_2 is a stable one and has very little secondary component in it as indicated by little or no change in direction during demagnetization. A vector diagram for thermal demagnetization of this specimen and a similar diagram for A.F. demagnetization of 314 A_3 are given for comparison. Stable and identical directions were obtained by both methods. Fig.3H is the vector diagram of A.F. demagnetization of another specimen, 192 A_2. The NRM direction of this specimen changed considerably on demagnetization up to a field of 300 Oe. indicating the removal of a soft, but large, secondary component. From 300 Oe. onwards the direction remained stable up to 900 Oe.

Effectiveness of A.F. demagnetization in cleaning rocks affected by lightning   An attempt was made to clean a few specimens suspected of lightning effects by subjecting them to thermal and A.F. demagnetization. Two examples are given below in which A.F. demagnetization was either partially or completely successful in cleaning whereas thermal demagnetization failed completely. During stepwise heating of these specimens hardly any change in direction was noticed indicating the possibility that the blocking temperature of the domains remagnetized by IRM is very near or at the Curie temperature.

Sample 257, in all probability, was struck by lightning as all specimens from it showed very high natural intensities.

Fig.3K shows the vector heating diagram for one of the specimens (257 A_2), from which it can be inferred that the directions in the specimen did not change on stepwise heating in zero field.

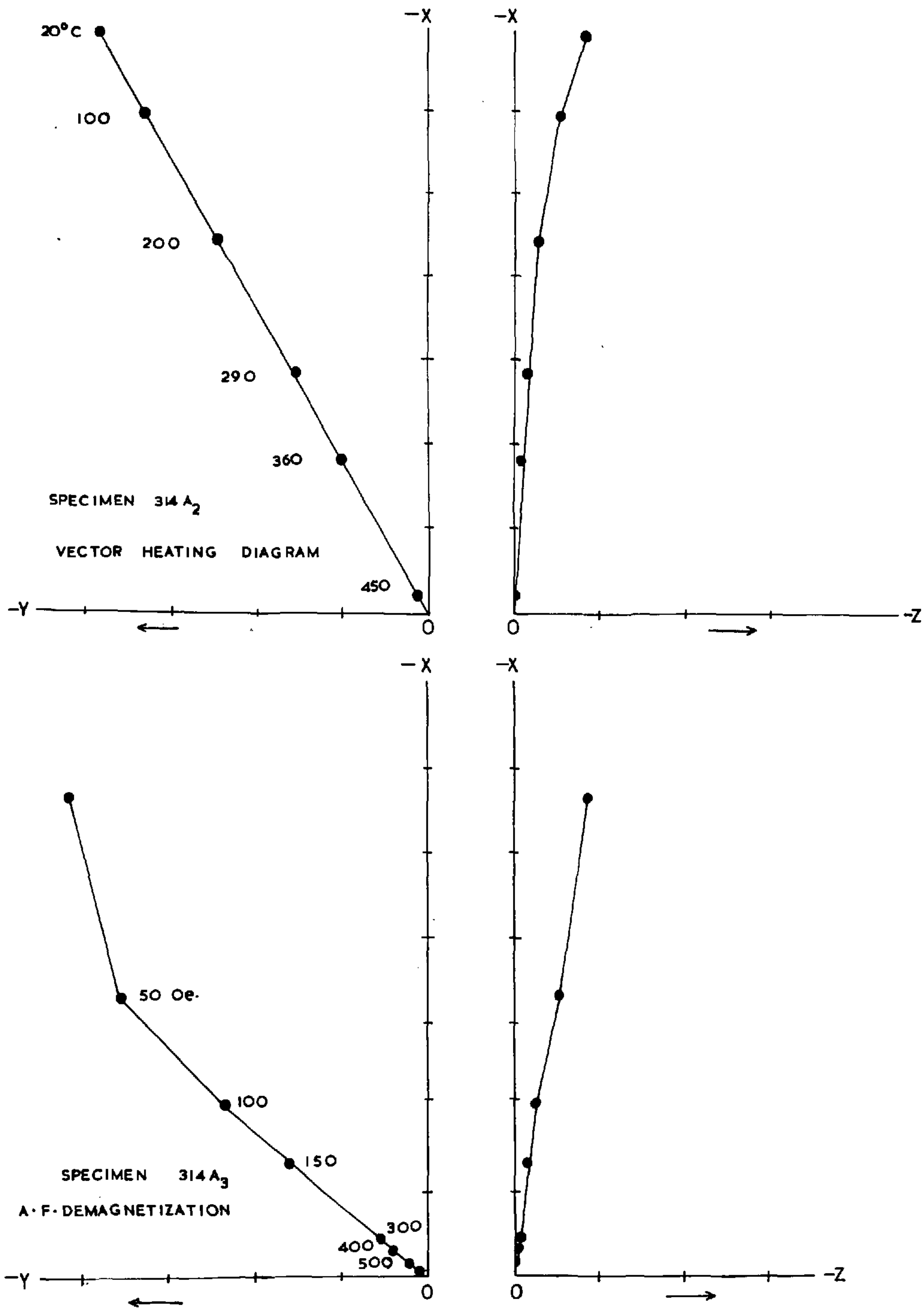


FIG · 3G − COMPARISON OF VECTOR DIAGRAMS OF THERMAL AND A·F· DEMAGNETIZATION

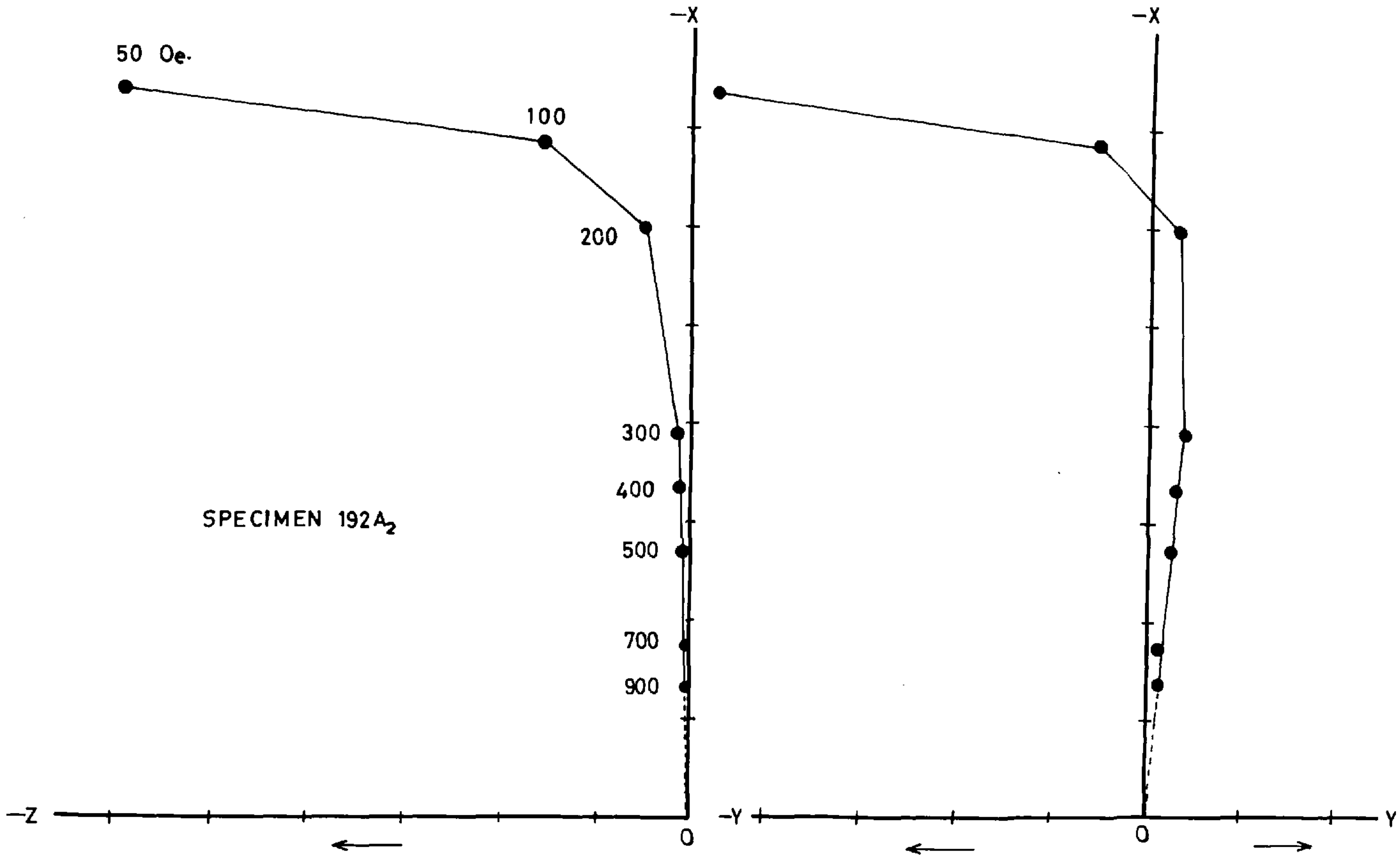


FIG. 3H – VECTOR DIAGRAM OF A.F. DEMAGNETIZATION OF A SPECIMEN WITH LARGE SOFT SECONDARY COMPONENT

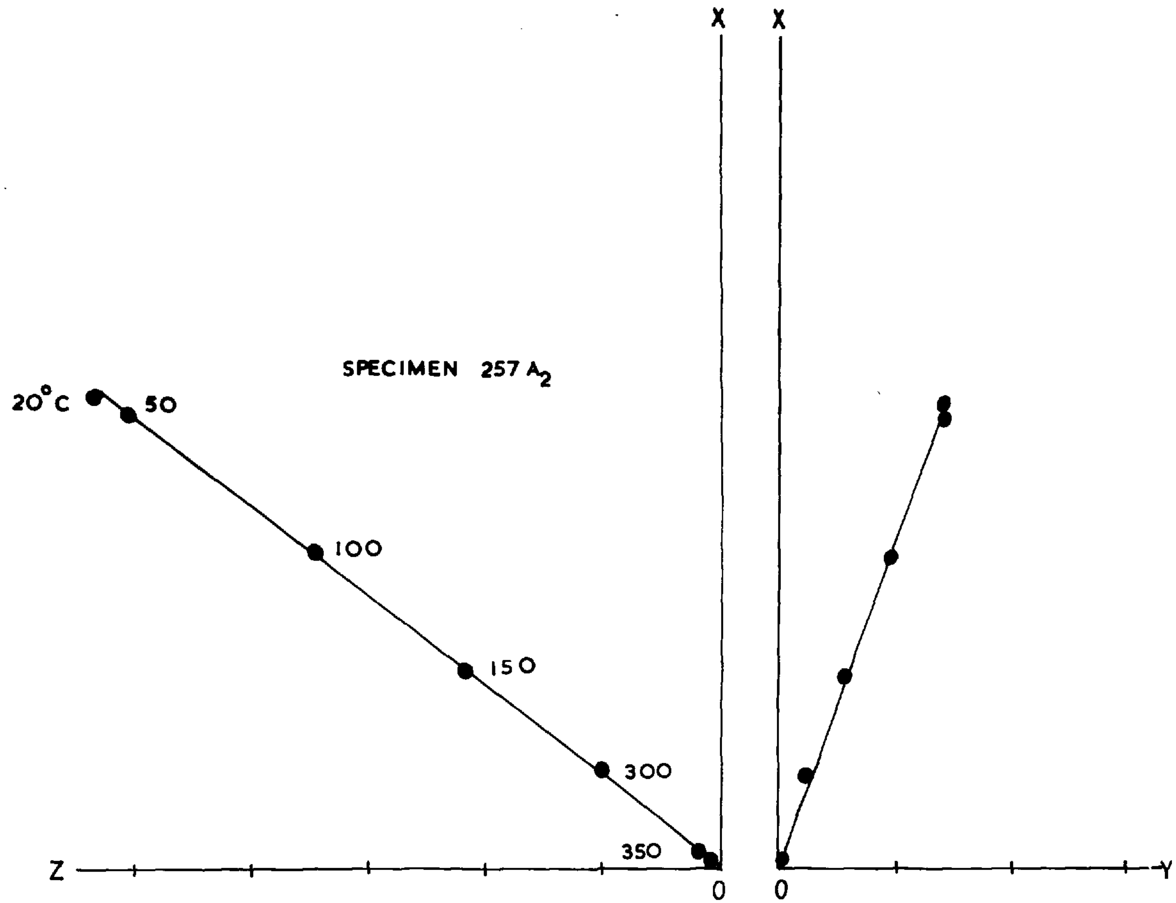


FIG · 3K – VECTOR HEATING DIAGRAM FOR A SPECIMEN AFFECTED BY LIGHTNING

On the other hand specimen 257 A_3 and 257 A_4 could be cleaned by progressive A.F. demagnetization, the peak field required being 1000 Oe. The changes in direction during cleaning of the pilot specimen 257 A_3 are illustrated by polar projections of the directions on an equal area stereogram (Fig.3L).

For comparison, changes in direction of specimen 258 A_1 cut from sample 258 are also shown. This sample, collected only a few yards away from 257, in view of its low natural intensity was not affected by lightning, and required only 400 Oe. field for cleaning.

A.F. cleaning of specimen 606 C_2 was only partially successful (Fig.3L). The NRM intensity of this specimen was 197 x 10^{-4} emu/gm, compared to an average natural intensity of 11 x 10^{-4} emu/gm for three specimens from sample 607 collected only 12 feet away from 606. During A.F. demagnetization, the directions in specimen 606 C_2 changed appreciably in peak fields of up to 300 Oe., always tending towards the stable directions of the specimens from 607. However, no change in direction was observed on demagnetization in higher fields. Specimen 606 C_1 which was given thermal treatment showed hardly any changes in its natural direction.

The results of A.F. and thermal cleaning are given in Table 3.

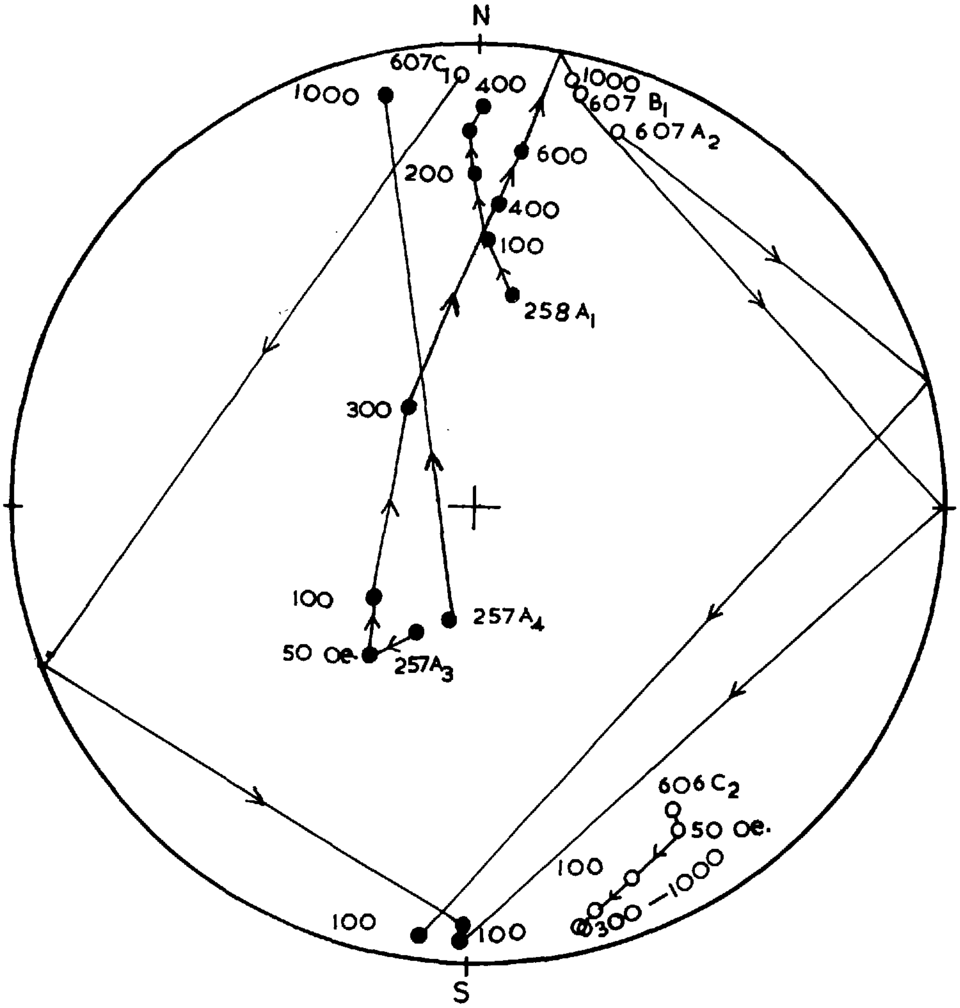


FIG. 3L – STEREOGRAPHIC PROJECTION OF CHANGES OF DIRECTIONS IN SPECIMENS AFFECTED BY LIGHTNING DURING A.F. DEMAGNETIZATION

TABLE 3

Specimen No.	Intensity in emu/gm x 10^4	Directions before cleaning		Directions after cleaning A.F.		Directions after cleaning Thermal	
		D°	I°	D°	I°	D°	I°
257 A_3	60	207	65	12	-5		
A_4	56.4	193	69	348	9		
A_2	49.1	217	52			214	51
606 C_2	197	146	-22	165	-6		
C_1	350	149	-30			150	-29

The stereogram also shows that the specimens from 607 required a peak field of only 100 Oe. for cleaning.

These results indicate that A.F. demagnetization is a powerful technique and in cases such as cited above can be quite effective even when thermal demagnetization fails. McElhinny and Opdyke (1964) have also observed that they were able to clean lightning affected Pre-Cambrian dolerites of Eastern Southern Rhodesia by A.F. demagnetization when their attempts by cleaning thermally failed. On the other hand, Opdyke (1964) found that thermal demagnetization was more effective in cleaning the partially unstable Permian red beds of South-West Tanganyika than the A.F. technique. The secondary magnetization in the red beds due to CRM was unaffected even in fields up to 900 Oe. whereas the component was removed by heating the specimen to above 300°C. The logical conclusion emerging from this is that both the A.F. and the thermal technique should be considered as equally effective and used in a complementary way.

3.8 Stability criteria From the foregoing discussion it is clear that the examination of stability (or knowledge of stability) of magnetization in rocks is extremely necessary for utilising the magnetic directions in rocks for palaeomagnetic investigations. Towards this, various criteria have been suggested by different workers in the field, e.g. Nagata et al (1957), Radhakrishnamurty and Sahasrabudhe (1967) for ascertaining the magnetic stability in rocks. These criteria are based on certain parameters such as Curie temperature, the ratio $Q_n = \frac{J_n}{J_i}$ where J_n is the NRM intensity and J_i is the induced intensity of magnetization in the specimen in a field of 0.5 Oe. and the ratio $Q_{tn} = \frac{J_n}{J_t}$ where J_t is the TRM acquired in the present earth's field when the rock is cooled from its Curie temperature to room temperature.

Nagata et al (1957) have proposed a set of practical tests to be applied on the rock specimen when its natural remanent magnetism is to be used for palaeomagnetic studies. According to them, rocks satisfying the following conditions should be regarded as stable.

1) The ratio J_n/J_t should be nearly equal to unity.
2) The shapes of thermal demagnetization curves of NRM and TRM should be similar.
3) The shapes of A.F. demagnetization curves of NRM and TRM should be similar.
4) The ferromagnetic mineral contained in the rock should be a "single phased Ti-poor titano-magnetite" with a single Curie point $> 300°C$.
5) Thermal demagnetization curve of saturation remanence should be reversible.

The above tests were applied to a large number of stable specimens and it was found that only a small number among them satisfied the above conditions in full. Three typical cases presented below will show that all the above conditions need not be obeyed even by stable rocks.

Specimen 314 A_3 is a basalt and its A.F. demagnetization curves of NRM and TRM are not similar in shape as can be seen from Fig.3M. The ratio J_n/J_t is 0.45 for this rock specimen and according to the above authors it should be considered as a specimen of dubious reliability. The heating and cooling curves in a field of 1500 Oe. are similar showing only a single Curie point. Both A.F. cleaning and thermal cleaning have, however, shown that the NRM of the specimen is stable.

178 A_2 is a trachyte. Fig.3N shows that the demagnetization curves of NRM, TRM and saturation remanence are all similar. However, the ratio J_n/J_t for this specimen is only 0.17. High field heating and cooling curves are similar provided the experiment is performed quite fast. It was noticed however, that heating the specimen for about ten minutes at a temperature of 700°C resulted in its taking a large TRM which probably explains the low value of the ratio J_n/J_t. Half an hour of heating increased the value of this component. Further, heating the specimen has lowered the Curie point from 580 to 520°C. These changes, shown in Fig.3P, were certainly produced by heating and must be assumed as due to ionic disordering mechanism. A.F. demagnetization of the specimen showed no change in direction up to 1000 Oe., testifying to the reliability of NRM.

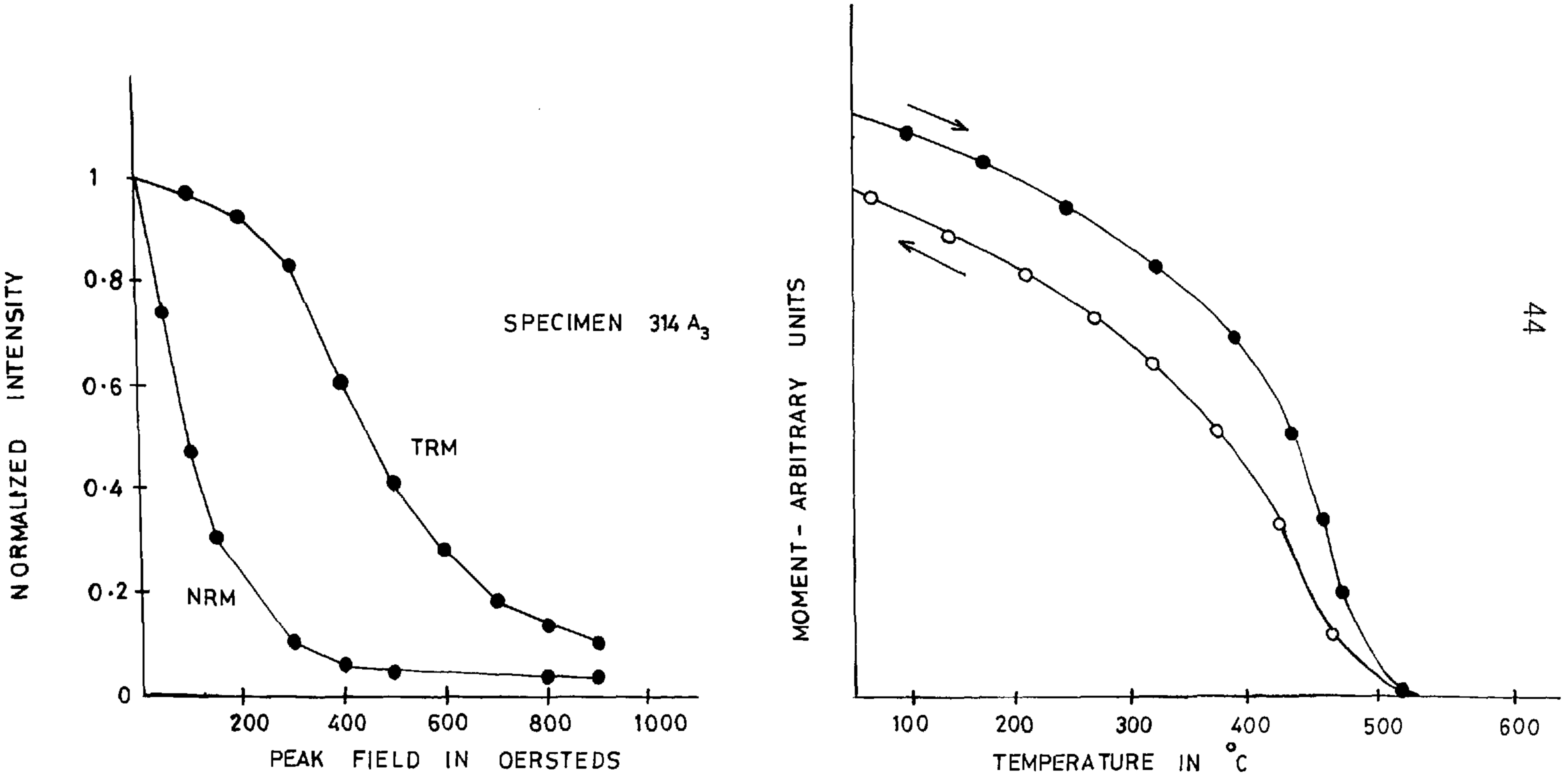
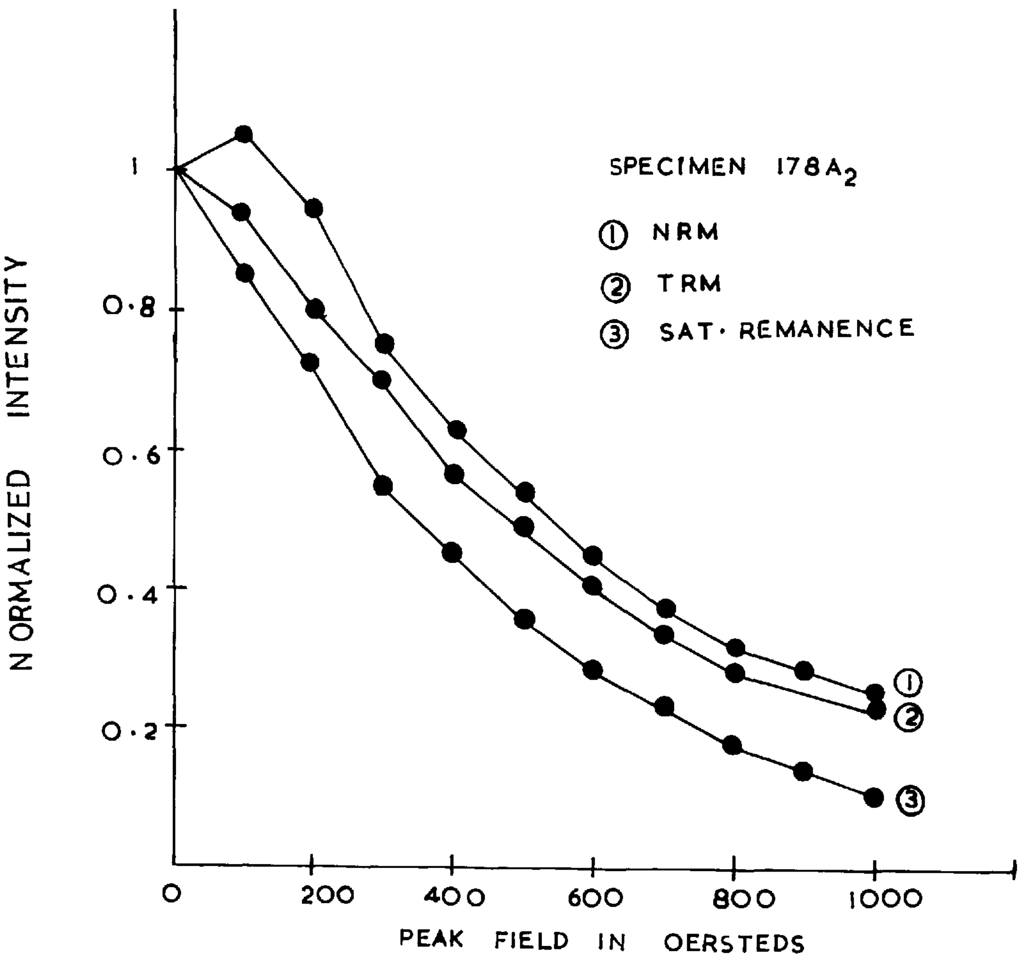


FIG. 3M – A.F. DEMAGNETIZATION CURVES OF NRM AND TRM OF A STABLE SPECIMEN AND ITS HIGH FIELD HEATING AND COOLING CURVES



FIG·3N – A·F· DEMAGNETIZATION CURVES

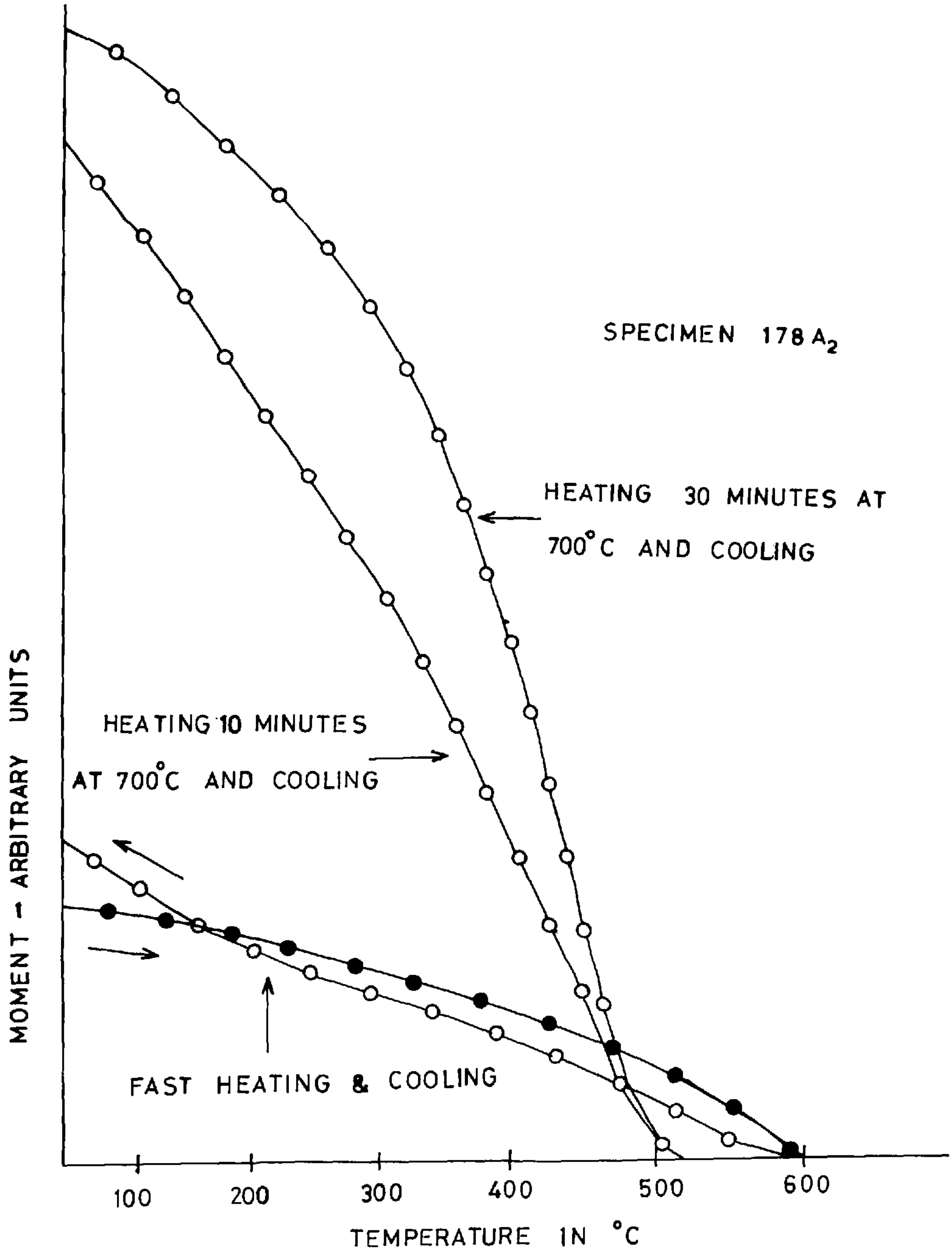
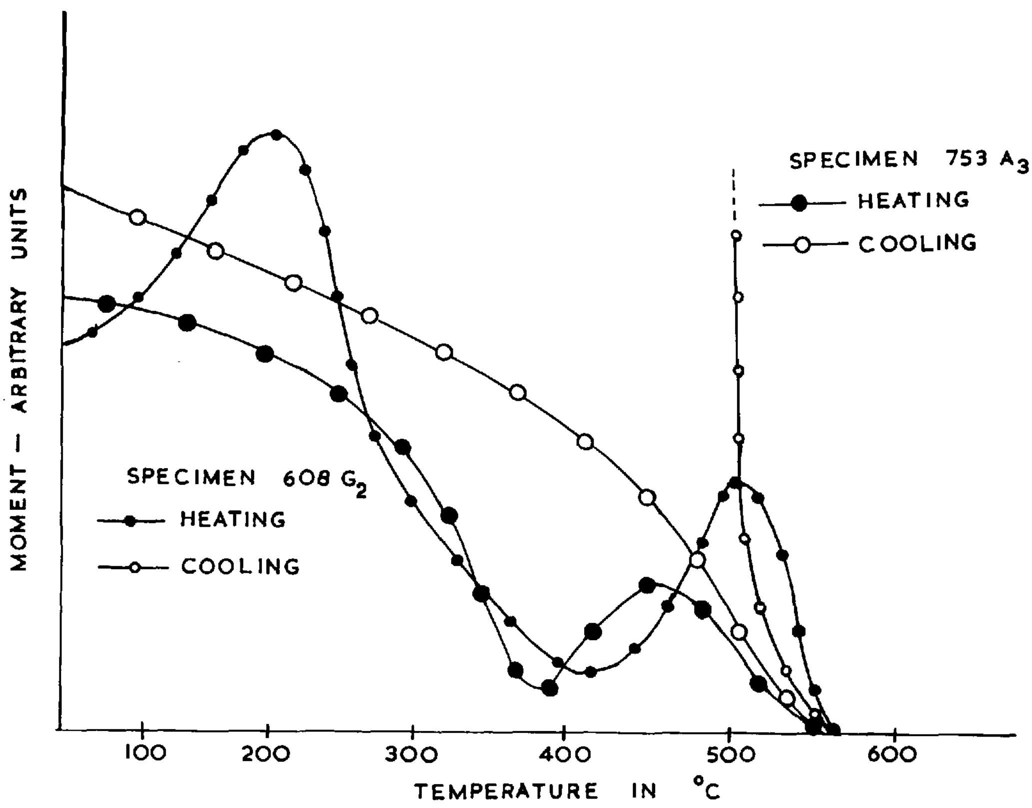


FIG. 3P - HIGH FIELD HEATING & COOLING CURVES

Fig.3R shows the high field heating and cooling curve for specimen 753 A_3. The secondary maximum in the heating curve indicates that titanomagnetite exists in two phases in this specimen. The Curie point, 370°C, is not reproduced on cooling. J_n/J_t ratio is about 0.78. Similarly in sample 608 also, titanomagnetite exists in two phases. The J_n/J_t ratio for specimen 608 G_2 from this sample is only 0.16. The NRM in these specimens were, however, found to be quite stable. The above results are given in tabular form (Table 4). It can be seen that the directions of NRM of the specimens did not change either on A.F. or thermal cleaning indicating the reliability of these directions. The conclusion to be drawn from these experiments is that rock specimens which are magnetically stable may not satisfy all the conditions given above. This arises from the inherent complexity of rocks which contain magnetic grains of varying size and different mineral and chemical composition.

3.9 <u>Q_n values as a test of stability</u> Recently Radhakrishnamurty and Sahasrabudhe (1967) made a detailed study of magnetic and mineralogical properties of a large number of basaltic samples from the Rajmahal and the Deccan traps. They found that rocks giving high Q_n values and low Curie temperatures (about 250°C) exhibit a high degree of stability compared to those giving low Q_n values and Curie points of about 580°C.



FIG·3R – SLOW HEATING AND COOLING CURVES

TABLE 4

Specimen No.	Directions of NRM D°	Directions of NRM I°	Directions after A.F. or thermal cleaning D°	Directions after A.F. or thermal cleaning I°	$\frac{J_n}{J_t}$	Curie point °C
314 A_2*	8	- 9	8	- 5	0.45	475
B_1	9	- 4	357	- 2		
A_3	11	- 8	1	- 4		
178 A_1	181	1	181	1		
A_2	181	5	179	6	0.17	580
753 A_1	173	-11	175	- 6	0.78	370
A_2	176	-10	175	- 6		
A_3*	172	-10	172	- 2		
608 G_2	176	2	183	12	0.16	350
H_1	171	12	184	11		

* Indicates that the specimen was cleaned thermally

In the present study, I have applied this criterion to a large number of specimens and the results are given in Table 5, which gives only a few typical examples. It was noticed that, in general, rocks with Q_n values between 3 and 35 were the most stable. There was very little scatter in the NRM directions and intensities of specimens from these samples and on cleaning either by thermal or A.F. technique, little change in direction was noticed. Many of these rocks gave Curie points between 300 and 450°C. On the other hand, rocks with Q_n values less than 2 were either partially stable or unstable. Those in the former category on cleaning, gave directions very much different from NRM directions.

Stacey (1967) has recently pointed out that high Q_n values indicate the presence of single domain grains, which he thinks are responsible for the TRM of the rocks.

It is clear, therefore, that the value of Q_n can be used as a general criterion for assessing the magnetic stability of rocks. The measurement of Q_n values is quick and simple and once the values are known, the stability of NRM in the rocks can be assessed. This will help limit cleaning to a minimum number of specimens.

TABLE 5

Sample No.	Q_n	Curie point (°C)	Remarks
268	0.5	450	Unstable
282	0.5	580	Unstable
262/63	0.5	580	Partially stable
278/79	0.8	400	Partially stable
297	1.7	400	Partially stable
692	0.6	570	Partially stable
657	0.7	620	Partially stable
311/12	2.6	600	Stable
318/19	4.5	350	Stable
677	5.9	630	Stable
700	15.9	420,570	Stable
753/54	4.5	370	Stable
621/22	32	350	Stable
607/608	12.4	350	Stable
618	17.2	570	Stable
791	6.8	380	Stable
635/36	337	300	Lightning
241/42	331	570	Lightning
606	1240	350	Lightning

CHAPTER 4

EFFECTS OF HEAT TREATMENT

4.1 Introduction The natural magnetization of rocks is due to the ferromagnetic minerals present in them. These minerals are usually present in rocks as oxides and sulphides. Magnetite (which frequently contains titanium), hematite, maghemite, ilmenite and ulvospinel are the most common oxides. Variations in the magnetic properties of rocks such as Curie point, saturation intensity etc., may be attributed to the varying proportion of titanium in the oxides.

Changes like oxidation, ionic disordering and phase homogenization take place during heating of rock specimens. It might be thought that heating and cooling rocks in vacuum or in an inert atmosphere would eliminate the chances of chemical and magnetic changes taking place. However, this is not so. Weaving (1960) has observed that the Linga basalts increased in hardness depending on the time of heating irrespective of whether heating was done in vacuum, air or reducing atmosphere such as coal gas.

4.2 Irreversible changes on heating Fig.4A shows typical heating and cooling curves of magnetization obtained with rock specimens from Turkana and the central rift. A modified version of the Curie balance of Chevallier and Pierre (1932) was used and Curie point determinations of more than 200 specimens were made in a permanent magnetic field of 1500 Oe. The Curie points of many specimens were within the range 500 - 600°C indicating that titanomagnetite is the main constituent of these rocks.

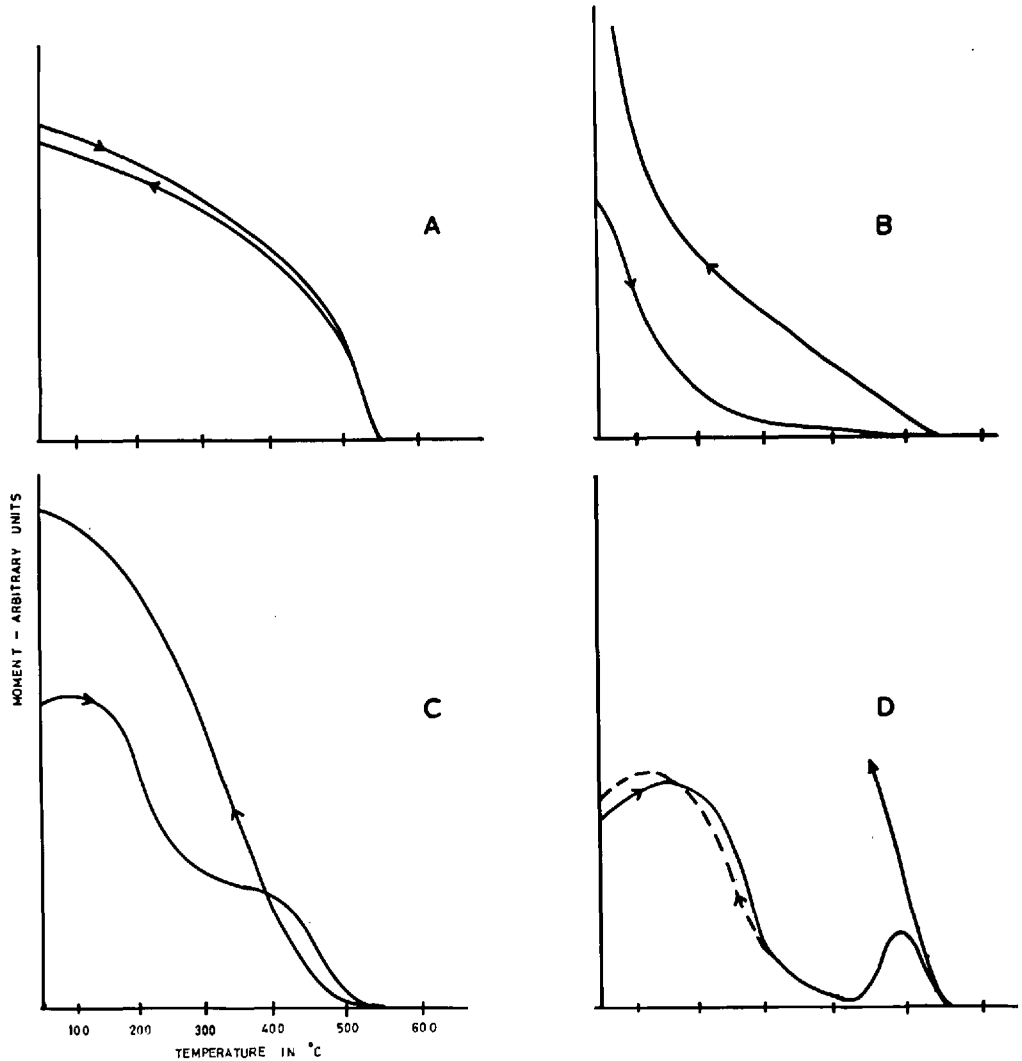


FIG. 4 A - TYPICAL HEATING AND COOLING CURVES

In many cases heating and cooling curves were smooth as shown in 4A(A). Some specimens, however, gave more than one Curie point as in Fig.4A(C) and in such cases, the lower Curie point never showed itself on cooling. Some other specimens gave Curie points as low as 150 - 200°C (Fig.4A(B)). They were often not well defined and the heating curves showed long tails.

The curve shown in Fig.4A(D) is characterized by an initial maximum or hump at about 150°C followed by a sudden decrease in intensity representing a Curie point of about 350°C. There is no doubt that this decrease in intensity is due to a Curie point as this portion of the curve is reproducible as shown in the figure, by dotted line, provided the rock is not heated above 450°C.

4.3 Secondary maximum or anomalous magnetization On heating the rocks giving 4A(D) type of curve, above 450°C, slowly in the field due to the permanent magnet in the apparatus, the magnetization increased by an amount depending on the time of heating, giving rise to a secondary maximum. Fig.4B shows the growth of this secondary maximum depending on the time of heating. This increase in intensity may not be observed if the heating was done rapidly. Simultaneous with the appearance of the secondary maximum, the Curie point of the specimen increased to about 560°C suggesting that the proportion of magnetite in the specimen has increased on heating. On cooling, the heating curve was never reproduced and the intensity of the specimen in the field due to the magnet increased by a factor of more than 4 - 5 compared to the intensity it had at the start.

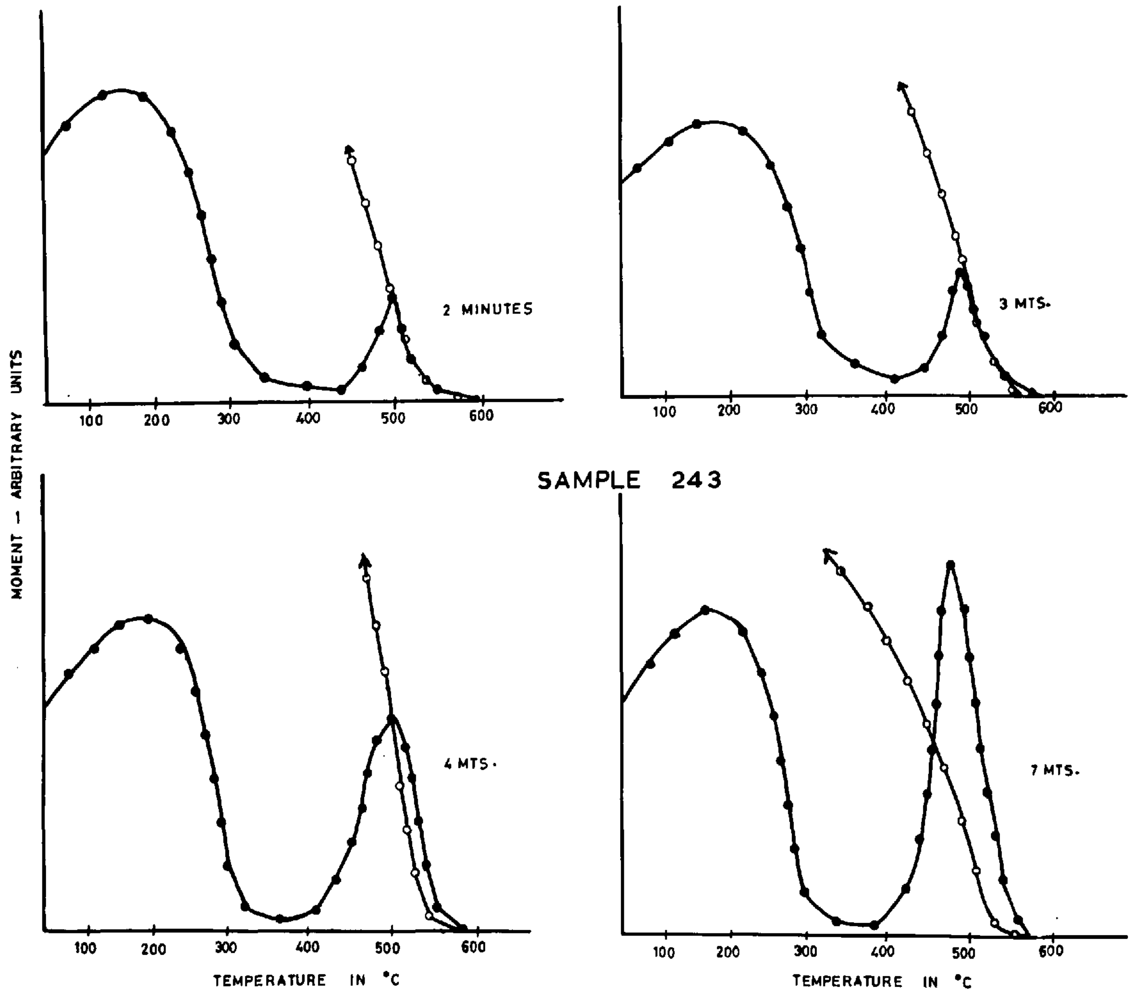


FIG. 4B — INCREASE IN ANOMALOUS MAGNETIZATION WITH HEATING TIME

(TIME TAKEN TO HEAT FROM 350°—550°C IS MARKED ON EACH DIAGRAM)

<u>Oxidation on heating</u> Nagata et al (1957) have observed such an anomalous increase of magnetization on heating titanomagnetite extracted from biotite rhyolite pumice from Niisima island. According to the above authors the constituent with the higher Curie point must have been developed by oxidation of the lower Curie point constituent. They also noticed that the percentage of FeO, $Fe_2 O_3$ and $Ti O_2$ varied in the heat treated sample depending on the time of heating. Also, heating the sample for 12 hours resulted in the disappearance of the anomalous increase in intensity which made them conclude that all the lower Curie point constituent has been oxidised to the higher Curie point one by prolonged heating.

It is likely that oxidation is one of the causes for the changes in intensity and Curie point of the rock specimens which gave the D type of curve.

The appearance of the secondary maximum may be due to two members of the titanomagnetite series in the rock specimen re-exsolving into two new phases on heating as explained by Parry (1957) who observed similar changes on heating the Deccan trap basalts.

4.4 <u>Changes in magnetic hardness and saturation remanence</u> In order to study the changes occurring in the magnetic hardness on heating, two specimens, 243 B_1, a phonolite of normal polarity and 608 K_1, a basalt of reversed polarity were heated to different temperatures and cooled in the earth's field. Both specimens belong to the category which gave the D type of heating curve. TRM and PTRM thus acquired were demagnetized in a progressively increasing alternating field. Fig.4C shows the demagnetization curves. Since the transformation of the lower

Curie point constituent to the higher Curie point one starts between 425 and 450°C, heating the specimen to 400°C and cooling in the earth's field gives a total TRM to the constituent with lower Curie point. Heating the specimen to 500°C results in the formation of the higher Curie point constituent which acquires a PTRM on cooling. The intensity acquired on cooling from 600°C must, therefore, be entirely due to the TRM intensity of the newly formed higher Curie point constituent.

A gradual increase in the magnetic hardness of the specimens can be observed from the shapes of the demagnetization curves, as the specimens were subjected to heating at higher temperatures.

Radhakrishnamurty and Sahasrabudhe (1965) have also observed an increase in coercivity of heat treated basalts. Their study was based on observing the hysteresis loops of the basaltic specimens before and after heat treatment. The increase in coercivity is also in agreement with similar results obtained by Nagata et al (1957) who observed that the coercive force of heat treated titanomegnetite samples showing two Curie points abruptly increased at temperatures nearly equal to the lower Curie point of the two phases concerned.

4.5 Effect of prolonged heating Both specimens were baked at 700°C for three hours and cooled in the earth's field. Whereas the specimen from sample 243 showed a decrease in TRM intensity, the basalt specimen from 608 showed a slight increase compared to the TRM acquired when the specimen was heated to 600°C and cooled. Both specimens were then baked for 15 hours at 700°C and given TRM. This time the intensity of 608 also decreased.

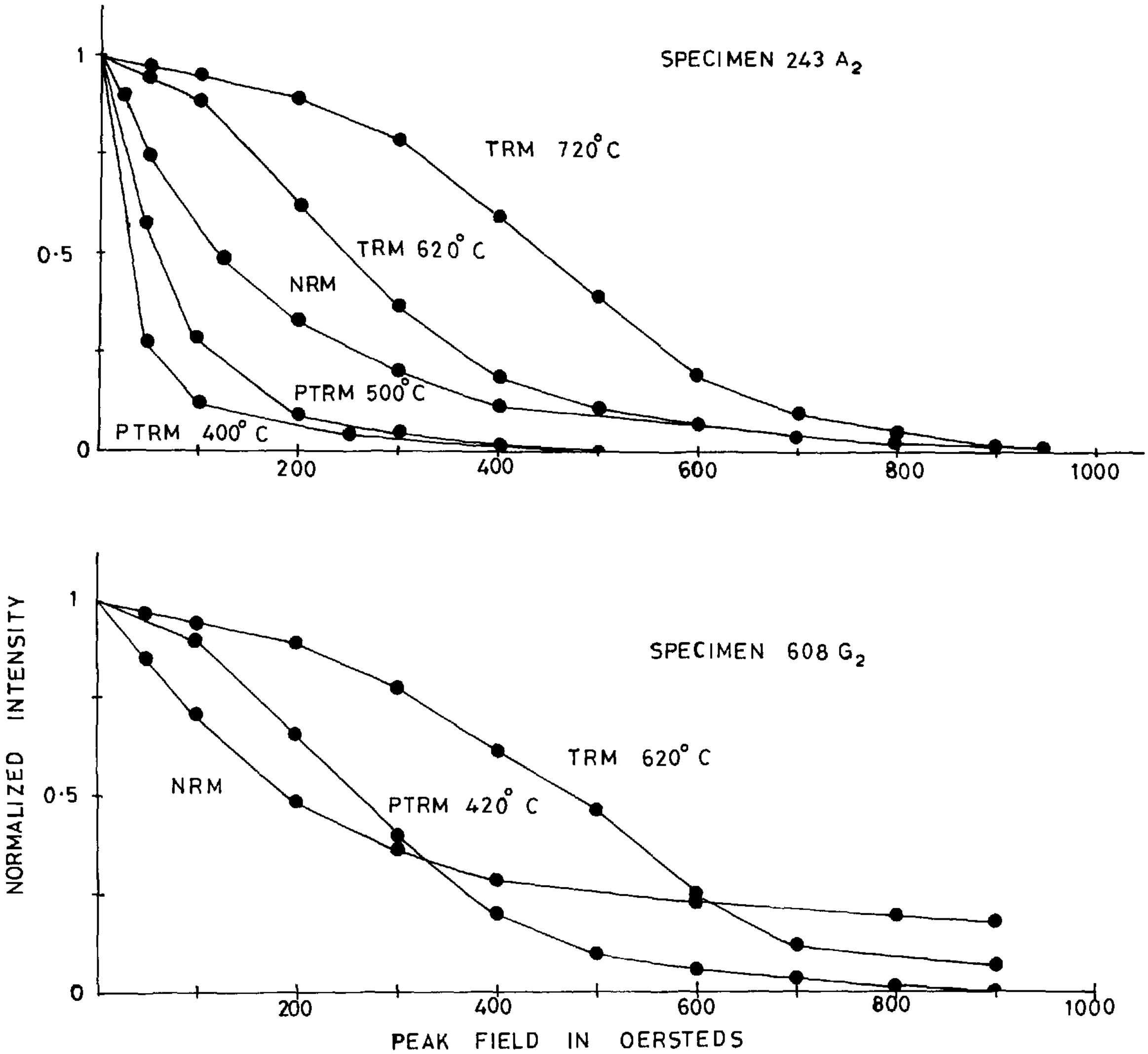


FIG. 4C – A.F. DEMAGNETIZATION CURVES OF NRM, TRM & PTRM

These changes are shown in Table 6.

The above specimens were also saturated in 3000 Oe. field after the same heat treatments mentioned above. It can be seen from the table that changes in the saturation remanence follow the same pattern as changes in TRM.

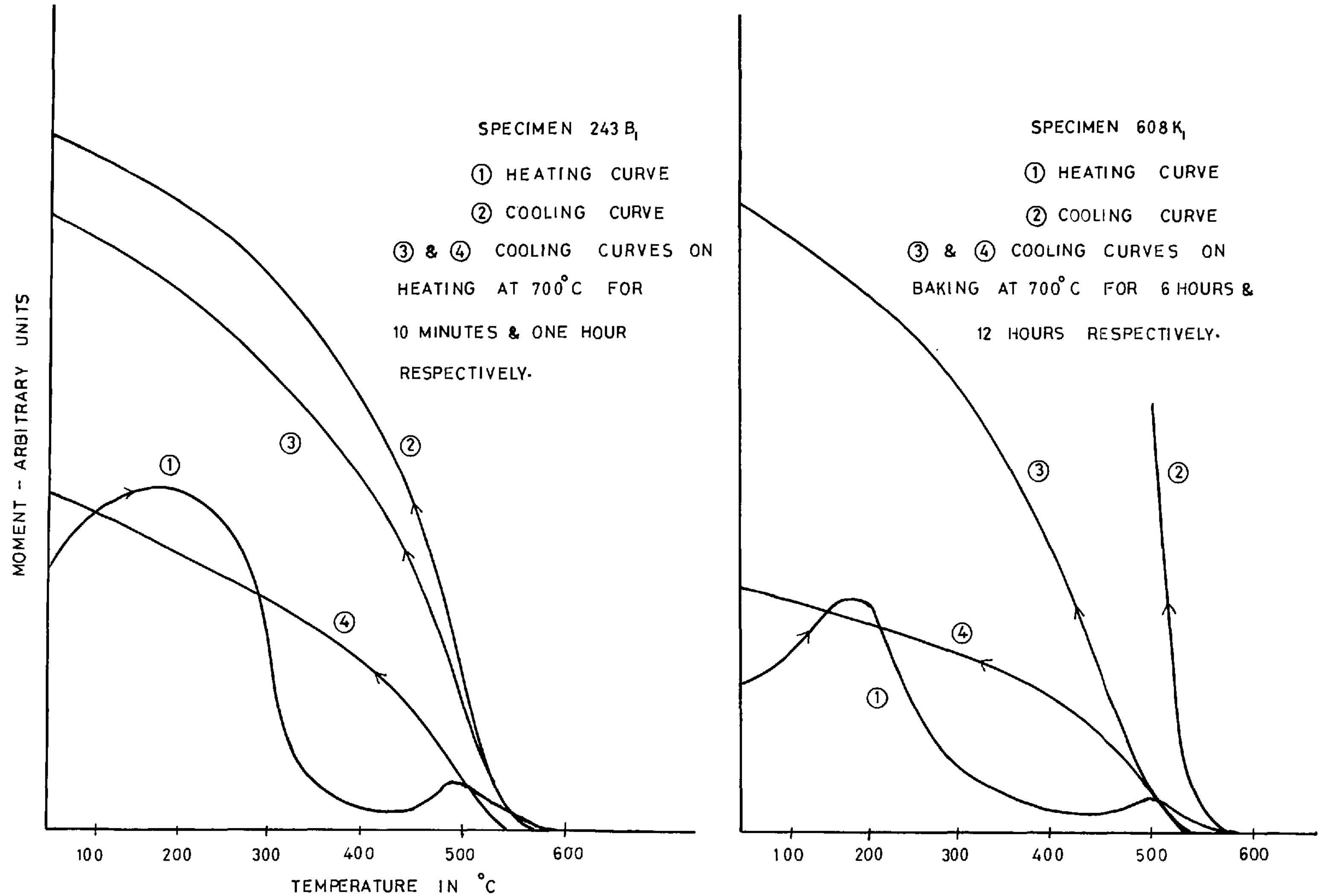
Curie points of baked specimens   Fig.4D shows that Curie points of the specimens were lowered by about 50°C on baking. Further prolonged heating did not however lower the Curie point from the value of 510°C.

Pouillard (1950), working with spinel of cell dimensions intermediate between Fe_3O_4 and Fe_2TiO_4 has shown that the Curie point of magnetite is considerably affected by ionic replacement.

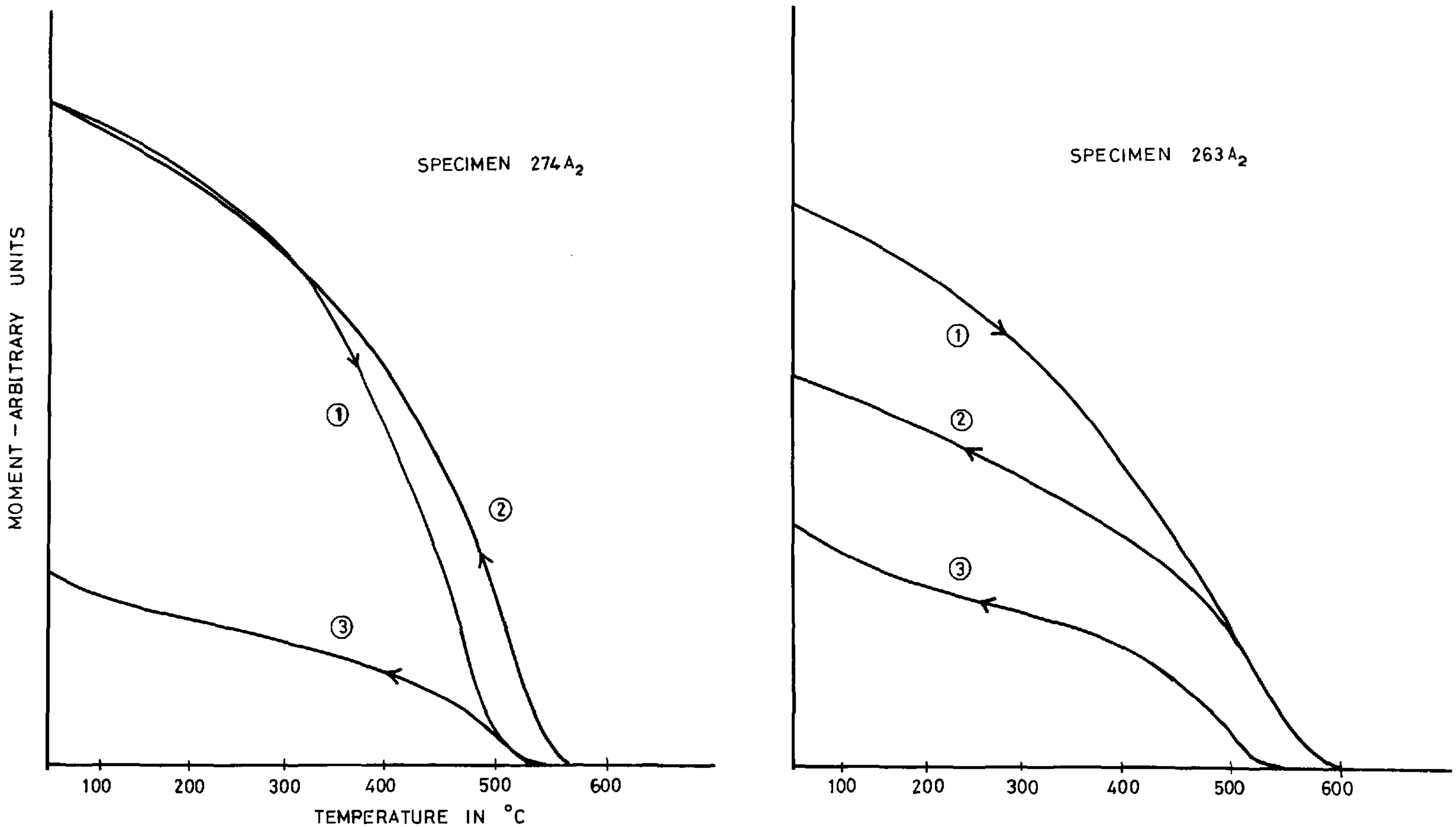
The decrease in Curie point and saturation intensity suggests that an ionic disordering mechanism opposite to the one which took place when the virgin specimens were heated from 450 - 600°C must have occurred on prolonged heating. It is possible that in the first case it was either oxidation or exsolution of two titano-magnetic phases and in the second case an ionic disorder mechanism that brought about the changes mentioned above. Prolonged heating must have made the titanomagnetite in the rock specimen, titanium richer, thereby decreasing the saturation intensity and lowering the Curie point. It is also evident that this mechanism progressed at a slower rate in specimen 608 than in 243.

TABLE 6

	Sample	Heating to 500°C and cooling	Heating to 600°C and cooling	Baking for 3 hours at 700°C	Baking for 15 hours at 700°C
TRM (emu/gm) x 10^4 acquired in the earth's field	608	104.8	128.6	178.4	139.3
	243	26.6	37.0	14.3	14.0
Saturation remanence in 3000 Oe. (emu/gm)		Virgin Specimen			
	608	0.231	1.47	1.67	0.883
	243	0.139	0.612	0.187	0.155



FIG·4D-HEATING & COOLING CURVES OF HEAT TREATED SPECIMENS



FIG· 4 E - CHANGES IN INTENSITY AND CURIE POINT ON HEATING

① HEATING CURVE ② COOLING CURVE ③ COOLING CURVE AFTER HEATING THE SPECIMEN FOR 10 MINUTES AT 700° C

Similar changes on prolonged heating were also observed in rocks with a single Curie point. Two such examples are illustrated in Fig.4E. In both these specimens 10 minutes' heating at 700°C produced considerable decrease in the intensity (in 1500 Oe.). In specimen 263 A_2, the decrease in the Curie point was also appreciable.

All the specimens except 263 A_2 used in the above experiments were stable. 263 A_2 is partially stable. It has been shown that the TRM intensity changes that occur in rocks follow the same pattern of changes in saturation remanences, on heating the rocks. Figs.4D and 4E illustrate how the intensity varies according to the time of heating. In specimen 274, only 10 minutes' heating has produced a decrease of about 75% in intensity compared to the intensity acquired when the specimen is heated to 650°C and immediately cooled.

For stability studies, the time of heating a specimen at temperatures above the Curie point depends on the experimenter. As the thermo-remanence acquired by the rock depends on this time, it once again emphasises the point that the ratio J_n/J_t cannot be taken as a sure criterion for testing the stability of rocks for palaeomagnetic study. This point has also been emphasised in Chapter 3.

CHAPTER 5

MAGNETIC PROPERTIES OF RIFT VOLCANICS

5.1 Low field hysteresis In Chapter 3, I have broadly classified the A.F. demagnetization curves into four groups. The curves under group C are characterized by fluctuations in intensity during demagnetization in progressively increasing fields. Similar fluctuations in intensity were noticed by Opdyke (1964) during A.F. demagnetization of the Permian Red beds of South West Tanganyika. As reported by Raja et al (1966) these specimens showed irregular changes in direction and could not be cleaned by A.F. demagnetization. Wilson (1961) has found that while he was successful in recovering the primary directions of magnetization in the unstable laterite specimens by thermal magnetization, his attempts at cleaning them by A.F. demagnetization failed. The following study on the hysteresis behaviour of rock specimens in low fields has shown that the instability of magnetization in some specimens could be attributed to the phenomenon of "disaccommodation".

5.2 Disaccommodation The term "disaccommodation" is used to describe the phenomenon of decrease of susceptibility of a magnetic material with time. According to Craik and Tebble (1965), this phenomenon was first noticed by Webb and Ford (1934). Since then a number of alloys and compounds have been found to show this time dependent effect. Brissonneau (1958) has noticed that the magnetization of a dilute solution of carbon in iron at $-21.3^{\circ}C$ changed with time. He attributed this to the reorientation of displaced domain walls from the initial equilibrium position through a process of diffusion.

Sholpo (1966) observed that the initial susceptibility of a mixture of natural magnetite (about 5% by weight) in clay decreased by 6 - 10% of the value obtained by measurement 1 minute after demagnetization by an alternating field, in about 70 days. This decrease in susceptibility was attributed to the manifestation of magnetic viscosity.

Disaccommodation in rocks   Recently Radhakrishnamurty and Sahasrabudhe (1967) have reported that some rocks also exhibit this phenomenon of disaccommodation. They have referred to this by the term "Magnetic Memory". An extensive study of the hysteresis behaviour of a large number of basalt and dolerite specimens from India and East Africa has revealed that some rock specimens do show this time dependent magnetic effect (Radhakrishnamurty et al, 1968).

5.3 Low field hysteresis and Rayleigh loops   The hysteresis loop of a magnetic material in fields very weak compared to its coercive force is known as the Rayleigh loop. In this low field region, the magnetization of materials obey the following empirical relationships deduced by Lord Rayleigh (1887)

$$J = AH + BH^2$$

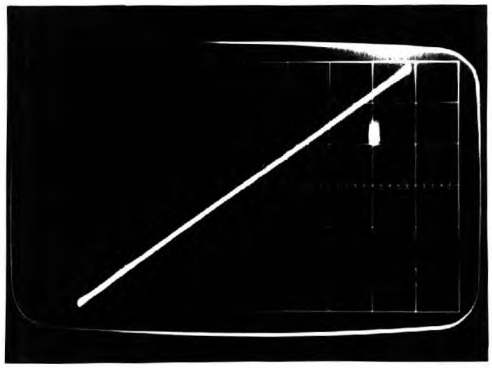
$$J_H = (A + B\,H_m)H \pm \frac{B}{2}(H_m^2 - H^2)$$

where H_m is the maximum field used
and A and B are constants
A is known as the reversible susceptibility and $B\,H_m$ the irreversible susceptibility.

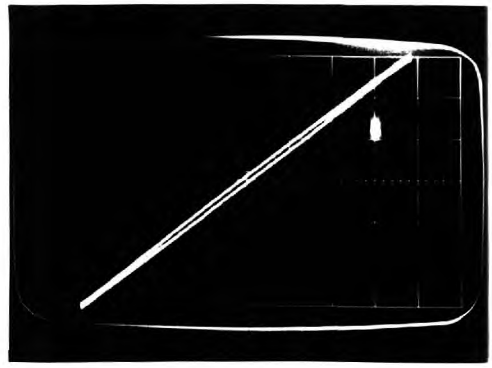
The second relationship holds good in the region $-H_m < H < H_m$ and it represents an elliptical curve.

Nearly a hundred specimens - mostly basaltic - from Turkana and the central rift were subjected to low field hysteresis study in the apparatus developed by Likhite and Radhakrishnamurty (1966). In this apparatus, the standard rock specimen of $^7/8$ inch diameter and about an inch in length is placed at the centre of a double coil which is balanced to a very high degree of precision at the working frequency which was 140 c.p.s. The double coil is placed coaxially at the centre of large Helmholtz coils which supply the energising field. The differential emf induced in the double coil, which is proportional to the rate of change of magnetic moment of the specimen is fed to the Y plates of an oscilloscope after integration and amplification. The emf across a small resistance in series with the Helmholtz coils, which is proportional to the energising field, is fed to the X plates of the scope after amplification and phase correction. An energising field of $\pm$10 Oersteds was used.

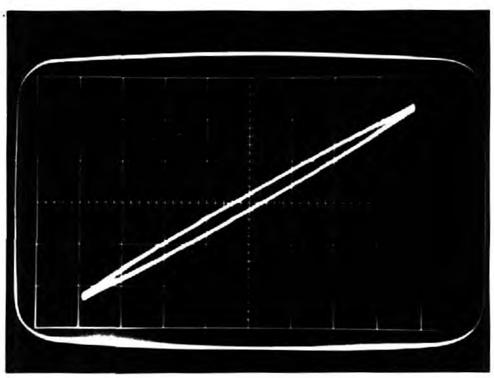
5.4 <u>Types of minor loops</u> The Rayleigh loops given by all the specimens can be classified into four different types as shown in Fig.5A. Similar types of loops were also obtained by Likhite and Radhakrishnamurty (1966) with the Indian rocks. It is evident from the figure that for rocks showing almost a line (as in a), the coefficient B in the Rayleigh relationship is negligible, whereas for loops of the type shown in b and c, the values of $B\,H_m$ are quite comparable to that of A. It can also be seen that even in fields of $\pm$10 Oe. there is a pronounced variation in the magnetization of rocks giving loops of the types b, c and d.



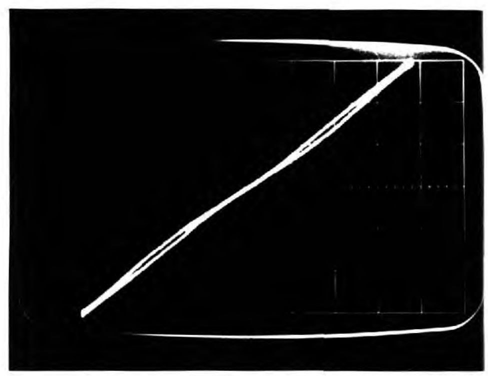
a



b



c



d

FIG. 5A – TYPES OF RAYLEIGH LOOPS FOR BASALTS
SCALE : H-AXIS ; 1 SMALL DIVISION = 0.5 Oe.
M-AXIS ; 1 SMALL DIVISION = 25×10^{-3} EMU

5.5 <u>Constricted minor loops</u> Of the four types of minor loops the constricted loop (d) is the most interesting. Certain high permeability alloys like perminvar give constricted major loops on annealing at high temperature. However, the constriction was found to disappear permanently on magnetic annealing. Recently Radhakrishnamurty and Sahasrabudhe (1965) reported that some Deccan trap basalts gave constricted major loops. The constriction in such cases disappeared on heat treatment. The presence of more than one magnetic phase in the rocks was given as a possible cause of constriction by the above authors.

The constriction in the minor loops was found to disappear when the rock was subjected to A.C. or D.C. fields of about 50 Oe. or when the specimens were heated or cooled by a few degrees. Mechanical shocks such as a blow with a light hammer also made the constriction disappear. Similar treatment given to some rocks giving line (type "a") made the line change into loops. However, the important thing in these cases was that the loops were found to regain their original shape when left undisturbed for some time in the earth's field, the time of recovery being different for different specimens and ranging from 10 minutes to several hours or weeks.

The typical behaviour of specimen 745 A_1 with a recovery time of ten minutes is illustrated through Fig.5B (a-d). It is clear that small magnetic fields, temperature changes and mechanical shocks increase the susceptibility of the rock specimen and induce in it a considerable I.R.M. It should, however, be made clear that these changes are not due to induced anisotropy "as the induced anisotropy involved in disaccommodation is generally small, typically of the order of 100 erg/cm^{-3} compared

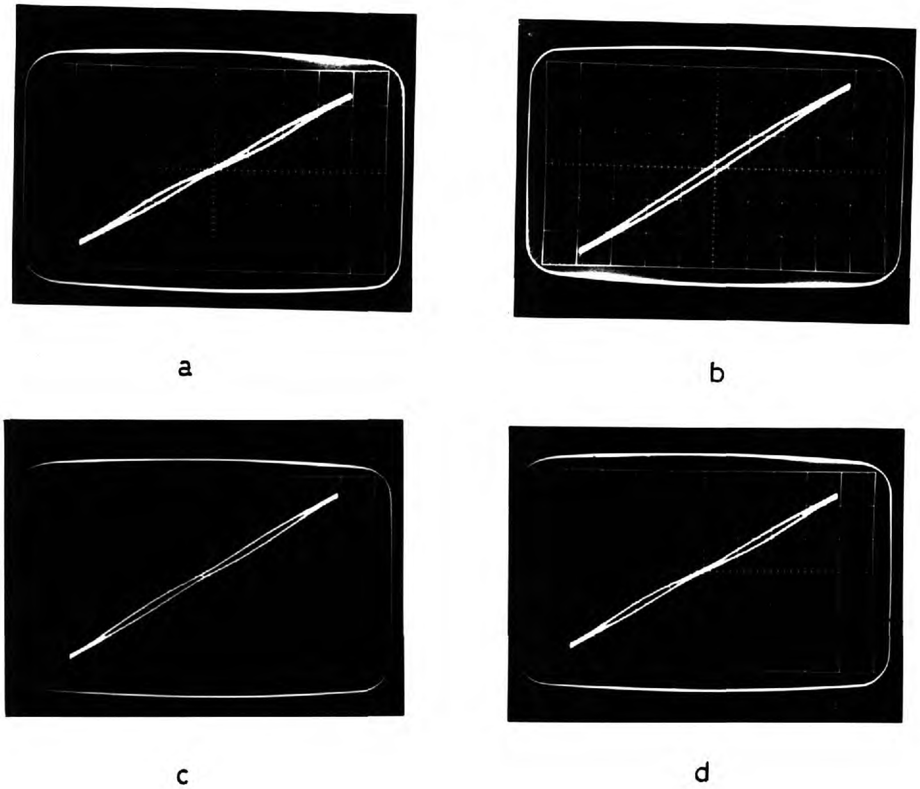


FIG. 5 B – STAGES IN THE RECOVERY OF THE CONSTRICTED LOOP FOR SPECIMEN 745A WITH 10 MINUTE RECOVERY TIME. (a) INITIAL (b) AFTER SUBJECTING TO 50 Oe. (c) ONE MINUTE LATER (d) 10 MINUTES LATER

with magnetocrystalline anisotropies of 10^4 erg.cm^{-3}" (Craik and Tebble, Page 270). The susceptibility due to rotation being inversely proportional to anisotropy, this should give very small changes in susceptibility compared to the much larger observed values. Further, the orientation of the specimens with respect to the applied field direction did not produce any change in the shape of the loop.

5.6 Domain wall stabilization The foregoing observations have shown that the magnetization of rocks showing disaccommodation takes time to reach the equilibrium value. This delay in reaching equilibrium condition cannot be attributed to eddy currents, as their recovery time is too large to be accounted for by eddy currents, changes due to which take place in a few seconds.

Three possible mechanisms are suggested in order to explain this phenomenon of disaccommodation. According to Craik and Tebble (1965, Page 267) it was Snoek (1949) who first suggested the process of Bloch wall stabilization as being the cause for the phenomenon in ferromagnetic materials. According to him, there exists in certain materials a stable arrangement of domain walls, which configuration if disturbed will take time to return to the original state of stabilization. The parameters like susceptibility and intensity decay exponentially with time, until equilibrium is reached.

Diffusion of interstitial atoms is given as another cause for the decay of susceptibility with time.

The presence of single domain grains of different relaxation times may be one of the causes for this reversible phenomenon in volcanic rocks according to Radhakrishnamurty and Sahasrabudhe (1967).

5.7 Bearing of disaccommodation on A.F. demagnetization and stability of rocks In Fig.5C are given the minor loops of two specimens which showed fluctuations of intensity and gave irregular directions during A.F. demagnetization. It also gives the demagnetization curves for the two specimens - 277 A_2 and 268 A_1. The virgin specimen 277 A_2 gave a wide loop thus indicating that it can take up fairly large I.R.M. in small fields. Specimen 268 A_1 showed initially a constricted loop which changed into a normal loop on disturbing by application of A.C. field of about 50 Oe., showing change in I.R.M. even in a small field. It took a few days for both specimens to revert to equilibrium conditions.

It can be seen from the loops obtained on disturbing the stable configuration, that in the disturbed state, these rocks could take up considerable amount of induced magnetization which will take several hours to decay. Since A.F. demagnetization involves subjecting rock specimens to fields of over 50 Oe., it is clear that rock specimens such as mentioned above will be in a disturbed state throughout the process. They could, therefore, pick up spurious magnetization on stepwise cleaning and measurement, to give erratic directions and intensity.

The above observations have made it clear that rocks showing disaccommodation phenomenon take up a large I.R.M. when they are subjected to disturbing factors such as magnetic fields (A.C.

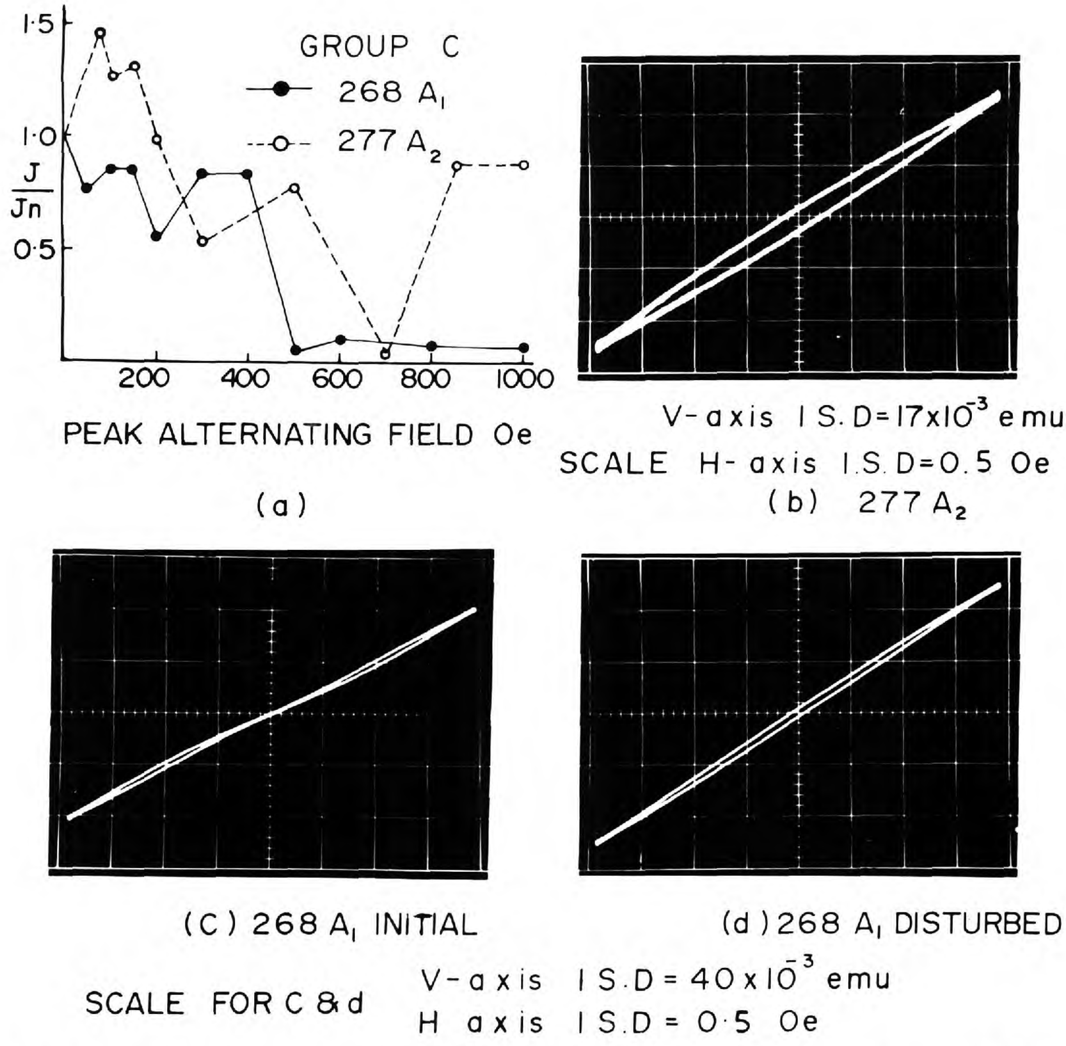
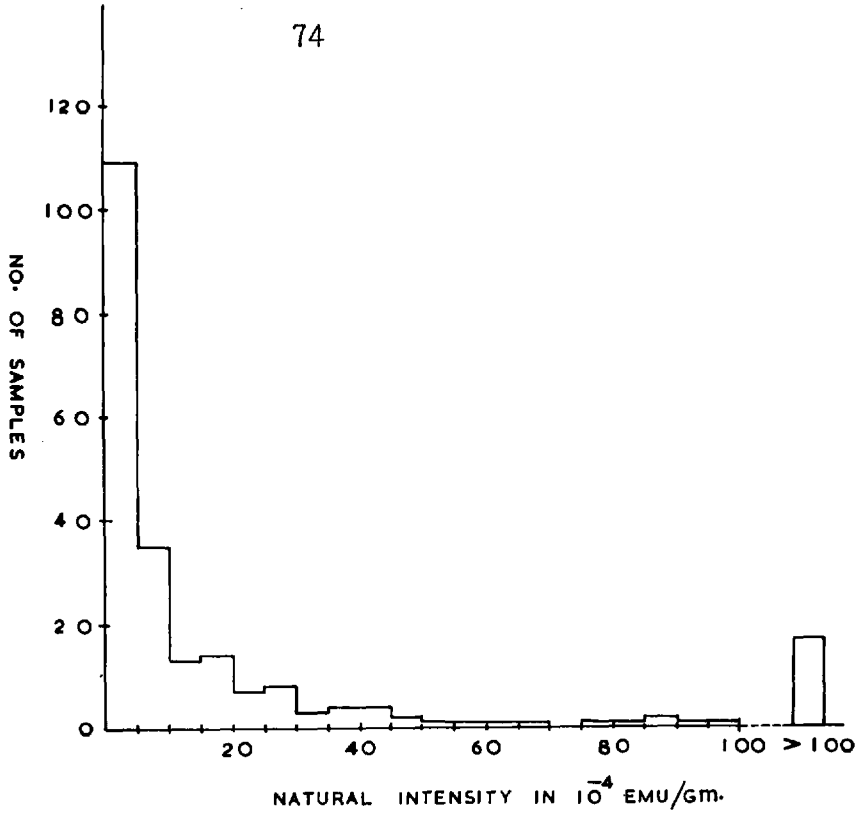


FIG. 5C - ALTERNATING FIELD DEMAGNETIZATION CURVES & RAYLEIGH LOOPS FOR C-GROUP ROCKS or D.C.), temperature changes or even mechanical shocks. Since the decay of magnetization and susceptibility are slow, accurate measurements of direction and intensity of such specimens will be difficult to carry out.

5.8 Distribution of intensity and susceptibility The intensity of natural remanent magnetization of a rock sample depends on factors such as (a) the magnetic minerals present in the sample and their percentage (b) the intensity of the earth's magnetic field at the time the rock was formed and (c) the amount of change produced by weathering, viscous magnetization, partial thermoremanence etc., since the time the rock was formed. It is reasonable to expect these parameters of susceptibility and intensity to be distributed similarly since the induced magnetization a rock acquires in a field depends on the susceptibility of the rock.

Tarling (1966) has found that the intensities and susceptibilities of a large number of Cenozoic and Jurassic rocks are log-normally distributed and even in those cases where the distribution is not log-normal, these parameters are better described by the average and standard deviation of their logarithms than by the arithmetic values. Irving et al (1966) have also noticed that a log-normal distribution describes the distribution of intensities and susceptibilities of Torridonian sandstones better than a Gaussian distribution.

An attempt is made to find the best fit for the distribution of these parameters with respect to the lavas of Turkana and the central rift.



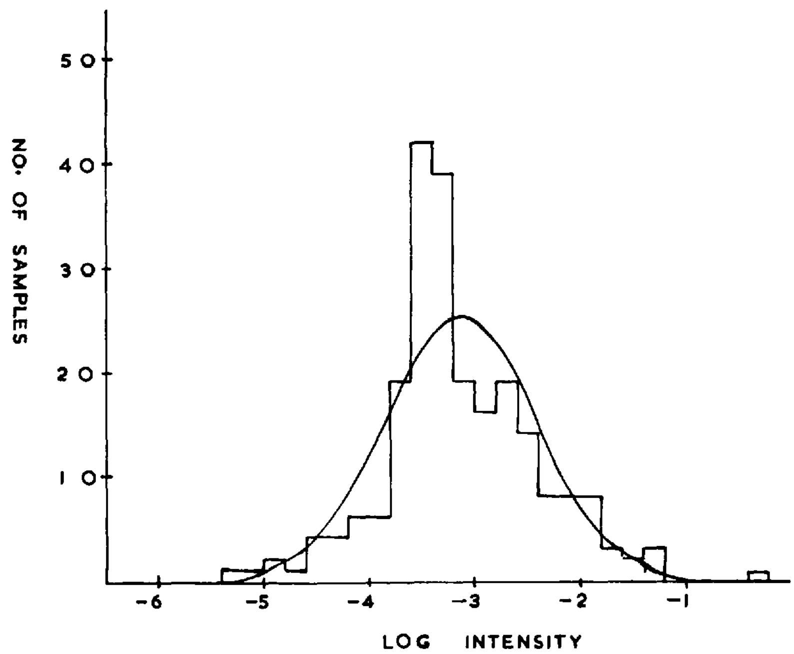


FIG. 5D – HISTOGRAMS OF INTENSITY AND LOG INTENSITY

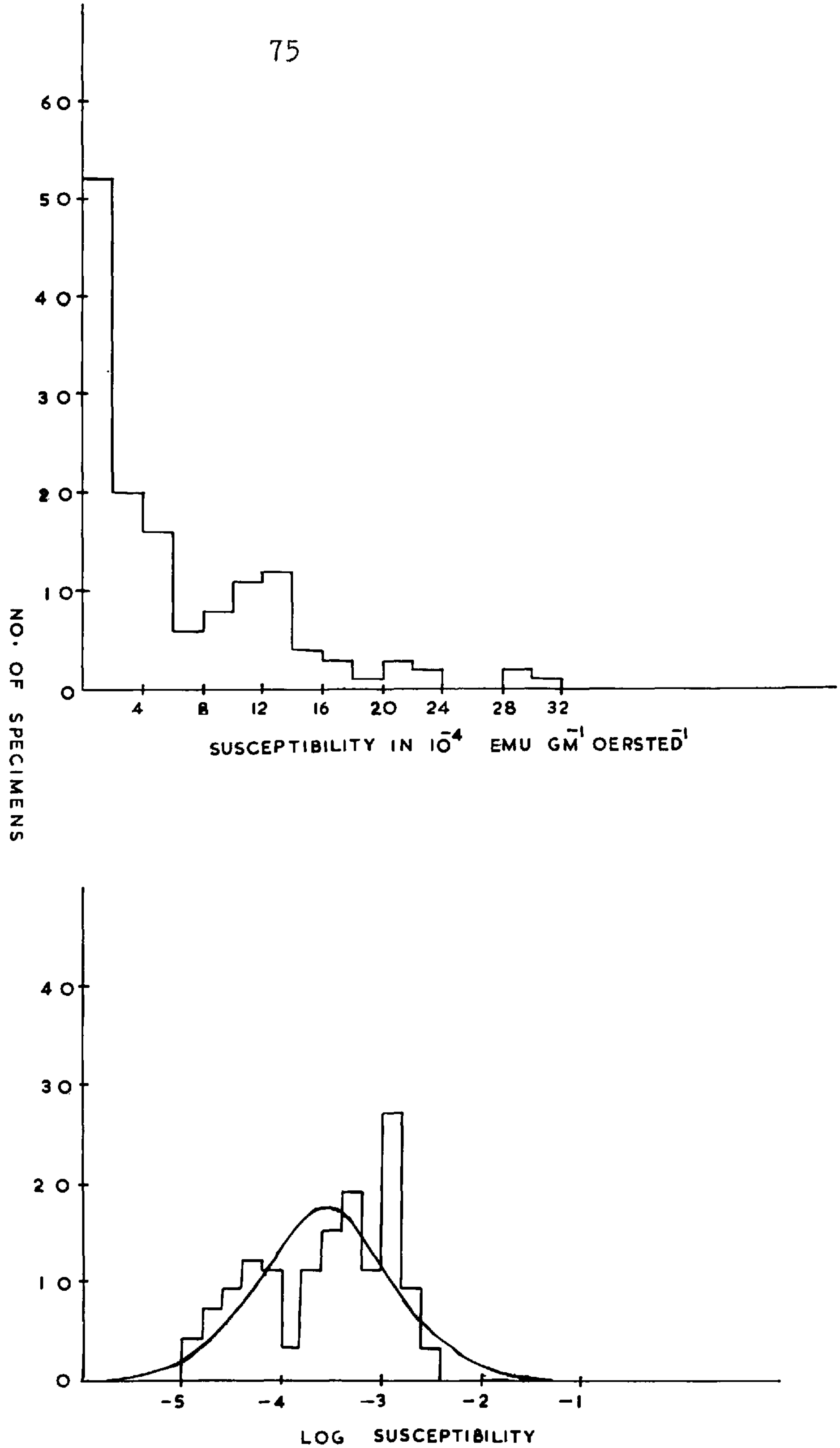


FIG. 5E— HISTOGRAMS OF SUSCEPTIBILITY

Susceptibility measurements These were made on disc shaped specimens of diameter 7/8 inch and length $\frac{1}{2}$ inch using the apparatus built by Likhite and Radhakrishnamurty (1966). All measurements were made in an energizing field of 0.5 Oe. at 140 cycles per second. In all, susceptibilities of 141 specimens were measured.

Intensities (emu/gm) of all specimens were measured with the astatic magnetometer. For each sample intensities of at least two specimens were measured. In many cases four specimens were cut from the samples and their intensities measured. The arithmetic mean of intensities of specimens from the same sample were calculated and this value taken as the mean intensity of the sample. Intensity values were thus calculated for 226 samples, which included even those suspected of lightning effects.

Fig.5D shows the distributions of intensities and logarithms of intensities using histograms and Fig.5E gives the corresponding histograms for mass susceptibility and their logarithms. It is clear from the histograms that the actual intensities and susceptibilities are not symmetrically distributed. The arithmetic means of these parameters will, therefore, not be meaningful. On the other hand, it can be seen from the above figures that these parameters fit better when the distribution is expressed log-normally, even though the chi-squared test did not indicate a good fit. The following table gives the results.

It should be assumed that even when the distribution is not log-normal as in the present case, the parameters are better described by the average and standard deviation calculated from logarithmic values than from arithmetic values.

TABLE 7

SUMMARY OF VALUES

	No. of samples	Arithmetic average (x 10^4)	Standard Deviation	Average from log. values (x 10^4)	Logarithm standard deviation
Intensity (emu/gm)	226	47.82	302	7.39	0.71
Mass susceptibility	141	6.31	6.76	2.80	0.65

5.9 Correlation between bulk magnetic properties and polarity

An attempt is made to correlate the polarities of rocks with their bulk magnetic properties such as (1) natural intensity (2) saturation magnetization (3) susceptibility in 0.5 Oe. and (4) Curie points in 1500 Oe.

Natural intensity   Intensities were calculated for 109 samples (58 normal and 51 reversed) from Turkana and 49 samples (13 normal and 36 reversed) from the central rift by finding the arithmetic mean of the intensities of all the specimens from each sample. Samples suspected of being affected by lightning and those that did not give stable directions on cleaning were omitted. It can be seen from the histogram (Fig.5F) that no significant difference could be noticed in the distribution of intensities between normal and reversed rocks except that

(a) there are more low intensity samples in the reversed group, and

(b) the samples with high intensities are more evenly distributed in the reversed group than in the normal one.

Two reasons may be attributed to the larger number of low intensity samples in the reversed group:

(1) All rhyolite samples except those from one site are reversely magnetized and their natural intensities are very small, and

(2) reversed rocks must have taken up viscous magnetization due to their being in the present earth's field, thereby decreasing their natural remanence acquired at the time of formation.

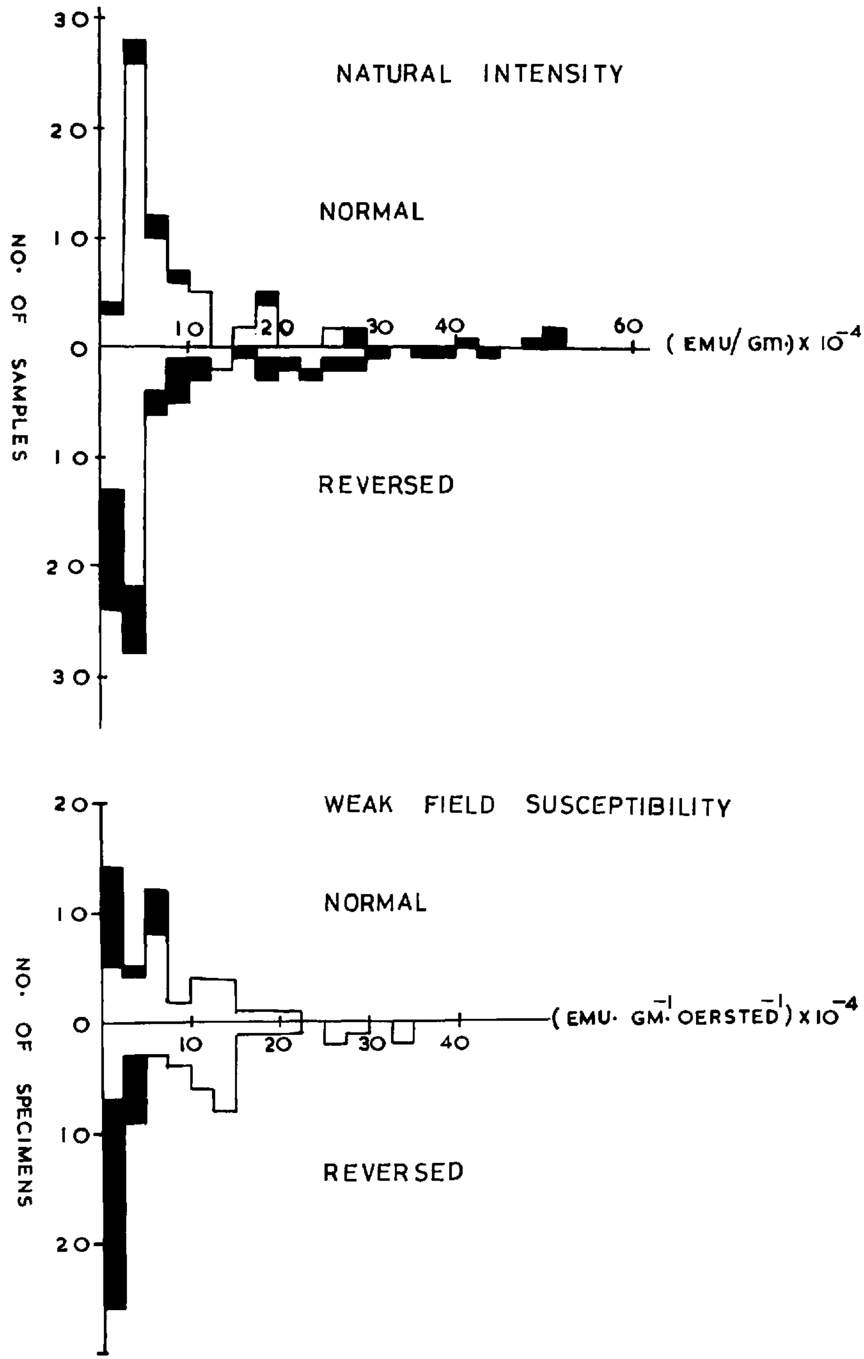
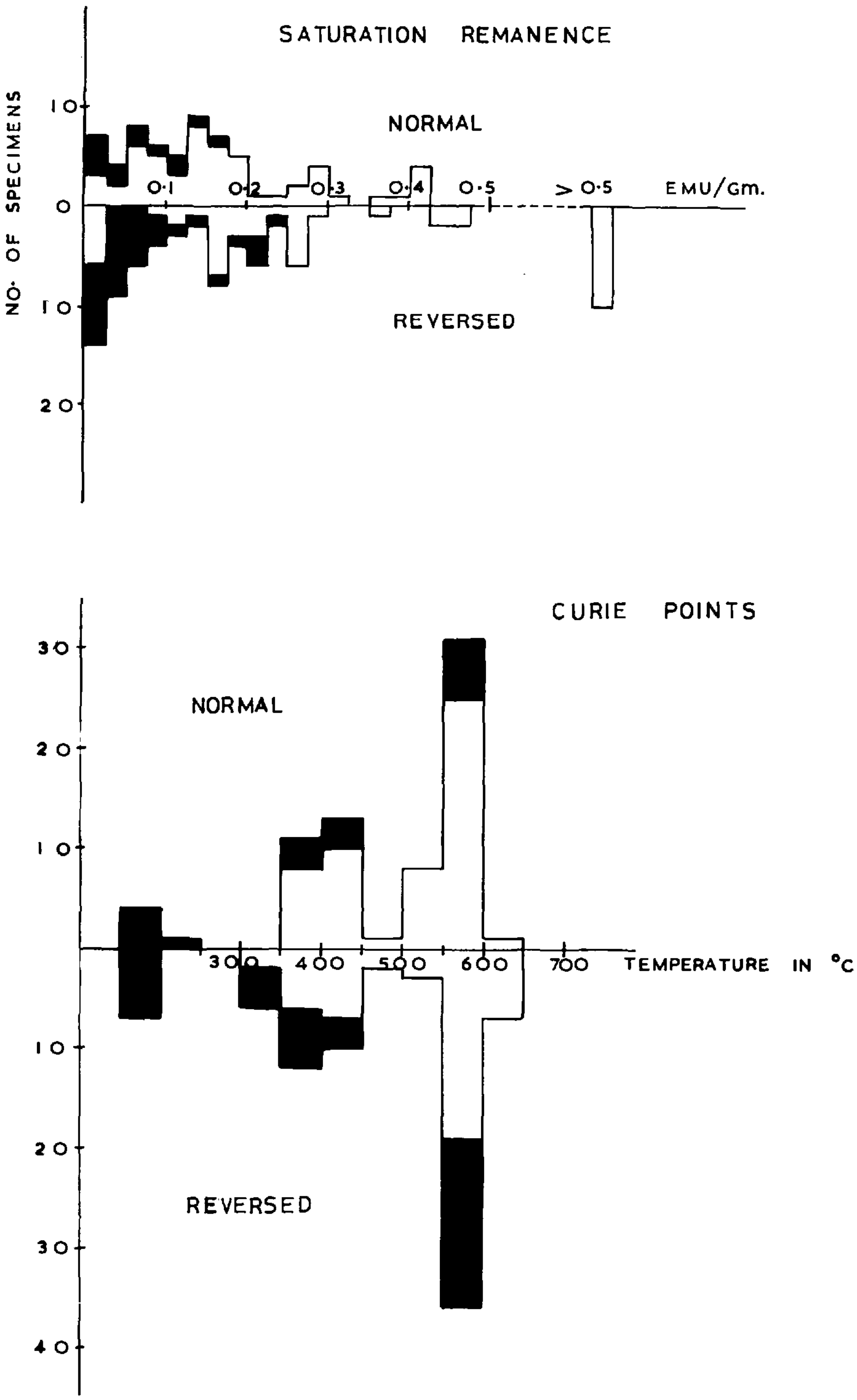


FIG. 5F - DISTRIBUTION OF INTENSITY OF NRM AND SUSCEPTIBILITY FOR NORMAL AND REVERSED SAMPLES

Weak field susceptibility The second histogram in Fig.5F displays the susceptibilities of 108 specimens, 44 normal and 64 reversed. The following differences in the distribution may be noticed. The susceptibilities of specimens from the central rift are all grouped within the range 0 - 7.5 whereas those of the specimens from Turkana are spread out giving some specimens with high susceptibility.

Saturation remanence in 3000 Oe. 144 specimens (66 normal and 80 reversed) were saturated in about 3000 Oe. field of an electromagnet and their moments measured with an astatic magnetometer. These are shown on the histogram (Fig.5G). There is no significant difference in the distribution of saturation remanence of normal and reversed specimens except that about ten specimens acquired very high ($>5000 \times 10^{-4}$ emu/gm) remanence. All these specimens had high susceptibilities ($>12 \times 10^{-4}$) too. As can be seen from Figs.5F and 5G, the distribution of saturation remanences is different from the natural remanence distribution. The natural remanence in a rock sample depends on the past history of the rock and hence is unlikely to give a correct indication of the amount of magnetic material in the rock. On the other hand saturation remanence is a better indicator of the bulk magnetic property of the rock.

Curie point distribution Curie points of 150 specimens are displayed on the histogram. Curie points were determined using the Curie balance as explained earlier. Only a small fragment of rock specimen was used in these determinations. Curie points of 50 specimens were determined using whole rock samples and the non-magnetic furnace. These values were checked with those



FIG·5G—DISTRIBUTION OF SATURATION REMANENCE & CURIE POINTS

☐ TURKANA ■ CENTRAL RIFT

obtained with the balance. Values obtained by both methods agreed well. Again no marked difference is noticeable between the distribution of the Curie points of normal and reversed specimens.

The absence of any significant difference in the bulk magnetic properties of lavas investigated suggests that normal and reversed polarities cannot be attributed to any difference in the magnetic properties of minerals in the lavas.

5.10 <u>Microscopic examination of polished sections</u> About 50 specimens chosen at random from among normal and reversed specimens were polished and examined under a microscope to study the magnetic minerals and the degree of alteration. They were classified* into six classes according to the degree of alteration. Curie points of all these specimens were determined later. The histogram (Fig.5H) shows the correlation between Curie point and degree of alteration. Since the above classification was done on a broad basis, they are represented on the histogram as three groups only, class I and II in group I, class III and IV in group II and class V and VI in group III.

The following observations can be made from the histogram

(a) basalts with low Curie points ($<400^{\circ}C$) are the least oxidised.

(b) Most of the rocks in group II have Curie points between 450 and $550^{\circ}C$.

(c) Group III rocks are all in the high Curie point group.

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* This classification was done my Mr. T.A. Reilly and it is gratefully acknowledged here.

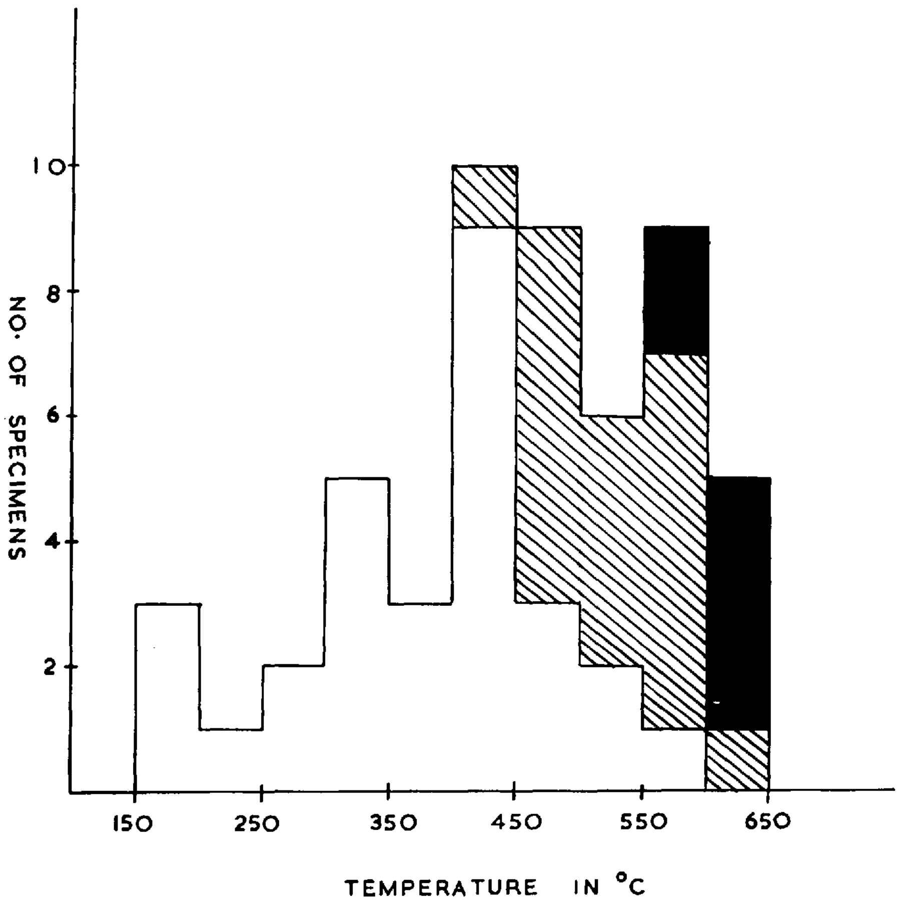

FIG. 5H – CORRELATION BETWEEN OXIDATION & CURIE POINT

CLASS I & II   CLASS III & IV   CLASS V & VI

These clearly show that oxidation raises the Curie point of rocks. It is also significant that specimens in Group I with Curie points near 500°C, all contained traces of ilmenite lamellae.

These findings agree with Ade Hall et al's (1965) findings that oxidation of titanomagnetite raises the Curie point of rocks and that ilmenite lamellae would result from oxidation.

CHAPTER 6

BAKED CONTACT EVIDENCE FOR FIELD REVERSAL

6.1 Introduction About half of all the rocks of all ages studied so far have been found to be magnetized in a direction roughly opposite to the present direction of the earth's field. This could be explained only in two ways. Either the earth's field has often inverted its polarity in the past or the reversed rocks contain minerals which possess the property of acquiring magnetization in a direction opposite to the applied field. The latter property is knwon as self reversal. The self reversal mechanisms suggested by Neel (1955) are now well known and, therefore, need not be mentioned here.

Self reversals have been produced in the laboratory on synthetic minerals (Gorter and Schulkes, 1953, Carmichael, 1962, Bhimasankaram, 1964). The example of self reversal found in Haruna dacite (Uyeda, 1958) is unique in that it is the first instance of self reversal in a naturally occurring rock. So far no self reversal has been produced in titanomagnetites which are the main magnetic constituents of basalts. It should, therefore, be assumed that self reversal in rocks is a rare phenomenon and large masses of reversed rocks possessing magnetic properties identical to those of their normally magnetized counterparts cannot be expected to have reversed in polarity due to the inherent property of self reversal.

In addition, radiometric dating of rocks combined with determinations of their polarity by palaeomagnetic methods have produced results which strongly support the hypothesis of goemagnetic field reversal. During the past six years, such studies of age and polarity of rocks from widely different localities have enabled Cox et al (1963, 1964, 1967), McDougall and Tarling (1964) and McDougall and Chamalaun (1966) to construct polarity time scales extending to 4 m.y. This hypothesis of periodic reversals of the earth's magnetic field has been further supported by evidence from polarity changes observed by Opdyke et al (1966) in deep sea sediments and from the study of the magnetic profile of the ocean floor by Vine (1966).

6.2 Evidence from baked rocks The hypothesis of reversals of the earth's magnetic field can be tested by comparing the direction of magnetization of igneous rocks and of their associated baked rocks. A baked rock is one which is heated by an adjacent igneous rock. During the process, the baked rock is remagnetized and both the igneous and baked rock acquire the direction of the ambient geomagnetic field while cooling through their respective Curie points. The essence of the test is that if the baked rocks in all cases have the same polarity as their associated igneous rock, then there is good evidence for field reversal. But if the polarities of the baked and baking rocks disagree in about 50 percent of the cases, then field reversals are less likely to have occurred and the disagreement in direction should be attributed to self reversal.

Raja (1964) has found that the sense of direction of nine Scottish dykes agreed with the directions of their associated baked contacts. Wilson (1966) has presented baked contact evidence for field reversal which shows that the polarities of 87 baked contacts were the same as those of the corresponding baking rocks. Only three cases of disagreement were noticed. A further 21 examples of agreement between Scottish Tertiary dykes and their baked contacts have been found by Smith (1966). A convincing test of ancient field polarity has been published by Everitt and Clegg (1962) based on their studies on baked rocks at various distances from the contact interface.

In Turkana, in spite of the common occurrence of dykes cutting various units, it was possible to sample only two dykes and their contacts, as suitable baked contacts were not observed for other dykes.

The baked contact of dyke 657 was sampled at the interface. The intensities of the specimens cored from this sample were high enough to be measured when progressively demagnetized in A.C. fields of even up to 1000 Oe. It was noticed that the intensity of specimens cored from the same block decreased rapidly as their distance from the interface increased. Differences in colour and texture were also appreciable as one moved away from the contact.

For dyke 290 the nearest available baked sediment was 6 inches away from it. The intensities of specimens cut from this sample were too low (0.11×10^{-4} - 0.17×10^{-4} emu/gm) to allow measurement after cleaning. Hence the directions quoted for this sample are the NRM directions. Another block collected about 20 feet away from the dyke was too weak to be measured with the astatic magnetometer.

Measurement of natural moments of the specimens from the dykes showed wide scatter in directions and intensity. Routine stability tests carried out on the specimens indicated that they

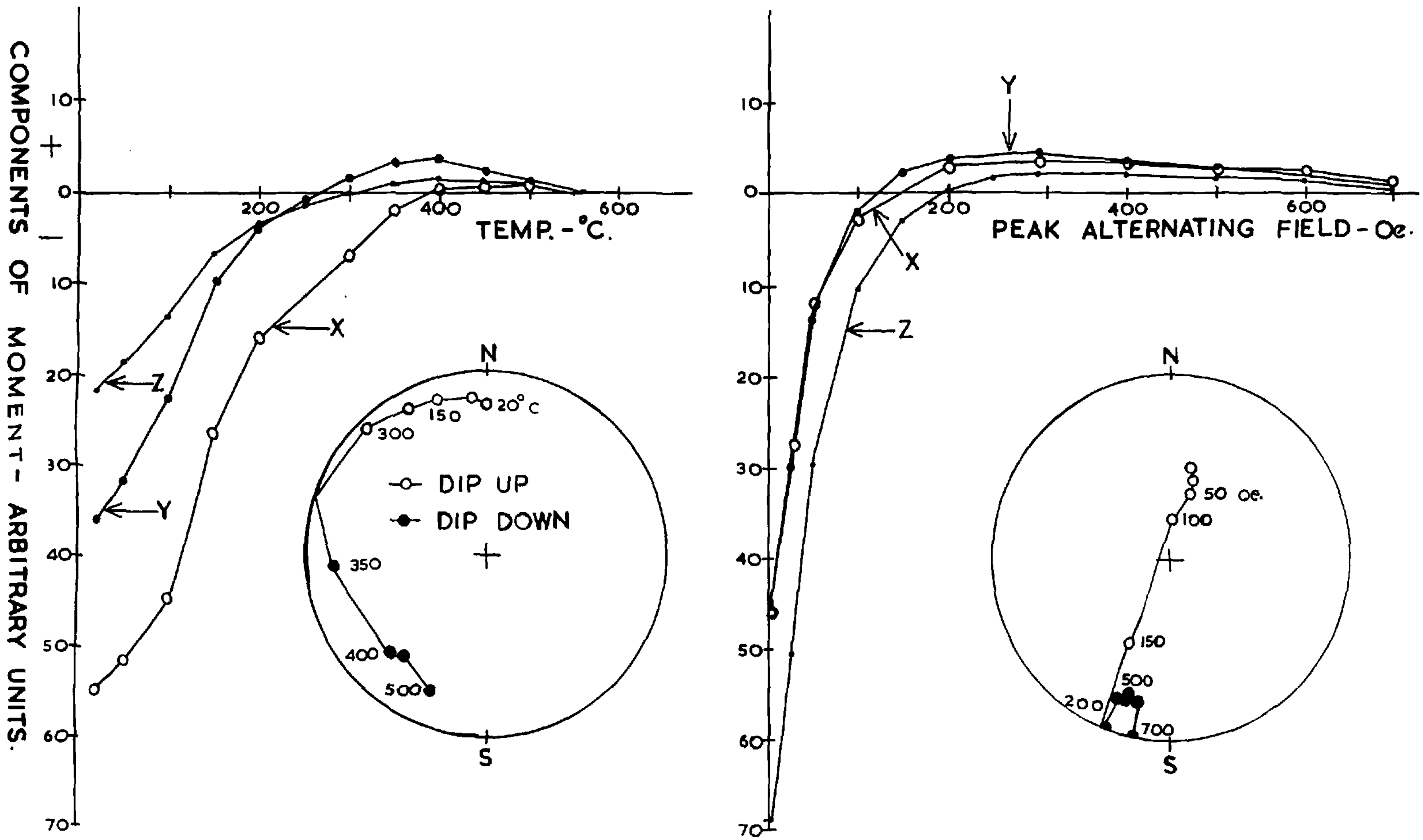

FIG. 6 A - BEHAVIOUR OF DYKE SPECIMENS DURING THERMAL AND A.F. DEMAGNETIZATION.

are magnetically stable for palaeomagnetic work. The following observations support this

1) Results of thermal and alternating field cleaning agreed
2) Directions of igneous and baked rocks agreed; both gave directions opposite to that of the present earth's field
3) Shapes of A.F. demagnetization curves of natural remanence and saturation remanence were similar
4) High field heating and cooling curves were similar in shape.

Typical behaviour of dyke specimens during A.F. and thermal demagnetization is shown in Fig.6A. In both cases all the three components of magnetization reversed their directions indicating the presence of large viscous components. A.F. demagnetization was found to be more effective in this case since it was noticed that the blocking temperatures of the high coercivity grains were not far removed from the Curie temperature and that the intensity of the specimen fell to a very small value at such high temperatures.

Fig.6B displays high field heating and cooling curves. The Curie point of dyke 657 was more than 600°C as compared to 570°C for the dyke 290. This may be due to the presence of hematite either as a secondary or primary mineral in the specimen.

A.F. demagnetization curves of NRM and TRM of the igneous and baked rocks are reproduced in Fig.6C. The gradual decrease in the natural remanent moment of the sediment suggests that the rock is one with a broad coercive spectrum indicating a wide range in grain and domain size. Also the identical shapes of A.F. demagnetization curves of TRM and NRM of the sediment show

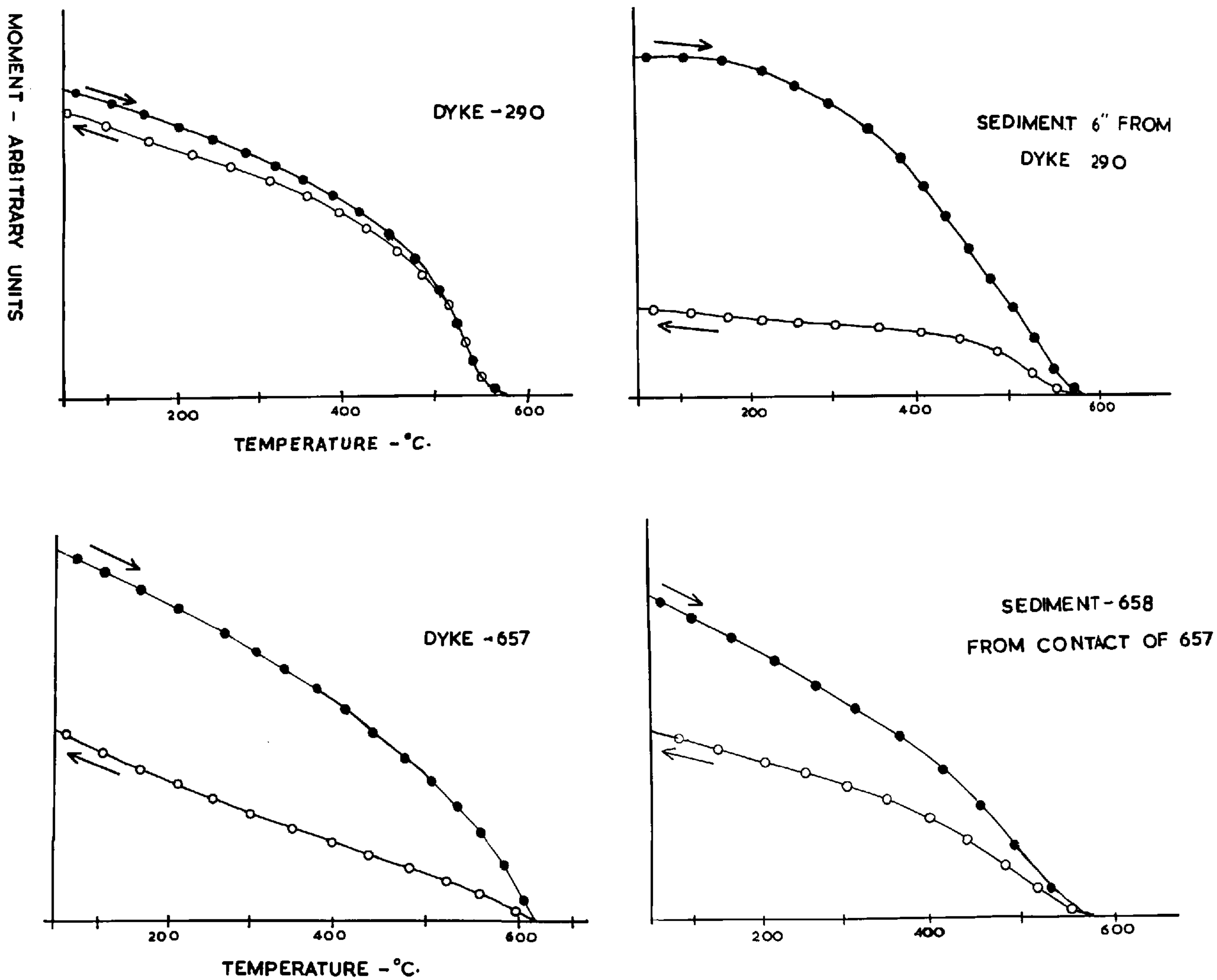

FIG. 6B - HIGH FIELD HEATING AND COOLING CURVES FOR DYKES AND BAKED SEDIMENTS.

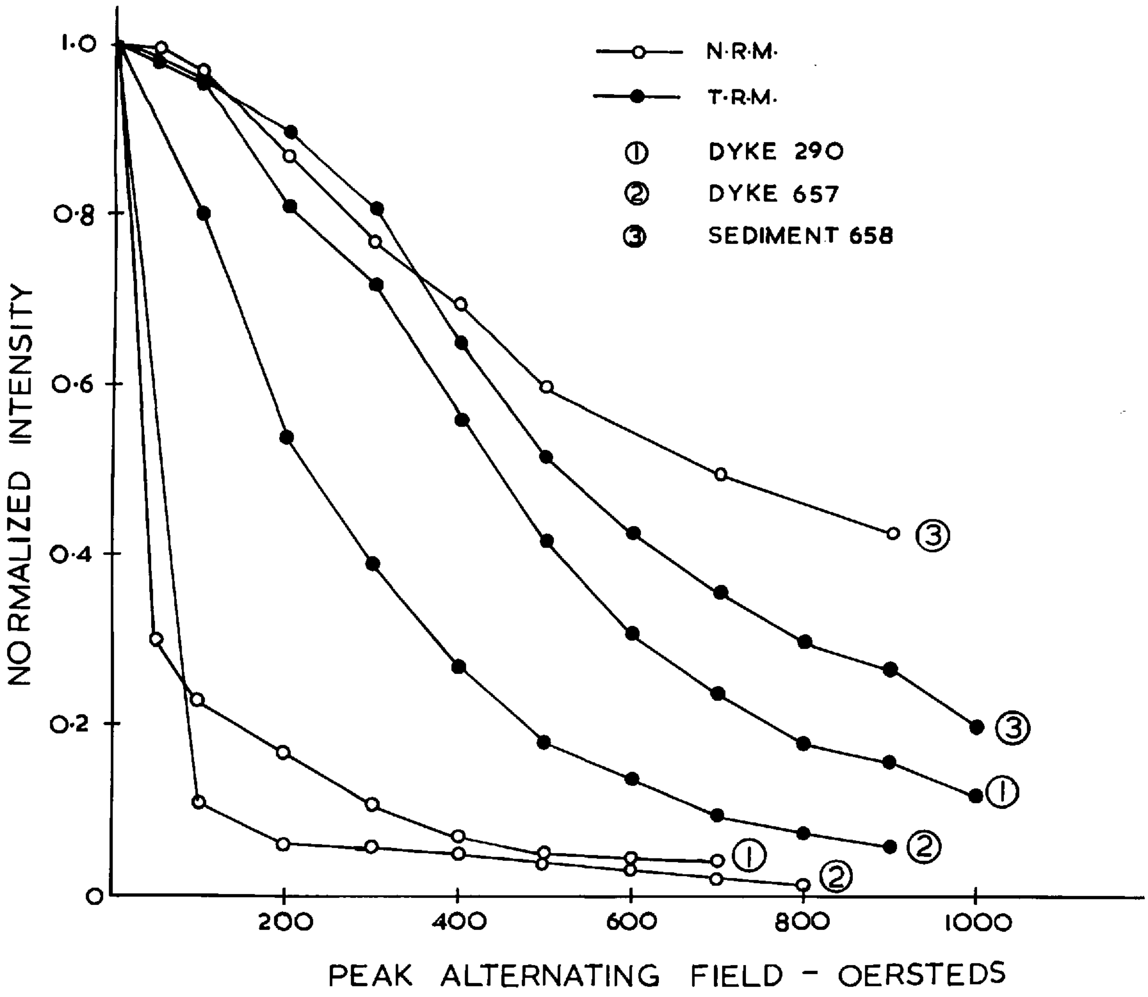

FIG. 6C - A.F. DEMAGNETIZATION CURVES OF N.R.M. AND T.R.M. OF DYKE AND BAKED SEDIMENT that its NRM is of thermoremanent origin, and that the coercivity spectrum of NRM and TRM are identical. Heating the specimen to 700°C in air did not produce any obvious alterations in the magnetic properties.

On the other hand the A.F. demagnetization curves of NRM and TRM of the dykes are not similar in shape. This shows that their NRM is not of thermoremanent origin only. The dissimilarity between the shapes of the A.F. demagnetization curves of TRM of dyke and sediment suggests that the igneous and baked rocks contain different magnetic materials.

Fig.6D shows the stereographic projection of the directions of the specimens before and after cleaning. It can be seen that cleaned directions of the dyke agree with the directions of their associated baked sediments.

6.3 Microscopic study Polished sections of dyke specimens were examined under a microscope to study the minerals and the degree of alteration. Large corroded mottled titanomagnetite grains were found to be present. Reddening was generally low except in the case of 657 which has a higher Curie point than 290. It is not likely that the reversed polarity of sample 657 is due to the high degree of oxidation in it. Though correlation between degree of oxidation and polarity has been found in the case of lavas (Wilson and Watkins 1967) their conclusion was that self reversal of magnetization cannot explain this correlation.

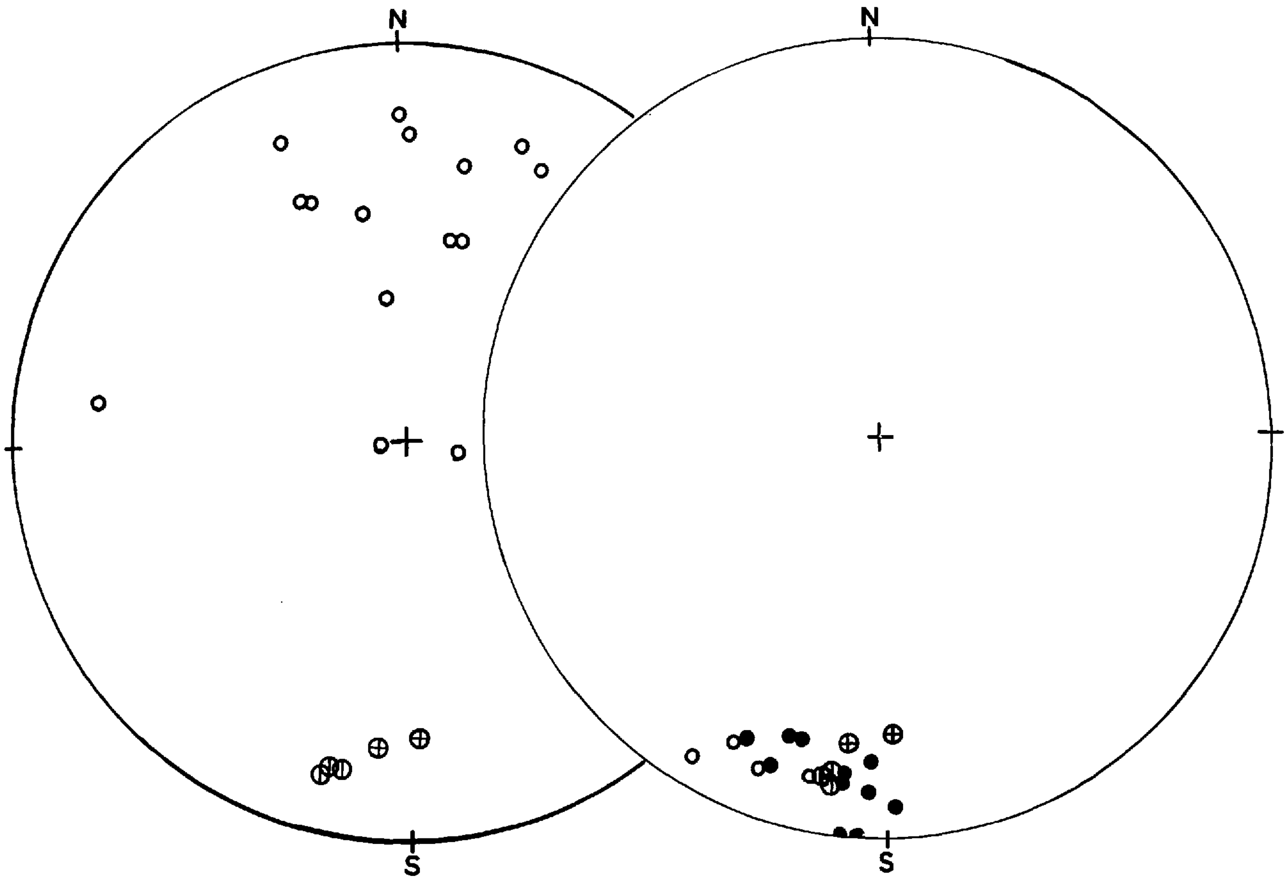

FIG. 6D - DIRECTIONS OF MAGNETIZATION BEFORE AND AFTER CLEANING

DYKES - ● DIPS DOWN, o DIPS UP

SEDIMENTS - ⊕ DIPS DOWN, ⦶ DIPS UP

The agreement between the directions of magnetization of the dykes and baked contacts supports the hypothesis of reversals of the earth's magnetic field in the past and suggests that the reversed direction of dykes is not due to any self reversing mechanism. These dykes are feeder dykes to the basaltic lavas in the Lokitaung gorge which have been dated at upper Oligocene to lower Miocene (Reilly et al 1966). It is, therefore, concluded that a field reversal must have occurred during this period.

CHAPTER 7

PALAEOMAGNETIC RESULTS AND CONCLUSIONS

7.1 Introduction For palaeomagnetic purposes, a site is usually defined as a volume of rock which has acquired primary magnetization over a short time compared with secular variation. Thus the mean direction of a single site represents a point in time. Therefore, in order to average out the secular variation during the period in which the rock formation became magnetized it is necessary to sample many sites from the formation and find the mean of their directions. In the present study such an extensive collection has been carried out only from the Turkana lavas. In the case of lavas from the central rift, sampling was done on a reconnaissance basis except in the Pleistocene lava from Loperot and in the phonolites from Kisumu. Therefore, directions from the central rift volcanics have been used only to establish reversals. On the other hand, directions from the Turkana lavas have been interpreted both with regard to geomagnetic field reversals and determination of pole positions.

7.2 Age and polarity of central rift volcanics Table 8 summarizes the polarity and available dates from the rock units sampled from the central rift*. The existance of both polarities in the Kisumu phonolites has been established.

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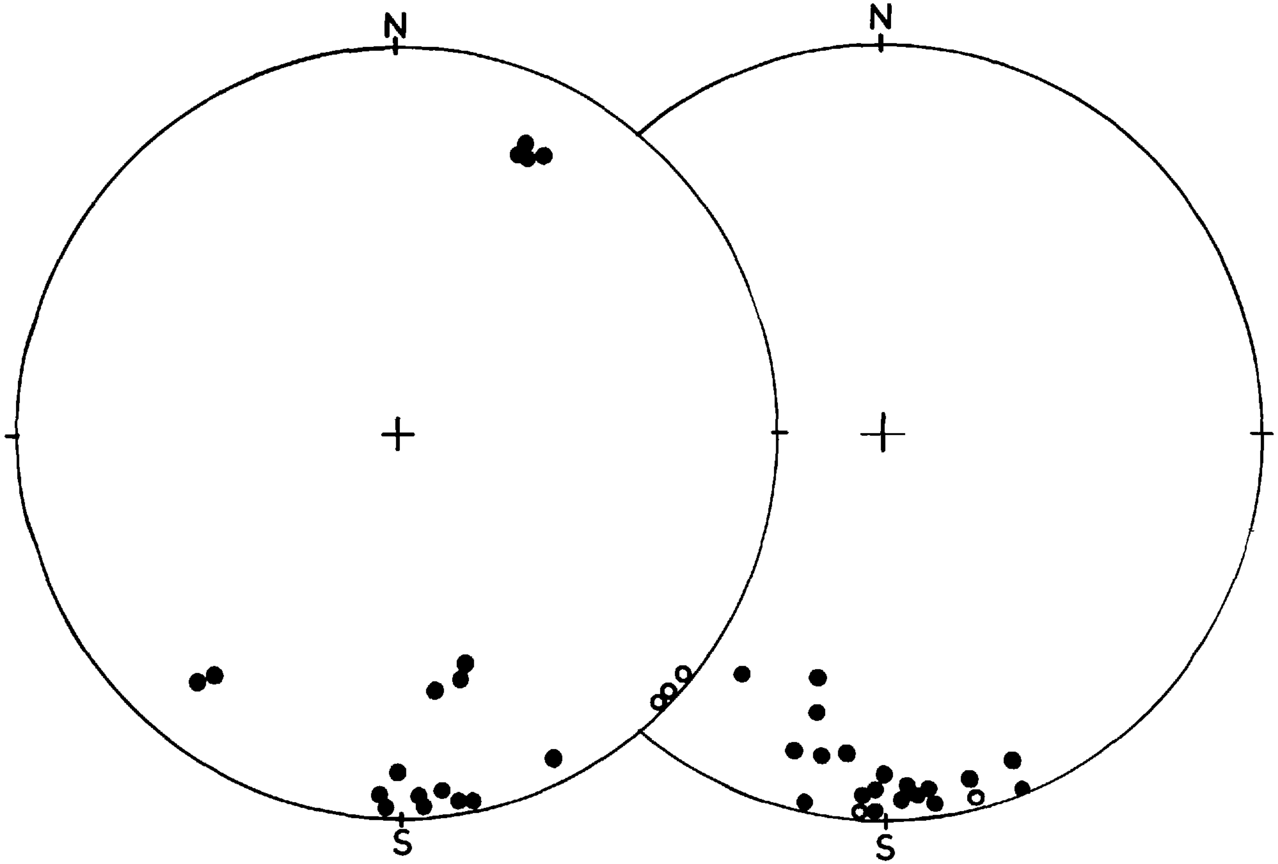
* I am grateful to the Department of Mines and Geology, Kenya, for allowing me to include these dates in my thesis.

The Kenya type of phonolite is normal and the Losaguta type is reversed. The Kericho phonolite is also reversed. This is consistent with the two polarities observed in the Kapiti phonolites (Patel, 1968) which are of approximately the same age as the Kisumu phonolites.

As mentioned earlier the Loperot Pleistocene lava was sampled in some detail. Thermal and A.F. demagnetization tests showed that they were magnetically stable. All the 21 specimens cut from 8 samples from 4 sites gave consistently reversed polarity (Fig.7A) indicating that the formation must have acquired the primary magnetization at a period when the geomagnetic field direction was opposite to the present direction. The age of the lava (2.5 $\pm$ 0.2 m.y.), within the limits of error is approximately the beginning of the Matuyama reversed polarity epoch, as it is now believed to be 2.5 m.y. old (Cox et al, 1967).

Recent palaeomagnetic and K-Ar studies of the upper Miocene and the Pliocene lava from Western United States by Dalrymple et al (1967) suggests that the frequency of field reversals during Pliocene times may have been comparable with that of the last 3.6 m.y. The existance of both polarities in the lavas of the central rift supports the above suggestion.

7.3 <u>Age and polarity of the Turkana lavas</u> The stratigraphic units comprising of the Turkana lavas have already been mentioned in Chapter 2. Four lavas were dated by Grasty in 1966 (Reilly et al, 1966). The ages obtained along with the polarities are given in Table 9.



FIG·7A- LOPEROT PLEISTOCENE LAVA SPECIMENS – DIRECTIONS BEFORE AND AFTER CLEANING· ● DIPS DOWN· o DIPS UP

TABLE 8

Rock Unit	Age (m.y.)	Analyst	Polarity
Loperot (Pleistocene) lava	2.5 ± 0.2	Geochron Lab.	R
Gilgil volcanics	-	-	R
Londiani trachyte	-	-	R
Kabernet trachyte	7.2 ± 1.0	J. Miller	R
Laikipian basalt	-	-	R
Nyeri tuff	-	-	N
Thomson's Falls phonolite	6.4 ± 0.5	J. Miller	?
Kisumu phonolite	12.3 ± 0.2	J. Miller	N & R
Kericho phonolite	(1) 12.4 ± 0.2 (2) 13.2 ± 0.2	J. Miller	R
Loperot (Miocene) lava	15.8 ± 1.2	Geochron Lab.	N
Samburu basalt	20.4 ± 3.0	J. Miller	R
Rumuruti phonolite	-	-	?
Uasin Gishu phonolite (lower)	13.6 ± 0.6	J. Miller	N
Uasin Gishu phonolite (upper)	12.3 ± 0.2	J. Miller	N

TABLE 9

Rock Unit	Sample No.	Age (m.y.)	Polarity
Lower basalts	260)	32.2 ± 0.5	R
	261)	31.5 ± 0.7	R
	264)	20.7 ± 0.4	R
	265)	23.0 ± 0.7	R
Upper basalts	293)	23.5 ± 1.1	R
	294)	23.3 ± 0.2	R
Phonolites and nephelinites	243)	14.9 ± 0.5	N
	250)	12.5 ± 0.3	N

The ages given in the table (9) should be accepted with reservation. It is now believed that the upper and lower basalts are younger than suggested by these dates. The oldest in the series - the lower basalts - according to Walsh (1968) "closely resemble and are probably equivalent to the Samburu basalts" of the central parts of the Kenya Rift Valley. As shown in Table 8, Samburu basalts gave an age of 20.4 ± 3 m.y. There is also discrepancy between the dates of samples 260/61 and the apparently underlying ones 264/65. Though this discrepancy has been attributed to either argon loss in sample 264/65 or to the local repetition of the succession due to faulting, the age 20.7 ± 0.4 seems to be the more reliable one due to its agreement with the age of Samburu basalts.

Lower and upper basalt samples collected from areas south of Lokitaung and dated by Geochron Laboratories have yielded the dates shown in Table 10.

The phonolites and nephelinites are definitely younger than the basalts, but could be older than the rhyolites. No date is available for the rhyolites. Since they cap many mountain ranges in the locality, they are considered to be the youngest of all the units. Some fossil wood found in the rhyolite 60 Km. north of Lokitaung hints at a Mio-Pliocene age. Fairburn and Matheson (Report in preparation) were able to subdivide the rhyolite succession into two groups, a lower and an upper one separated by an andesite group. Two samples each of andesite and rhyolite collected from Tarach were both of normal polarity. All the eight samples of rhyolites collected from Lokitaung were reversed in polarity and of very low intensity compared to the rhyolites from Tarach. It should be

TABLE 10

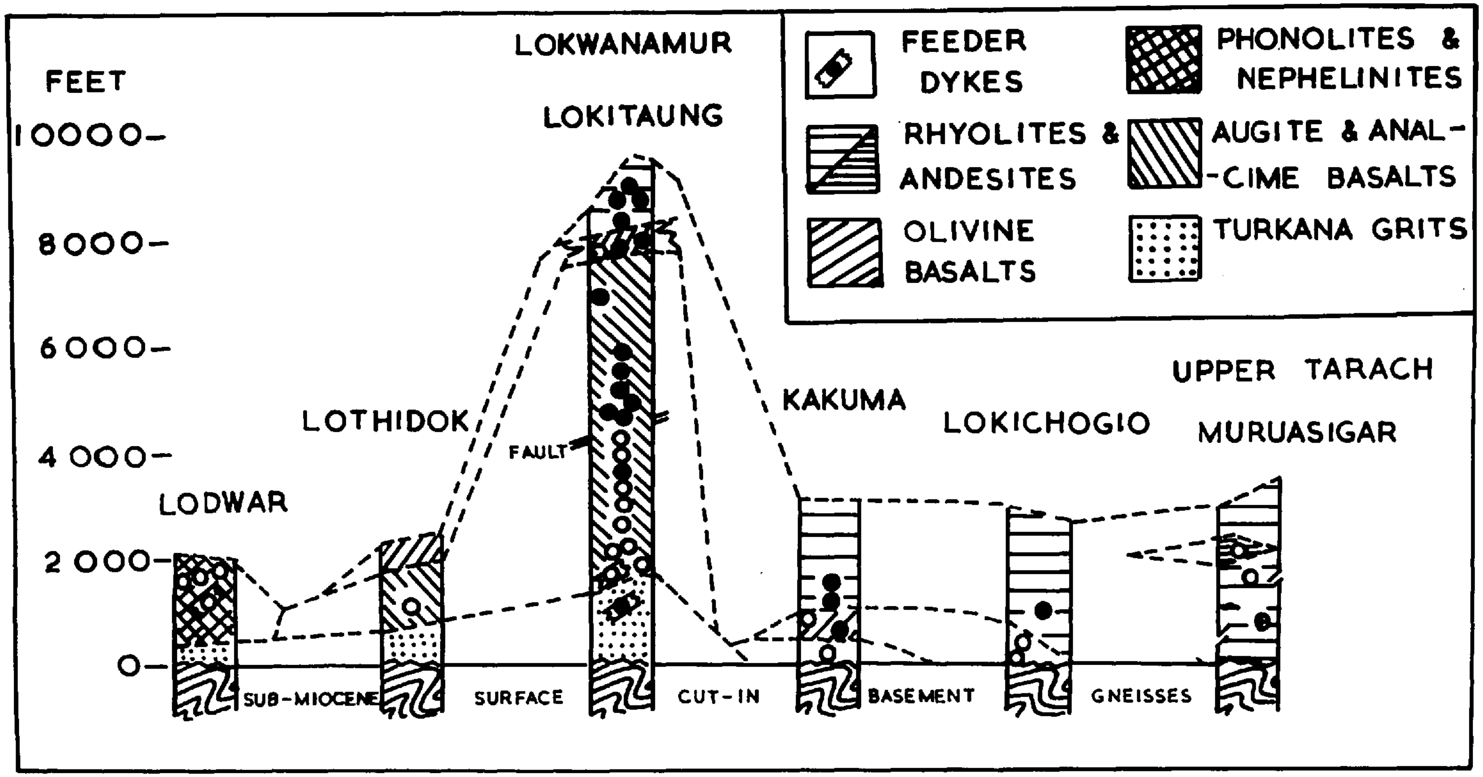
Rock Unit	Location	Age (m.y.)
Lower basalt	Loperot (Top of Turkana grit)	17.5 ± 0.9
Lower basalt	Anwerwer Hills $2^{\circ}16'$N, $35^{\circ}15'$E	16.7 ± 0.8
Upper basalt	Lothidok $3^{\circ}17'$N, $35^{\circ}49'$E	14.0 ± 1.2

assumed, therefore, that the rhyolite extrusion in Turkana and in Tarach took place at different periods.

7.4 Reversals in the Miocene period Fig.7B shows the relationship between the different stratigraphic units and the vertical distribution of sampling. Only those sites whose heights have been determined are shown in the figure. No reversed polarities were observed below the fault. The reversed polarities occur in many rock types, an agglommerate horizon having a consistently reversed polarity. Tectonic repetition may have occurred; isolated cases of self reversal are not ruled out. Even so, the dominance of reversed polarities over the period from the middle of the lower basalt to the beginning of the rhyolite extrusion supports the hypothesis of field inversion during this period. This is further supported by the baked contact evidence described in Chapter 6.

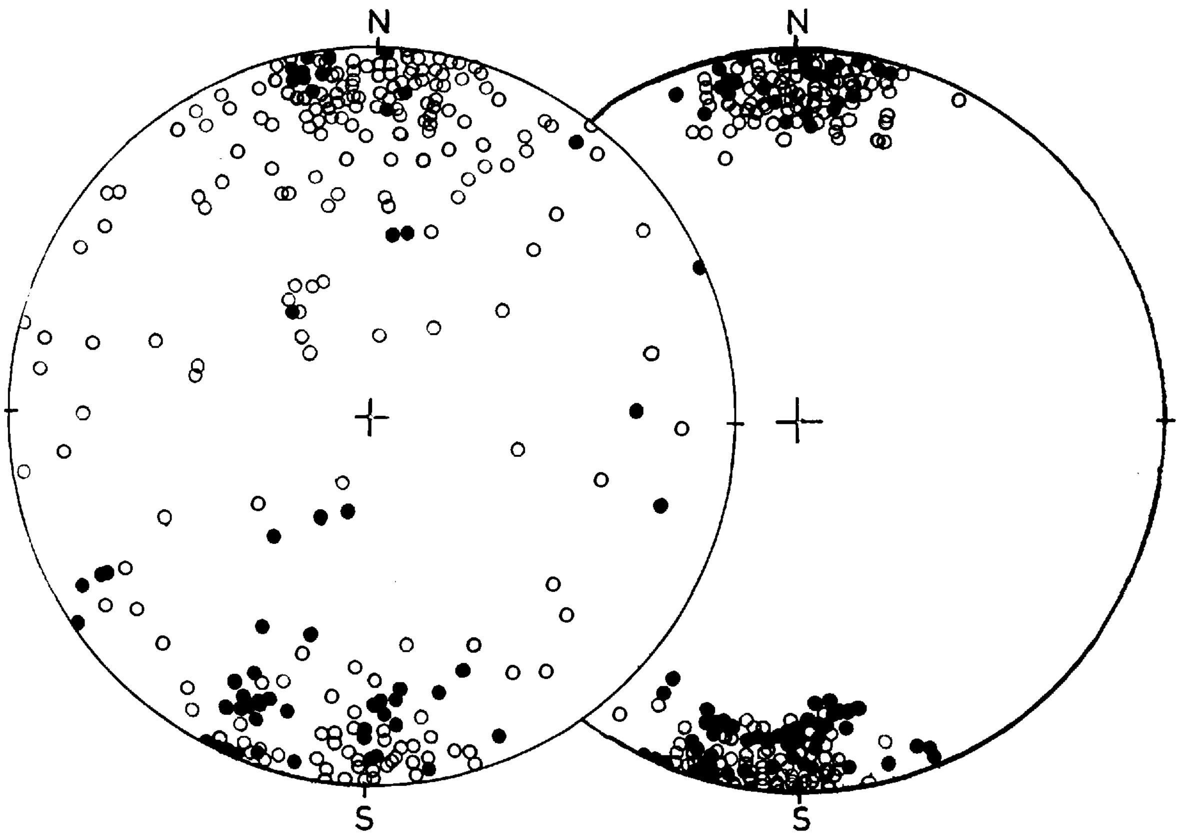
7.5 Pole position for the Miocene period Fig.7C shows the directions of magnetization of all the specimens from Turkana before and after cleaning. On the assumption of a Fisherian distribution, mean directions and pole positions with their circles of confidence were calculated. In order to find out whether the poles, calculated for the normal and reversed groups differed from each other, the angle between them was calculated.

The angle between the northern hemisphere poles calculated from the reversed and normal groups was found to be $2\overset{\circ}{.}9$. This is less than α_{95} for each group, $3\overset{\circ}{.}6$ and $3\overset{\circ}{.}0$ respectively, which shows that there is no reason to regard the two mean pole positions as distinct. Accordingly, reversed and normal



FIG·7B - STRATIGRAPHY OF TURKANA AND VERTICAL DISTRIBUTION OF SITES

O NORMAL ● REVERSED ⊕ SITES THAT COULD NOT BE CLEANED



FIG· 7C–POLAR PROJECTIONS SHOWING DIRECTIONS OF MAGNETIZATION OF TURKANA LAVA SPECIMENS BFFORE & AFTER CLEANING

● DIPS DOWN
o DIPS UP

groups can be combined and Table 11 gives the mean directions after tilt correction for the 62 sites from Turkana. It also shows the mean of the 62 site poles which can be regarded as the new palaeomagnetic pole position from the Turkana lavas. It differs only slightly from that reported earlier (Raja et al, 1966), but owing to the larger number of sites, it has a smaller circle of confidence.

The angle between the mean pole and the geographic pole is $5.^{\circ}2$ which is significant since A_{95} is $2.^{\circ}3$. It is worth noting that it is only when the number of sites is large enough to produce a small circle of confidence that angular differences as small as 5° can be distinguished in palaeomagnetism.

This result indicates a small but significant eastward divergence in the Miocene pole for Africa. It is interesting to compare this with the work of Irving and Tarling (1961) based on results from the Plio-Pleistocene Aden volcanics, which suggests an anti-clockwise movement of the Arabian peninsula relative to Africa. The movement was of such a magnitude as to explain the formation of the Red Sea by rotation of Arabia away from Africa. The authors themselves pointed out (Irving, 1964) that palaeomagnetic results from both sides of the Arabian sea would be required before the rotation could be firmly established.

TABLE 11

Directions of Magnetization and Pole Positions for Miocene lavas from Turkana (Long.35°.8'E, Lat.4°.2'N)

Polarity	St.	Sm.	Sp.	Directions				Pole positions			
				D	I	k	α_{95}	Long. (E)	Lat. (N)	K	A_{95}
Normal	30	52	116	2°.9	-0°.4	43.0	4°.1	179°.7	85°.0	80.1	3°.0
Reversed	32	57	150	185°.3	-3°.6	30.3	4°.7	149°.7	84°.3	51.5	3°.6
Combined	62	109	266	4°.1	1°.7	35.0	3°.1	163°.3	84°.8	61.9	2°.3

St., Number of sites

Sm., Number of samples

Sp., Number of specimens

D, Declination

I, Inclination

k)
K) Precision parameter (Fisher 1953)*

α_{95})
A_{95}) Semi angle of 95% Confidence Cone (Fisher 1953)*

NOTE: Sites have been assigned unit weight in the above calculations

* Fisher, R.A., (1953) Dispersion on a sphere. Proc.Roy.Soc.Lond.A, 217, 295.

Reilly (1968) has made a thorough palaeomagnetic study of the rift volcanics south of the equator. He observed that no rotation of Africa occurred in the post middle Pliocene; but he has found a significant and similar eastward shift in the mean declination of the Group III (10 - 14 m.y.) rocks.

It cannot, however, be stated at this stage whether this small eastward divergence signifies a clockwise rotation of the continent of Africa or a small polar wander. Probably results from the Ethiopian lavas (on which work is now being done by Dr. A. Brook and Dr. P. Gacii) which is considered to be slightly older than the Turkana lavas, might reveal the actual trend.

APPENDIX

SITE DIRECTIONS AND SITE POLES

KEY TO APPENDIX

NOTE: Unit weight assigned to sample. All site poles are Northern hemisphere poles.

Site No.	Stratigraphic Unit	Site Position	
		Long.°E	Lat.°N
1	Lothidok basalts	35.8	3.2
2 - 47	Lokitaung gorge basalts	35.8	4.2
48 - 49	Kakuma basalt	35.0	3.7
50	Songot basalt	34.3	4.1
51 - 54	Lodwar phonolites and nephelinites	35.6	3.1
55	Muruasigar phonolite	35.0	3.1
56 - 59	Lokitaung rhyolite	35.8	4.2
60	Lokichogio rhyolite	34.3	4.1
61 - 62	Tarach rhyolite - andesite	34.7	3.0
63	Gilgil volcanics	36.3	-0.5
64	Kabernet trachyte	35.8	0.3
65 - 69	Kisumu phonolite	34.7	-0.1
70	Kericho phonolite	35.2	-0.2
71	Laikipian basalt	37.0	-0.5
72	Laikipian basalt	37.0	-0.3
73	Laikipian basalt	36.8	-0.1
74	Londiani trachyte	35.5	-0.3
75 - 78	Loperot Pleistocene lava	36.0	2.3
79	Loperot Miocene lava	36.0	2.3

KEY TO APPENDIX (Continued)

Site No.	Stratigraphic Unit	Site Position	
		Long.°E	Lat.°N
80	Mbaruk basalt	36.2	-0.3
81	Naivasha trachyte	36.3	-0.7
82	Nyeri tuff	37.0	-0.4
83	Samburu basalt	36.0	0.5
84	Thiba basalt	37.1	-0.5
85	Thiba basalt	37.3	-0.6
86	Uasin Gishu phonolite	35.5	0.4

TURKANA

Site No.	No. of Samples	No. of Specimens	Site Direction D°	Site Direction I°	Site Pole Long.° (E)	Site Pole Lat.° (N)
1	3	6	0.8	17.4	43.70	84.24
2	2	7	206.2	0	134.27	63.49
3	4	14	180.0	- 9.8	35.80	89.26
4	3	7	178.0	-10.8	337.94	87.65
5	2	4	181.5	10.0	206.57	80.64
6	2	6	0.2	-10.0	214.56	80.76
7	2	4	358.0	- 2.0	236.87	84.43
8	1	2	359.8	-15.2	216.76	78.06
9	3	6	355.0	- 1.8	260.32	82.86
10	2	2	2.0	11.0	91.58	87.59
11	1	2	354.5	0.5	270.23	83.23
12	1	2	350.0	11.8	316.26	79.88
13	2	5	0	- 1.8	215.80	84.90
14	2	3	3.5	- 9.0	193.93	80.60
15	4	10	186.8	4.0	168.06	80.80
16	1	3	195.0	-23.0	97.23	73.25
17	1	4	184.0	-23.0	62.51	81.27
18	1	3	0	12.5	35.80	87.87
19	1	4	179.8	- 6.0	225.31	88.79
20	3	9	181.8	-12.0	79.57	87.41

TURKANA (Continued)

Site No.	No. of Samples	No. of Specimens	Site Direction D°	I°	Site Pole Long.°(E)	Lat.°(N)
21	3	9	186.5	3.0	166.94	81.36
22	3	9	191.5	-12.0	116.06	78.40
23	1	2	175.0	18.0	236.15	75.68
24	1	2	167.5	3.8	280.00	76.10
25	1	2	7.5	- 6.0	169.57	79.60
26	2	5	185.2	- 2.5	155.25	84.03
27	1	2	181.0	18.0	211.56	76.54
28	1	4	198.0	- 7.0	127.36	72.03
29	1	3	161.0	2.0	290.89	70.31
30	2	4	177.8	-18.0	12.43	84.52
31	1	2	181.0	13.0	210.51	79.17
32	1	3	193.0	- 2.0	139.29	76.63
33	2	4	359.5	- 7.5	219.40	82.02
34	1	4	0	0	215.80	85.80
35	1	4	6.0	- 0.5	162.24	82.53
36	1	2	195.8	-12.0	118.37	74.15
37	4	8	359.5	- 7.5	219.40	82.02
38	1	2	190.0	- 1.8	143.81	79.48
39	1	2	20.0	- 8.5	148.54	68.30
40	1	2	11.0	- 1.0	148.70	78.05

TURKANA (Continued)

Site No.	No. of Samples	No. of Specimens	Site Direction D°	I°	Site Pole Long°(E)	Lat°(N)
41	1	2	5.0	-11.5	189.25	78.82
42	2	5	359.5	7.5	264.80	89.34
43	2	4	175.0	-22.0	1.66	81.25
44	1	2	190.8	7.0	161.20	76.74
45	1	2	183.0	-10.0	110.02	86.89
46	2	8	176.0	-10.0	317.83	85.93
47	1	2	3.0	11.0	101.35	86.72
48	1	2	349.0	7.0	304.37	79.02
49	2	2	190.0	- 9.5	118.45	79.97
50	3	9	4.7	- 5.9	180.59	81.52
51	1	4	9.1	2.3	137.51	80.70
52	2	2	15.0	5.0	127.49	75.01
53	2	7	6.7	0	150.32	82.62
54	2	3	359.7	9.3	24.89	86.39
55	2	4	21.3	-15.4	152.35	66.10
56	3	6	200.0	8.0	147.90	68.39
57	2	7	192.0	0.5	145.88	77.21
58	1	2	183.8	8.0	190.96	80.95
59	1	2	201.8	-13.0	118.57	68.17
60	2	4	178.7	- 4.2	247.36	87.62

TURKANA (Continued)

Site No.	No. of Samples	No. of Specimens	Site Direction		Site Pole	
			D°	I°	Long.° (E)	Lat.° (N)
61	2	5	10.5	-21.4	178.30	72.46
62	2	4	358.3	17.3	18.66	83.91
CENTRAL RIFT						
63	3	5	181.8	4.2	168.01	87.59
64	2	6	161.6	4.6	297.65	71.42
65	4	9	158.8	- 7.4	315.13	68.47
66	1	5	2.6	-16.3	197.27	81.38
67	1	4	21.0	- 4.5	130.71	68.90
68	2	5	164.5	-23.1	343.51	70.40
69	2	8	179.6	7.3	221.09	86.41
70	2	4	195.4	7.5	138.44	74.20
71	2	8	183.6	5.3	157.96	85.81
72	1	4	183.5	5.6	162.66	85.70
73	2	5	176.7	11.4	246.96	83.45
74	1	5	196.4	- 6.8	136.44	73.32
75	3	9	178.0	7.5	234.24	83.61
76	1	2	162.5	9.5	283.94	71.14
77	3	5	195.6	20.5	165.97	69.82
78	1	4	200.5	3.8	137.43	69.08
79	2	4	0.3	-18.7	214.57	78.09

CENTRAL RIFT (Continued)

Site No.	No. of Samples	No. of Specimens	Site Direction		Site Pole	
			D°	I°	Long.°(E)	Lat.°(N)
80	2	3	184.8	- 2.5	108.29	84.96
81	2	3	163.3	22.5	272.09	70.11
82	2	4	359.3	- 4.8	236.24	87.88
83	2	5	180.9	-10.8	46.27	84.97
84	2	7	4.9	- 0.8	125.95	85.10
85	2	8	354.1	13.3	358.67	80.59
86	3	15	19.0	11.0	109.95	70.35

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On the Magnetic Memory Phenomenon in Rocks and its Bearing on Palaeomagnetic Measurements

By C. RADHAKRISHNAMURTY[1], P. W. SAHASRABUDHE[2]) and P. K. S. RAJA[2])

Summary – The results of recent extensive studies on the low field hysteresis in basalts from India and East Africa and the memory phenomenon observed in some of the rocks have been found to have a direct bearing on the various parameters such as $Q\,n$, Q_{tn}, stability by the A.C. field technique etc. which are of great importance in rock-magnetism. It has been found that rocks having low Curie temperature (θ_c) and not exhibiting memory phenomenon are ideally suited for palaeomagnetic studies. Also, rocks having relatively higher θ_c often exhibit memory phenomenon, give inconsistent NRM directions and show an irregular behaviour on A.C. field cleaning. In using the latter rock types for palaeomagnetic work one has to take a number of precautions which are clearly brought out by the studies described in this paper.

1. Introduction

Several rock types acquire at the time of their formation a magnetization parallel to the prevailing geomagnetic field and retain the same for millions of years. In addition to this primary magnetization, some of the rocks after formation pick up a secondary magnetization which may distort the directions of the primary one. The presence of secondary components is often revealed by the inconsistent directions observed in the different samples from the same rock formation. The secondary magnetic components in rocks can be removed by the two standard techniques of alternating field demagnetization and thermal demagnetization. These techniques together with their relative merits have been described earlier by RADHAKRISHNAMURTY and SAHASRABUDHE [1][3]). It has been noticed by several workers, especially by WILSON [2] and RAJA *et al.* [3], that in some cases the alternating field cleaning seems to impart an irregular magnetization to rocks rather than cleaning the secondary components present in them. The reasons for this were not clear to them; WILSON [4], even suspected that it may be due to insufficiently refined equipment. The recent studies on hysteresis behaviour of rocks in low fields by LIKHITE and RADHAKRISHNAMURTY [5], and on the magnetic memory phenomenon by RADHAKRISHNAMURTY and SAHASRABUDHE [6], have thrown light on some of the unsolved problems in rock magnetism and yielded important

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information regarding the precautions one has to take in carrying out paleomagnetic measurements. Following this, similar extensive studies have been made on basalts, dolerites from India and Africa and the results obtained lead to some interesting and fairly general conclusions concerning particularly the assessment of magnetic stability in different rock types.

2. *TRM of basalts*

Basaltic specimens contain a few percent of magnetic mineral grains which are usually of titanomagnetites and have Curie temperatures (θ_c) varying from 120° to 580°C, depending upon the amount of titanium present in the solid solution. These acquire a magnetization when the lavas cool from a high temperature to that of the surroundings in the geomagnetic field. The magnetization thus acquired is known as the thermoremanent magnetization (TRM) and basaltic specimens have TRM intensities ranging from 1×10^{-3} to 10^{-2} cgs units. NEEL [7] has discussed the various theoretical aspects of TRM, and RADHAKRISHNAMURTY and SAHASRABUDHE [8] have recently reported several interesting correlations between the magnetic and mineralogical properties of basalts. Some of the correlations are as follows:

i) Rocks having low (200°C) θ_c possess a much more stable TRM than those having high (500°C) values of θ_c.

ii) Rocks with low θ_c often contain ore mineral grains in the form of crystallites or possessing skeletal crystal structure, whereas those with high θ_c have larger grains (100μ) which may or may not show exolved ilmenite lamellae in them.

iii) The susceptibility of rocks with low θ_c is lower and the intensity of TRM higher compared with those having θ_c around 500°C. Consequently, the former rock types give values of about 50 or more for Q_n (the ratio of NRM intensity to that acquired in a field of 0.5 Oe by induction) whereas the latter ones show Q_n values of around 10.

iv) Rocks containing mixed types of grains having high and low θ_c components show properties in between the two extreme categories mentioned above.

3. *Low field hysteresis of basalts*

The hysteresis loop of a magnetic material in fields much lower than its coercive force (H_c), is known as its Rayleigh loop. The magnetization of material in low fields normally obeys the empirical laws deduced by LORD RAYLEIGH [9] which are as follows:

$$J = A\,H + B\,H^2 \qquad (1)$$

$$J_H = (A + B\,H_m)\,H \pm \tfrac{1}{2}\,B(H_m^2 - H^2) \qquad (2)$$

Where H_m is the maximum field used, and A and B are constants; A is known as the reversible susceptibility and B can be regarded as the coefficient of irreversible susceptibility. The second equation represents an elliptic curve and holds good in the region, $-H_m < H < H_m$.

NEEL [7], pointed out that rocks containing a few percent of magnetite grains may obey the Rayleigh laws in fields of -10 to $+10$ Oe. However, in the case of rocks there could be more than one magnetic mineral phase giving rise to different values of A and B. Thus, inspite of the applied field being well within the Rayleigh region, such rocks, because of their complex nature, may not apparently obey the two laws.

LIKHITE and RADHAKRISHNAMURTY [5], observed four types of Rayleigh loops for basaltic rocks which are shown in Fig. 1a to b. The numerical value of B is negligible compared to that of A for the specimen giving the loop shown in Fig. 1a, while it is 2% and 10% for specimens corresponding to Figs. 1b and 1c respectively. The specimen showing the constricted loop (Fig. 1d) is a more complex case and for it the value of B can not be accurately and reliably deduced. It may be mentioned here that the different types of loops obtained for rocks are not due to anisotropy in them as the shapes of loops remain the same for different orientations of the samples with respect to the applied field. Also, the very thick loop (Fig. 1c) and the constricted loop (Fig. 1d) are peculiar cases shown only by rocks as there is no mention in the literature so far about such loops having been obtained for magnetic materials. It is very interesting to note that rocks showing loops of the types shown in Figs. 1b and 1c can acquire in a field of a few oersteds, an intensity of isothermal remanent magnetization (IRM) comparable with or a few times that of the TRM. However, the IRM thus acquired can be easily removed by subjecting the rock to an A.C. field equal to or slightly more than the coercive force of the rock as obtained from its loop.

The magnetic stability of the rocks showing these loops was examined in several cases and it was found that highly stable rocks show loops like Fig. 1a and occasionally like Fig. 1c, whereas partially stable ones show any of the four types though more often like the ones in Figs. 1b and 1d.

4.a. Magnetic Memory Phenomenon in rocks

The 'Constriction' and 'Line' memory effects in rocks recently reported by RADHAKRISHNAMURTY and SAHASRABUDHE [6], have a great significance in relation to the alternating field cleaning of rock. Briefly, the memory effects are that some of the rocks showing constricted loops or tilted straight lines initially, show thick loops after they are subjected to fields of over 50 Oe A.C. or D.C., or to heating or cooling by about 20°C with respect to the room temperature or even slight mechanical shocks such as due to hammering. Afterwards, left to themselves, both these rock types recover their initial states and show exactly the same Rayleigh loops as they did initially, after fixed durations (or recovery times) which have so far been found to range from a few minutes to a few weeks. The initial and disturbed low field hysteresis loops of both the rock types are shown in Figs. 2a and b, and 2c and d respectively. For the sake of present discussion it is sufficient to state that the large hysteresis as well as the memory effects shown by some of the rocks are due to the presence of interacting

single domain grains having different relaxation times. The constriction of some of the loops can be attributed to the negative contribution of grains having very small relaxation times.

It is noteworthy in the case of 'Line' memory effect that the rock having a small ($<5\times10^{-3}$ emu) initial isothermal remanence can take up an intensity of 30×10^{-3} emu in a field of just 10 Oe in the disturbed condition (meaning, subjecting it to fields, temperature changes or shocks). This particular rock (Fig. 2a) had a thermo-remanent magnetic moment of 1×10^{-3} emu initially and in the disturbed state it took up an equal amount of isothermal remanence in a field of about 3 Oe. The isothermal magnetization acquired by such rocks would automatically vanish after their respective recovery periods, or it can also be removed by demagnetizing it in a few A.C. field. Similarly, the rocks exhibiting the 'Constriction' memory phenomenon, also show a smaller intensity of IRM initially than that in their disturbed state. In such cases the amount of initial remanence shown by the rocks depends on the amount of constriction in their initial Rayleigh loops. The difference between the IRM intensities of rocks in their disturbed and initial states may be termed their magnetic memory intensity (MMI). All these features have been verified in the case of several rocks.

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4.b. The D.C. method for observing memory phenomenon in rocks

The magnetic memory phenomenon in rocks has been attributed to the presence and combined effect of large and very fine interacting single domain grains with widely different relaxation times. [6] This being so, it may be displayed by any type of rocks ranging from the magnetically strong igneous rocks to week sediments. It may not be possible to detect the memory effects in weekly magnetic rocks if their low field hysteresis loops cannot be displayed with an A.C. apparatus. In such cases a more sensitive D.C. method which has been evolved for checking the results obtained with the A.C. method can be used, which is as follows:

After measuring the direction and intensity of NRM of a rock, it is magnetized in a D.C. field of 10 Oe in a particular direction and then in an exactly opposite one and NRM+IRM are measured in the two cases. If the intensity is different in all the three cases, then this at least means that the rock shows some low field hysteresis. Now the rock is subjected to an A.C. field of about 50 Oe and remeasured to check that no spurious magnetization has been taken up by the rock. Then it is magnetized in 10 Oe D.C. field in two antiparallel directions and NRM$\pm$IRM in the two cases are remeasured. If there is a difference in the total intensities in the normal and disturbed states then it definitely means that the rock will display a memory effect, though it may not be easily possible to know whether it is a case of Constriction or Line memory. If need be, the recovery time can be determined by following the decay of the memory intensity. In the case of rocks saturated by thunderbolt this method has to be slightly modified in that the initially large IRM has to be demagnetized first, and then for checking for the memory effect the second half of the total procedure alone can be immediately undertaken as the rock will be in a disturbed state.

5. *Alternating field demagnetization of rocks*

When components of secondary magnetization are present, the rocks are demagnetized in successively higher A.C. fields ranging from 50 to 1000 Oe and remeasured until no change in the magnetic direction occurs on further demagnetization. It may be mentioned here that the secondary components are generally present in slightly altered rocks which also often display the memory phenomenon.

In 1964 some of the specimens which were initially measured in Nairobi were brought to Bombay by RAJA for cleaning purposes. Some of them showed widely different directions on remeasurement before cleaning, thus revealing that some change had taken place just because of a lapse of a few months. Also, in their studies RAJA *et al.* [3] encountered quite a few rocks which gave inconsistent directions to start with and required cleaning. Some of their rocks (group *C*) which behaved irregularly even after cleaning were later on found to display either large low field hysteresis or memory effects. The typical A.C. demagnetization curves for two specimens 277 A_2 and 268 A_1 are shown in Fig. 3a, and their low field hysteresis loops in Fig. 3b and 3c. Specimen 277 A_2 exhibits a large hysteresis whereas 268 A_1 has a Constriction memory. The loop in Fig. 3d is the one obtained for 268 A_1 in its disturbed condition. It is obvious that such rocks can take up a large isothermal remanence in low fields, due to hysteresis or memory effects, in the disturbed state compared to what they have in the normal one. Since the A.C. demagnetization involves subjecting the rocks to fields of over 50 Oe, it is clear that the rocks exhibiting memory will be in a disturbed state throughout the process. Thus every time any of the above types of rocks is demagnetized it might pick up an appreciable remanence in a small D.C. field which it may see in the laboratory during and after the demagnetization and before measurement. If such a rock is taken too close to the magnetometer chamber during the process of measurement it may acquire a sufficient remanence in the resultant field of the astatic system. All these irregular behaviours of rocks can now be explained on the basis of large low field hysteresis or memory phenomenon.

In the light of the foregoing discussion, it is now also clear that rocks can have two types of secondary magnetic components, one, acquired due to chemical changes or influence of geomagnetic field etc., subsequent to formation in situ and the other, acquired in the laboratory in small fields when the rock is in the disturbed state due to fields, temperature changes or mechanical shocks. These two types of secondary magnetizations may be termed as, field secondary magnetization (FSM), and laboratory secondary magnetization (LSM), respectively. Clearly, the LSM would disappear automatically in times corresponding to the recovery periods in the case of rocks showing memory effect, whereas it would require a small field for its removal if the rocks concerned have thick low field hysteresis loops. Also, the LSM is the more troublesome to avoid and its presence is most probably the cause of the general observation that some rocks give different directions after simple storage and remeasurement.

6. *Thermal cleaning and Q_{tn} ratio*

It has been mentioned that temperature changes also disturb the initial equilibrium condition of the rock showing memory phenomenon. When the temperature of such a rock is raised by a few tens of degrees above the room temperature one may observe an increase in the NRM. More important is the case when such a rock is cooled to the room temperature to study its thermal behaviour. Rocks showing the memory effect initially are often changed drastically on heating whereas the latter induces the same phenomenon in other rocks. If the rock has not been affected much or has acquired a memory by heat treatment and has a short recovery period then during cooling round about room temperatures it may show a constant intensity or a fall in it depending upon the negative contribution of the very fine grains. The latter observation can be easily mistaken for a partial self-reversal. Thus in such cases, only after confirming the absence of memory effect can the fall in intensity on cooling be attributed to a partial self-reversal.

The ratio Q_{tn}, of the intensity of NRM (J_n) of a rock to that (J_t) it acquires in cooling from above its Curie temperature in a field of about 0.5 Oe was first used by KOENIGSBERGER [10], and is considered as a good indicator of the reliability of a rock for palaeomagnetic purposes. He suggested that rocks having Q_{tn} of around unity may be regarded as reliable. However, the results of extensive studies on basalts by RADHAKRISHNAMURTY [11], showed that highly stable rocks having normally low Curie points ($\sim$200°C) give values of Q_{tn} of around 0.3, and those with high Curie points ($>$500°C) show values of about 3.0. The low value observed in the former case is due to the change in the magnetic state of the rock as pointed out by RADHAKRISHNAMURTY and SAHASRABUDHE [12], whereas the high value in the latter case is due to the combined effect of the presence of secondary magnetic components and the memory phenomenon in the rocks. The J_t of a rock having memory effect has been found to decrease with time so that this is apt to affect the Q_{tn} obtained for such rocks. Since the J_t used for computing Q_{tn} is the one measured immediately after the rock acquires the room temperature, its value may be quite high if the rock has a long recovery time. As it is, the rocks showing unity for Q_{tn} are quite rare, and such cases are therefore more apt to be accidents than a general feature. It develops from this that, contrary to general belief, the ratio Q_{tn}, as a useful parameter, will often have an ambiguous meaning in palaeomagnetic studies.

In general, rocks showing appreciable low field hysteresis or memory effect behave better in thermal cleaning than in A.C. field cleaning because of the lesser handling and the meagre chance of acquiring LSM involved in the former process.

7. *Effects of mechanical shocks*

The delicate nature of the magnetic state of rocks showing the memory phenomenon has been pointed out earlier [6]. A few hammer blows or even dropping the rock from heights of a few feet disturb the initial state of the sample and invoke the memory phenomenon in it. For palaeomagnetic studies the rocks are drilled and cut into cylindrical specimens with the help of machines having steel components such as motor casings, shafts etc. During shaping, the rock is obviously subjected to a good deal of mechanical shocks and vibrations and its state will therefore be easily disturbed. The rock can then pick up a large IRM in the appreciable fields provided by the steel components of the machines and this will distort the directions of the NRM. It would be interesting to quote our experience relating to rocks in which distorted directions were observed, and which can now be definitely attributed to the memory phenomenon.

In 1959, twenty samples collected from five dykes were shaped into sixty specimens and their NRM was measured. About ten specimens were drilled and cut in the morning and measured the same evening. To our surprise, all the specimens showed magnetic directions vertically downwards with widely different azimuths. Though we attributed this to some secondary magnetization picked up during shaping the reasons were then obscure to us. On A.C. cleaning, there was a little improvement in the directions but the behaviour of the rocks remained irregular and they were therefore rejected for further studies. Samples from the same dykes were again collected in 1962. But this time there was a gap of several weeks between the shaping of the specimens and the measurement of the directions in them, and practically no LSM was observed in the specimens which also showed much less scatter in the directions. Recently, specimens from both the collections were checked for their memory effects and we found that most of them exhibited the memory phenomena with recovery times of about a month. From this it became obvious that in the second collection we did not notice the effects of secondary components which were due to MMI because of their automatic decay with time.

8. *Susceptibility and Q n ratio*

The susceptibility of rocks exhibiting the 'Constriction' and 'Line' memory effects have been determined in their initial and disturbed states in a field of 0.5 Oe using the apparatus developed by LIKHITE and RADHAKRISHNAMURTY [13]. There was often a large difference in the two values of the susceptibility, the one in the disturbed state being larger by as much as 50% in some cases.

The ratio $Q\ n$, of the intensity of NRM to that acquired by the rock in a field of 0.5 Oe, introduced by KOENIGSBERGER [10], is a good indicator of the magnetic stability of rocks as has been emphasized by RADHAKRISHNAMURTY and MISHRA [14], and more recently by RADHAKRISHNAMURTY and SAHASRABUDHE [8]. However, in the light of the foregoing discussion, the $Q\ n$ ratio obtained for rocks showing the memory effect can be wrong for two reasons. Firstly, the intensity of NRM is likely to have been measured when the rock was in the disturbed state, and secondly the susceptibility, and hence the intensity induced in 0.5 Oe, measured may have been affected by the state of the rock. In determining the correct value of the $Q\ n$ ratio of rocks showing memory effect one has therefore to take the above factors into account.

9. *Significance of results in palaeomagnetic studies*

Basaltic rocks having low Curie temperatures show high values of J_n and Q_n and often do not exhibit either low field hysteresis or magnetic memory phenomenon. These rocks are least affected by the normal palaeomagnetic experimental procedures and are therefore best suited for such studies.

Rocks with high Curie temperatures normally show low values of Q_n, easily pick up secondary magnetic components and often exhibit memory phenomenon. In the case of these rocks a number of precautions have to be taken so that they can be used for palaeomagnetic work with the minimum amount of cleaning etc.

The experimental procedure which has been found most suitable for palaeomagnetic measurements of at least basalts is as follows. After shaping, the specimens are left undisturbed for a month or two before their NRM is measured. This will make the memory intensity vanish if acquired by some of the rocks in shaping. The next step is to determine the Q_n ratio for all the specimens preferably with an A.C. method which will not disturb the rocks. Rocks showing high values of Q_n and irregular directions of NRM often mean thunderbolt magnetization and can be rejected for further studies straight away. Consistent magnetic directions and high Q_n values in rocks indicate the presence of low Curie temperature components and such rocks can therefore be taken as highly reliable ones. By comparing the directions of NRM and the Q_n values of other rocks with those of the reliable ones it will be easily possible to limit the cleaning work to the minimum. Even in the case of horizons wherein the low Curie point rocks are not present, those giving values of about 10 for Q_n may be considered as representative of the stable ones for purposes of NRM directions. Rocks showing values of Q_n between 1 and 10 may require cleaning and may in all probability reveal the primary NRM directions; some of these may exhibit large low field hysteresis or memory phenomenon. This can be checked by A.C. or D.C. method, and those showing a memory intensity comparable to or larger than their respective NRM intensities can be straight away rejected for at least the A.C. field cleaning as they are sure to behave irregularly if adequate precautions are not taken. All the above mentioned points have been checked in many cases. The measurement procedure outlined has been followed by RAJA in his studies of the East African rocks which made his task easier especially in view of the large scatter observed in the preliminary directions; part of the scatter was traced to thunder bolt effects and some to the memory phenomenon in the rocks concerned.

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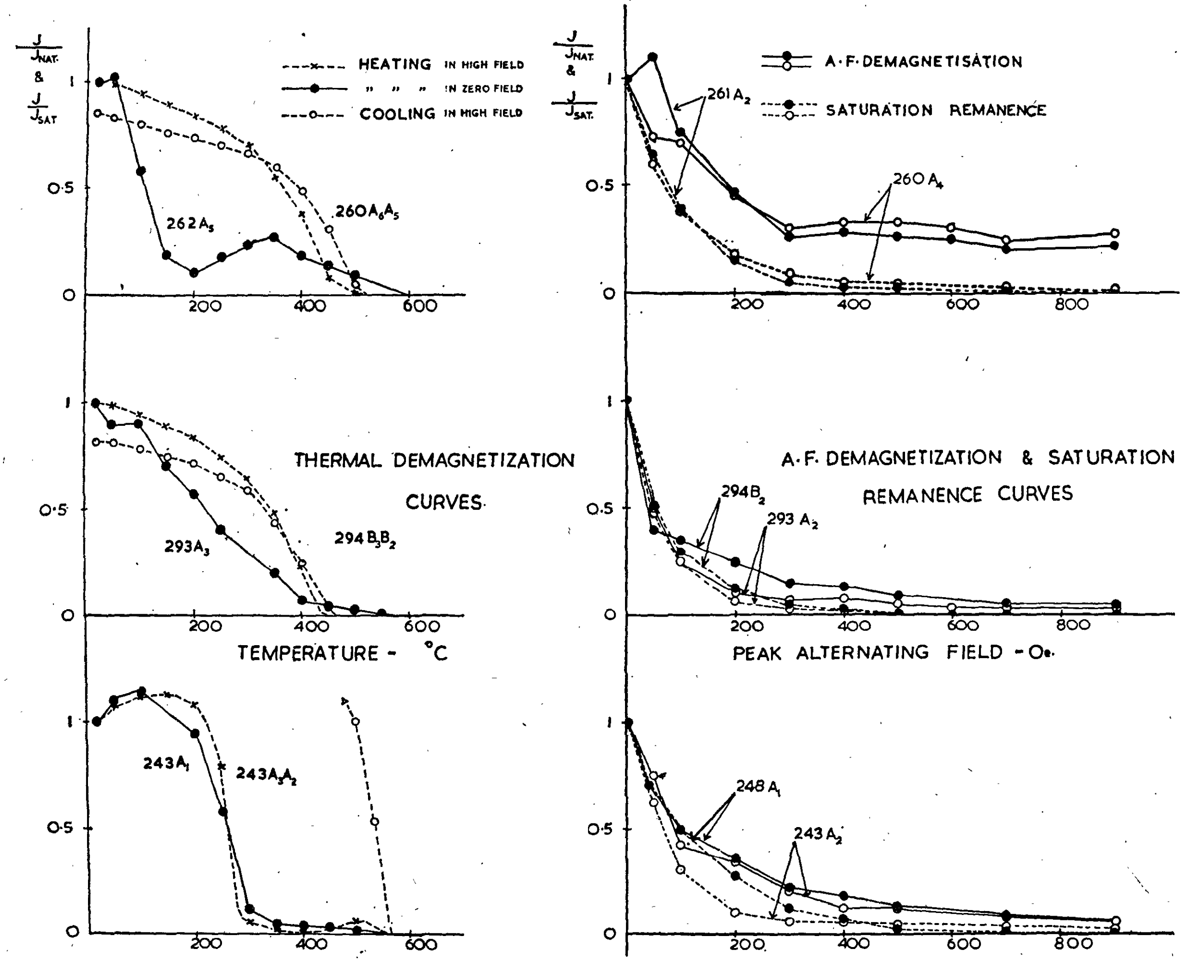

Fig. 2. Behaviour typical of dated sites during thermal and alternating-field demagnetization of natural remanent magnetism, alternating-field demagnetization of saturation remanence and high-field heating and cooling curves

same flow as 260/1, had a polarity which became reversed after cleaning by either thermal or alternating-field demagnetization.

The existence of both polarities above the Lokitaung fault has been confirmed by 150 block measurements made in the field (1965) using an astatic magnetometer. No reversed polarities were observed below the fault. The reversed polarities occur in many rock types, an agglomerate horizon having a consistently reversed polarity, whereas highly mineralized fault breccias are magnetized normally.

Self-reversal and tectonic repetition are probably both present, but the foregoing observations support the previous suggestion of a field reversal in the Upper Oligocene preceded by a period of normal polarity.

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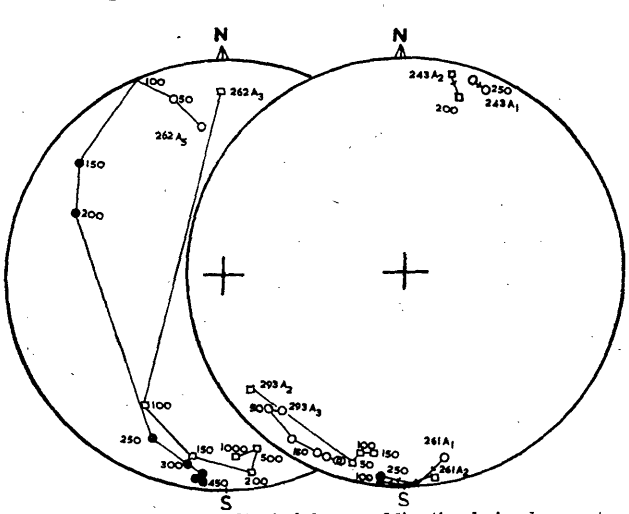

Fig. 1. Polar projection of typical changes of direction during demagnetization. ●, Dips down; ○, dips up: thermal demagnetization—numbers indicate temperatures in °C. ■, Dips down; □, dips up: alternating field demagnetization—numbers indicate peak field in oersteds

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Age and Polarity of the Turkana Lavas, North-west Kenya

THE extension of the Trap Series of Ethiopia into north-west Kenya has previously been suggested on stratigraphical and petrological grounds[1]. This area has recently been mapped on the basis of a reconnaissance[2], and the following succession suggested:

Rhyolites and andesites	*Tvr, Tvd*
Olivine basalts	Tvb_2
Phonolites and nephelinites	*Tvp*
Augite and analcime basalts	Tvb_1
Turkana grits	*Tm*

The age of the lavas has hitherto been based on a sparse mammalian fauna found in grits intercalated in basalts (Tvb_1 ?) at Lothidok, 25 km north-east of Lodwar. Initially thought Burdigalian[3], recent work[4] has suggested that it is younger (Up. Miocene) in age. Some fossil wood found in the rhyolites 60 km north of Lokitaung (*Dryoxylon* sp.) hints at a Mio-Pliocene age.

Four lavas have been dated (R. L. G.) at the University of Cambridge; Table 1 gives the results obtained on whole rock samples.

Field mapping showed that the basalts and rhyolites interdigitated in two localities, but neither were observed to overlie phonolites or nephelinites. The *Tvp* group is thus younger than both basalts (but could be older than the rhyolites), and comparable in age with the Lothidok grits and the Kapitian phonolites. The basalts (Tvb_1 ?) at Lothidok are unconformably overlain by basalts which are considered, on petrological grounds, to be equivalent to the Tvb_2 basalts in the north. However, palaeontological evidence indicates that the Lothidok basalts are much younger, and this discrepancy remains to be resolved.

Table 1

Sites	K_2O (per cent)	Vol. of $^{40}Ar/g$ (mm^3)	Atmos. contam. (per cent)	Age (m. yr.)	Polarity
260/1	1·31	$1{\cdot}406 \times 10^{-3}$	38·9	$32{\cdot}2 \pm 0{\cdot}5$	*R*
(Tvb_1)		$1{\cdot}375 \times 10^{-3}$	36·7	$31{\cdot}5 \pm 0{\cdot}7$	
264/5	0·61	$4{\cdot}210 \times 10^{-4}$	48·2	$20{\cdot}7 \pm 0{\cdot}4$	*R*
(Tvb_1)		$4{\cdot}686 \times 10^{-4}$	46·4	$23{\cdot}0 \pm 0{\cdot}7$	
293/4	0·90	$7{\cdot}04 \times 10^{-4}$	78·0	$23{\cdot}5 \pm 1{\cdot}1$	*R*
(Tvb_2)		$6{\cdot}99 \times 10^{-4}$	51·7	$23{\cdot}3 \pm 0{\cdot}2$	
243/50	3·84	$1{\cdot}90 \times 10^{-3}$	54·3	$14{\cdot}9 \pm 0{\cdot}5$	*N*
(*Tvp*)		$1{\cdot}56 \times 10^{-3}$	66·5	$12{\cdot}5 \pm 0{\cdot}3$	

The disagreement between samples 260/61 and the apparently underlying sample 264/65 might be due to loss of argon in sample 264/65, which shows a high chlorite content, or to local repetition of the succession by faulting: a similar wide scatter has been observed in five dates[6] (30–69 m. yr.) for the Abbai basalts of Ethiopia. The age and character of the Turkana basalts are comparable with those of the (Upper) Magdala Group of the Ethiopian trap series (25 and 33 m.yr.).

The lava succession is best seen in the Lokitaung gorge, where 5,000 ft. of lavas, pyroclastics and sediments are exposed. The complex faulting in the vicinity of Lokitaung has also complicated the sequence of magnetic polarities previously described in the Lokitaung section[8]. The samples of the dated lavas appear to be magnetically stable. The results of thermal and alternating-field cleaning were found to agree closely (Fig. 1), and the shapes of the alternating-field demagnetization curves of the saturation remanence and of the natural remanence were similar (Fig. 2). High-field heating showed only single curie points—a value of 450°–500° C for the basalts, and 150°–300° C for the phonolites and nephelinites (*Tvp*). The last-mentioned, on heating, developed a new, strongly magnetic component with a curie point of about 500°–550° C. Preliminary examinations of the opaque minerals showed a low state of oxidation, with some maghemitization.

The polarities of the sites radiometrically dated are given in Table 1. A further site, 262/3, probably in the

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The Paleomagnetism of the Turkana Lavas[1]

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Abstract. Directions of magnetizations obtained after cleaning the Miocene lavas from northwest Kenya are presented. The pole position thus obtained, together with similar data from eastern Africa, indicates that no significant change has occurred from late Eocene to recent times. Observed directions suggest that a late Miocene reversed epoch has occurred.

Introduction. As part of a paleomagnetic study of the Rift Valley volcanics of eastern Africa, 65 oriented samples of lavas from the Turkana area of northwest Kenya were collected in August 1963. These were collected either as blocks or as cores using a portable drill similar to that of *Graham and Keiller* [1960]. The directions of the natural remanent

[1] Abstract from a thesis to be submitted by P. K. S. Raja in partial fulfillment of the requirements for the Ph.D. degree of the University of London.

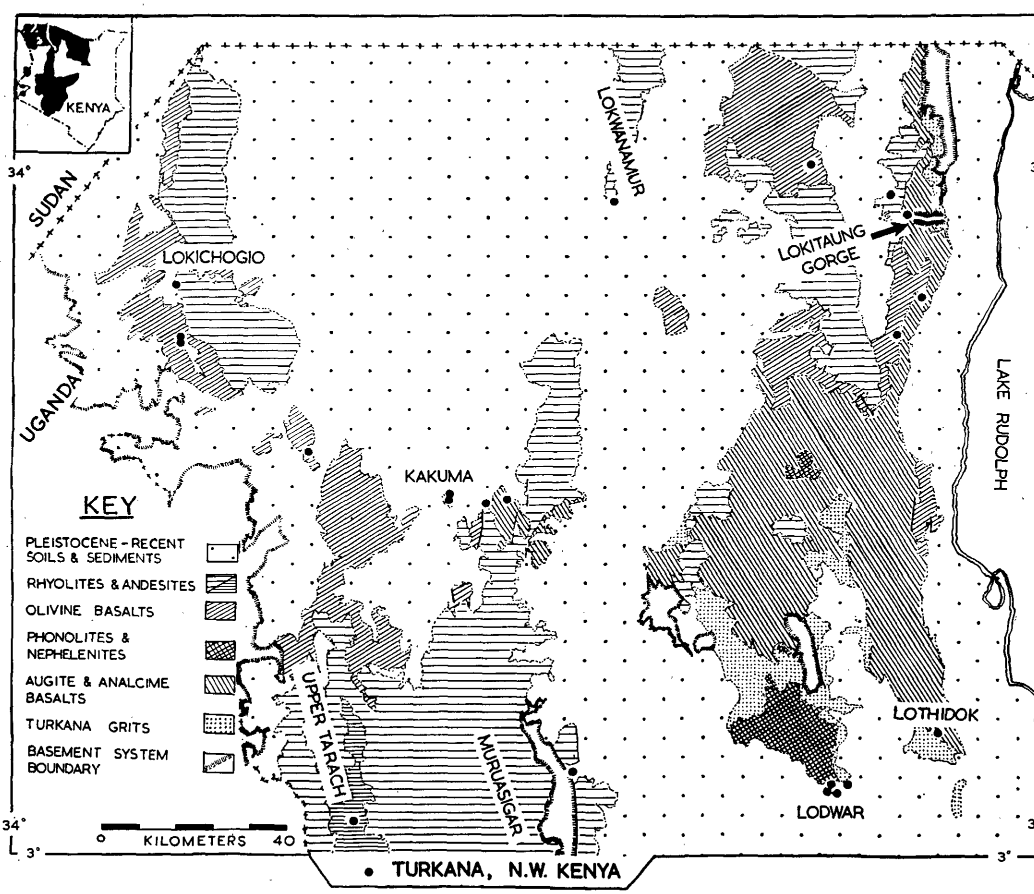

Fig. 1. Geological sketch map of the Turkana area of northwest Kenya. The Rift volcanics are indicated by solid shading in the key.

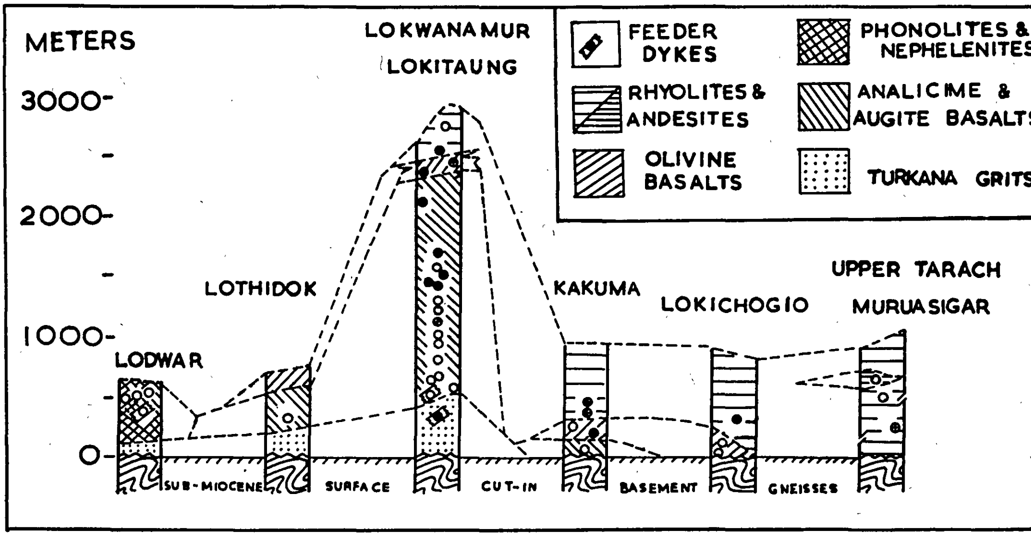

Fig. 2. Diagramaatic stratigraphic section of the Turkana area.
● Sites with normal polarity.
○ Sites with reversed polarity.
⊕ Sites that could not be cleaned. Polarity unreliable.

magnetizations of specimens 22 mm in diameter and 25 mm long, taken from these samples, showed a high degree of scatter when measured under an astatic magnetometer. Preliminary results, based on a scatter criterion for the selection of samples, have been reported by *Mussett et al.* [1964].

Geology of the area. Figure 1 indicates the major stratigraphic units of the Turkana area and shows the sampling sites. The relationship between these units and the vertical distribution of sampling is shown by the diagrammatic sections of Figure 2, in which the sub-Miocene surface has been restored to horizontal to remove the complications of rift faulting. The augite and analcime lower basalts were extruded after the deposition of the Miocene Turkana grits to the east. The olivine upper basalts represent a basic basaltic phase only locally developed. This was probably preceded by extrusion of the phonolites and nephelenites of the Lodwar area, although no contact between them and the upper basalts is seen. Intercalations of rhyolites with basaltic lavas east of Lokwanamur suggest that at the start of rhyolite emplacement, both upper and lower basalts were being extruded at different localities.

Within each stratigraphic unit there is much variation in composition, grain size, vesicularity, etc. Severe weathering and mechanical breakdown is common in the lower basalts and

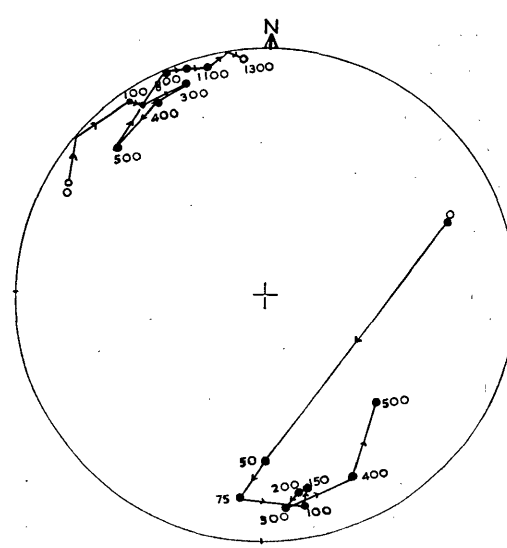

Fig. 3. Polar projection showing changes in direction of magnetization during alternating field demagnetization.
● Dips down. ○ Dips up.

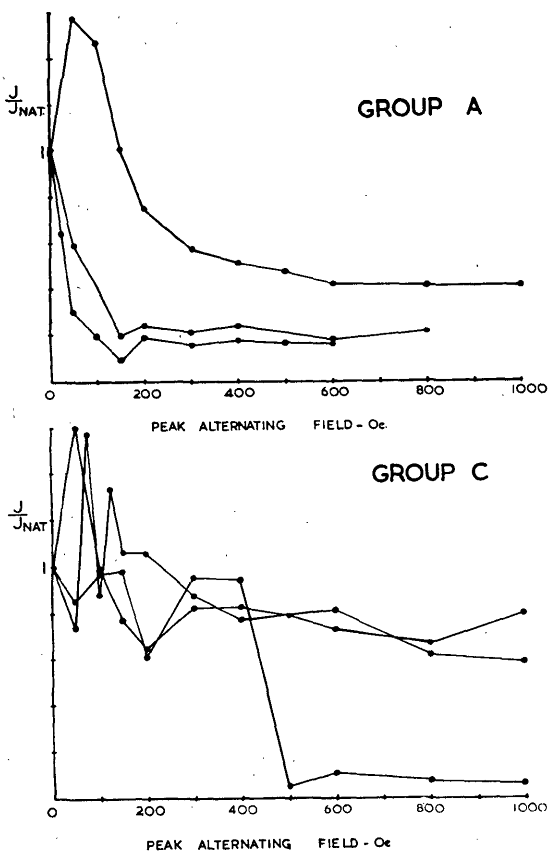

Fig. 4. Alternating field demagnetization curves. Intensities, J, are normalized.

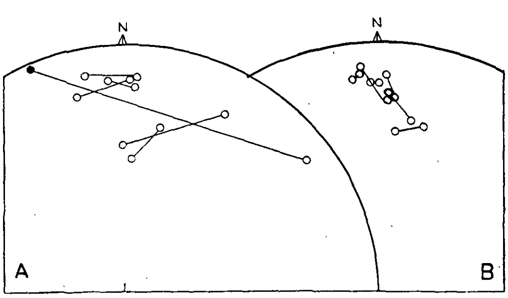

Fig. 5. Comparison of thermal and alternating field demagnetization.
A. Solid lines link specimens from the same sample before cleaning.
B. Thermally cleaned specimens are linked with specimens from the same sample cleaned by alternating field demagnetization.

● Dips down. ○ Dips up.

occurs to a lesser degree in the other units. The occurrence of secondary minerals such as iron ores, quartz, calcite, uralite, and chlorite is common, and the glassy groundmass of many of the rhyolites is often devitrified. Polished sections have not been examined in detail. Feeder dikes cutting all units are common, and four of these were sampled. No suitable baked contacts were observed. Intercalated pyroclastics and sediments occur most often lower in the succession.

Alternating field demagnetization. Remeasurement of the natural remanent magnetization of specimens after storage of more than 1 year gave different directions from those formerly observed, which indicates that the specimens had acquired viscous magnetization during storage. *Nairn* [1964] has observed that Miocene lavas collected from the Nairobi area behaved similarly. Secondary magnetizations were subsequently removed by progressive alternating field demagnetization, the method employed being similar to the one described by *McElhinny and Gough* [1963]. We demagnetized at least one specimen from each site in fields progressively increased up to 1300 oe. The field at which the directions of magnetization remained constant while the intensity of magnetization decreased was chosen as the demagnetizing field for all the other specimens from the site.

Figure 3 shows typical changes in direction of magnetization in two specimens during progressive demagnetization. The first specimen (rhyolite) required a peak field of nearly 1300 oe to reach a stable direction, whereas the second (basalt) needed only 150 oe. The direction of magnetization of this specimen then showed little change below 300 oe but became scattered in higher fields.

Altogether 128 specimens from 65 samples collected from 35 sites were demagnetized as described above. When the normalized intensities of the demagnetized specimens were plotted against the demagnetizing fields, the curves were found to fall roughly into four groups as shown in Figure 4.

The curves of group A shows an initial rapid change of intensity in low fields, thereafter showing little change. This is attributed to a soft secondary component which may make an arbitrary angle with the stable component. The group consists mainly of basalts that could be cleaned in fields of about 200 oe.

The curves of group B do not show initial rapid changes of intensity, which presumably indicates the absence of a soft secondary component. This group contains only rhyolites, which could be cleaned in high fields as illustrated in Figure 3.

The curves of group C are characterized by fluctuations in intensity. These specimens showed irregular changes in direction of magnetization, and they could not be cleaned.

The curves of group D fall very rapidly to less than 1% of their initial intensity in low demagnetizing fields. The following observations suggest that the specimens of this group might have acquired isothermal remanent magnetization from lightning current:

1. High itensities: $> 100 \times 10^{-4}$ emu/g.
2. Typically steep or shallow dips and scattered directions (due to vertical or horizontal currents?).
3. Although the surface specimen of one core could not be cleaned, the bottom ones could be cleaned in high field.
4. Nearby samples showed normal intensities, and they could be cleaned in low fields.

Similar effects of lightning were noticed by *McElhinny and Gough* [1963] and *Graham* [1961].

Thermal demagnetization. Some specimens

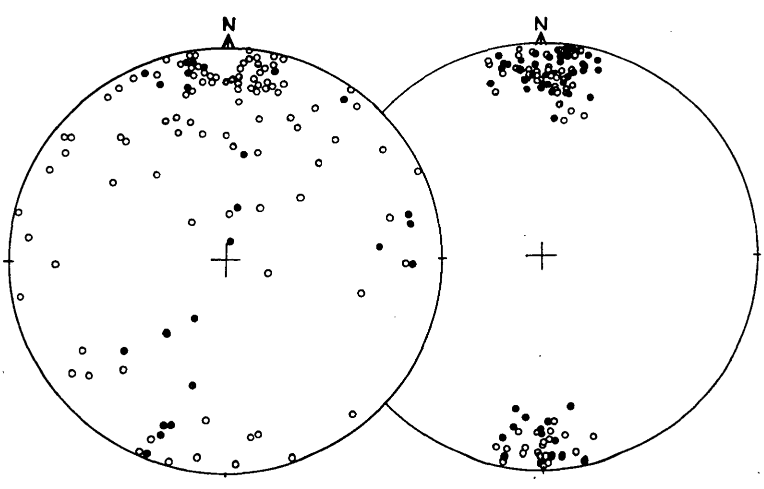

Fig. 6. Polar projection showing directions of magnetization before and after cleaning. ● Dips down. ○ Dips up.

TABLE 1. Summary of Paleomagnetic Results for Tertiary Volcanics of Eastern Africa

Age, Locality, and Reference	Collection Data				S. W.	Polarity	Directions of Magnetization				Cleaning	Pole Positions		
	F	St	Sm	Sp			D°	I°	K	α°		Lat°N	Long°E	α^1/α^2
Pleistocene (Nakuru, Kenya) *Nairn* [1964]	4	5	11	27	Sm	N + R	[11.9	−11.3	40	7.3]*	Af	[76.9	207	3.8/7.4]
Pleistocene (Olduvai, Tanzania) *Grommé and Hay* [1964]	4	1	4	12	Sp	N	4.8	+1.6	220	0.9	Af + Th	84.7	100	[0.45/0.9]
Plio-Pleistocene (Rungwe, Tanzania) *Nairn* [1964]	4	3	9	32	Sm	N + R	[16.2	−28.6	22	11.3]	Af	73	214	6.8/12.4
Plio-Pleistocene (South Rift, Kenya) *Mussett et al.* [1964]	22	35	83	167	Sp	N + R	358.9	+6.6	9	5.1	Sr	86	203	2.6/5.1
Mio-Pliocene (Nairobi, Kenya) *Nairn* [1964]	6					N + R	7.6	+5.1	46	9.9	Af	82	139	[4.9/9.9]
Miocene (Turkana, Kenya) *Mussett et al.* [1964]	4	11	23	54	Sm	N + R	2.1	−8.5	22	6.6	Sr	81	202	3.4/6.7
Miocene (Turkana, Kenya) Present paper	4	35	57	108	Sm	N + R	2	−1	30	3	Af + Th	85	193	1.5/3
Eocene (Ethiopia) *Grasty* [1965]	7	11	21	42	Sm	N	3	+14		7	Th	86	86	3.7/7.7

F, number of flow units included in calculating results.
St, number of sites included in calculating results.
Sm, number of samples included in calculating results.
Sp, number of specimens included in calculating results.
$\alpha°/\alpha^1/\alpha^2$, semiaxis/semiaxes of cone/oval of 95% confidence.
Af, cleaning by alternating field demagnetization.
Th, cleaning by thermal demagnetization.
Sr, site rejection based on scatter of NRM's.
S. W., statistical weighting.
N, normal polarity.
R, reversed polarity.
D°, declination in degrees.
I°, inclination in degrees (positive down).
K, dispersion parameter [*Fisher*, 1953].
[ ]*, calculated from published results.

were also thermally demagnetized beneath an astatic magnetometer and their high-temperature directions deduced from vector heating diagrams as described by *Wilson* [1961]. Figure 5 compares the results obtained by thermal demagnetization with those obtained by alternating field demagnetization, and the close agreement shows that both methods are equally acceptable.

Results of demagnetization. In Figure 6 the directions of magnetization for all specimens before cleaning are compared with the directions after cleaning for all specimens that could be cleaned.

The mean direction of magnetization and statistical data [*Fisher,* 1953] after cleaning is given in Table 1, and the results, based only on selected natural remanent magnetizations [*Mussett et al.,* 1964] agreed with it. The means were calculated after reversing the directions of the reversed specimens. Dips due to block faulting are low and do not significantly affect mean directions of magnetization. Mean directions calculated for each of the main stratigraphic units agreed within their circles of confidence.

Polarity changes. Cox et al. [1964] have investigated polarity changes back to 4 m.y. ago and have concluded that these changes are systematic, a given polarity being dominant over a period of the order of 1 m.y. Such polarity 'epochs' may be interrupted by short switches of polarity, which they have termed 'events.' The distribution of the site polarities has been indicated in Figure 2. These polarities may be due to self or field reversal. It can be seen that reverse polarities are dominant over the period from the middle of the lower basalts to the beginning of rhyolite extrusion. It could tentatively be suggested that this represents a reversed epoch, during which the few normal sites may represent normal events. Further sampling is needed to test this working hypothesis.

Note added in proof. K-Ar datings for samples of the upper and lower basalts near Lokitaung and the phonolites and nephelenites near Lodwar have been recently carried out by R. L. Grasty and J. A. Miller of the Department of Geodesy and Geophysics of Cambridge University, England. These indicate an upper Oligocene to lower Miocene age for the basalts and a mid-Miocene age for the phonolites and Nephelenites. Details and discussion of these results will be published in the near future.

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The Palaeomagnetism of some Scottish Tertiary Dykes and their Baked Contacts

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(Received 1963 December 3)*

Summary

This paper presents results of measurements of the directions of magnetization of dyke samples and the associated baked sediments collected from Ayrshire in Scotland. The results suggest that these reversely and normally magnetized rocks are due to inversions of the Earth's magnetic field rather than to any self-reversal mechanism.

1. Introduction

The reality of apparent reversals of the past Earth's magnetic field polarity can be tested by comparing the direction of magnetization of igneous rocks *and* of their associated baked rocks. The essence of the test is that if the baked rocks almost always have the same polarity as their associated igneous rocks, then there is a good case for field reversal; but if the polarities of baked and igneous rock disagree in about 50 per cent of the cases, then some physical mechanism within the rocks ought to be responsible for self-reversal, and then field reversals will not have occurred. A review of the baked rock evidence has been published by Wilson (1962). The evidence is strongly in favour of reversals of the Earth's magnetic field polarity. A particularly convincing test of ancient field polarity has been published by Everitt & Clegg (1962), who measured baked rocks at varying distances from the contact interface.

This paper presents the results of further measurements carried out by the author on samples of dyke rocks and their associated baked Permian and Old Red Sandstones collected from Ayrshire in Scotland (Lat. 56° N and Long. 5° W).

Specimens of diameter $\frac{7}{8}$ in. and length 1 in. were cored out of the samples and their directions measured with an astatic magnetometer. Each dyke specimen was then thermally demagnetized in a furnace, by heating to above its Curie point, taking measurements of directions every 50 °C. The cleaned direction of each specimen was deduced from the high temperature value on the vector heating diagrams. As a test of stability (Brunhes & David 1903), the directions of associated baked Permian sandstones were also measured after cleaning them by heating to about 300 °C and cooling in zero field, since they were too weakly magnetized to measure while hot. Table 1 shows the result of these measurements. Figure 1 is the stereographic projection of directions of single dyke samples before and after cleaning, and Figure 2 that of directions of cleaned dykes and mean directions of

* (Received in original form 1963 July 26).

Table 1

Dyke directions (single specimens)

Specimen	Location of dyke	Before thermal demagnetization: Declination east of true north	Before thermal demagnetization: Inclination	After thermal demagnetization: Declination east of true north	After thermal demagnetization: Inclination	Width of dyke	Type of Sandstone baked by dyke	Distance of baked sample from contact	Number of baked specimens measured after cleaning	Mean direction of baked specimens after cleaning: Declination East of true north	Mean direction of baked specimens after cleaning: Inclination
R A I	Dykes	5°	77° down	346°	74° down	3 ft	Permian.	4 in.	6	282°	76° down
R A V	Crossing	132°	19° up	148°	31° up	3 ft 3 in.	Permian.	16 ft	3	146°	0°
R A VI	River	224°	62° up	214°	60° up	3 ft	Permian.	–	3	204°	51° up
R A VII	Ayr.	188°	11° up	185°	16° up	3 ft	Permian.	6 in.	3	174°	4° up
D I	Dipple on coast of Ayr.	213°	40° up	188°	62° up	9 ft	Old Red Sandstone.	2 ft	2	152°·5	58°·5 up
CU II	Culzean Bay.	123°	48° up	153°	62° up	37 in.	Old Red Sandstone Bleached grey at contact.	1 in.	2	147°	55° up
S III	Seamills	9°	15° down	301°	68° up	7 ft	Old Red Sandstone baked first by sill and then by dyke.	Right on contact.	3	234°	58°·5 up
SK I	Skelmorlie	203°	65° up	209°	66° up	14 ft	Old Red Sandstone greatly metamorphosed.	9 ft	3	186°	49° up
IK I	Inverkip	240°	58°	233°	67° up	45 ft	Red Sandstone.	20 ft	2	223°	67°·5 up

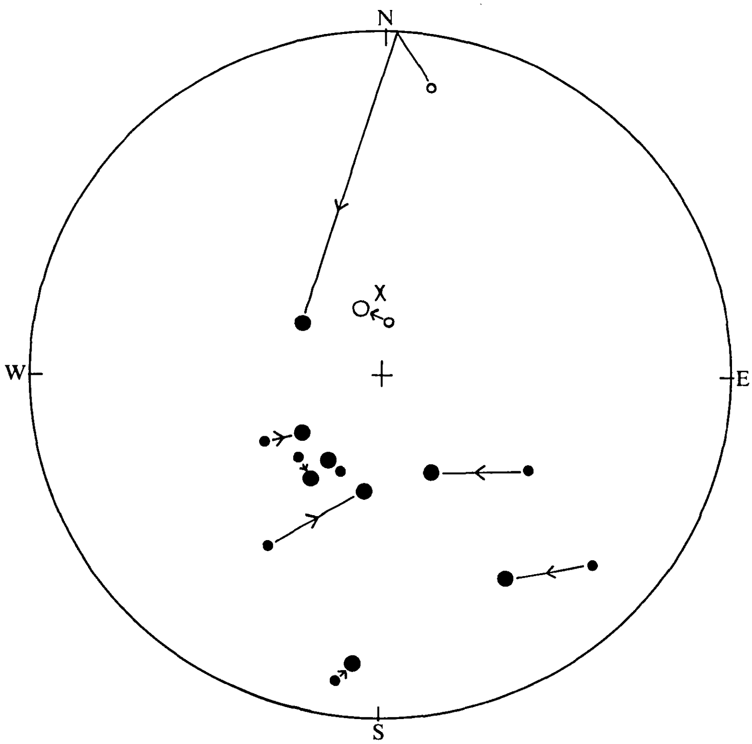

FIG. 1.—Directions of magnetization of dykes before and after thermal demagnetization.

● Dips up
○ Dips down
Solid line links the uncleaned specimen (small symbol) with the cleaned one (large symbol)
× Present dipole field

associated baked rocks. Mean directions were found by averaging the directions cosines, as suggested by Fisher (1953).

2. Results and discussion

Of the nine dyke specimens, one from each dyke, one showed normal and eight showed reversed directions after cleaning. The mean directions of the baked rocks agree fairly well with those of the corresponding dyke rocks (Figure 2), although one error made was to collect baked specimens not extremely close to the dykes, so they were not so highly baked as could be desired.

RA V and RA VII have shallow dips and may indeed be of Permian age. The rest of the dykes are judged to be of Tertiary age because of their directions of magnetization and their NNW bearings in the field. However, the baked rocks always have the same sense of magnetization as the dyke rocks, regardless of the ages of the dykes.

Table 2 gives the mean directions of British Tertiary rocks measured by Bruckshaw & Vincenz, and Blundell, Khan and Wilson. The mean axis of the

Table 2

Author	Location and type of rock	Direction of Magnetism Declination east of true north	Inclination
Bruckshaw & Vincenz (1954)	Mull lavas	166°	73° up
Blundell (1957)	Lundy and Lee dykes	197°	59° up
Khan (1960)	Skye–Lavas and intrusives	186°·1	59°·7 up
	Ardnamurchan–Gabbro	184°·1	54° up
	Rum–Layered Gabbro	181°·0	55°·1 up
Wilson (1961) and Hospers & Charlesworth (1954) (Combined result)	Northern Ireland Basalt lavas, dykes, sills and non-igneous rocks	188°	62°·8 up
Present result of dyke measurements	Dykes from Ayrshire, Scotland	189°	62°·7 up

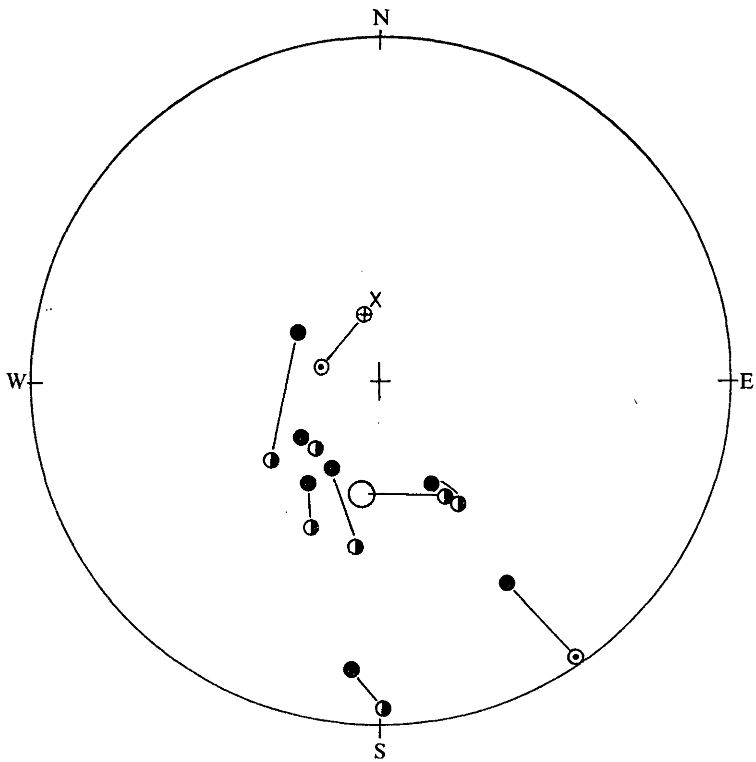

FIG. 2.—Directions of dykes and associated baked rocks.
○ Mean dyke direction ● Dyke with dip up
⊕ Dyke with dip down ◑ Baked rock with dip up
⊙ Baked rock with dip down
Solid line links the dyke with the associated baked specimen
× Present dipole field

nine dykes is directed 189° (E.T.N.), 62·7° up. This compares well with the results of the previous authors given in Table 2.

The agreement of sense of dykes and associated baked samples supports the idea of reversals of the Earth's magnetic field, and suggests that the reversed dykes are not due to some self-reversing mechanism.

Acknowledgments

I thank Professor P. M. S. Blackett for suggesting this work and for giving me facilities to work in his department in Imperial College. I am greatly indebted to Dr R. L. Wilson for the help given at various stages of this work and for lending me the rocks which he collected from Scotland. I should also like to record my thanks to the British Council for providing me with a travel grant to the U.K.

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1963 *December.*

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PALAEOMAGNETISM IN EAST AFRICA
A Progress Report on the Tertiary Volcanics

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ABSTRACT

Rocks, when magnetized, can retain a record of the Earth's field at the time. By measuring the magnetism of East African rocks it is found that the geographic pole has not departed significantly from its present position since Miocene times, a conclusion in agreement with world results.

The Earth's magnetic field reverses its polarity from time to time, and some recent periods of reversal have been dated. Reversals are known to occur in East Africa, and the feasibility of using these 'polarity epochs' to help correlate the geological succession associated with the Rift Valley is investigated.

SAMPLING

Miocene to Recent lavas in Kenya have been covered by sampling in two regions, around Nairobi and Turkana: Figure 1 shows the distribution of sites.

Samples were taken as blocks; or, as 5 in. cores, using a portable drilling rig similar to that described by Graham and Keiller.[1] To reduce errors due to the magnetic field of the rock, azimuths were determined with a magnetic theodolite at a distance, using solar azimuths when possible, as a check. In a few cases a compass-clinometer was used on the rock surface.

A site is defined as a small area of a single flow, or intrusion, from which a number of samples (blocks or cores) have been taken. Cylindrical specimens are cut from the samples and are measured under an astatic magnetometer.

POLE POSITIONS

Selection Criterion

Only the natural magnetizations (N.R.M.'s) have been measured; the directions are often scattered, so that the following criterion has been used to eliminate unsuitable specimens. If the angle between the directions of magnetization of any specimens from a site is greater than 45° all specimens of the site are rejected. For purposes of statistics, equal weight has been given to samples, not specimens.

The assumption behind this criterion is that scattering mechanisms—viscous magnetization, lightning, weathering, minor tilting—are unlikely to affect all specimens of a site equally; on the other hand if, for example, a tilt has occurred large enough to disturb the whole site, this would be observable in the field. In support of this assumption, it was found that sites having a large scatter of the directions of their component specimens usually had a wide range of intensities, indicating that the scattering mechanism has involved a remagnetization.

This criterion does not eliminate errors due to secular variation and it is for this reason that an angle of scatter as large as 45° has been chosen. It is assumed that secular variation has been eliminated by sampling over a sufficient period.[2]

Miocene Pole Positions

Miocene samples were collected throughout the Turkana succession. This region has recently been surveyed geologically by Walsh and Dodson[3] who determined the succession as indicated in Figure 2*a*. The lower limit of the lavas is determined by fossils found[4] in Turkana Grits intercalated with lower basalts at Lothidok. These may be slightly younger[5] than the Rusinga Beds, which have been dated radiometrically as 16-18 m.y.[6] The upper limit of the rhyolites has been estimated by fossil wood[7] (Dryoxylon sp.) as possibly Upper Miocene to Lower Pliocene: in this paper the rhyolites have been included

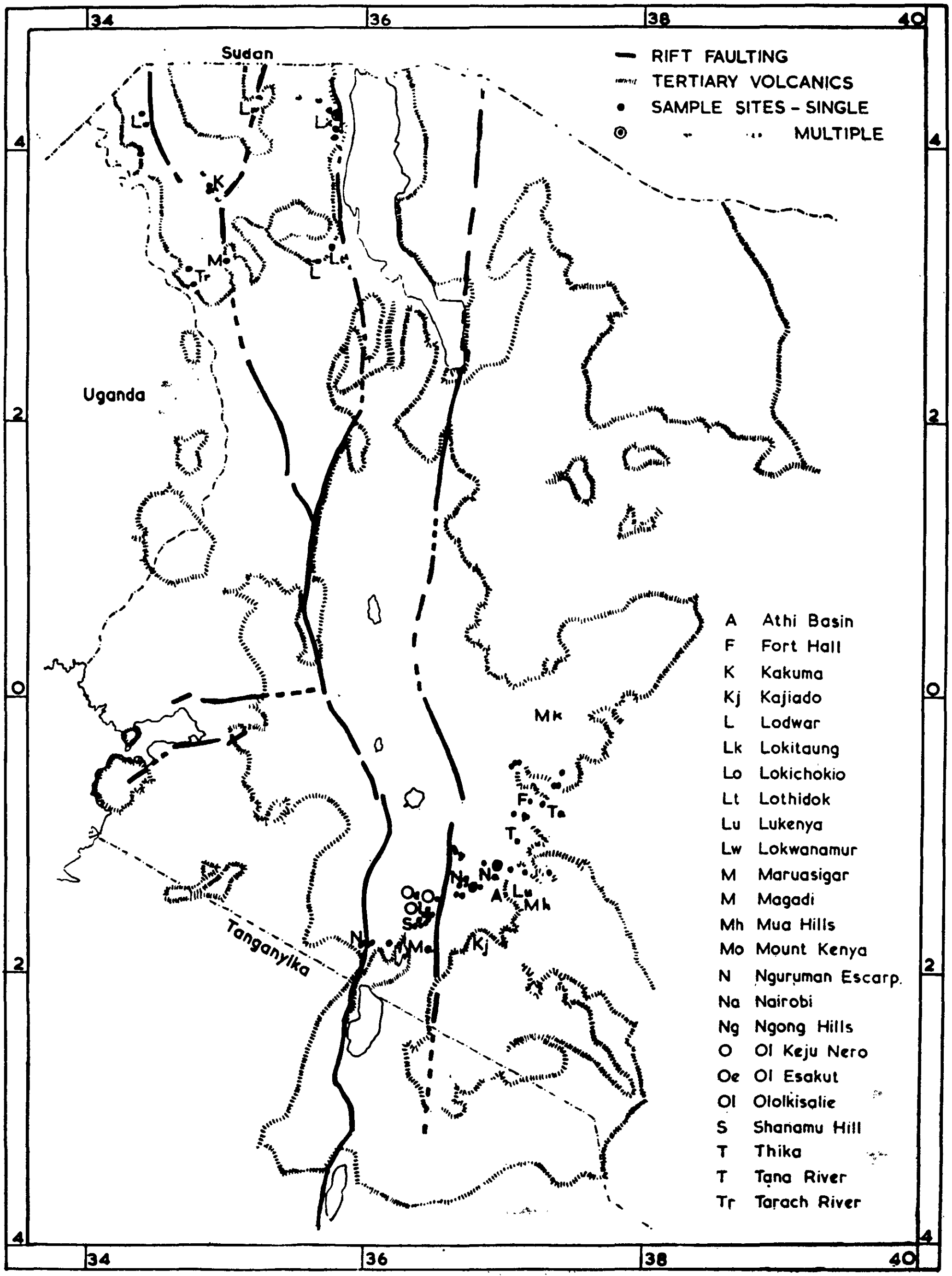

Fig. 1

in the Miocene. Samples of Turkana Grits were unsuitable for palaeomagnetic measurements.

Sites were rejected as above and the directions of magnetization of the remaining samples were combined using Fisher's statistics[8], to yield a mean direction of magnetization for the period, from which the pole position was calculated. (For sites having reverse magnetization, their directions were reversed before combination). These data, together with that of other workers is given in Table I. Mean directions of the component horizons are shown in Figure 3.

Plio-Pleistocene Pole Position

Samples were taken in the Nairobi region, throughout the succession, as indicated in Figure 2B. The Kapiti Phonolite is included here, though dated radiometrically as 13 m.y.[6] No lavas younger than Middle Pleistocene have been included.

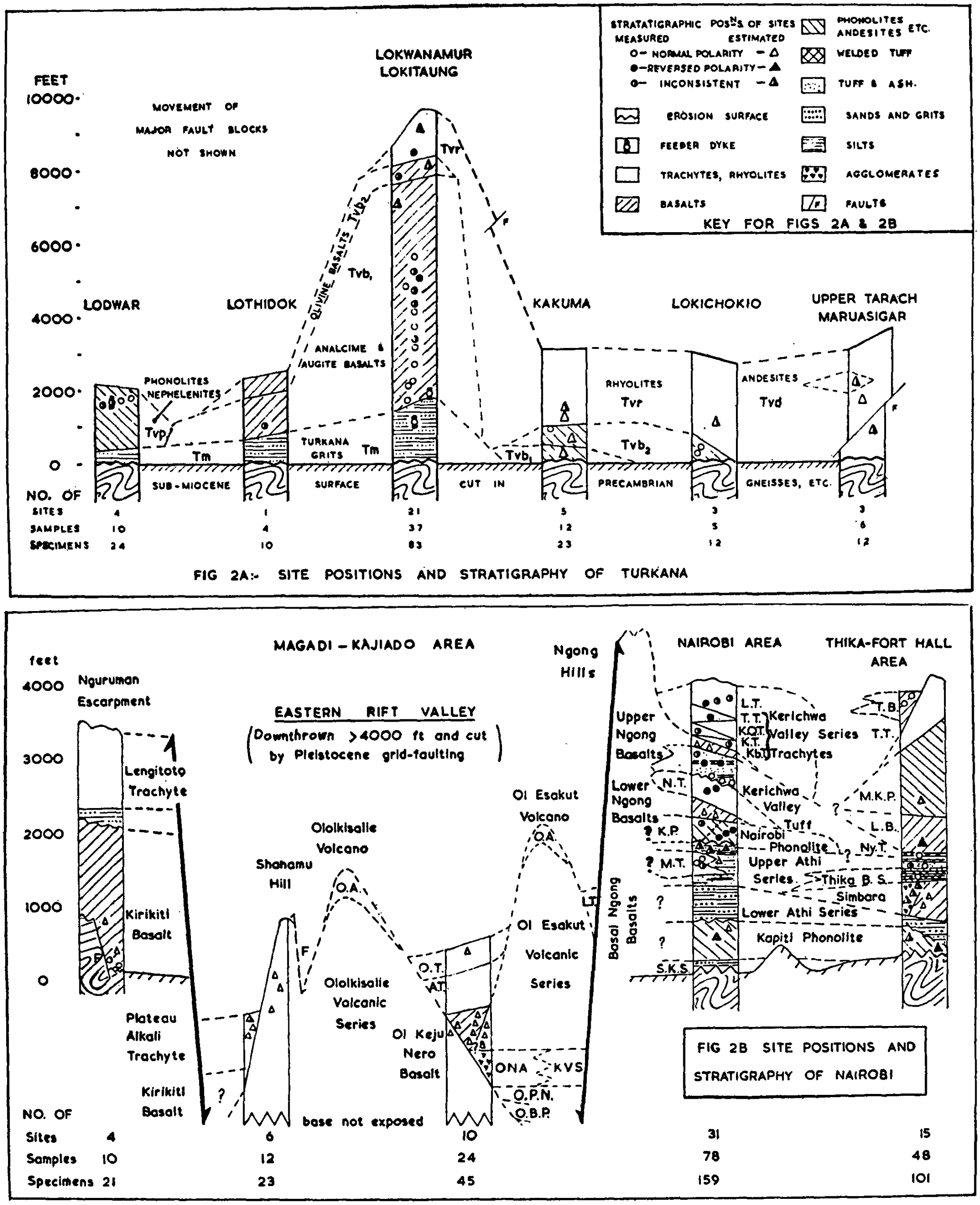

FIG 2A:- SITE POSITIONS AND STRATIGRAPHY OF TURKANA

FIG 2B SITE POSITIONS AND STRATIGRAPHY OF NAIROBI

Fig. 2

Three sites remaining after applying the acceptance criterion showed a consistent high dip. Of these, one was shown to have been tilted by drag on an obvious fault and has been eliminated. This may be true for the others, for they are situated in fault zones, or on possible fault line features; these sites have not been rejected. Otherwise, no correction for tilt has been applied in the Nairobi area, as borehole evidence shows tilts to be not greater than a few degrees[12], but tilting due to N-S grid faulting within the Rift Valley has been corrected. Our results, together with those of other workers, are shown in Table 1.

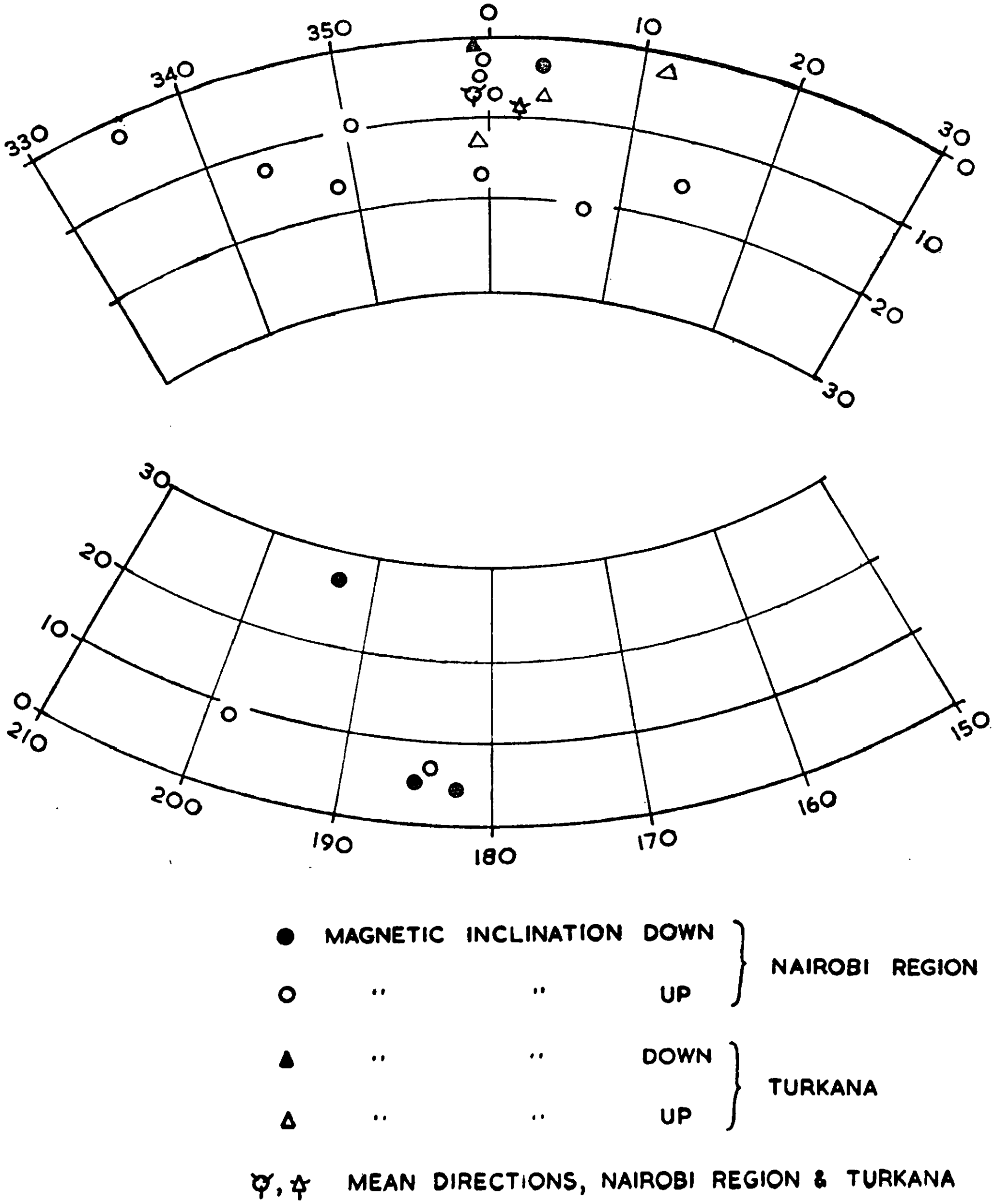

Fig. 3 Directions of Magnetisation of Horizons

Table 1

POLE POSITIONS FROM EAST AFRICA

Authors	*Locality*	*No. of samples*	*DIRECTION OF MAGNETIZATION*					*POLE POSITIONS*			*Statistical weighting*
			D	*I*	*K*	α	*Polarity*	*Lat.*	*Long.*	α	
MIOCENE:											
Present paper ..	Turkana ..	23	2.1°	+ 8.5°	22	6.6°	N and R	82°N	200°E		Samples
PLIO-PLEISTOCENE											
Present paper ..	Nairobi region	83	358.9°	+ 6.6°	9	(5.1°)	N and R	88°N	244°E		Samples
++Nairn[9]	Nairobi area	/	/	/	/	(9.9°)	N R	82°N 82°S	139°E 41°W		Horizons
Nairn[9] ..	Kenya and Tanganyika	6 14	9.2° 196.1°	—22.7° + 9.1°	16 12		N R	74°N 74°N	135°E 45°W	10.3	Horizons
Grommé and Hay[10]	Olduvai Gorge	4	4.8°	+ 1.6°	2200	0.9°	N	84.7°N	100°E		Specimens

D declination
I inclination (—down)
(+ up)
K precision factor
α semi-angle of circle of 95 per cent confidence.
Certain figures have been deduced from the authors' published data.
++ Nairn follows Sikes[11] in assigning these rocks to the Miocene, but we have placed them in the Plio-Pleistocene[6].

Conclusion

The mean magnetization of East African volcanic rocks has not departed significantly from that due to a dipole along the geographic axis. This is interpreted as showing that Africa has kept its present position relative to the geographic poles since Miocene times.

POLARITY EPOCHS

Rocks are formed sequentially and a horizon may be dated in the succession in three ways:—

(1) relatively, by stratigraphic position.
(2) approximately, by palaeontological evidence.
(3) absolutely, by radiometric dating.

For any particular horizon not all these can be applied.

Additional datum is provided by the magnetism of the rock, for the Earth is known to have reversed its field at intervals. The time spent in transition is short compared to that spent in one direction[13], so that the Earth's field in the past may be divided into 'normal' and 'reversed' periods; these periods Cox and Doell[14] have termed 'polarity epochs'.

The magnetization of rocks can be used, in conjunction with absolute dating, to establish the duration and position of polarity epochs. Ideally this requires a complete stratigraphic column, dated radiometrically. However, this is not possible, for the column is not complete at one place, nor can all rocks be dated, with present techniques. A further complication is the existence of magnetic self-reversal, for in many cases self-reversal cannot be detected in the laboratory, but only by comparison with other rocks of the same age. In practice, therefore,the sequence of polarity epochs will only be synthesized using stratigraphic and palaeontological evidence in addition to radiometric dates.

If an absolute age could be assigned to every horizon the stratigraphy would be known completely; but as explained, this is not possible, and there is often uncertainty in correlating the successions of different areas. A knowledge of past polarity epochs could help, provided the geologist has sufficient knowledge of a horizon's stratigraphic position to avoid assigning it to another epoch of the same polarity.

It will be seen that while the two ideas of establishing the dates of polarity epochs and of using dated reversals to help correlate stratigraphy are distinct, in practice they proceed simultaneously.

Polarity of Horizons

We have used only natural magnetizations to determine the polarities of East African rocks (Nairn[9] and Grommé and Hay[10] found little change in direction on cleaning). Accepting the evidence that the Earth's mean magnetic axis has always been near the geographic axis, normal or reversed polarity has been assigned to a site if all the directions of its specimens lie within 90° of the geographic pole, and the majority within 45°.

A few samples may have been magnetized during a polarity reversal; this might explain the four directions of stable and shallow magnetization away from the mean field. Three sites had stable magnetization well away from the north-south direction and are not shown on Figure 3, but have been included in the statistics.

Some of our sites contain specimens of both polarities—presumably due to self-reversal—and have been eliminated by the criterion used; the possibility remains of complete sites being self-reversed, but no allowance for this has been made.

Geographic and stratigraphic details of site positions, together with their polarities, are shown in Figures 1 and 2.

Stratigraphy and Polarity Epochs

The stratigraphic columns of Figure 2 have been compiled from the published work of Fairburn[15], Sykes [11], Baker[16,17] and Walsh and Dodson[3] modified in the light of later unpublished work by Saggerson[18], Gevaerts[19], Matheson[20] and Fairburn[21].

In the Turkana area ages are known only from the limited palaeontological evidence, and this makes it impossible to date the two reversals shown in Figure 2*a*, but the upper of these could have its equivalent in the Nairobi area. It is interesting that two reversed lava sheets have been found in Japan in the Middle to Upper Miocene[22].

The stratigraphy of the Nairobi region is complicated by the occurrence of localized lava and tuff flows, which may occur apparently above or below their true positions, on a dissected surface of older rocks. All these Tertiary rocks lie above the erosion surface of the sub-Miocene peneplain cut in the Basement System. Since then three major periods of erosion have occurred; post Kapiti Phonolite pre Athi Series; post Athi Series pre Nairobi Phonolite, post Nairobi Trachyte pre Kerichwa Valley Tuff.

Polarity epochs have only been defined radiometrically back to 3.4 m.y.[6] The present normal epoch N_1 has lasted since 0.98 m.y.; the preceding reversed epoch R_1 extends back to 1.9 m.y.; the results of the period 1.9 to 2.5. m.y. are still confused. The normal magnetization of the Olduvai Gorge (Tanganyika) basalt, dated at 1.9 m.y.[10] is thus in question. The preceding normal period N_2 has been found to extend back to 3.3 m.y. and a reversal has been found at 3.4 m.y.

The East Africa Plio-Pleistocene results approximate stratigraphically to this pattern, and may be assigned as shown in Table 2.

Table 2

SIMPLIFIED STRATIGRAPHY AND POLARITY OF THE NAIROBI REGION

Million Years	*Polarity*		*Magadi-Kajiado Area*		*Nairobi Area*		*Thika-Fort Hall Area*	
	N	PLEISTOCENE						
1	R_1		Plateau Trachytes {orthophyre, alkalai}	N			Thiba Basalts	N
2	?		Lengitito Trachyte	R	Limuru-Trachyte	R	Tumu-Tumu Trachyte	?
					Kerichwa Valley Trochytes	R	Mt. Kenya Phonolite	?
			Kirikiti Basalts	N	Kerichwa Valley Tuffs: upper	R	Laikipian Basalt	R
	N_2				middle	N	? thin basalts	N
3			Ol Kejo Nero Basalts	N	lower	N	? trachytic tuffs	N
					Nairobi Trochyte	R		
4	R_2	PLIOCENE						
5					? Lr Ngong Basalts	N		
6	NOT YET KNOWN		Ol Esakut Volcanics	R	Nairobi, Kandizi Phonolite	R		
					? Lukenya tuff	R		
7			Ololkisailie Volicanics	N	Mbagathi Trachyte	N	Thika Building Stone	N
					? Thin basalt flows		(?=Kerichwa Valley Tuffs)	
8		MIOCENE						
9					Middle Athi Series		Simbara Basalts	N
10					(absent)		(and=agglomerates)	
11					Lower Athi Series		Lower Athi Series	
12		UPPER			(unexposed sediments)	?	(unexposed sediments)	?
13			Kapiti Phonolite	N	Kapiti Phonolite	N	Kapiti-Yatta Phonolite	R
					? basal Ngong basalts		? Sub-Kapiti sediments	?
14								

Prior to R_1 three reversals are found in the rocks between the Limuru Trachyte and the Nairobi Phonolite, which indicates epochs shorter than the epochs mentioned above, none of which is much less than 1 m.y. This assumes that no self-reversals have occurred in this period and that our sites in the Ngong Basalts are correctly assigned. The Nairobi succession has been shown abutting against the 2,000 feet or more of basalts and nephelinites exposed in the Ngong Hills (though this has not been confirmed below the Nairobi Trachyte), with some Ngong basalts intercalated. Boreholes show 20—250 feet of Lower Ngong Basalts overlying Nairobi Phonolite and basaltic sands intercalated with the Kapiti Phonolite[19]. Suggerson[18] has described an Upper Ngong Basalt overlying and cutting Kerichwa Valley Tuff, although this has not been found in the boreholes. Extrusion of Ngong Basalts may thus have occurred aperiodically through the Pliocene. Until the position of our sites within the Ngong Basalts has been clarified by further stratigraphic and palaeontological evidence, and self-reversals have been eliminated by comparison with other rocks of the same age the number of epochs here is uncertain.

No reversal has been found in the Athi Series, except for the horizon of tuff sampled at Lukenya. As these latter are topographically higher than the Nairobi Phonolite, and are interbedded with sediments, they are probably the equivalent of tuffs removed from the Athi Basin before extrusion of the Nairobi Phonolite.

Fairburn[15] considers the Thika Building Stones to represent the Athi Series in the Thika area. These are overlain by trachytic tuffs and thin basalt flows which he considers equivalent to the Kerichwa Valley Tuff and representing early Laikipian basalts. Gevaerts[12], however, has described a similar thin basalt underlying the Nairobi Phonolite. Therefore, correlation of this part of the succession to the north is tentative.

The Simbara Agglomerates were found to be magnetically unstable but Fairburn[21] and Gevaerts[12] consider the Simbara Basalts to be of the same age.

The Lower Athi Series is represented by 450 feet of silts and clays, found only in boreholes. This suggests a considerable time interval, which could not be measured magnetically. A Lower Pliocene basalt in France, has been found reversely magnetized[23] and suggests that a reversal may occur in this unsampled interval, though late Miocene and early Pliocene sediments in America[24] and early Pliocene Japanese volcanics[22] have shown normal polarities.

The Kapiti Phonolite which locally reaches 500 feet is known to consist of several flows separated by sediments. Stratigraphic relationship between the reversed horizon found just above the basement contact at Tana River, and the normally magnetized Kapiti Phonolite of the Nairobi area is not known.

Conclusion

Polarity epochs in the Upper Tertiary have occurred sufficiently often to assist in correlating successions of different areas. The number and positions of the polarity epochs need to be defined throughout the Upper Tertiary, but this can only been done in conjunction with further stratigraphic, radiometric and palaeomagnetic work.

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