

A PALEOMAGNETIC STUDY OF VOLCANIC
ROCKS OF NAIROBI AREA.

BY

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THIS THESIS HAS BEEN ACCEPTED FOR
THE DEGREE OF MSc 1989
AND M.C. MAY 1
UNIVERSITY OF NAIROBI

A thesis submitted in partial fulfilment of
the requirements for the degree of Master of science
of the University of Nairobi.

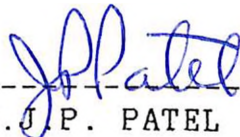
1989.

This thesis is my original work and has not been presented for a degree in any other University.



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PROF. J. P. PATEL

ACKNOWLEDGEMENTS

I am greatly indebted to the thesis supervisor, Professor J. P. Patel, who not only introduced me to Paleomagnetism but patiently devoted a lot of time to offer constant guidance, suggestions, and encouragements, which became a source of my motivation throughout the project and for his personal involvement in every stage of the evolution of the thesis.

I also wish to express my sincere thanks to the Federal Republic of Germany, through its agency DAAD, for giving me the scholarship for my Msc. study and to the University of Nairobi, through the Department of Physics, for the research facilities.

Appreciation is also extended to Miss Loi M. Indiazi for typing the thesis and the ensuing revisions, and finally, though not least to the Members of Staff of the Department of Physics of the University of Nairobi.

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ABSTRACT

The thesis presents paleomagnetic results of volcanic rocks of lower Tertiary age from Nairobi area. The rock units sampled for the study are the Limuru trachytes (1.72 my), Nairobi phonolites (5.2 my), Ngong basalts (5.3 my) and Mbagathi phonolitic trachytes (5.7 my). Alternating field demagnetization technique was used in isolating the primary component of the natural remanence of the samples. The cleaned mean directions have been classified as normal, intermediate or reversed. The mean intermediate direction for the Ngong basalts is calculated at declination $D = 84.5^{\circ}$, Inclination $I = 0.8^{\circ}$ ($\alpha_{95} = 23.8^{\circ}$). The Limuru trachytes, the Mbagathi phonolitic trachytes and the Nairobi phonolites each gave mixed directions of intermediate and reversed polarities. The mean intermediate and reversed directions for the Limuru trachytes are calculated at $D = 99.8^{\circ}$, $I = 22.65^{\circ}$ ($\alpha_{95} = 1.2^{\circ}$) and $D = 171.5^{\circ}$, $I = 14.93^{\circ}$ respectively; for the Mbagathi phonolitic trachytes the mean intermediate and reversed directions are calculated at $D = 73.71^{\circ}$, $I = 39.97^{\circ}$ ($\alpha_{95} = 17.3^{\circ}$) and $D = 151.1^{\circ}$, $I = 24.2^{\circ}$ ($\alpha_{95} = 21.0^{\circ}$) respectively while for Nairobi phonolites the mean intermediate and reversed directions are calculated at $D = 251.0^{\circ}$, $I = 0.1^{\circ}$ and $D = 169.6^{\circ}$, $I = 2.5^{\circ}$ ($\alpha_{95} = 9.6^{\circ}$) respectively. The corresponding paleomagnetic poles for all the rock formations have also

been evaluated. The mean paleomagnetic pole for the Ngong basalts is computed at 125.0°E , 0.93°N ($A_{95}=15.2^{\circ}$). The Limuru trachytes gave poles at 114.73°E , 9.82°S ($\delta_m=1.23^{\circ}$, $\delta_p=0.65^{\circ}$) and 88.9°E , 79.3°S from the intermediately and reversely magnetized mean directions; Nairobi phonolites gave 126.49°E , 18.9°S and 127.3°E , 79.6°S ($\delta_m=9.6^{\circ}$, $\delta_p=4.8^{\circ}$) from its intermediate and reversed mean directions while the Mbagathi phonolitic trachytes yielded corresponding poles for the intermediate and reversed mean directions at 102.9°E , 14.4°N ($\delta_m=20.8^{\circ}$, $\delta_p=12.53^{\circ}$) and 104.0°E , 59.2°S ($\delta_m=22.5^{\circ}$, $\delta_p=12.0^{\circ}$) respectively. A tentative magnetostratigraphy of these rocks of Nairobi area, based on their polarity, has been suggested. An attempt has been made to correlate this magnetostratigraphy of Nairobi area with other stratigraphic columns from other areas of Kenya. Optical petrological analysis was also carried out on specimens of various sites of the units. The results indicate that titanomagnetite grains are the principal carrier of the natural remanence. The low coercivity of the natural remanence exhibited by some rock units is believed to be due to the multi-domain nature of the titanomagnetite grains.

INTRODUCTION

Paleomagnetism is the study of the history of the Earth's magnetic field. It relies on the record of the field preserved as fossil magnetization. Although most rock forming minerals are non-magnetic, all rocks exhibit some degree of magnetic properties due to the presence of various iron oxides as accessory minerals making up only a few percent of the rock. The magnetization of the accessory minerals is termed as fossil magnetism which, if acquired at the time the rock was formed, may act as a fossil compass and be used to determine both the direction and intensity of the geomagnetic field over the geological time scale.

Paleomagnetism involves such disciplines as the study of the physical processes involved during acquisition of rock magnetism, the study of the nature and origin of the Earth's magnetic field and the study of age and tectonic history of the rocks under analysis. The three basic assumptions in most paleomagnetic work are that the time averaged field is a geocentric dipole, the remanence used in any analysis is primary in origin and that the time span in acquisition of this primary remanence is negligible as compared to the age of the rock.

Evidence for 'reversals in polarity' of dipole axis is based on observed occurrence of reversals in the polarity of fossil magnetism of rock units. This field reversal theory is used for precise stratigraphic correlation of normally and reversedly magnetized strata and tectonics and is also ultimately connected to paleogeography. From the knowledge of fossil magnetism, it is also possible to study the paleolatitude of a particular type of deposit and hence its paleoclimate. Study of paleoclimates attempt to trace the variations in the position of the Earth's paleogeographic pole and past positions of land masses relative to the Earth's pole and to each other. Such distribution provide a test of the hypothesis of polar-wandering and continental drift by a method which is independent of geological evidence. The fossil magnetism of rocks is termed as natural remanent magnetism (N.R.M). The mechanism by which N.R.M is acquired depends upon the mode of formation, and subsequent history of rocks as well as the characteristics of the magnetic minerals. Thermoremanent magnetization (T.R.M), Chemical remanent magnetization (C.R.M), Isothermal remanent magnetization (I.R.M), and Detrital remanent magnetization (D.R.M) are the main types of magnetization (discussed in the next chapter) normally acquired by rocks.

During the last quarter of a century various research groups from the University of Nairobi and elsewhere have

carried out detailed studies of a very wide spectrum of rocks from the East African Rift Valley. Early paleomagnetic studies of the rift volcanics were carried out by Nairn (1964) who published paleomagnetic results of the Nakuru-Naivasha section of the rift valley on purely reconnaissance basis and Musset et al. (1964) who undertook a paleomagnetic study of the Tertiary volcanics of the rift valley.

The plio-Pleistocene deposits of Lake Turkana region have been the object of considerable attention in recent times due to discoveries important to palaeontology, anthropology, and archaeology. A paleomagnetic study of the Koobi fora formations, east of the Lake Turkana, forms part of an M.Sc. thesis by Ndombi (1974). Other results from this region include Raja (1968), who published magnetic directions and pole positions for the Miocene lavas of Lake Turkana, Brock and Isaac (1974) and Hillhouse et al. (1977) who undertook paleomagnetic analysis to strengthen the magnetostratigraphy of the hominid bearing sediments exposed east of Lake Turkana and suggested approximate match between the observed magnetozones and the geomagnetic polarity time scale. Hillhouse et al. (1986) re-evaluated the regional magnetostratigraphy, due to new developments concerning the stratigraphy plus new paleomagnetic studies of the Koobi fora formation, to include previously unpublished data from the uppermost part of the formation which

correlate to parts of Bruhnes and Matuyama epochs. The Lake Turkana lavas have been radiometrically dated between 12.5 - 32 my by Reilly (1966). Further to the north of the Lake Turkana formations, Brock et al. (1970) determined paleomagnetic pole positions of the Ethiopian flood basalts succession near Addis Ababa and concluded that the pole position for these basalts, considered Eocene-Oligocene in age, shows a 9° deviation from the present pole position as compared to 5° during the Miocene period.

In the central and southern rift valley, Dagley et al. (1978) collected paleomagnetic samples and published geomagnetic polarity information of the igneous and sedimentary units in the sequences exposed in the Tugen (Kamasia) hills west of Lake Baringo and in Elgeyo escarpment. The Baringo basin has, in general, been a fruitful source of Neogene vertebrate fossils including fossil hominoids. Paleomagnetic and K/Ar age determinations for the type section of the middle Miocene Ngorora formation in this basin is reported by Tauxe et al. (1985) who correlated the obtained magnetostratigraphy to the geomagnetic time scale while extensive study of volcanics of central and southern part of the Gregory rift valley were made by Reilly (1970) who obtained satisfactory results of the pole positions for the late Tertiary volcanics. A paper by Reilly et al. (1976) describes the results of a large scale reconnaissance

survey of the volcanics involving 184 sites mainly south of the equator and conclude that secular variations for East Africa have been large and in accord with predictions for the near equatorial sites for at least the past 7 my.

Nine stratigraphic groups ranging in age from Miocene to Pleistocene were sampled by Patel and Raja (1979b) and computed results of this paleomagnetic study carried out on the volcanic rocks exposed on the western side of the south Kenya rift valley presented. They determined paleomagnetic directions for the different age ranges although their proposed secular variation levels for the age range 1.6 - 6.9 my differed from those predicted by Brock (1970) for the near equatorial sites. Earlier Brock et al. (1972) had undertaken a paleomagnetic study of the Precambrian Kisii series of western Kenya from which they suggested that the Kisii pole forms part of a previously undefined polar wander path for Africa for the late Precambrian. Further to the west, Raja and Vise (1973) suggested a polar wander path for Africa from Mesozoic to present based on paleomagnetic measurements on the pre-Miocene carbonatite of Tororo, south east Uganda.

The paleomagnetic results of the Kapiti phonolites which crop out on the eastern flank of the Kenya rift valley are presented in a paper by Patel and Gachii (1972) who deduced the pole position for the upper Miocene. The

Kapiti phonolites are one of the earliest Tertiary lavas to be extruded on the eastern flank of the Gregory rift valley and rests on the sub-Miocene peneplain.

Apart from this study of the Kapiti phonolites, no other rock units on the eastern flank of the rift valley have been studied paleomagnetically. The present paleomagnetic analysis has been undertaken with an aim of producing reliable paleomagnetic directions and pole positions for rock units of Nairobi area. This will be used to facilitate a basis for correlation of magnetic stratigraphy of the Nairobi area lava flows with those of rock units within and on either flanks of the rift valley. The polarity matching in the stratigraphic column to equivalent intervals in the time scale will also provide age limits for the different sampled formations.

CHAPTER 1

ROCK MAGNETISM AND PALEOMAGNETIC STATISTICS

1.1.1. Thermoremanent Magnetization (T.R.M.)

The thermoremanent magnetization of a rock is the remanence acquired upon cooling through a certain temperature interval in the presence of a magnetic field. The remanence during cooling from the maximum Curie point to room temperature is called the total T.R.M. Upon cooling from a high temperature, spontaneous magnetization appears at the Curie point, T_C , and this assumes an equilibrium magnetization in the presence of an applied field. Grains of different volumes will each have different blocking temperatures, T_B . As the temperature cools below T_C and passes through each T_B , the relaxation time of each of these grains increases very rapidly. The equilibrium magnetization becomes 'frozen in' and subsequent changes in the field direction occurring at temperatures below each T_B are ineffectual in changing the direction of magnetization of that grain. The T.R.M. is not all attained at the Curie point, T_C , but over a range of blocking temperatures from the Curie point down to room temperature. The total T.R.M. may be considered to have been acquired in steps within successive temperature intervals. The fraction of the total T.R.M. acquired in

these temperature intervals is called partial thermoremanent magnetization (P.T.R.M) for each temperature interval. The sum of successive P.T.R.M.s acquired in each consecutive temperature intervals between Curie and room temperature is the total T.R.M. The P.T.R.M acquired in any temperature interval depends on the field applied during that interval and is not affected by the field applied at subsequent intervals on cooling. The acquired T.R.M. is normally parallel to the applied external field.

Acquisition of stable thermoremanent magnetization is basically found in igneous rocks and there is evidence that the high stability N.R.M. in these igneous rocks is carried essentially by the mono-domain and pseudo-single domain (PSD) fractions although many coarse grained minerals contain a large fraction of multi-domain carriers (Stacey, 1967, Lowrie and Fuller, 1971). These multi-domain carriers may occasionally dominate the magnetic properties of the rocks as stated by Tucker and O'Reilly (1978).

1.1.2. Chemical Remanent Magnetization (C.R.M.)

Chemical remanent magnetization is acquired during the formation of a magnetic mineral at low temperatures (below the Curie point) by chemical or phase change in the presence of an applied field. Oxidation or reduction often occurs at suitable conditions causing mineralogical

phase changes which include acquisition of a stable remanence controlled by the ambient field. Investigation of various oxidation or reduction phenomena have been done by various researchers, (Hedley (1968), Strangway et al. (1968), and Kobayashi (1959)).

1.1.3. Isothermal Remanent Magnetization (I.R.M.)

A magnetic mineral can acquire a remanence at constant temperature. This remanence, referred to as isothermal remanent magnetization (I.R.M), is normally induced by an applied field greater than the smallest coercive force within a mineral. I.R.M. is small and unstable as it is carried by low coercivity domains and is therefore easily removed by partial demagnetization. Its value increases to a saturation maximum. Lightning induces this type of remanence in exposed volcanic rock outcrops. The time dependent I.R.M. is called viscous remanent magnetization (V.R.M.), that magnetization acquired by a rock if exposed for long periods to a weak external field. V.R.M. is proportional exponentially to temperature (Strangway, 1970). It is caused by thermal fluctuations which occur randomly tending to displace domain walls slightly and with time, the walls will reorganize themselves to give greater magnetization in the direction of the applied field to which it is exposed.

1.1.4. Detrital Remanent Magnetization (D.R.M.)

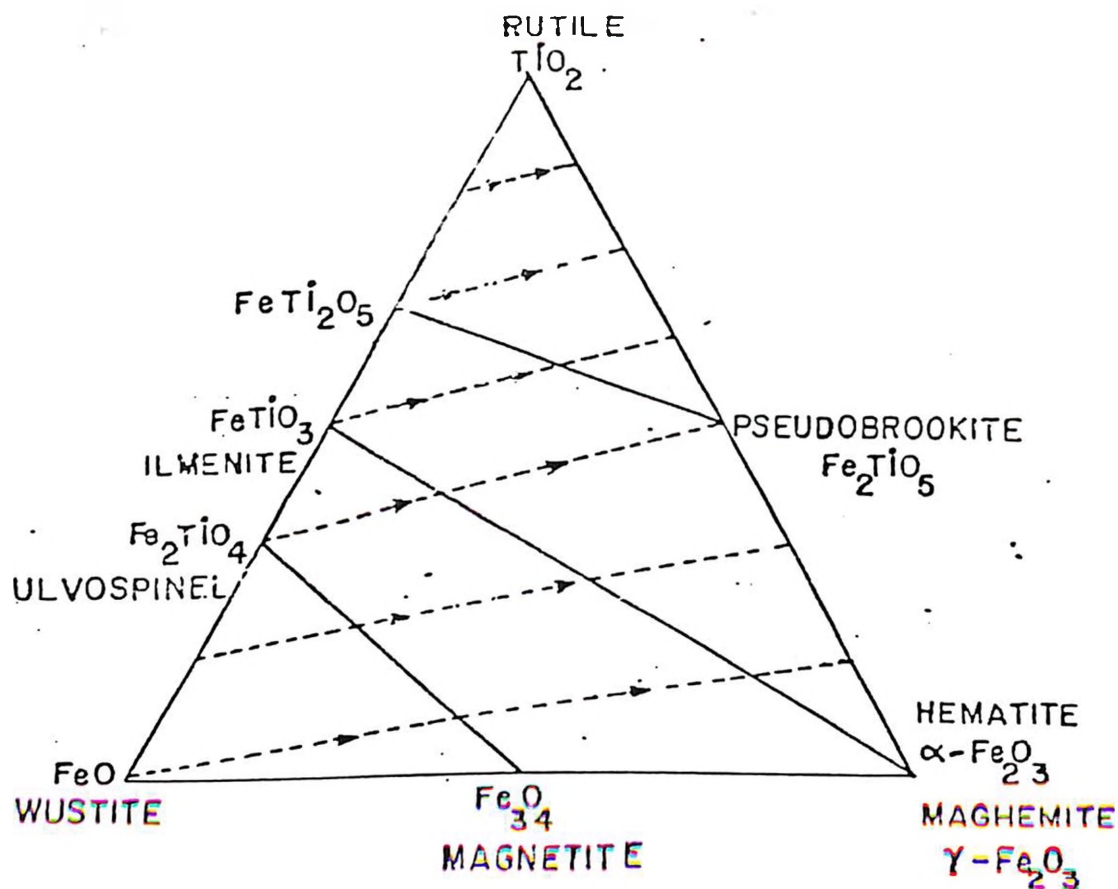
Sediments of magnetic minerals on deposition often have their magnetic directions, the resultant domain directions aligned in the direction of the existing external field. This kind of remanence is referred to as detrital or depositional remanent magnetization (D.R.M.).

The magnetic grains in a rock are not equally easily magnetized in all directions. This is because magnetic characteristics of a rock is affected by the shape of the grains. The existence of crystalline anisotropy determines the locations of energy barriers on the crystal form. Stress or magnetostriction forces are time dependent as many rocks remain under duress throughout their histories. Deformation on the other hand re-aligns the resultant direction of the magnetization. This, in fact, is the reason why during sampling, deformed beds are avoided.

1.2.0. Magnetic Minerals in Rocks

Many minerals contain magnetic elements, particularly iron, but majority of these have Curie temperatures below zero and are therefore non-useful for paleomagnetic work. Some which have higher Curie temperatures are extremely rare such as free iron and nickel-iron alloys. The $\text{FeO-TiO}_2\text{-Fe}_2\text{O}_3$ ternary system in Fig. 1a below, shows the distribution of magnetic

minerals which are largely responsible for carrying the natural remanence in rocks.



(Fig. 1a.: FeO-TiO₂-Fe₂O₃ Ternary system showing principal solid solution series (solid lines). The dashed lines are of constant Fe:Ti ratio along which oxidation may proceed in the direction of the arrows (Akimoto et al. (1957))

Various oxidation series may also be distinguished from the ternary diagram. There are the strongly magnetic cubic oxides like magnetite (Fe₃O₄), maghemite (γ -Fe₂O₃) and the solid solutions of magnetite with ulvospinel (Fe₂TiO₄) which are known as titanomagnetites. The more weakly rhombohedral minerals are based on hematite

(α -Fe₂O₃) and its solid solutions with ilmenite (FeTiO₃) which are known as titanohematites.

The members of the orthorhombic pseudobrookite series are all paramagnetic above liquid oxygen temperatures and need to be considered further because paramagnetic substances lose their magnetic properties as soon as the applied field is removed and therefore do not retain any remanence. The complete solid solutions of the above types of magnetic minerals occur only at high temperatures, in which case, oxidation proceeds along the dashed lines, as shown in the ternary diagram in Fig.1a.

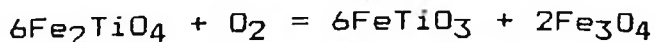
The only iron sulphide that is ferrimagnetic is pyrrhotite (FeS_{1+x}), whose Neel transition to the paramagnetic state occurs at 300°C. Below this temperature, it is antiferromagnetic when $0 < x < 0.09$ and ferrimagnetic when $0.09 < x < 0.14$ (x is a numerical variable in the given range) while the two naturally occurring oxyhydroxides of iron are goethite (α -FeOOH) and lepidocrocite (γ -FeOOH) which dehydrate to oxides at temperatures between 100°C and 300°C. The three main solid solution series in the above ternary diagram (Fig. 1a) are briefly discussed below.

1.2.1. Magnetite-Ulvospinel Solid Solution Series

Magnetite and ulvospinel form a complete solid solution series, as already mentioned, in which they are

the end members. Magnetite is the most common magnetic mineral oxide and sometimes forms up to 5% of the total rock. It frequently contains Ti as impurities, which influences its Curie temperature and intensity of saturation, depending on its content. The titanium content also affects the lattice parameters as stated by Nagata (1961). Ulvospinel, though difficult to find in nature as an independent mineral, is often found as an intergrowth with magnetite.

In the process of cooling from a liquid state the solid solution series formed by magnetite-ulvospinel may react with residual, oxygen rich, liquids resulting in oxidation. Their composition then changes towards the ilmeno-hematite series. Ulvospinel forms at high temperatures but during the cooling, it becomes unstable and oxidizes to form ilmenite and magnetite as shown by the equation below (McElhinny, 1973).



This ilmenite does not form a solid-solution with magnetite since it has a different structure and exsolves into irregular volumes with exsolution lamellae parallel to (111) crystallographic planes of the host magnetite thus sub-dividing the large magnetite grains into a number of magnetically independent smaller grains. The result is that small particles of magnetite and ilmenite are formed.

Only magnetite is magnetic at ordinary temperatures so that the material now consists of very fine grains of magnetic minerals separated by a non-magnetic ilmenite. Graham (1953) pointed out that the magnetic stability is enhanced as a result of sub-division of magnetic grains by the non-magnetic ilmenite lamellae. Akimoto and Kushiro (1960), from their studies of the dolerite dykes of Japan, also showed that stability is increased in volume of ilmenite lamellae in magnetite. Similar views have been expressed by Powell (1963) and Larson et al. (1969).

1.2.2. Magnetite-Maghemite Solid Solution Series

Maghemite ($\gamma\text{-Fe}_2\text{O}_3$) is the oxidation product of magnetite at temperatures below 275°C . Above this temperature, a more stable hematite ($\alpha\text{-Fe}_2\text{O}_3$) is formed. Maghemite is commonly found in nature and is closely associated with the stability of the remanence in rock specimens (Akimoto and Kushiro, 1960).

1.2.3. Ilmenite-Hematite Solid Solution Series

The end members of this solid solution series, hematite and ilmenite, are weakly magnetic, rhombohedral and quite common in nature. Hematite is predominantly anti-ferromagnetic but carries a superimposed weak ferromagnetism often referred to as parasitic ferromagnetism, cause of which is unknown. In addition to this intrinsic weak ferromagnetism, there is an additional component which arises from interaction between

antiferromagnetism and lattice defects or impurities. This defect ferromagnetism is observable below the Morin transition temperature (-20°C) and between 680°C and the Neel point of 725°C (McElhinny, 1973) and because defect ferromagnetism is sensitive to structure, it is altered by stress or heating and could provide spurious paleomagnetic information.

In the ilmenite-hematite series, there is a complete solid solution above 1050°C . At lower temperatures, the solid solution is restricted and the intermediate composites are represented by intergrowths of the end members. Ionic replacement in the solid solution series is in the same form as that of the titanomagnetite series. As the proportion of the ilmenite increases, the cell dimensions increase and the Curie temperatures of the intermediate composites decrease.

It has been pointed out by Uyeda (1958) that a certain compositional range of this series is associated with the self-reversing properties. Approximately between 45% - 60% ilmenite, in synthetic specimens show self-reversal. Since pure hematite is already in its highest oxidation state, progressive high temperature oxidation in the temperature range 600°C - 1000°C is observed in the other end member of the series, ilmenite. Progressive high temperature oxidation in discrete ilmenite grains proceeds towards the rutile-hematite side of the ternary

diagram. As in the case of titanomagnetites, stable natural remanence in this series is carried by small particles basically the ilmenohematite lamellae 5-10 microns long one micron wide containing about 10% ilmenite as showed by Carmichael (1961).

The final oxidation of the titanomagnetite or the ilmenite-hematite series minerals results into the pseudobrookite solid solution series. According to Nagata (1961), the pseudobrookite solid solution series occurs at temperatures above 850°C from the ilmenite-hematite rich phase. When this series incorporates excess of titanium at below 850°C, rutile (TiO₂) is produced.

1.3.0. Stability of Remanent Magnetism

All paleomagnetic studies are concerned with the direction and intensity of the geomagnetic field at a specific time in the geological past. The primary component of magnetization is acquired when the rock is formed and it is this remanence which is important in paleomagnetic studies. This remanence is carried by domains with relaxation times, related to the blocking temperatures and coercivities, greater than the age of the rock and therefore magnetically more stable than most secondary magnetizations.

The coercive force is defined as the field required to flip the magnetization of an already magnetized stable domain, or simply the reverse field which reduces the

domain remanent magnetism to zero, and is determinable from the magnetic hysteresis loops. In general, it is well accepted that the coercive force increases with decrease of particle size (Strangway, 1970). The dimensions of ferromagnetic grains in igneous rocks are generally large, ranging from one micron to several hundred microns. Well developed exsolution textures of magnetite and non-magnetic ilmenite are common in such rocks. Larson et al. (1969) showed that a homogeneous grain of 50 microns readily produces 500 sub-grains of 5 microns or less in size through an exsolution process. They proved that after that process, the coercivity spectrum was totally changed after the sub-division of the large grain, to that of a stable specimen. They also concluded that rocks with large opaque grains have low coercive force and possess no stable component.

The shape of the grains also affect the magnetic characteristics of a rock. This is because the existence of crystalline anisotropy determines the locations of energy barriers on the crystal form. Strangway et al. (1968) presented evidence that elongated magnetic particles which developed after heating in air for hours at 800 °C, were responsible for the increase in coercive force and stable remanent magnetization. The magnetism carried by these shapes of magnetite will possess a maximum coercive force of 280 mT. Such magnetic particles have been observed by Strangway (1970) to carry an extremely

stable remanence and high coercive force in rocks.

Evans and McElhinny (1966) pointed out that elongated rods of varying lengths observed in pyroxenes of Modipe Gabbro from Zimbabwe, were possibly single domain magnetite while Hargraves and Young (1969) found that rodlets embedded in pyroxenes and plagioclase, whose size could not be resolved by a microscope, were the source of stable remanent magnetism in the Lambertville diabase from Canada. Similar observations have been made by others with a general conclusion from both theoretical and experimental evidence that magnetizations was carried by fine single-domain needles of magnetic in plagioclase feldspar.

Further, there is evidence (e.g. Stacey 1967, Lowrie and Fuller 1971) that the high stability natural remanence in igneous rocks is carried essentially by the mono-domain and pseudo-single domain (PSD) fractions although many coarse grained minerals contain a large fraction of the multi-domain particles. These multi-domain carriers may occasionally dominate the magnetic properties of rocks as concluded by Tucker and O' Reilly (1978).

1.4.0. Statistics of a spherical distribution

In paleomagnetic studies, data is collected in the form of a number of directions of magnetizations of oriented rock samples. In order to make a statistical

analysis of these available data, Fisher (1953) developed a method for statistical analysis based on sets of vectors. He suggested that these directions will, when regarded as points on a unit sphere, be distributed over the sphere with a probability density, P , given by

$$P = (K/4\pi \sinh K) \exp (K \cos \theta)$$

where θ is the angle between the direction of a sample and the true mean direction at which $\theta = 0$ and the density maximum. The constant factor $(1/4\pi)$ ensures that the sum of the probabilities over the sphere is unity. K is the precision parameter, varying from zero for a perfectly random distribution to infinity for identical directions.

1.4.1. Statistical Parameters

In paleomagnetic studies, the directions of magnetization of rocks samples is specified by the declination (D) measured clockwise from the true north and the inclination (I) measured positively downwards from the horizontal. These directions may be specified by directional cosines thus:

$$\text{North component } \ell = \cos D \cos I$$

$$\text{East component } m = \sin D \cos I$$

$$\text{Down component } n = \sin I$$

The directional cosines X , Y , Z of the resultant of N samples are proportional to the sum of separate

directional cosines and are given by

$$X = \frac{\sum_i \ell_i}{R}, \quad Y = \frac{\sum_i m_i}{R}, \quad Z = \frac{\sum_i n_i}{R}$$

and the vector sum of these unit vectors will have a length R given by

$$R^2 = \left(\sum_i \ell_i \right)^2 + \left(\sum_i m_i \right)^2 + \left(\sum_i n_i \right)^2$$

The estimate k of the precision parameters is given by Fisher (1953) as

$$k = (N-1)/(N-R)$$

The accuracy of the mean direction may be calculated for any probability level (1-P). The mean lies within a circular cone about the resultant vector R with a semi-angle α given by Fisher (1953) as

$$\cos \alpha = 1 - (1/R)(N-R)\{(P)^{-1/(N-1)} - 1\}$$

1.5.0. Test for randomness of directions

Fisher (1953) showed that in a truly random population, $K=0$ although in practice it is never zero due to sampling fluctuations, while Watson (1956) has given a

statistical test can be used for testing randomness of directions based on the following argument. The length of the vector R , will be large if there exists a preferred direction. Assuming no preferred direction exists, a value R_0 can be evaluated which will be exceeded by R with any stated probability. He has tabulated values R_0 for various sample sizes for probabilities 0.05 and 0.01. In order to carry out the test, the value of R_0 , which will be exceeded with the given probability, usually 5%, is derived from Watson's table at the point of coincidence of the row corresponding to sample size, N and the column corresponding to the given probability. If the evaluated R is less than the tabulated R_0 , the directions are considered random, and may not be used in computation of the mean pole positions.

The stability index, developed by Briden (1972) has been used to select the optimum field for cleaning site specimens. The stability index (S) is defined by

$$S_{1-2} = 1 - J_{1-2}/J_1$$

Where J_{1-2} is the numerical magnitude of vector difference $\bar{J}_1 - \bar{J}_2$ and J_1 is the magnitude of the first vector at that field of demagnetization. J_2 is the magnitude of the vector at the next field of demagnetization.

Successive increments of 5mT has been used in determining the values of the stability index, S. The alternating field (a.f) at which S is maximum for a pilot specimen is taken as the optimum field for the site from which the specimen was extracted. Briden's (1972) criteria has an advantage over others (such as Tarling and Symons (1967), Wilson et al. (1968) and Ade Hall (1969) in that it accounts for both the intensity and the directional changes at every incremental step of demagnetization and that the stability of total natural remanence is not assumed unity.

Unit weights have been given to sites in the calculation of formation means, after taking samples as the units in determination of site means. Some sample directions of apparently stable directions were found to lie well outside the group formed by other directions. Such directions were rejected on the basis that they probably did not belong to the population sampled. The argument being that in each case, the divergent direction differed from a group mean by more than the angle $\theta_{95}=(140/K^{1/2})$, the radius of circle of 95% enclosure for the directions.

Watson's (1956) F-ratio test at 5% significant point has also been used to test two polar directions by defining

$$F_{2,2(N-2)} = (N-2) (R_1+R_2-R)/(N-R_1-R_2)$$

where $N = N_1 + N_2$, total number of samples of the two populations, R is the magnitude of the resultant of vectors \bar{R}_1 and \bar{R}_2 , individual resultants of the two populations with magnitudes R_1 and R_2 respectively and $F_{2,2(N-2)}$ is the calculated F-ratio for 2 and $2(N-2)$ degrees of freedom. If the evaluated value of F is less than that tabulated at 95% level, the polar direction are considered insignificantly different at that level.

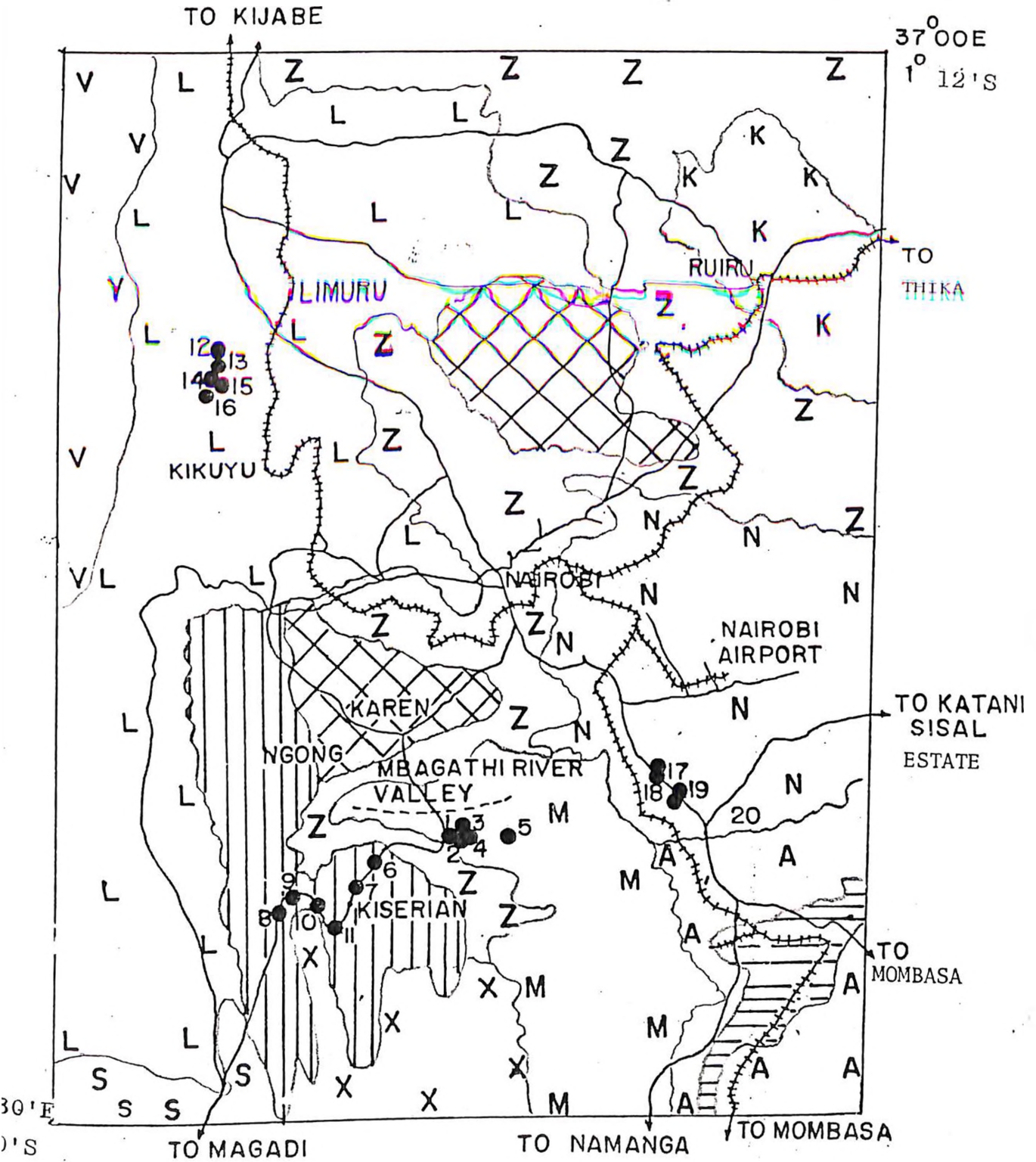
CHAPTER 2

GEOLOGY OF NAIROBI AREA

2.1.0. General geology

The country surrounding Nairobi is a small segment of the eastern ramp of the Kenyan rift valley comprising an area of about 1660 km². This area included in Map 1. lies between 36°30' and 37°00' east longitude and 1°12' and 1°30' south latitude.

The eastern flank of the rift valley transverses the region from north to south and occupies the western part of the area. As in other parts, except where streams have extended their courses by erosion through the boundary walls, or recent volcanism has superimposed new drainage lines, the eastern edge of the rift valley is a watershed between the Indian ocean drainage and the rift valley drainage. In general, the inclined plateau of the ramp rises in elevation at an average gradient of about 1% and 3% (Sikes, 1939) in distances varying between 30 to 60 km from Athi river between watershed line along the Ngong hills and Kikuyu escarpment. The undisturbed plateau sloping gently upwards from Athi river across Athi plains and the Kikuyu highlands is built on successive sheets of lava intercalated with tuffs. In general, these sheets have a gentle eastward or southward dip, the lower members resting on the gneiss of the basement complex.



MAP 1: SIMPLIFIED GEOLOGICAL MAP OF NAIROBI AREA AND LOCATIONS OF SAMPLING SITES.

SCALE: 4KM

KEY TO MAP 1



Roads



Railway line



Limuru trachytes



Ol Esayeiti oligoclase tephrites



Nairobi trachytes



Lower Kerichwa Valley tuffs



Middle and upper Kerichwa Valley tuffs



Nairobi phonolites



Ngong Basalts



Mbagathi phonolitic trachytes



Athi tuffs and lake beds with chert band



Ol Esayeiti volcanics (undifferentiated)



Ashes, pyroclastics and sediments of the
Kedong Valley



Kapiti phonolites



Dotted and numbered locations of sampling
sites.

The Geology of the East African rift system as a whole has been summarised by Baker et al. (1972) and the sequences and geochronology of the Kenya rift volcanics is discussed by Baker et al. (1971). The Kenya rift volcanics erupted nearly continuously from early Miocene to Holocene times. Miocene volcanism was mostly nephelinites, alkali basalts and phonolites. Pliocene activity was trachytic, and nephelinitic in central, and southern parts of the rift valley, while contemporaneous basaltic volcanism took place along its whole length. The only extensive rhyolitic activity occurred in the north western Kenya in Pliocene times (Sikes, 1939). Late Pliocene and Quarternary volcanism was mainly trachytic in the rift floor and basaltic to the east.

The formations of which the country surrounding Nairobi is built for the Quarternary and Tertiary volcanics include Limuru trachytes, Nairobi phonolites, Ngong basalts, tuffs and agglomerates, Mbagathi phonolitic trachytes, Nairobi trachytes and Kerichwa valley trachytes, tuffs and agglomerates. Each group consists of lavas, tuffs or/and agglomerates associated with each other petrologically, stratigraphically and in chemical composition.

Detailed below are the specific Geology of the lava flows sampled for this paleomagnetic analysis. Suitable exposures of some rock formations of Nairobi area (such as the Nairobi trachytes) could not be found as most of their

outcrops were found boulderly and consequently no samples were collected for paleomagnetic work.

2.1.1. The Limuru Trachytes

These group of trachytes cover an area of about 600 km² within the area delineated on the Map (1), and have their thickest visible local development in the vicinity of Limuru and Uplands, and have in consequence been called the Limuru trachytes. Their principal foci of eruption were apparently in the rift valley along the north-south chain of vents which were destroyed by the Naivashan faulting at the end of middle Pleistocene and are now buried under later accumulations.

The lava flows have a general, but gentle eastward or south-eastward dip. The lavas around Limuru and the rift escarpment are associated with much pyroclastic ejection with little intervening pyroclasts (Sikes, 1939). The Limuru trachytes are characteristically highly porphyritic with numerous stumpy crystals of alkali feldspar in a grey groundmass. It weathers easily and seldom exhibits cleavage. Phenocrysts of feldspar are sparse but usually consist of needles with less frequent pyroxenes and soda amphiboles.

2.1.2. Nairobi Phonolites

These phonolites are believed to have been caused by isolated, spasmodic local eruptions which gave rise to

coarse and fine grained types of bedded tuffs.

The Nairobi phonolites are exposed over 260 km² of the Athi plains including parts having a thin covering at a very low gradient. It overlies the Mbagathi phonolitic trachytes in the Mbagathi river valley and its tributaries, appears to be about 120 m thick under Nairobi and may consist of two main sheets as believed by Sikes (1939). The field appearance of the phonolites exhibit long conspicuous crystals of feldspar and small nephelines. A fissile trachytic texture is sometimes found with fluxion arrangement of minute feldspar laths around microphenocrysts of nepheline, which themselves often have a border of soda-amphiboles. Nepheline occurs in small phenocrysts, but is frequently replaced by sodalite.

2.1.3. The Ngong Basalts

These are a varied series of basic lavas, tuffs and agglomerates which constitute the Ngong hills and the foothills to the east of them. The basic rocks have an area of 130 km². The eastern decline of the hills is in general, a dip slope and the western face is one of the older rift valley scarps, now much eroded, which cuts off extension to the west. On the steep scarp, over 600m of lavas, tuffs and agglomerates is believed to be exposed, pyroclastic ejection predominating (Sikes, 1939). The locus of the principal foci of eruption is believed to

have been along the north-south line, westward of the hills now covered by the younger Limuru trachytes.

Petrologically the Ngong basalts consist of basic volcanics providing an interesting alkaline series from black dense nephelinites containing prominent pyroxene phenocrysts together with undifferentiated basanites, atlantites, ankaratrites, basic tephrites to phonolitic tephrites, tuffs and agglomerates. The nephelinites have sporadic crystals of augite in an aphanitic base, which is sometimes platy or fissile. These grade into tephrites with increase of plagioclase content. The basic tephrites are well exposed on the eastern flank of the hills and grade into more acidic types with the increase of the plagioclase and decrease of the augite and magnetite contents.

2.1.4. Mbagathi Phonolitic Trachytes

They are exposed over an area of about 130 km² within the boundaries of the Map (1) in the vicinity of Mbagathi river and southward from it. The eruptions were associated with much pyroclastic ejection. In different parts, the base rests on the basement complex, and the Kapiti phonolites. Their thickness is believed to be small.

In the field, the Mbagathi phonolitic trachytes exhibit numerous closely spaced laths of feldspar in a

rather coarse trachytic base. At the surface, it is vesicular and easily weathered. As is the case in most phonolites, the texture and prevalence of individual minerals vary considerably in different parts of the same mass. Pyroxenes are uncommon as compared to amphiboles. The lava is considered intermediate between the more acidic phonolites and the quartz free trachytes.

According to Baker et al. (1971), the ages of Nairobi lava flows are as given below.

rock unit -----	age ---
Limuru trachytes	1.55 my 1.59 my 1.72 my
Nairobi trachytes	3.17 my 3.45 my
Nairobi phonolites	5.2 my
Ngong basalts	5.3 my
Mbagathi phonolitic trachytes	5.7 my

It is usually found that successive younger flows of lava have terminated at shorter distances from the edge of the rift valley than the older flows on which they are superimposed. Consequently and in general, rocks are progressively younger as one climbs towards the rift valley.

CHAPTER 3

SAMPLING, MEASUREMENTS AND INSTRUMENTATION

3.1.0 General Sampling

For this study extensive collections of block rock samples was undertaken from each of the lava flows within selected sites around Nairobi. The selected lava formations include the Limuru trachytes, Nairobi phonolites, the Ngong basalts and the Mbagathi Phonolitic trachytes. A site is described as a small area of exposure of a single lava flow or intrusion from which a number of oriented block samples have been taken and which is assumed to represent a single point in time and a spot reading of the paleomagnetic field.

Freshly exposed rocks at road cuttings, stream beds, railway cuttings or quarries were sampled whenever possible but outcrops with obvious geological displacements (e.g. boulders) or those which are badly weathered were avoided, as they are unsuitable for paleomagnetic analysis. The block samples were first dislodged from the parent position with a sledge hammer, then carefully replaced in their original position before noting the orientation angles.

The collection and orientation of the block samples has been done as described by Collinson et al. (1964).

Each individual block sample was oriented in situ using a compass and an inclinometer, recording the dip and strike of the formation. The bearing, latitude and longitude were also noted for every sample. The maximum error in strike, dip and position angles is less than 2% of a degree while in bearing measurement it is upto 1° (degree).

The rock units were sampled as follows:-

The Limuru trachytes (sites 12-16), the Nairobi phonolites (sites 17-20), the Ngong basalts (sites 6-11) and the Mbagathi phonolitic trachytes, (sites 1-5) (see Map 1) and are discussed below.

3.1.1. The Limuru Trachytes

This rock unit having their thickest visible local development in the vicinity of Limuru and Uplands townships, were sampled at four quarries or stone excavations about 25 km north-west of Nairobi at latitude 1° 08'S longitude 36° 36'E. The Limuru trachytes, sites 12-16, yielded 16 oriented block samples. The lava flows are very soft and easily weathered. The perpendicular height between the lowest and the highest sampled layers was about 50 meters.

3.1.2. Nairobi Phonolites

The Nairobi phonolites crop out to the east of Nairobi as illustrated in Map 1. Four sites were sampled at a road cutting on the Nairobi-Mombasa road about 8 km from Nairobi, yielding 10 oriented block samples. It was observed that most surface units of the natural outcrops were badly weathered and were therefore not sampled. Average sampling location was at latitude $1^{\circ}21'S$ longitude $36^{\circ}54'E$.

3.1.3. Ngong Basalts

Sampled along the south-westerly Nairobi-Magadi road, mostly at road cuttings, the Ngong basalts are presumed to cover about 130 Km^2 constituting Ngong hills and adjacent foothills. A total of six sites were obtained from this formation yielding a total of 20 oriented block samples. All the sites were sampled around Kiserian township latitude $1^{\circ}25'S$, longitude $36^{\circ}42'E$ (see Map 1) but with sites 8-11 from the western edge of the Ngong hills with site 8 being at the bottom progressively to site 11 at the top. The perpendicular height between these sites (8,11) was about 100 meters with the other sites 9, 10 along the adjoining slanting edge of an incline of about 30° .

3.1.4. The Mbagathi Phonolitic Trachytes

This rock unit was sampled in the vicinity of

Mbagathi river at latitude $1^{\circ}24'S$, longitude $36^{\circ}47'E$ about 15 kilometres south of Nairobi (see Map 1). A total of 5 sites from two quarries were sampled yielding 17 samples. The rock unit is vesicular and weathers easily.

3.2.0. Measurements

The block samples collected in the field were taken to the laboratory and re-oriented in the same position as in situ and cores of diameter 2.5cm drilled out. The cores were then cut into sizeable specimens of length about 2.5cm, which were then used in magnetic analysis of the remanence. Each specimen had its natural remanence measured at zero field and at each demagnetization step. Cleaning of the specimens was done utilizing the alternating field (a.f.) demagnetizing equipment. All rock specimens were demagnetized and at each demagnetization step, their remanence was measured using a spinner magnetometer. The optimum cleaning field of a site was pre-determined using site pilot specimens.

The pilot specimens for each site were demagnetized upto 100mT or until the optimum cleaning field was attained, in steps of 5mT using the alternating field demagnetization equipment. At each step of demagnetization the natural remanence was measured on the spinner magnetometer. The demagnetization vector plots and the stability curves were then computed. The optimum field intensity, the field necessary to clean the secondary

magnetism of the rocks of a given site was then deduced from the plots. The choice of the optimum field from the stability index curves is as explained by Briden (1972), already stated. The stability index (S.I) is defined for successive equal increments of alternating fields of 5mT. During the successive demagnetization, the field at which S.I. is maximum is chosen as the most suitable cleaning field. All site specimens were then demagnetized with a field 10mT below and above this chosen field. The field which then gave the smallest α_{95} (radius of cone of confidence) is selected finally as the true site cleaning field. All further samples of the site were cleaned and their magnetism measured at this field. In some sites, a single field suitable for all site specimens could not be found. Most of the specimens then required full step by step demagnetization before an end point could be identified. In addition, it was necessary to discard a number of specimens which behaved erratically either by not giving a distinct grouped end direction on the stereo nets, decay curves, or stability index curves. In such cases, the specimens were subjected to Watson's (1956) test for randomness at 5% significant level before discarding.

Examination of polished and thin sections of site representative specimens under the reflected and the transmitted light respectively in a microscope was undertaken to facilitate identification of grains

responsible for the magnetism in the rock units. For this purpose, one specimen from each site of every rock formation was selected for reflected light examination while three to four thin sections were used for transmitted light analysis from every rock unit.

3.3.0. Instrumentation

The general operational modes of the basic measurement equipments used in the analysis are detailed below.

3.3.1 Spinner Magnetometer

Measurement of intensity and direction of the Natural remanent magnetization of each of the specimens at all steps of demagnetization was done using a 5 Hz Foster (1966) spinner magnetometer. A spinner magnetometer or a rock generator operates on the principle that a magnetic moment rotating within a coil about an axis in the plane of the coil will produce an alternating electromagnetic force whose amplitude and phase can be detected and measured.

Two reference signals separated by 90° ("in phase" and "quadrature") are generated by means of a light beam and photocell and the phase of the alternating e.m.f. measured with respect to these signals by means of a phase sensitive detector. The fundamental limitation of the sensitivity of spinner magnetometer is the thermal noise

in the pick up coils discussed by Johnson (1938). This is reduced by use of band pass filters.

Most shaft spinners operate at frequency between 5-100 Hz and in Foster (1966) type, it is possible to measure varying magnetic field strengths from steady fields to a low value. In spinner magnetometers, the component of magnetic moment in a plane at right angles and perpendicular to the spin axis are measured. This is done by spinning a specimen about 3 axes X,Y,Z whereby the three components are then measured. Generally a procedure involving six spins is used. In the spinner magnetometer used, it is difficult to measure samples with intensities less than 10^{-7} emu/cm³ whereas it is relatively simple to measure intensities above 10^{-6} emu/cm³, because of the design of pick up coils and amplifier sensitivity.

3.3.2. A.f. demagnetization

Analysis of the relaxation spectrum of individual specimens or isolation of components of long relaxation times is undertaken by subjection of specimens to alternating magnetic fields. Alternating field demagnetization is carried out by passing an alternating current through a coil, thereby producing an alternating field along its axis. It employs the principle that if a rock specimen is placed in an alternating field with peak value H , then all domains with coercive force less than

$H \cos \theta$, where θ is the angle between the domain coercive force and H , will follow the field as it alternates.

If the alternating field can be applied to all domain orientations, then as the alternating field is slowly decreased to zero, domains with progressively lower coercive force become fixed or blocked in different orientations, and hence ultimately, all domains with coercive force less than the applied field will be randomized. This assumes a weaker coercive force spectra for secondary magnetizations if they are to be cleaned and the primary remanence, assumed to have longer relaxation times be isolated.

The technique of alternating field demagnetization was first carried out on a routine basis by As (1957) where a specimen was demagnetized three times along three perpendicular axes at progressively higher peak alternating fields. Modifications have been made by Creer (1959) for a two axis tumbler but the type used in this analysis is that employed by Doell and Cox (1967). It has a more elaborate three-axis tumbling device. The specimen to be demagnetized was rotated about three axes in a field free space simultaneously and at the same time, the alternating field peak intensity was reduced gradually to zero thereby randomizing domains with coercive force equal to or less than it.

The remanent magnetization was then measured and the

process repeated with progressively higher alternating demagnetization fields in steps of 5mT. When the direction of the remanent magnetization was observed constant, or with very little change during further process of progressive demagnetization, it was assumed that almost all unstable secondary magnetizations had been 'cleaned' off. In case of a site with more than one specimen available, the field which gave the best precision within the site was defined as the 'optimum' field for that particular site. Field compensation is attained in an a.f demagnetizer by making use of two pairs of Hemholtz coils to automatically cancel components of the earth's field and its diurnal variations.

3.3.3. The Polarizing Microscope

The polarizing microscope is widely employed to examine transparent minerals. The optical properties of the different minerals are revealed with the aid of polarized light and identification of common minerals easily accomplished. It is extensively used to examine mineral fragments, rock grains and other crystalline aggregates and is particularly useful in the determination of the optical properties of individual crystals or aggregates and in the interpretation of textures, structures, and growth patterns. Several polarizing microscopes exist but the one used in this analysis is the Zetopan research and polarizing laboratory microscope. It

utilizes two polars with polarizing planes at right angles (X Nicols). Other distinctive features are the polarizing and analyzing devices, the amici-Betrand lens and several accessories including a compensator.

Useful magnifications with the polarizing microscope are frequently low, on the order of x30 or even less. At the other extreme, magnifications of x 1800 or thereabouts may be obtained if required. Various properties of a rock that can be observed include colour, shape or form, cleavage, refractive index and anisotropism. For polished surfaces, or polished thin sections containing metallic minerals, reflected light was used. This is because most metallic minerals are opaque and can therefore be examined to advantage in reflected light. This is accomplished through the attachment of a vertical illuminator above the microscope objective. Light from the vertical illuminator is reflected downward to the mineral surface, then reflected upward through the reflecting glass plate arrangement along the tube of the microscope to the eye.

In order to obtain photomicrographs of the grains, a camera designed for polaroid land film was fastened to the microscope and a viewing lens attached to the side of the tube. The assembly was arranged to fit the tube of the microscope above the ocular and the quality of illumination, focus, exposure and the area of photography set before shooting the photographs. In general the photomicrographs of thin sections were taken at low

magnifications to avoid interference of the depth of the thin section with the focus at higher magnifications.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1.0. Results

4.1.1. Limuru Trachytes

The paleomagnetic results of five sites of the Limuru trachytes, sites (12-16), are tabulated in Table 2. One specimen for every site was demagnetized fully in steps of 5 mT in order to determine the cleaning field for each site.

The characteristic stability index (SI) curves for pilot specimens of each site are plotted in Fig. 2(a). The optimum field deduced from these curves using Briden's (1972) criteria varied between 25-35 mT for the Limuru trachytes. The SI curves illustrated by pilot specimens LT 4 - 162 and LT 5 - 182 indicate stable N.R.M up to about 60 mT field of demagnetization. The SI curves for the remaining specimens tend to oscillate mainly after 30 mT and in general, it can be concluded from Fig. 2(a) that the Limuru trachytes have remanence with low coercivity. This remanence characteristics are also depicted in Fig. 2(b) which gives a plot of directional changes of pilot specimens from the Limuru trachytes. The small directional changes for some pilot specimens indicate stable remanence while the large changes in magnetic

TABLE 2 - LIMURU TRACHYTES

ST.	N	R	<u>Before a.f. Cleaning</u>				<u>After a.f. Cleaning</u>				He	Long.	Lat.	<u>Pole Position</u>			
			D	I	K	α_{95}	R	D	I	K				α_{95}	δm	δp	Polarity
12	3	2.71	305.3	8.3	6.8	51.6	2.98	151.8	22.9	94.7	12.7	30	104.2	60.0	13.5	7.2	R
13	3	2.79	96.8	38.9	9.6	42.2	2.99	99.9	22.4	181.0	9.2	35	114.9	-9.9	9.7	5.2	I
14	5	4.44	150.1	21.5	7.1	31.0	4.82	152.8	8.1	22.3	16.5	35	119.8	-62.7	16.6	8.4	R
15	3	2.84	137.6	17.4	12.5	36.7	2.96	190.4	12.8	45.5	18.5	25	90.2	77.13	18.9	9.6	R
16	2	1.98	277.4	24.5	49.5	8.0	1.97	99.7	22.9	28.8	10.5	35	114.6	-9.7	11.2	5.9	I

He = optimum cleaning field(mT)R=Resultant magnetic vector.

ST. = site number, N = number of samples, D = declination, I = Inclination, positive down, degrees, measured from true North, degrees

K = Fisher's precision parameter, A_{95}, α_{95} = radius of circle of confidence at 95% level of significance, degrees,

Polarity = Reversed (R) or intermediate (I)

Long., Lat. = longitude (East Positive), Latitude (North positive), $\delta m, \delta p$ = semi axes of oval of confidence, degrees

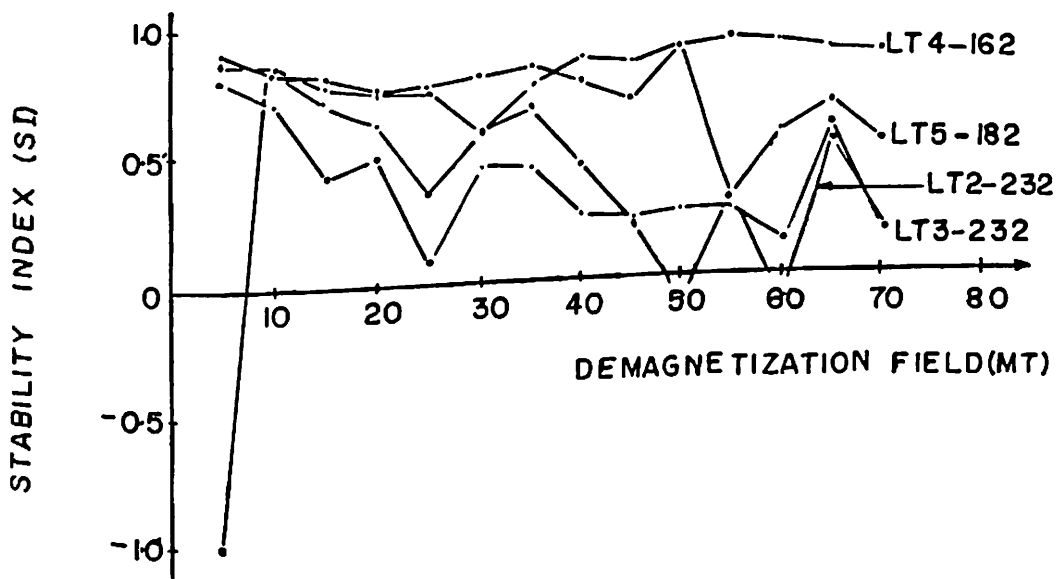
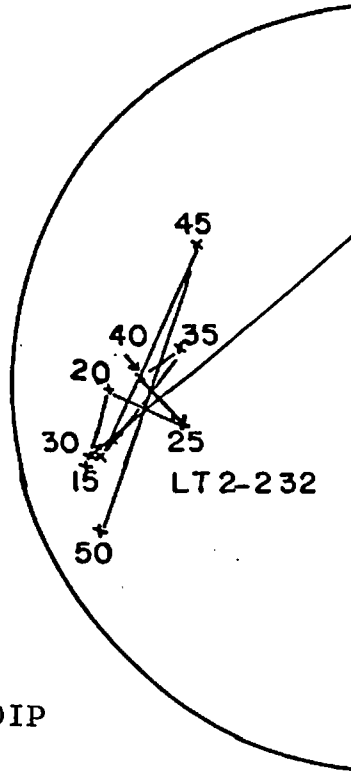


FIG. 2a: STABILITY INDEX CURVES FOR PILOT SPECIMENS OF LIMURU TRACHYTES.



- NEGATIVE DIP
- X POSITIVE DIP

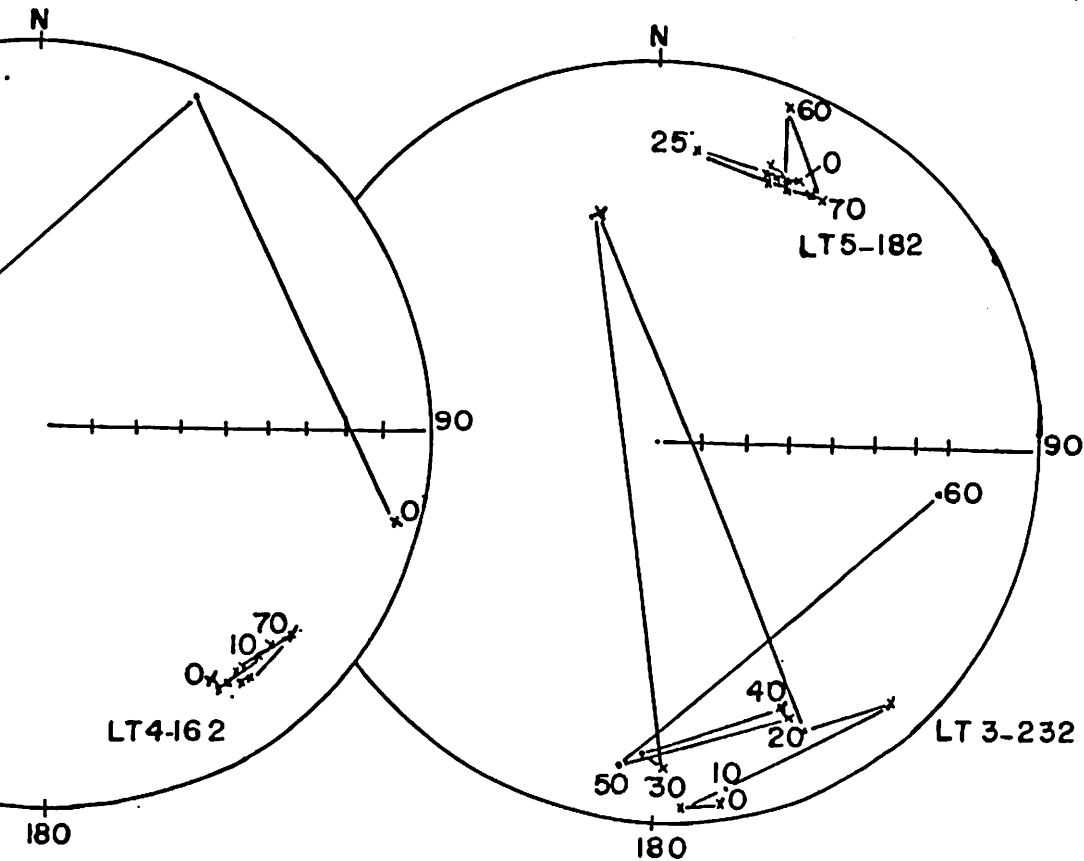


FIG2b : A PLOT OF DIRECTIONAL CHANGES OF PILOT SPECIMENS FROM THE LIMURU TRACHYTES

directions especially during the early stages of cleaning illustrates the progressive removal of secondary components of the remanence. Fig. 2(c) illustrate normalized demagnetization curves for the Limuru trachytes. The mean destructive fields, the fields required to reduce the initial intensity by 50%, for the Limuru trachytes is about 35 mT.

The plot of site directions on equal area stereo nets are given in Fig. 2(d). The total N.R.M directions before cleaning are observed to be scattered. The scatter of this directions was reduced on cleaning as reflected by the smaller values of radii of confidences, α_{95} , in Table 2 and the progressively smaller directional changes in the magnetic directions at fields close to the optimum cleaning field. These grouping of populations in all sites signify adequate cleaning of secondary components of magnetizations using a.f. techniques. The results of sites 14 and 15 could not be improved further owing to the low coercivity of the specimens and the large scatter observed within individual samples. This scatter may be attributed probably to inhomogeneous magnetizations of the samples or can be suspected to be caused by alterations due to chemical weathering of surface samples which could have produced a stable secondary component of magnetism. It has also been observed that except for site 12, the inclination vector I , becomes shallower on demagnetization.

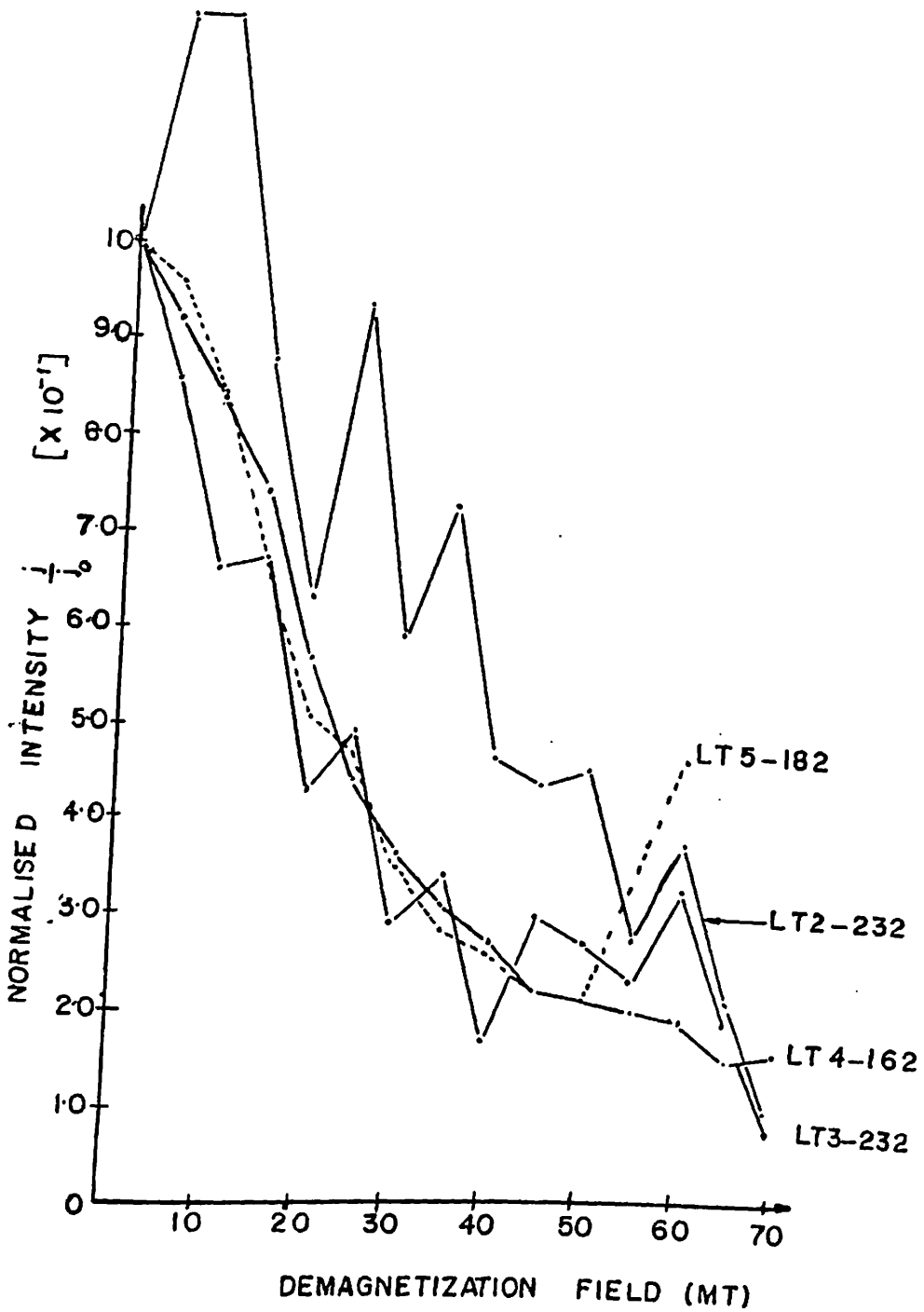


FIG. 2C: NORMALISED DEMAGNETIZATION CURVES FOR LIMURU TRACHYTES.

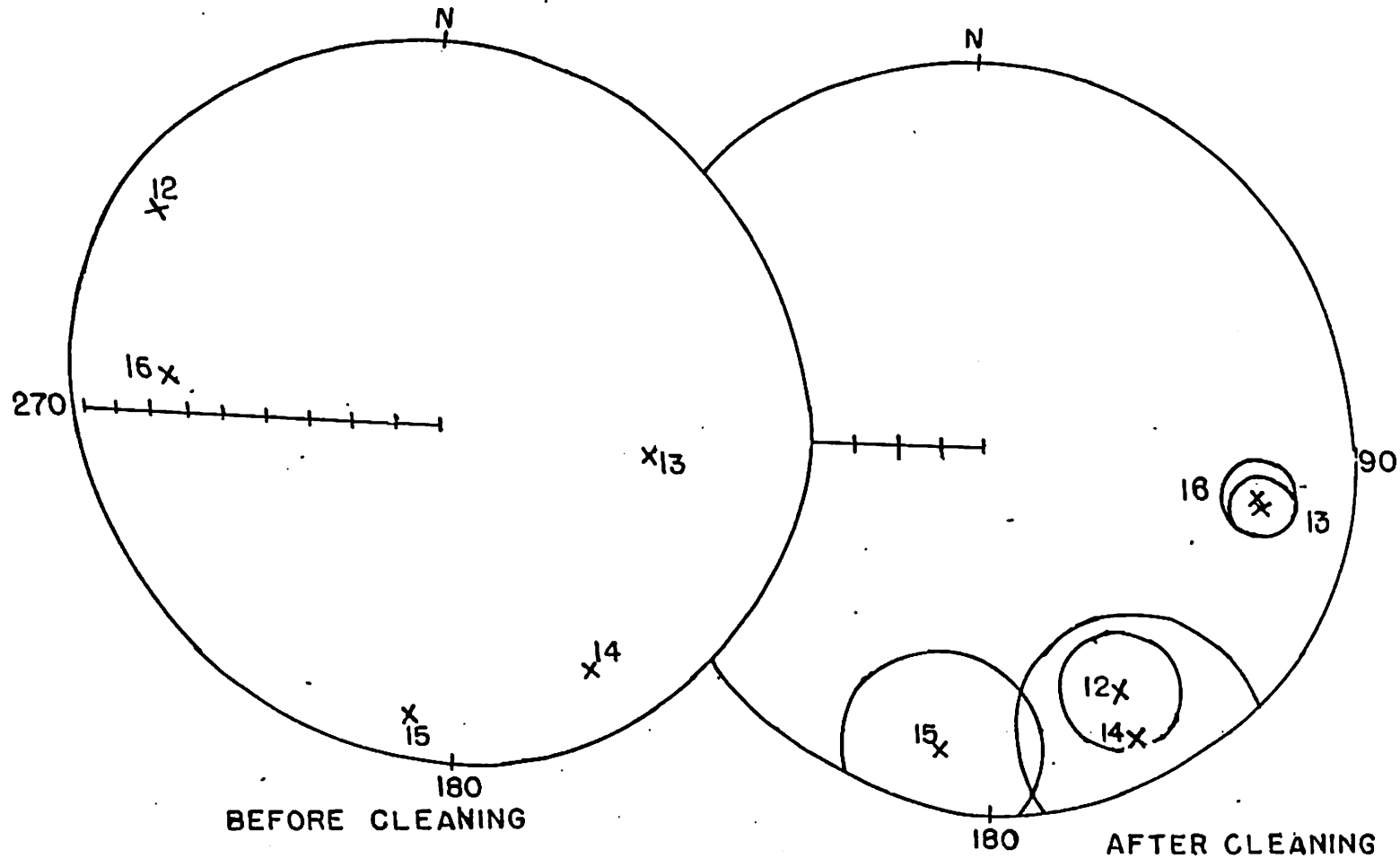


FIG 2d PLOT OF THE SITE MEAN DIRECTIONS BEFORE AND AFTER AF DEMAGNETIZATION FOR LIMURU TRACHYTES

The cleaned directions have been classified as 'intermediate' and 'reversed' according to Dagley et al. (1967). The intermediate directions may occur during the process of a magnetic field reversal. In this particular case, any direction which is not within 40° absolute from the normal or reversed direction of the dipole field is classified as intermediate. It is assumed that the rock specimens have been adequately cleaned so that the exhibited directions can not be due to remagnetization. No site from the Limuru trachytes gave a normal direction.

Similar observations have also been reported by Patel and Raja (1979a) in the case of plateau trachytes of Magadi area (aged 1.74 my) where only reversed directions were observed. Dagley et al. (1978) also reported that the Marigat trachytes (2.0 my) have only a reversed polarity.

From the sampling site, it was observed that the Lava flows of the Limuru trachytes occur in massive thickness of up to 50 m with visible intercalated sediments between the flows. The scattered cleaned magnetic directions for the sites show that the flows may have been extruded at different intervals of time. Therefore it may be concluded that the Limuru trachytes may have been formed just before the normal Gilsa event (1.70-1.60 my) when the magnetic field was in transition from reverse to normal polarity or just during the transition of the normal Gilsa

event to the reversed part of the Matuyama epoch between 1.60-0.92 my according to Heirtzler et al. (1968) polarity scale.

Sites 13 and 16 are insignificantly different by F-ratio test at 5% significant level. A similar conclusion is obtained for sites 12 and 14 while sites 14 and 15 are significantly different. All sites are non-random according to Watson's (1956) criteria of randomness at 95% probability.

The mean directions of each site of the Limuru trachytes listed in Table 2, are believed to represent a primary component of magnetization. This is because the improvement in grouping after a.f. cleaning of both site and sample directions is usually a strong evidence for an underlying stable primary direction.

The mean direction and the corresponding pole position for the trachytes, for the intermediately magnetized sites is calculated at Declination $D=99.8^\circ$ $I=22.65^\circ$ ($\alpha_{95}=1.2^\circ$) and 114.73° E, 9.82° S ($\delta_m=1.23^\circ$, $\delta_p=0.65^\circ$) and for the reversely magnetized sites at $D=171.5^\circ$ $I=14.93^\circ$ and 88.9° E, 79.3° S, respectively.

4.1.2. Nairobi Phonolites

The paleomagnetic results of the four sites of the Nairobi phonolites, sites 17 - 20, are tabulated in Table

3. One specimen for every site was demagnetized up to about 50 mT in steps of 5 mT in order to determine the cleaning field for each of the sites.

The characteristic stability index (SI) curves for each pilot specimen are plotted in Fig. 3(a). The optimum field deduced from these curves using Briden's (1972) criteria varied between 25 - 35 mT for different sites of the phonolites. The curves illustrated by NP 2 - 251 and NP 1 - 552 indicated stable N.R.M throughout their demagnetization range. This stable N.R.M is inferred from the plots of the directional changes in Fig. 3(b) of the specimens which show good grouping of the directions at demagnetization fields between 5 - 50 mT. The SI curve for the specimen NP 4 - 451 tends to oscillate about an apparent mean value between 0.5 - 0.8.

The demagnetization decay curves are illustrated in Fig. 3(c) from which it is deduced that the mean destructive fields (Mdfs) for the Nairobi phonolites ranges between 25 - 40 mT. The magnetic intensity of the phonolites rises initially above the intensity of the virgin specimens between 5 - 15 mT fields of demagnetization. This behaviour is suspected to be caused by a large secondary component of low coercivity, aligned in opposition to the primary magnetic component. Most viscous magnetizations appear to have been well cleaned after about 15 mT after which the intensity decay is generally non-oscillatory.

TABLE 3 - NAIROBI PHONOLITES

ST.	<u>Before a.f. Cleaning</u>						<u>After a.f. Cleaning</u>						<u>Pole Position</u>				Polarity
	N	R	D	I	K	α_{95}	R	D	I	K	α_{95}	He	Long.	Lat.	δm	δp	
17	2	1.97	170.3	15.9	30.8	46.7	1.998	171.8	2.95	468.1	11.57	25	125.9	-81.3	11.6	5.8	R
18	2	1.95	162.7	2.6	19.4	60.21	1.992	167.4	2.14	131.0	22.0	25	128.0	-77.4	22.0	11.0	R
19	3	2.2	234.98	15.02	2.5	105.2	2.96	274.04	5.37	52.5	17.2	25	124.3	-4.1	17.3	8.7	I
20	3	2.78	43.3	28.5	9.1	43.5	2.93	228.04	-5.2	26.7	24.3	35	129.5	42.0	24.4	12.2	I

(Symbols same as in Table 2)

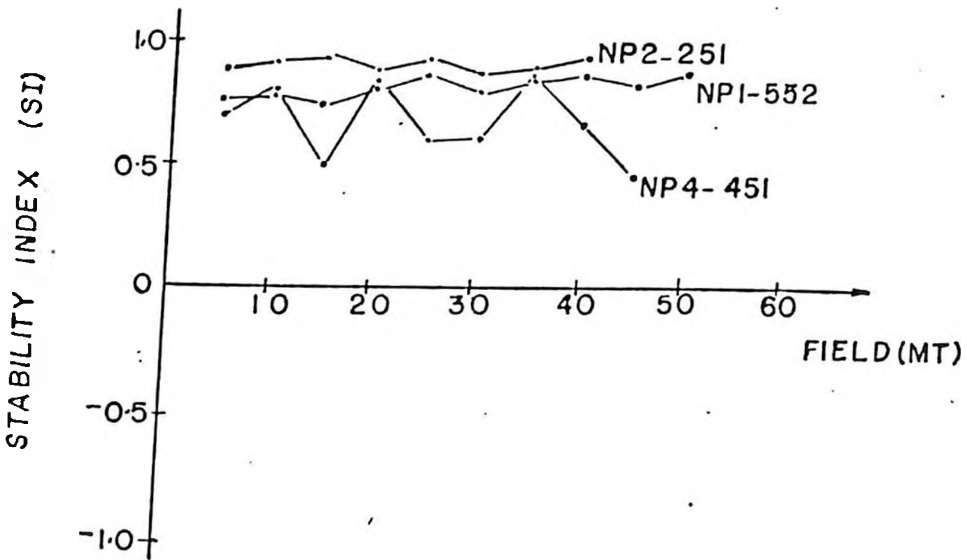


FIG. 3a: STABILITY INDEX CURVES FOR PILOT SPECIMENS OF NAIROBI PHONOLITES.

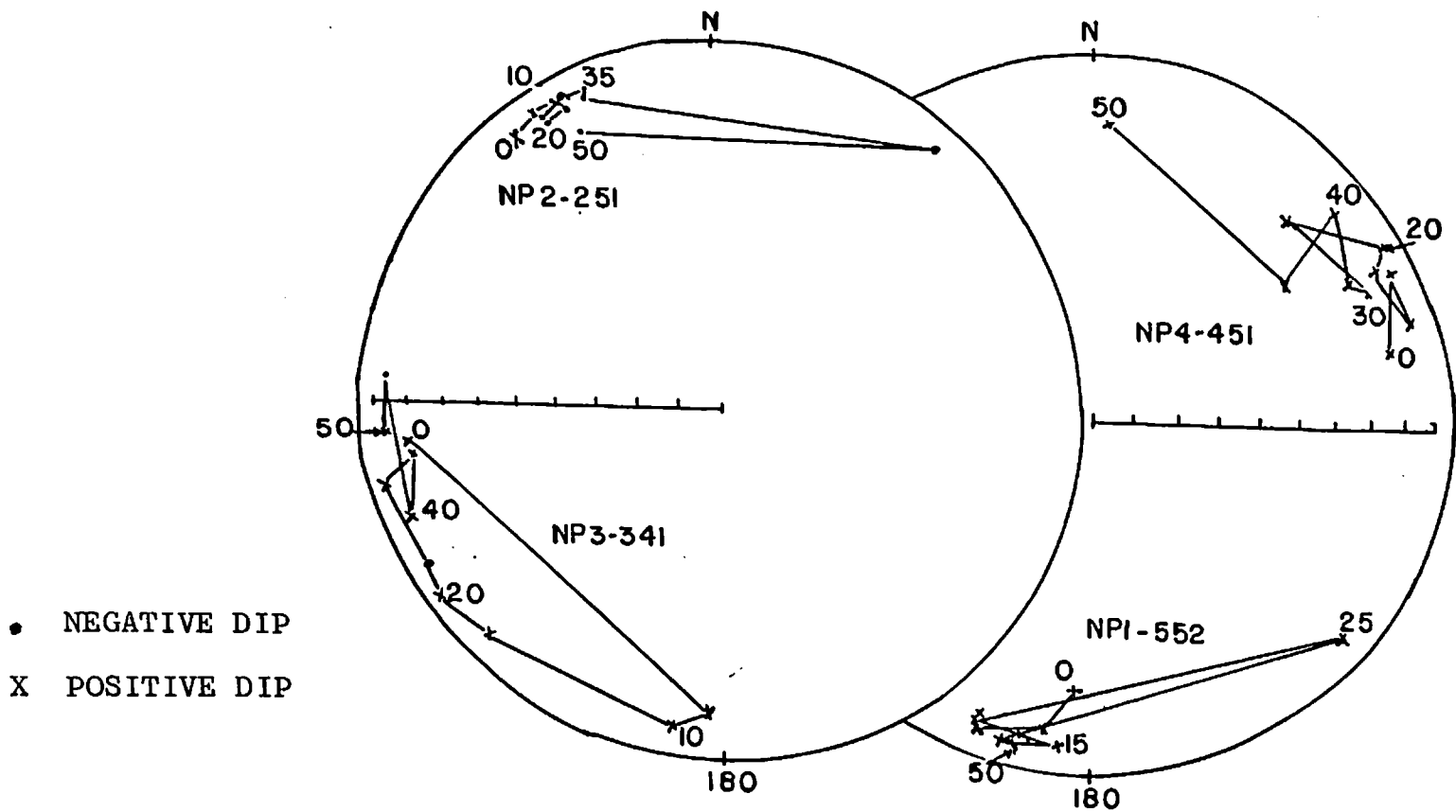


FIG 3b PLOT OF DIRECTIONAL CHANGES OF PILOT SPECIMENS FROM NAIROBI PHONOLITES

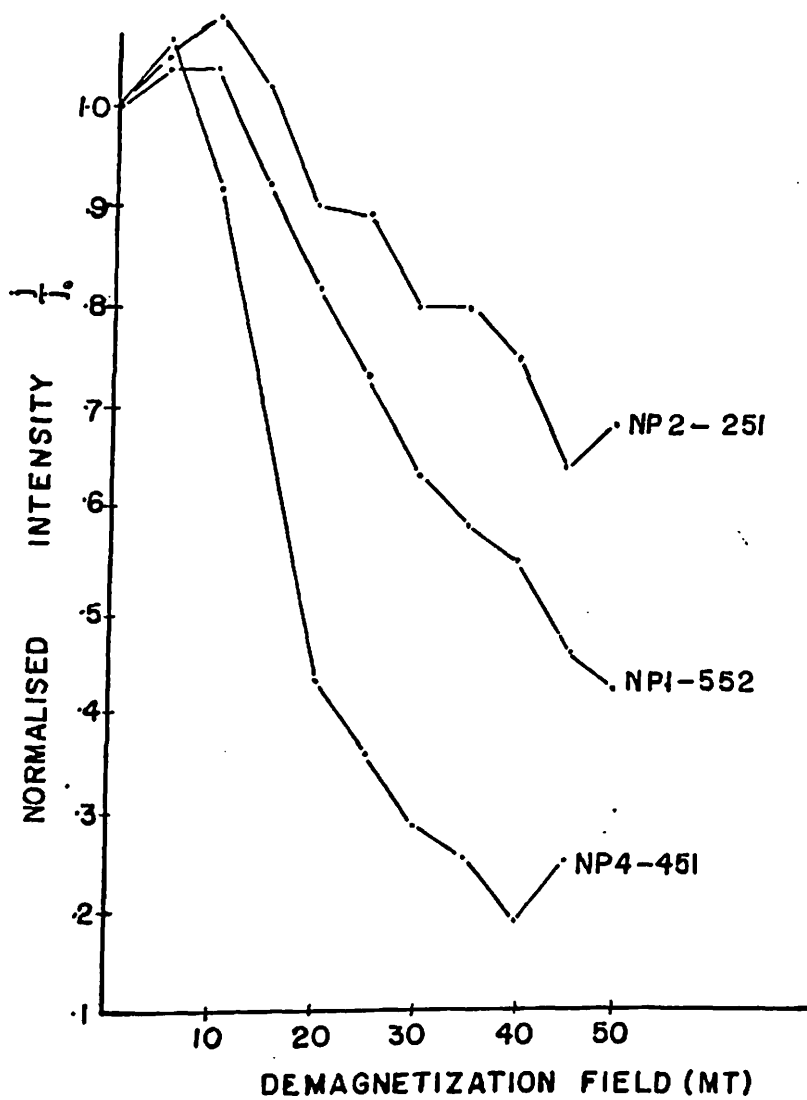


FIG. 3C: NORMALISED DEMAGNETIZATION CURVES FOR
PILOT SPECIMENS OF NAIROBI PHONOLITES.

The site mean directions before and after a.f. demagnetization given in Table 3 are plotted on equal area stereo nets in Fig. 3(d). The total N.R.M directions are observed to be randomly scattered on the net for the virgin samples. The scatter of these directions is reduced on a.f. cleaning as reflected by the significant increase in the values of the precision parameter k , after a.f. treatment although the results of sites 18 and 19 could not be improved further owing to the large scatter observed within their samples. It was also observed that the inclination vector I , for all sites became shallower on demagnetization, a similar observation as that made for the Limuru trachytes.

The cleaned directions have been classified as 'intermediate' or 'reversed' such as sometimes occur in sequences of lava flows (Dagley et al. 1967). It is generally assumed that intermediate directions occur during the process of a magnetic reversal.

Sites 17 and 18 have accordingly been classified as reversed while sites 19 and 20 are intermediate. No site samples from the Nairobi phonolites gave a normal direction. These results appear in accord to the deduced polarity of the Kirikiti basalts, dated 5.1. my (Baker, 1958) whose polarity has been published by Patel (1977).

From the sampling sites, the phonolites are known to occur in massive thickness of up to 100 m (Sikes, 1939).

- NEGATIVE DIP
- X POSITIVE DIP

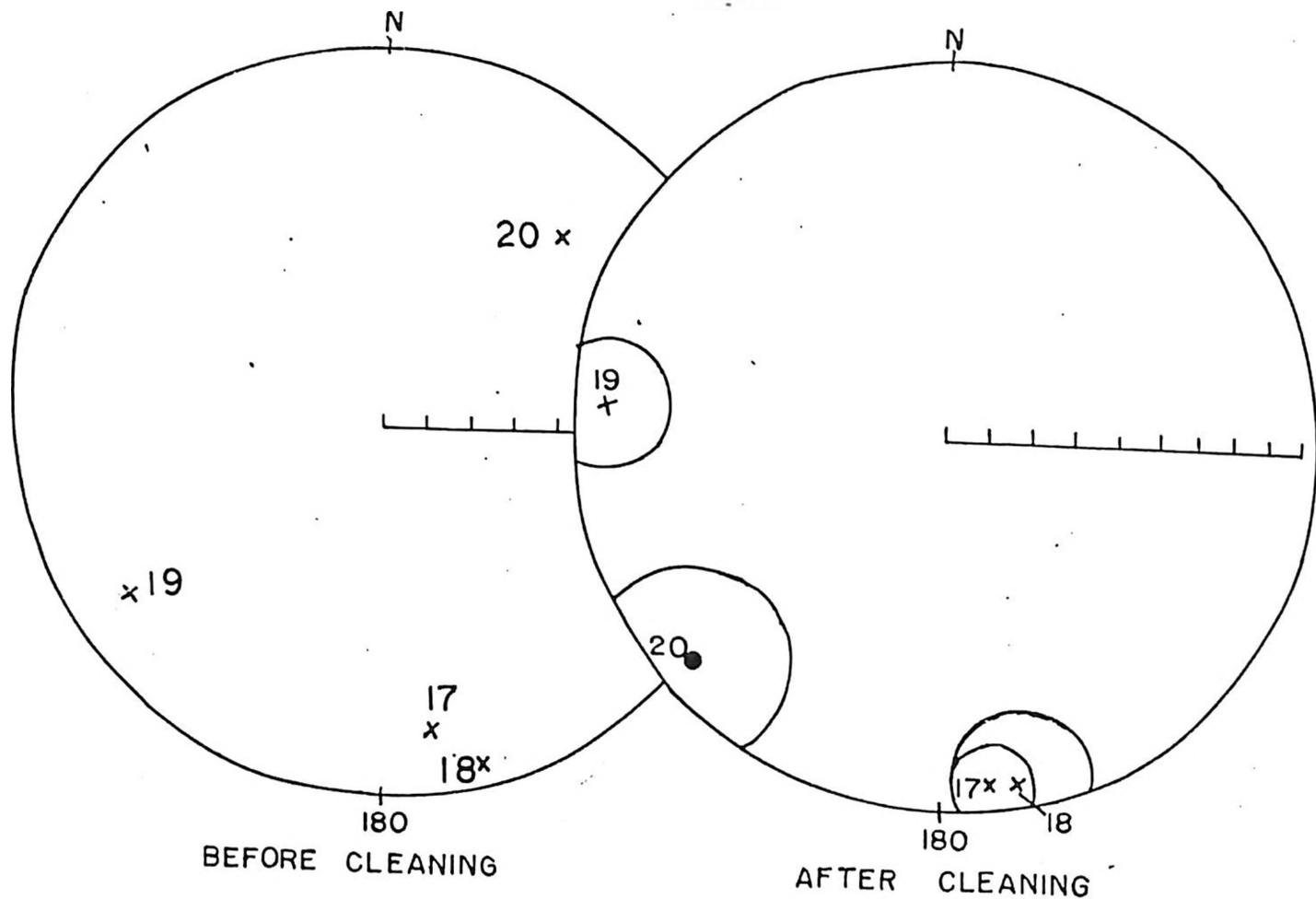


FIG 3d

PLOT OF THE SITE MEAN DIRECTIONS BEFORE AND AFTER CLEANING FOR NAIROBI PHONOLITES.

The directions obtained for the sampled sites may therefore represent those of multiple flows. Similar scatter in directions has also been reported for Kapiti phonolites by Patel and Gachii (1972).

All sites were non-random according to Watson's (1956) criteria of randomness at 95% probability. The directions and circles of confidences of sites 17 and 18 overlap suggesting that the two sets of results may be combined. Subjection to the F-ratio test concluded that the two sites are not significantly different at 5% level of significance and are therefore combined to yield a reversed direction. Sites 19 and 20 both gave intermediate directions.

The site mean directions used were obtained by averaging the sample mean directions of the site. Then a unit weight was assigned to the site mean direction in the evaluation of the mean direction of the rock unit. The paleomagnetic pole for each site was evaluated using the site mean direction. The average of the site mean directions yielded the mean paleomagnetic pole for the rock unit.

The mean direction and corresponding pole for the reversely magnetized sites is calculated at declination $D=169.6^\circ$, inclination, $I = 2.5^\circ$ ($\alpha_{95} = 9.6^\circ$) and longitude 127.3° E, latitude 79.6° S with errors ($\delta m = 9.6^\circ$, $\delta p = 4.8^\circ$) and for the intermediately

magnetized sites at $D=251.0^\circ$, $I = 0.1^\circ$ and longitude 126.49° E, latitude 18.9° S, respectively.

4.1.3. Ngong Basalts

A total of 20 samples of the Ngong basalts were collected from six sites, sites 6 - 11. The location of this sampling position is shown in Map 1. The site mean directions before and after a.f. demagnetization are given in Table 4.

At least one specimen from each site was fully demagnetized in steps of 5 mT in order to determine the site cleaning fields. The optimum field deduced from the stability index (SI) curves in Fig. 4(a) varies between 20 - 35 mT. All the SI curves show high stability of the natural remanence which initially rises from about 0.5 to 0.9 within their mean destructive fields (Mdfs) of between 20 - 40 mT. This phenomena is also exhibited in Fig. 4(b) of plot of directional changes of the pilot specimens where apart from the initial large variations at fields up to 20 mT, a noticeable grouping of the directions is evident. This indicates that most secondary components of magnetism has been cleaned.

The inference of high stability of the natural remanence of the Ngong basalts from Fig. 4(a) is also exhibited by the intensity demagnetization curves in Fig. 4(c). These demagnetization curves show varied

TABLE 4 - NGONG BASALTS

ST.	<u>Before a.f. Cleaning</u>						<u>After a.f. Cleaning</u>						<u>Pole Position</u>						
	N	R	D	I	K	α_{95}	R	D	I	K	α_{95}	He	Long.	Lat.	δm	δp	A_{95}	PLTY.	
6	3	2.51	248.0	20.7	4.1	70.5	2.96	83.6	1.64	46.9	18.4	35	125.7	6.4	18.4	9.2	-	I	
7	3	2.82	244.1	-7.4	10.9	39.2	2.85	74.2	-21.6	13.4	35.2	35	137.9	15.8	37.1	19.3	-	I	
8	2	1.997	244.5	-10.3	332.5	13.7	1.99	82.9	21.6	115.9	23.4	25	115.4	14.7	29.2	15.3	-	I	
9	4	1.86	217.9	67.2	1.4	154.0	3.75	74.8	20.4	11.9	27.8	25	136.9	-16.4	29.8	15.5	-	I	
10	5	4.29	129.2	-18.3	5.6	35.5	4.51	106.9	-18.2	8.1	28.7	30	115.3	6.7	24.7	13.0	-	I	
11	3	2.97	285.3	7.0	59.5	16.1	2.95	112.3	14.8	36.8	20.6	20	119.2	-22.3	21.1	10.8	-	I	
Mean							4.6	84.5	0.8	11.31	23.8		125.0	0.93				16.2	

(Symbols same as in table 2).

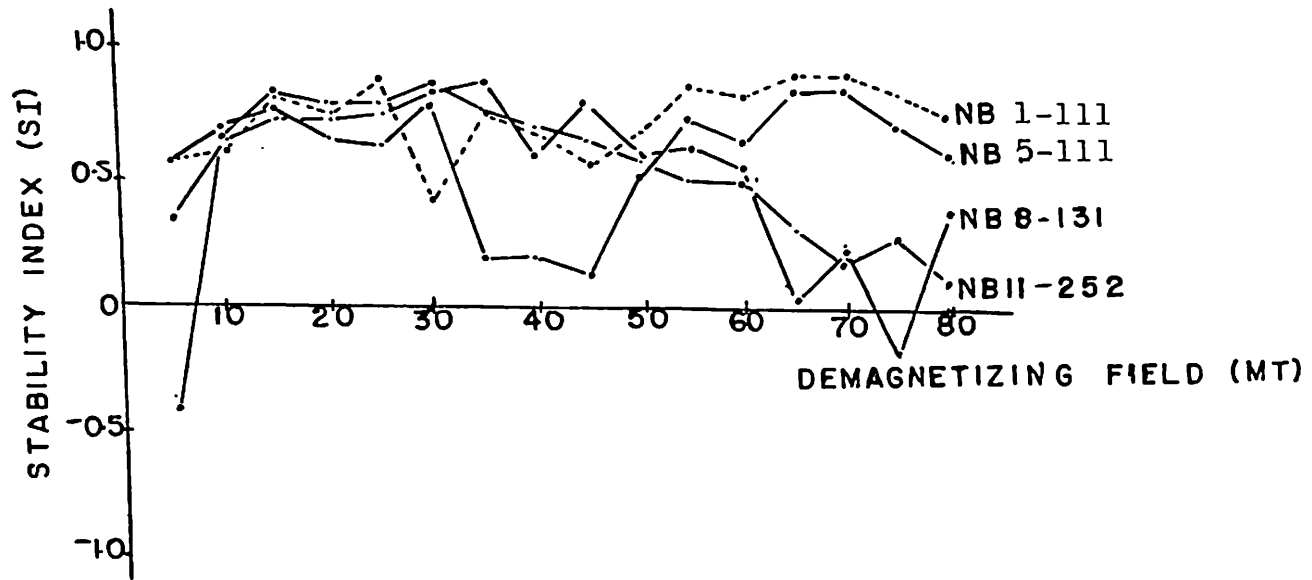


FIG. 4a: STABILITY INDEX CURVES FOR PILOT SPECIMENS OF NGONG BASALTS.

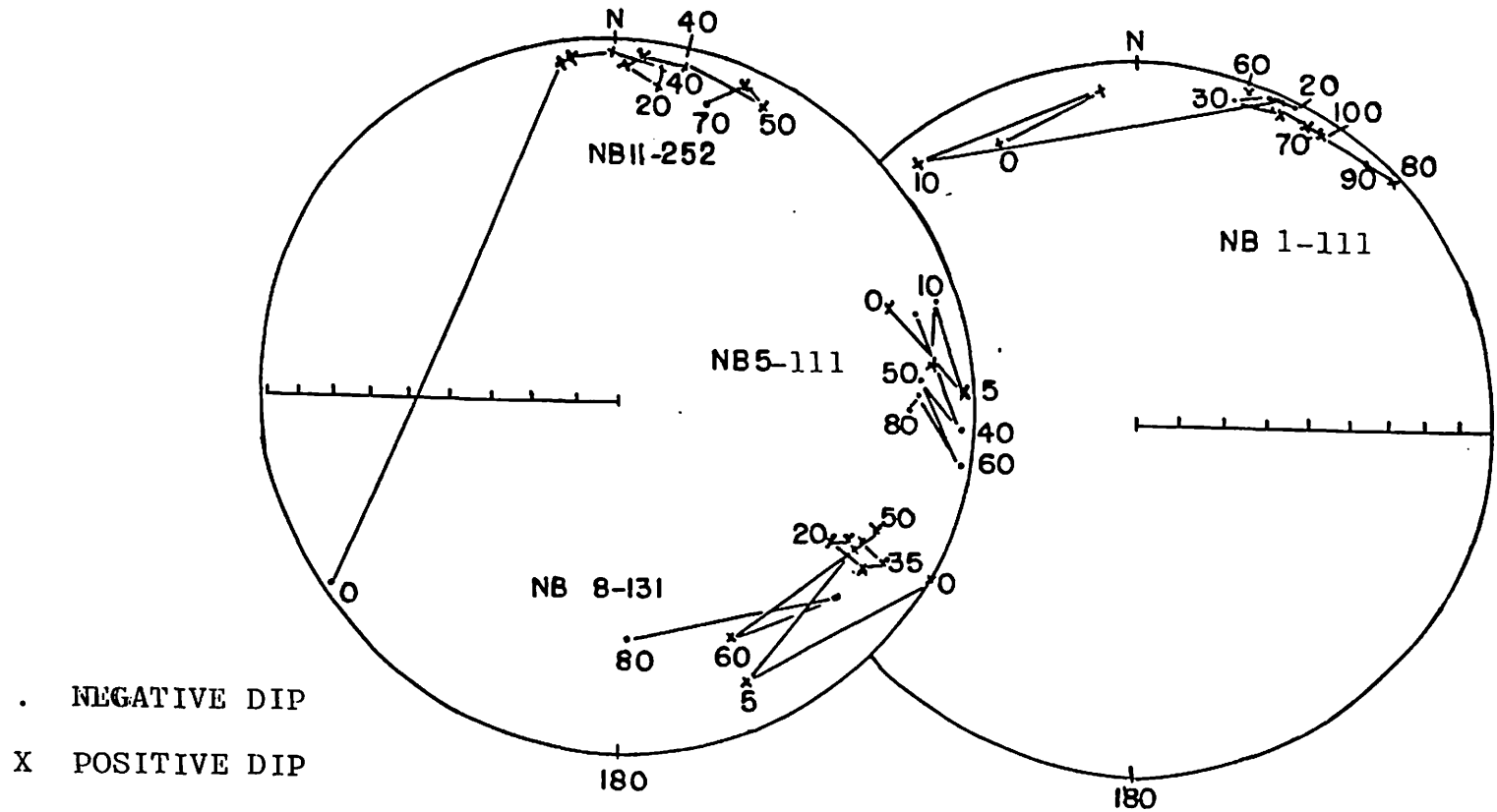


FIG 4b PLOT OF DIRECTIONAL CHANGES OF PILOT SPECIMENS FROM NGONG BASALTS

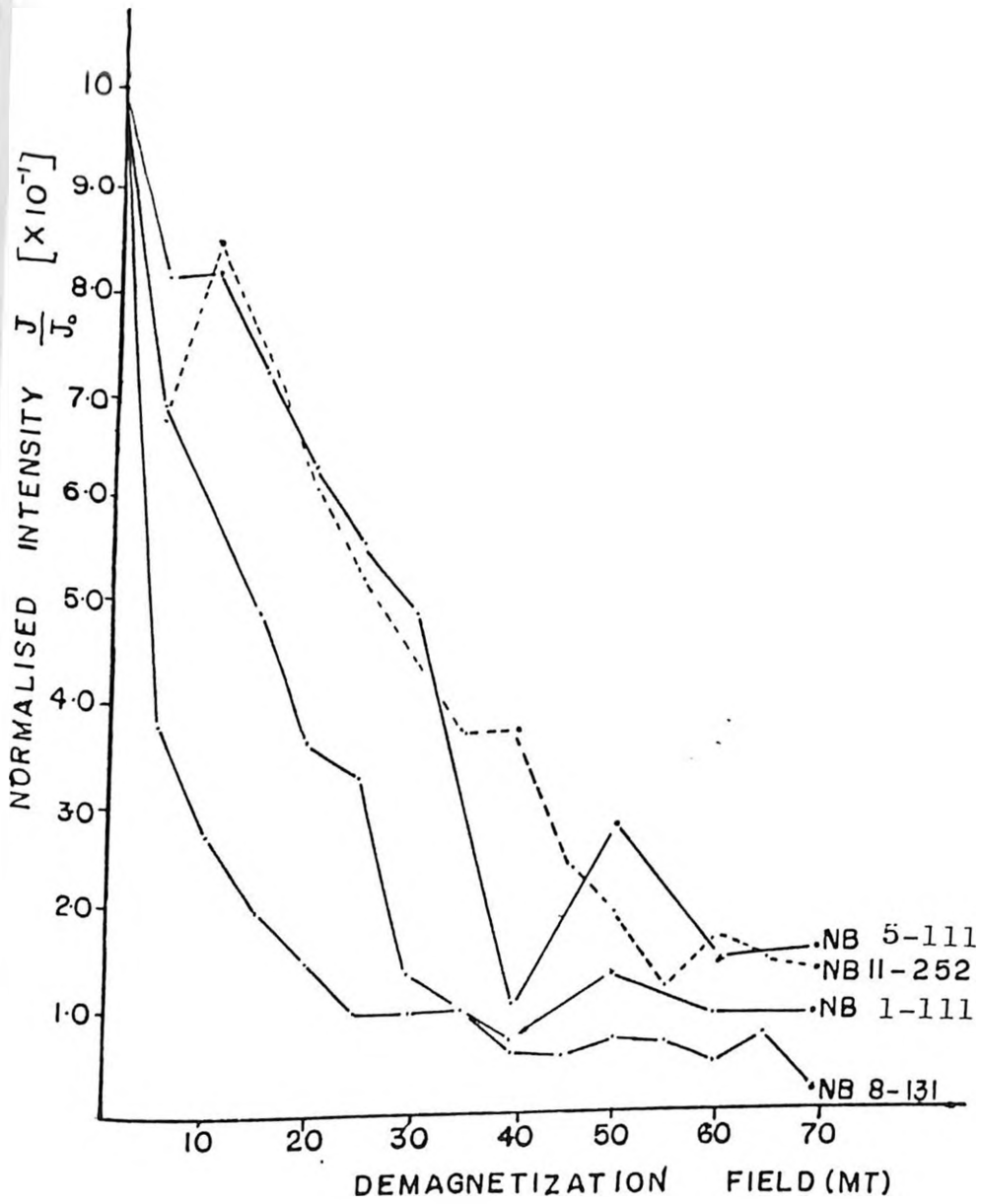


FIG. 4C: NORMALISED DEMAGNETIZATION CURVES FOR PILOT SPECIMENS OF NGONG BASALTS.

characteristics for the specimens with NB1- 511 and NB 11 - 252 having a much higher mean destructive fields than specimens NB 1-111 and NB 8 - 131. This large variation in the mean destructive fields indicate that the specimens of the Ngong basalts have a wide range of coercivities, the highest illustrated by the intensity decay curve representing NB 11 - 252 in Fig. 4(c).

The site mean remanent directions before and after a.f. demagnetization given in Table 4, are plotted on the equal area stereo nets in Fig. 4(d). The directions are distributed randomly before a.f. cleaning while a noticeable clustering of mean sample directions is apparent after a.f. cleaning. Significant increase in values of k , the estimate of Fisher's (1953) precision parameter with corresponding reduction of α_{95} , the radius of circle of confidence of 95% level of significance is evidence of adequate cleaning of secondary components of magnetizations using a.f. technique.

The cleaned directions have all been subjected to Watson's (1956) test for randomness at 95% probability and none has been excluded from the final analysis on this criteria. The cleaned directions have accordingly been classified as intermediate according to Dagley et al. (1967). No normal or reversed direction has been observed from the sampled sites of the Ngong basalts.

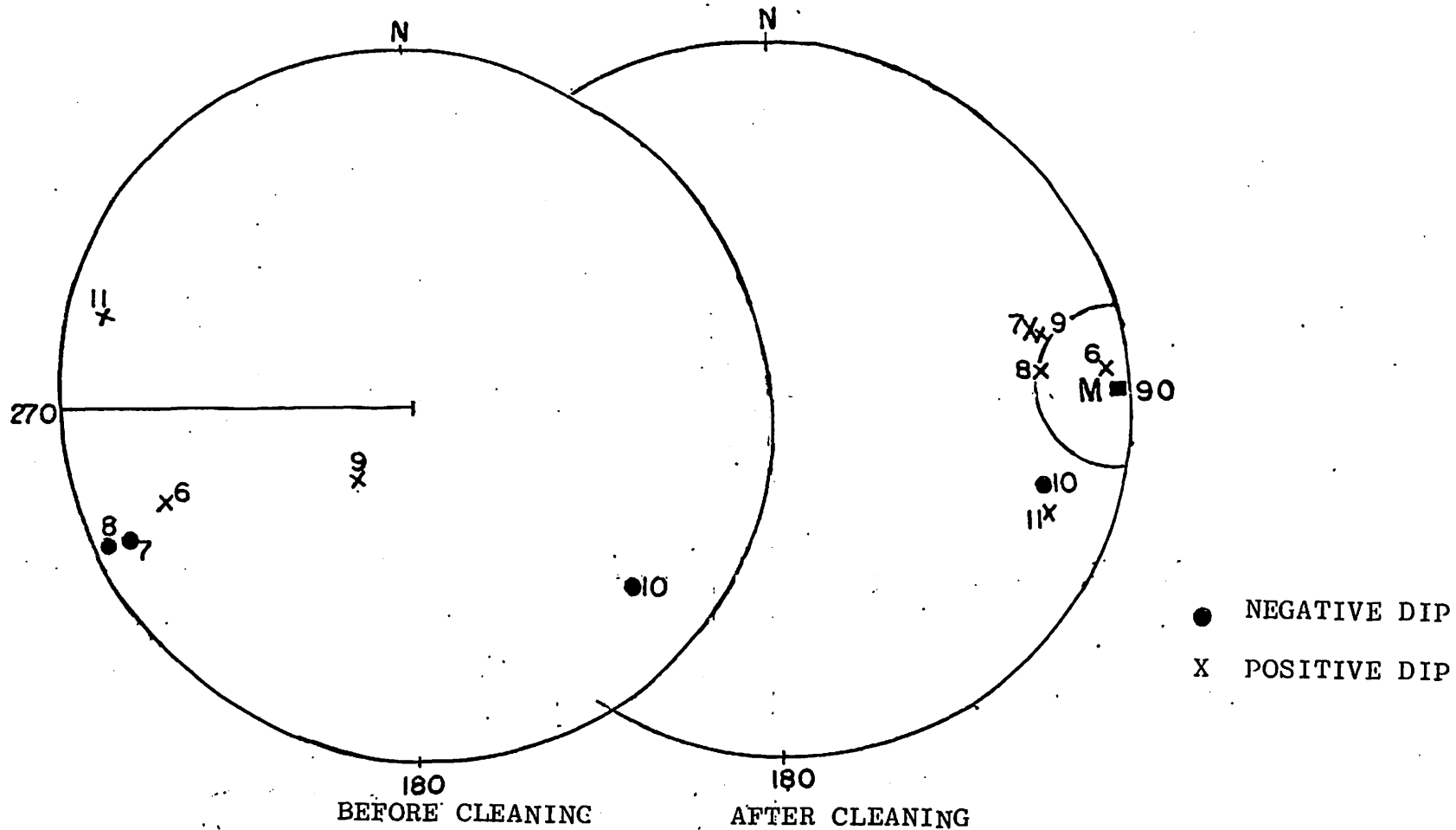


FIG 4d : PLOT OF THE SITE MEAN DIRECTIONS BEFORE AND AFTER A.F. DEMAGNETIZATION FOR NGONG BASALTS. THE FORMATION MEAN (M) IS ALSO SHOWN .

These results are similar to those obtained for the Kirikiti basalts (Patel, 1977) dated 5.1. my by Baker (1958) where normal and intermediate polarities were observed. In addition, the obtained directional results for the Ngong basalts are also similar to those already discussed for the Nairobi phonolites.

While sampling, it was noted that the basalts occur in massive thickness over the Ngong hills and the surrounding areas. Sampling for sites 6, 7 was done on the eastern side of the hills while sites 8 - 11 were sampled on the western side of the Ngong hills with site 8 at the bottom rising to site 11 at the top of the hill. From this observation, the significant but scattered cleaned mean directions of the sites of the Ngong basalts can be assumed to represent different flows which must have been extruded at different times.

The directions and circles of confidences of sites 10 and 11 overlap and the F-ratio test at 5% level of significance show that they are insignificantly different suggesting the two results are the same. Similar conclusion is obtained in regard to sites 8 and 9. All the remaining sites are significantly different.

An overall mean direction, declination $D=84.5^{\circ}$, inclination $I=0.8^{\circ}$ ($\alpha_{95} = 23.8^{\circ}$) has been calculated from the directions of the six sites (cf. Table 4). The paleomagnetic pole is calculated by two methods. A single

pole with an oval of confidence is obtained at 126.2°E , 5.5°N ($\delta\text{m}=23.8^{\circ}$, $\delta\text{p}=11.9^{\circ}$) from the mean of the site directions. The other pole with a circle of confidence is obtained at 125.0°E , 0.93°N ($A_{95} = 16.2^{\circ}$) from the average of site poles listed in Table 4. The mean paleomagnetic pole, computed from the site poles was preferred since the number of sites exceeds two and were geographically widespread.

These results are believed to represent a good estimate of the mean field direction and paleomagnetic pole for the sampled parts of the Ngong basalts because of the improvement in grouping of both sample and site directions after the alternating field cleaning. Sampling was carried out over a large area, thus averaging out possible errors due to secular variations.

4.1.4. Mbagathi Phonolitic Trachytes

Seventeen block samples of the Mbagathi phonolitic trachytes were collected from sites 1-5 shown in Map 1. At least one pilot specimen for every site was demagnetized fully in steps of 5 mT in order to determine the cleaning field for the rest of the specimens of the site.

Table 5 gives the mean site directions before and after a.f. demagnetization. In the analysis site means were calculated giving unit weight to the samples. The

TABLE 5 - MBAGATHI PHONOLITIC TRACHYTES

ST.	Before a.f. Cleaning.						After a.f. Cleaning						Pole Position				
	N	R	D	I	K	α_{95}	R	D	I	K	α_{95}	He	Long.	Lat.	δm	δp	Polarity
1	3	2.83	60.11	38.3	12.0	37.2	2.97	71.6	43.6	63.0	15.6	30	153.1	-19.2	19.5	12.1	I
2	3	2.61	145.8	30.8	5.15	61.1	2.96	143.8	31.3	49.7	17.7	35	101.1	-51.1	19.8	11.1	R
3	3	2.66	265.7	37.5	5.9	56.1	2.99	75.6	36.3	146.0	10.2	20	147.2	-14.0	11.9	6.9	I
4	4	2.85	73.4	36.8	2.6	71.5	3.89	145.6	13.8	27.5	17.8	40	116.5	-55.3	18.2	9.3	R
5	4	2.85	132.6	40.4	2.61	72.1	3.84	164.1	26.7	18.2	22.1	45	87.0	-69.8	24.0	13.0	R

(Symbols same as in table 2).

pole for each site was calculated from the site mean directions and the overall pole for the formation deduced from the mean of directions of significant sites using Fisher (1953) statistics.

The stability index (SI) curves for the pilot specimens from sites of the Mbagathi phonolitic trachytes are given in Fig. 5(a). The curves show an initial rise in stability with oscillation about an average value of 0.8. The SI curves also show large directional changes in fields greater than 60 mT probably due to induced rotational remanent magnetism discussed by Wilson and Lomax (1972). Typical variations in magnetic directions of the pilot specimens at various demagnetization steps are shown in Fig. 5(b). The viscous component of magnetization appears to have been removed after 10 mT and the changes in magnetic directions after this field become small indicating progressive clustering of the directions. The hard component of magnetization, the primary remanence seems to be of small magnitude and remains fairly stable after 25 mT with small fluctuations about a constant average value.

Typical a.f. demagnetization curves of the pilot specimen from significant sites are illustrated in Fig. 5(c). The decay curves indicate possession of generally low coercivities for the Mbagathi phonolitic trachytes. About 50% of the magnetic intensity of the natural

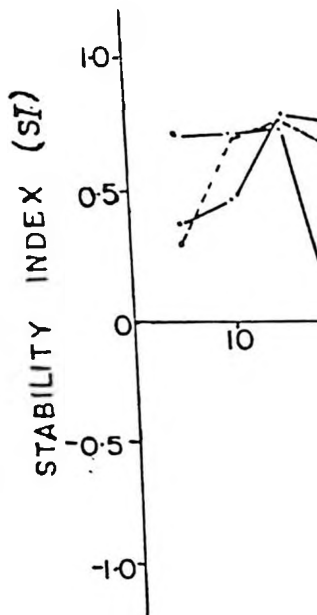
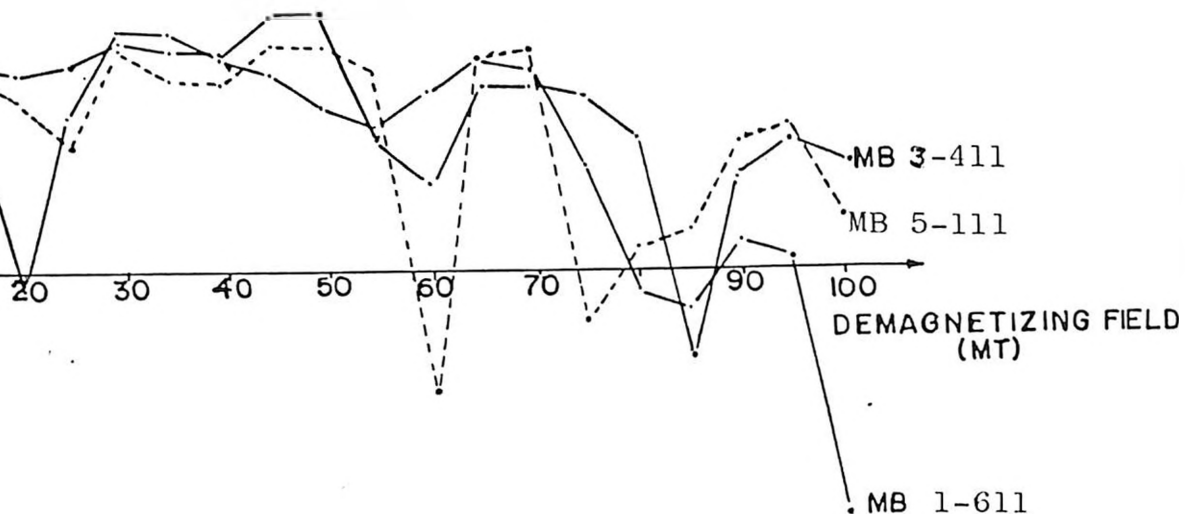
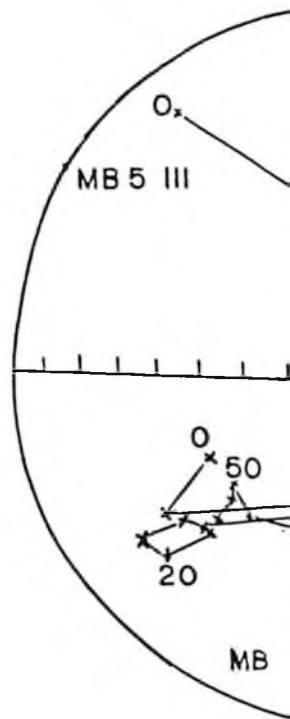


FIG. 5a:



STABILITY INDEX CURVES FOR PILOT SPECIMEN OF MBAGATHI PHONOLITIC TRACHYTES.



- NEGATIVE DIP
- X POSITIVE DIP

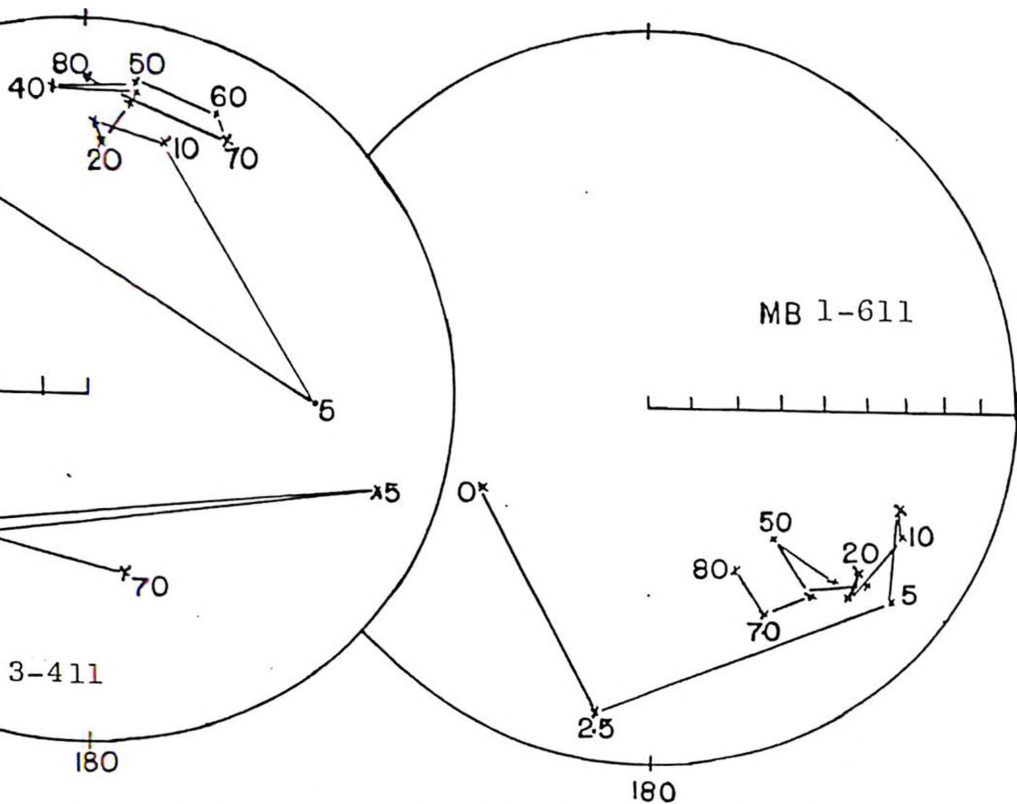


FIG 5b : A PLOT OF DIRECTIONAL CHANGES OF PILOT SPECIMENS OF THE MBAGATHI PHONOLITIC TRACHYTES

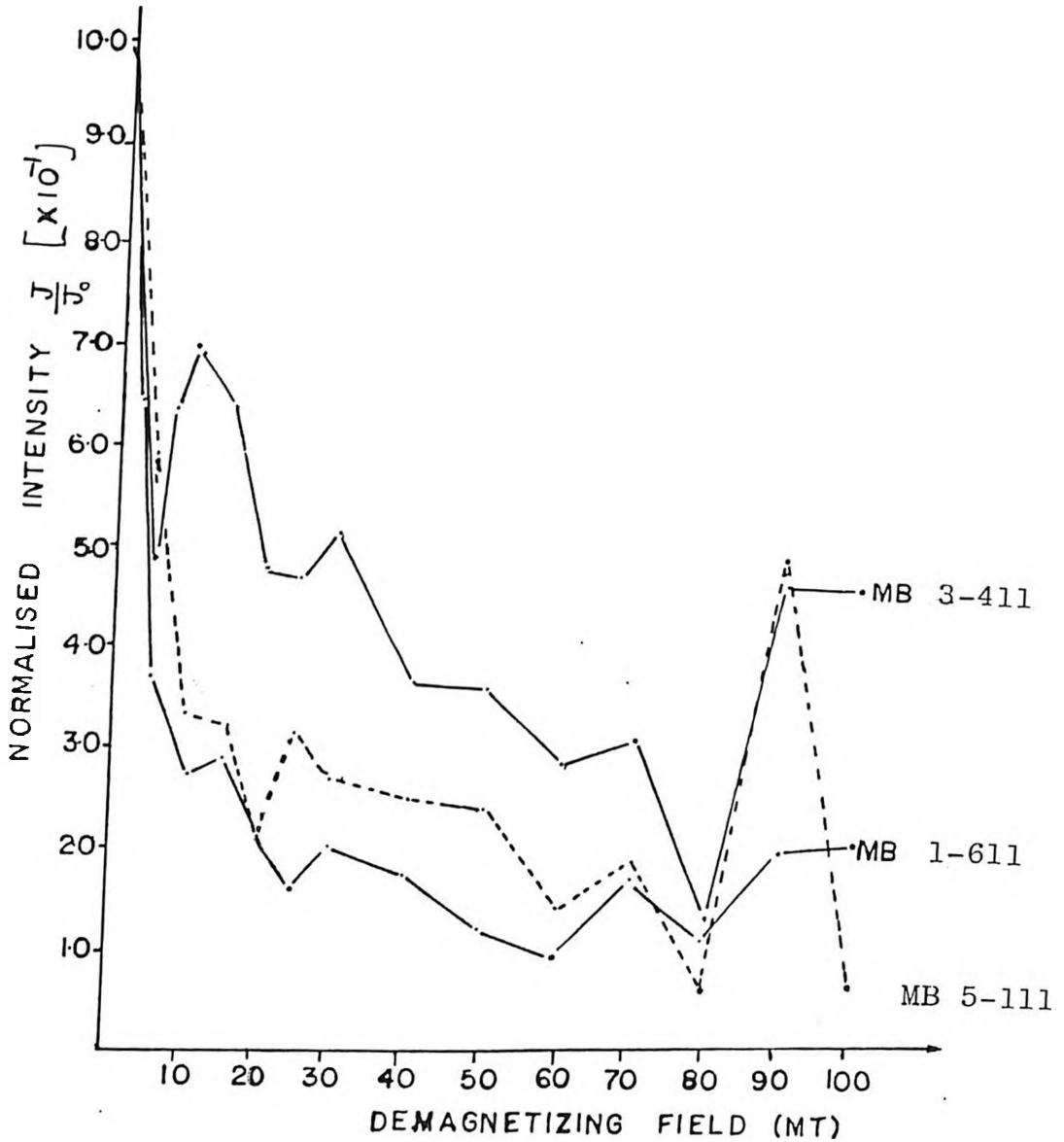
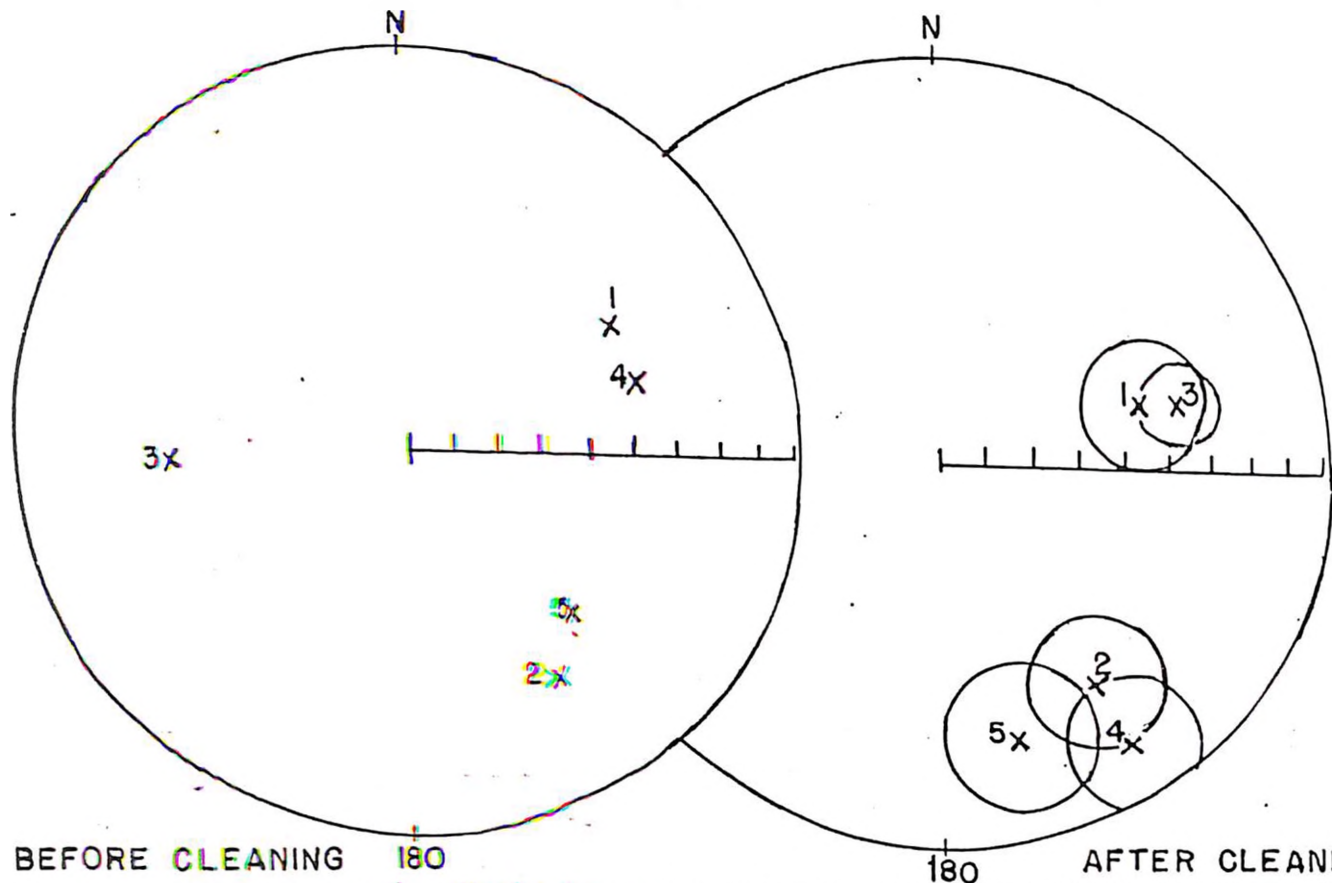


FIG. 5C: NORMALISED DEMAGNETIZATION CURVES FOR PILOT SPECIMENS OF MBAGATHI PHONOLITIC TRACHYTES.

remanence is lost on cleaning between 7.5 - 10 mT and the optimum cleaning fields of some of the samples were attained within their mean destructive fields (Mdfs) range. The plot of site mean directions before and after a.f. demagnetization is given in Fig. 5(d). The plot indicates that the site mean directions for the virgin samples are randomly distributed on the equal area stereo nets while after a.f. cleaning, the site mean directions become well grouped, showing significant increase in the value of k , the estimate of Fisher's (1953) precision parameter, corresponding reduction of α_{95} , the radius of a circle of confidence which would enclose 95% of the directions and a marked improvement in the values of R , the resultant magnetic vector.

All the sites sampled are statistically non-random by Watson's (1956) criteria of randomness at 95% probability. From the results in Table 5, it is seen that sites 1 and 3 yielded mean directions of intermediate polarities while the remaining sites 2,4 and 5 showed reversed polarities according to Dagley et al. (1967). None of the sampled sites of the Mbagathi phonolitic trachytes yielded a normal direction.

At the sampling site, it was observed that the Mbagathi phonolitic trachytes probably consists of thin sheets since the sampled sites were all at an approximately the same horizontal level whereas the



● NEGATIVE DIP
 X POSITIVE DIP

BEFORE CLEANING 180

180 AFTER CLEANING

FIG 5 d PLOT OF THE SITE MEAN DIRECTIONS BEFORE AND AFTER AF DEMAGNETIZATION FOR MBAGATHI PHONOLITIC TRACHYTES

paleomagnetic results indicate at least two distinct flows. The clustering of the cleaned directions in Fig. 5(d) and the overlapping of circle of confidences would seem to suggest that the results of sites 1 and 3 and of sites 2, 4, 5 may be combined. These sites were subjected to F-ratio test. It was observed that sites 1 and 3 are not significantly different at 5% level of significance and are therefore combined to obtain an intermediate direction and the corresponding paleomagnetic pole. Similar results were found for sites 2, 4 and 5 which are also combined to give a reversed direction and a corresponding pole for the Mbagathi phonolitic trachytes.

The mean direction and corresponding pole for the reversely magnetized sites is calculated at declination $D=151.1^\circ$, Inclination $I=24.2^\circ$ ($\alpha_{95} = 21.0^\circ$) and longitude 104.6° E, latitude 59.2° S ($\delta_m = 22.5^\circ$, $\delta_p=12.0^\circ$) and for the intermediately magnetized sites at $D=73.71^\circ$, $i = 39.87^\circ$ ($\alpha_{95} = 17.3^\circ$) and longitude 102.9° E, latitude 14.4° N ($\delta_m = 20.8^\circ$, $\delta_p=12.53^\circ$) respectively.

These directions are believed to be primary as the specimens were adequately cleaned in each case. They therefore, represent a good estimate of the mean field direction and paleomagnetic pole for the sampled part of the phonolitic trachytes. Sampling was done over a large area in order to average out possible errors due to secular variations.

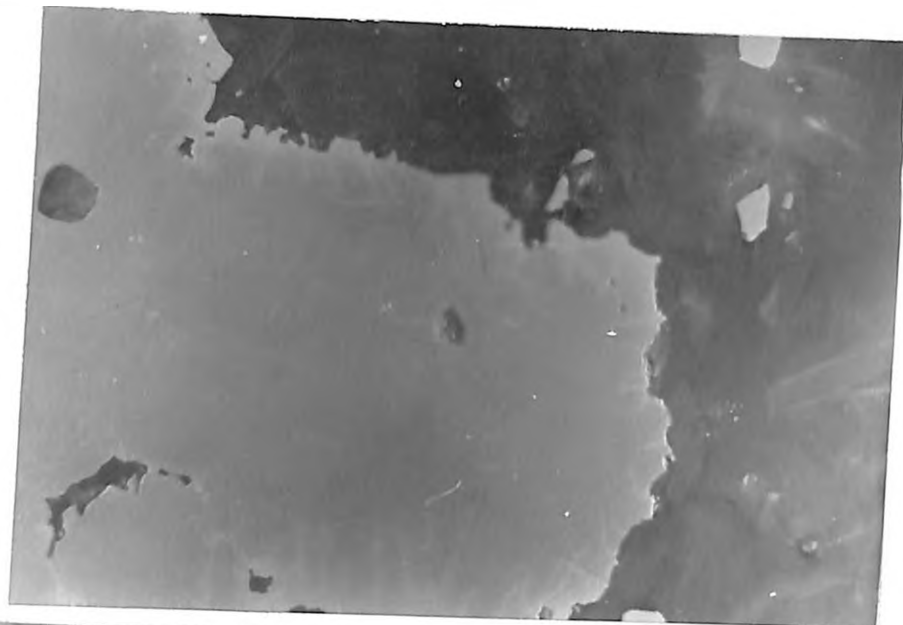
4.2.0. Polished section Petrology

Polished section petrological analysis was undertaken with an aim of identifying magnetic grains responsible for carrying the natural remanence in the minerals. The grains possessing the remanent magnetization exhibit a wide coercive force spectrum as can be inferred from the characteristic a.f. demagnetization curves of the units (Figs. 2(c), 3(c), 4(c) and 5(c)). This presumably indicates a large range in grain and domain sizes (Stacey, 1962).

The polished sections for the study were prepared by grinding successively with carborundum 80, unirundum 500 and 850 and Bauxilite 1200. Fine diamond paste (6W, 3W and 1W) of less than 2 microns in diameter were used for the final grinding.

An attempt has been made to correlate the polished section petrology with the stability of the natural remanence of the specimens of the sampled lava flows. Opaque grains were examined and studied under the reflected light using a polarizing microscope and photomicrographs in Figs. (6) taken.

For the analysis, one specimen from each site for all the rock units sampled was prepared. The observations made from the samples of Mbagathi phonolitic trachytes, the Limuru trachytes and the Nairobi phonolites indicated



Plate(a)

LT5-222



Plate (b)

MB142



Plate (c)

NB10-152

20 M

Fig. 6 Plates (a) and (b) illustrate homogenous and subhedral titanomagnetite grains while plate (c) shows ilmenite exsolution in a titanomagnetite grain.

that the titanomagnetite grains are sparsely distributed in the samples. The average grain size varies from 100-200 microns in diameter. Characteristic grains of these samples are illustrated on Fig. (6) plates (a) and (b). The grains are homogenous with no traces of ilmenite exsolution and have subhedral shapes.

This large homogenous titanomagnetite grains are believed to contain multi-domain regions with low energy barrier to domain wall motion and to domain rotation, therefore possessing low coercive force. These are suspected to be responsible for carrying the weak and unstable natural remanent magnetism in the specimens of these rock units as illustrated in the corresponding SI curves (Figs. 2(a), 3(a) and 5(a)).

The titanomagnetite grains in Ngong basalts in plate (c) of Fig. 6 are observed to contain exsolved ilmenite lamellae of light colour oriented in two planes of directions. This probably is the initial stage of high temperature oxidation as some few titanomagnetite grains in the same specimen were observed completely free from the ilmenite exsolution. This oxidation state may be assigned group B of Hargraves and Young (1969).

The titanomagnetites and their derivatives are the principal magnetic minerals in basaltic rocks and it is believed that their stability requires the mineral to be in the mono-domain state so as to necessarily retain an

original magnetic record (O'Donovan and O'Reilly, 1977). In this regard, exsolution of ilmenite lamellae in an homogenous titanomagnetite grain causes the sub-division of the magnetic titanomagnetite grain by the non-magnetic ilmenite lamellae thus approximating the sub-divisions to the single domain state described above; hence enhancing the stability of the natural remanence as stated by Carmichael, (1961).

It has therefore been concluded that the stable N.R.M of the specimens of Ngong basalts reside in the titanomagnetite grains which have been sub-divided into smaller independent grains by the ilmenite lamellae (Graham (1953) and Larson et al. (1969)) and that the higher magnetic stability of these basalts Fig. 4(a) compared to that of the Mbagathi phonolitic trachytes, the Limuru trachytes or the Nairobi phonolites may be due to the observed sub-division and the oxidation of the titanomagnetite grains.

4.3.0. Thin Section Petrology

Three to four thin sections were prepared from each rock unit and examined under the transmitted light. This analysis was undertaken to determine the state of weathering of the rock samples.

The main silicate minerals examined included the feldspars (plagioclase) predominantly fresh and un-altered

in the case of Mbagathi phonolitic trachytes; pyroxenes and soda-amphiboles. In addition, minute amounts of nepheline, which readily altered to sodalite, and hornblende were detected. The Ngong basalts contained sporadic green augite which turned colourless and zoned in thin sections and which readily altered to hornblende.

An attempt was made to correlate the silicate mineral alteration products to the stability of the natural remanence of the units. However, no significant correlation was deduced although Hargraves and Young (1969) and Murthy et al. (1971) have shown that opaque inclusions occurring in pyroxenes and plagioclase are magnetically stable. The non-magnetic silicates are mono-domain and when subjected to oxidation often produce microscopic to sub-microscopic needle like ferri-magnetic inclusions according to Evans et al. (1968). The existence of some of these silicate minerals in the sampled rock units could also be another source of the magnetic stability, probably a predominant source in the case of the Mbagathi phonolitic trachytes, the Limuru trachytes and the Nairobi phonolites which contained no ilmenite exsolution in their titanomagnetite grains.

4.4.0. Paleomagnetic Stratigraphy and Suggested Correlation

A tentative magnetic stratigraphy of volcanic rocks of Nairobi area is illustrated in Fig. 7, where all units

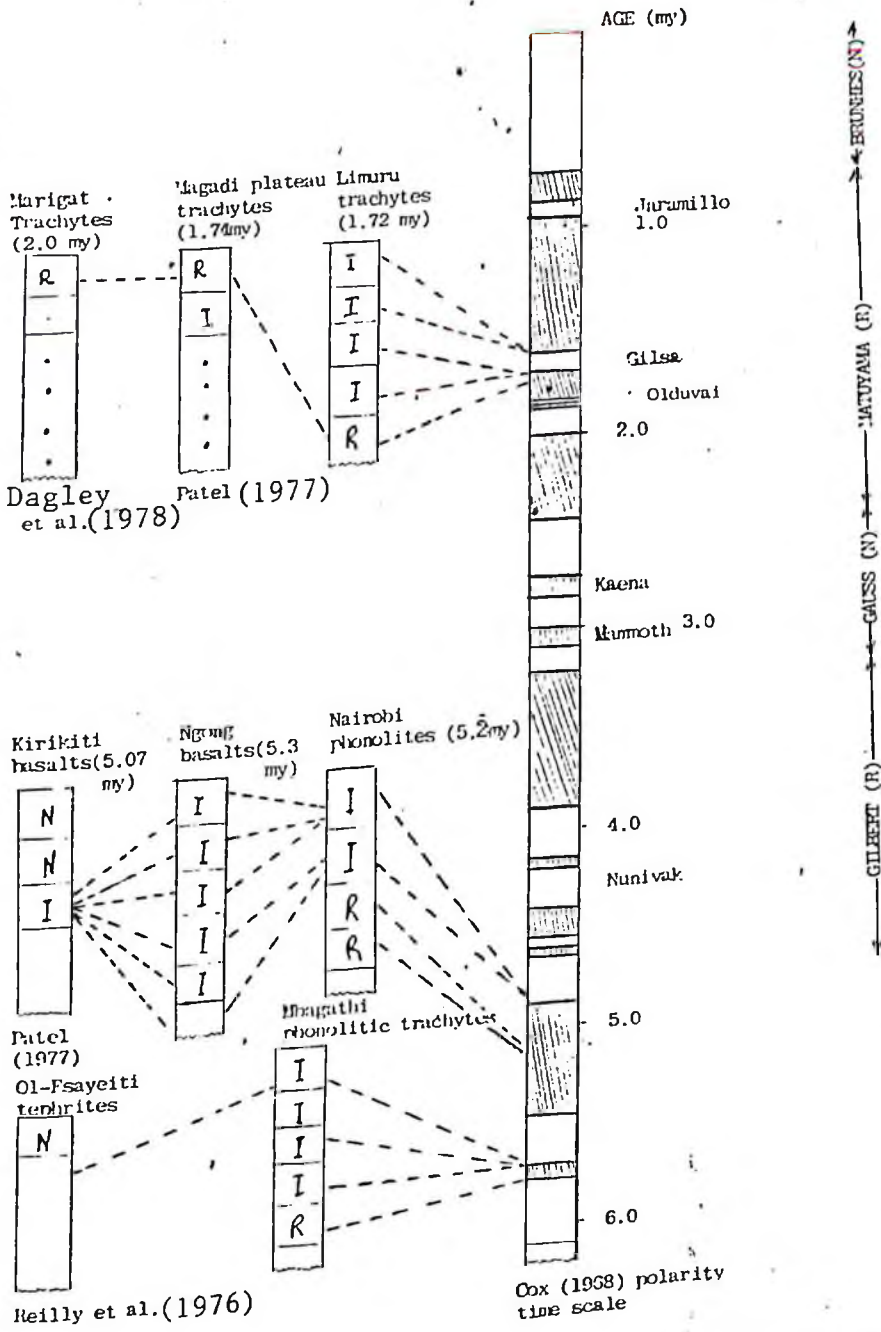


FIG 7: A tentative Magnetostratigraphy of rocks from Nairobi area.

collected at one locality are shown in the same vertical column. The positions of the units within a column represent relative age quoted from Baker et al. (1971). Correlation of the flows has been made based on identical magnetic directions, age and the standard time scale (Cox, 1968). This presupposes that the results obtained in this paleomagnetic analysis reflect original magnetic field directions. The accuracy of the results depend on the number of samples used and the accuracy of the method of analysis.

4.4.1. Limuru Trachytes

This is a group of porphyritic trachytes grouped under Plio-Pleistocene and radiometrically dated between 1.55-1.72 my (Baker et al. 1971). From the results of paleomagnetic analysis three distinct flows are identified. Two of the flows are intermediately magnetized while the other is reversedly magnetized.

The topmost flow, marked by sites 12 and 14 represents the youngest extruded flow sampled from the Limuru trachytes. Based on this supposition, it is suggested that the flow represented by sites 12, 14 was extruded just after the transition of the earth's magnetic field from the normal polarity between 1.70 - 1.6 my, the Gilsa event, to the reversed part of the Matuyama epoch between 1.60 - 0.92 my. Since site 15 represents a much lower flow than the flow represented by sites 12, 14 and

since it gives a paleomagnetically reversed direction, then it must have been formed during the reversed part of Matuyama between 1.86-1.70 my. The intermediate flow represented by sites 13, 16 must then have extruded earlier than the intermediate flow represented by sites 12, 14 probably at the transition stage around 1.6 my from normal to reversed polarity.

Correlation of the Limuru trachytes has been done by matching of polarity intervals of identical directions and almost same age with those of the Marigat trachytes (2.0 my), and Magadi plateau trachytes (1.74 my). The reversed polarity of the Marigat trachytes has been correlated to the top most reversed flow of the Magadi plateau trachytes with lowest flow sampled from the Limuru trachytes represented by the reversed site 15. The intermediate flows of the Limuru trachytes appears much younger than any of the flows of the correlating units.

4.4.2. Nairobi phonolites

The Nairobi phonolites are grouped as mid-Pliocene with a whole rock K/Ar isotopic date of 5.2 my. Samples from the sequences were collected from four sites a few kilometers east of Nairobi and two sites (17, 18) gave a perfectly reversed polarity while sites 19, 20 gave an intermediate direction.

It has been noticed that the result of a reversed

polarity from the flows represented by sites 17, 18 are in accord with the reversed epoch between 5.42-4.87 my, Cox (1968) scale; although the intermediate pole exhibited by sites 19, 20 cannot be harmonized with this scale unless the flows are regarded much younger or older than the radiometric age above, or that there must exist a polarity change around 5.1 my or that the results of sites 19, 20 be considered spurious.

Using the Heirtzler et al. (1968) polarity scale, the two polarities reversed and intermediate easily fit in as there is a reversed epoch between 5.61-5.01 my and a normal one between 5.01-4.81 my. In this scale then, the flow representing the reversed sites 18 and 19 precedes in age the flow representing the intermediate sites 19, 20. The reversed flow then needs to have been extruded just before the transition while the intermediate one would then have been extruded during the transition from the reversed to the normal epochs.

Correlation of the Nairobi phonolites has been done with respect to the Kirikiti basalts whose youngest flow has normal polarity; the lower flow has an intermediate polarity which has been correlated to the upper flow of the Ngong basalts and a probably intermediate unsampled lower flow of the Nairobi phonolites. The uppermost flows of the Kirikiti basalts are probably younger than the top flows of the Nairobi phonolites.

4.4.3 Ngong Basalts

This rock formation from the Ngong hills contains an alkaline series ranging from nephelinites, basanites to basic and phonolitic tephrites. Sampling was done on the eastern side (sites 6,7) and on the sloping edge of western side of the hills which possibly consist of multiple flows. The flows could not be distinctly identified in the field unlike those for the Limuru trachytes. However, magnetically, they divide into five groups of sites 6-11, each having intermediate but distinct directions.

Ngong basalts have been dated at 5.3 my. From the distribution of sites it is evident that the youngest of the sampled flows represented by site 11 has a direction of greatest declination which progressively reduces to that of site 7 suspected to be the oldest of the sampled flows. This implies that the field transition during eruption of Ngong basalts was from normal to reversed, and that since all the directions are intermediate and probably represent successive flows, then they must have been extruded during the same transitory event most probably during transition of field from the normal polarity between 5.69-5.43 my to the reversed polarity between 5.43- 4.87 my.

As has been stated for the Nairobi phonolites, it has been assumed that the sampled intermediate flows of the

Ngong basalts are much older than any of the flows of Nairobi phonolites and have therefore been correlated to an intermediate, possibly lower unsampled flow from Nairobi phonolites. The intermediate directional flows of the Ngong basalts may be correlated, tentatively, to one of the middle flows from the Kirikiti basalts.

4.4.4. The Mbagathi Phonolitic Trachytes

The Mbagathi phonolitic trachytes have been tentatively included in the group of mid-Pliocene phonolites and trachytes represented by two main formations of Kabarnet trachytes (6.7-7.3my) and Thomson falls phonolites (6.5 my), dated by Baker et al. (1971), though comparatively younger. The phonolitic trachytes rest upon the upper Miocene Kapiti phonolites and are overlain by local representatives of the Plio-Pleistocene group, the Limuru trachytes.

Paleomagnetic analysis yielded mixed directions of reversed and intermediate polarities for the five sampled sites of the Mbagathi river valley. The grouping of directions suggest two thin sheets for the formation since sampling was done at an approximately same horizontal level.

K/Ar determination assigns an age of about 5.7 my to the phonolitic trachytes which implies that the flow representing the reversed sites 2, 4 and 5 must have extruded on the reverse epoch between 5.69-5.78 my just

before the normal epoch between 5.69-5.43 my while the flows representing the intermediate sites 1 and 3 were formed during the transition period between the two epochs. If the normal polarity assigned to the Ol-Esayeiti tephrites (5.7 my) by Reilly et al. (1976) represents the polarity of the top flow, it is presumed that this is older than the top flow which yielded an intermediate direction from the Mbagathi phonolitic trachytes.

CHAPTER 5

5.1.0. Conclusions

The intended objectives of the research which included determination and compilation of paleomagnetic directions and pole positions for the Nairobi area rocks have been attained, and the results are tabulated for Limuru trachytes (Table 2), Nairobi phonolites (Tables 3), Ngong basalts (Table 4) and Mbagathi phonolitic trachytes (Table 5).

The natural remanent magnetic directions of the sampled rock units showed considerable dispersion and although the directional scatter was reduced by a.f. demagnetization, the precision of the site mean directions remained significantly low in most sites as indicated by values of α_{95} greater than 10^0 .

The majority of the specimens of the Mbagathi phonolitic trachytes possess low coercivity, ranging between 7.5-15 mT, of remanence and the directions of some specimens remained scattered at all fields of demagnetization while the specimens and samples from the Ngong basalts showed high stability. Some pilot specimens, from this unit did not in fact significantly change their remanent directions during step-wise a.f. demagnetization and most of them lost their secondary components at about 35 mT field of demagnetization.

Consequently, the Ngong basalts yielded consistent site results and site mean positions. The optimum demagnetization fields (O.D.F.) were determined to give characteristic direction to every site. All specimens (samples) of that site were then demagnetized at the determined optimum demagnetization field for the site. All sites have been considered magnetically non-random according to Watson's (1956) criteria of randomness at 95% level of probability.

The cleaned directions yielded 'intermediate' and 'reversed' polarities for all the sampled rock units except the Ngong basalts whose five sites all yielded intermediate directions and hence an intermediate mean pole for the formation.

The mean paleomagnetic pole for the Limuru trachytes is computed at 79.3° S, 88.9° E, and 9.82° S, 114.73° E, from its reversed and intermediate directions. The Nairobi phonolites gave 79.6° S, 127.3° E, from the reversed and 18.9° S, 126.49° E, from the intermediate directions respectively; The Ngong basalts gave a pole at 0.93° N, 125.0° E, from its intermediate mean direction while Mbagathi phonolitic trachytes gave 59.2° S, 104.0° E and 14.4° N, 102.9° E, from the reversed and intermediate directions respectively.

These paleomagnetic results appear in accord to those published by Reilly (1970) for the Miocene, and those

obtained for the Kapiti phonolites by Patel and Gachii (1972). The results are also believed to be primary because of the improvements in grouping of both sample and site directions after a.f. cleaning. Sampling was carried out over a large area in an effort to minimize or average out possible errors due to secular variations.

The correlation of the opaque petrology with the stability of the remanence of the four rock units appears significant. The titanomagnetite phase and its oxidation products appear to be the main contributor of the natural remanence in all these rocks. The specimens having ilmenite exsolution in the titanomagnetite grains were found to carry stable magnetization while those without any exsolution carry the the component of the natural remanence with low coercivity because of the homogenous nature of their titanomagnetite grains. On the other hand, thin section petrology gave no evidence of any correlation with the stability of the remanence.

A magnetostratigraphy of the rocks of Nairobi area has been suggested in Fig. 7. This is based on the polarity of the rocks studied. Intermediate polarity has been observed in most of the rocks of Nairobi area. This is not uncommon as similar observations have been made by Raja(1968), Patel(1977), and Patel and Raja (1979b).

The polarity time scale used in Fig 7 is according to Cox (1968) and the nature of the polarity episodes is

according to Gromme and Hay (1971). Matching of polarity columns has also enabled a tentative correlation of stratigraphy of Nairobi area rocks with other stratigraphical columns of rock units from other areas of Kenya. This correlation is based on the dates of the rocks available. However, large number of samples and more accurate dating of the rocks may change this magnetostratigraphy and its correlation with other rocks of the country.

APPENDIX 1

NOMENCLATURE OF THE ROCK SPECIMENS

Specimens used in this paleomagnetic analysis were assigned identity codes depending on where it was obtained (i.e. which rock unit), its sampling site within that formation and whether it is the first, second, etc. specimen from the first, second etc. core of a given block sample. Specimens are cut and numbered 1,2,3 from the top surface as it was before drilling out from the block. For example LT 4-162 means the specimen was the second (2) specimen cut from core six (6) of block one (1) of site four (4) of the rock formation LT - in this case LT stands for Limuru trachytes. Other rock unit codes used are NP = Nairobi phonolites, NB = Ngong basalts and MB = Mbagathi phonolitic trachytes. This naming method for specimens has been consistently used in the thesis and during field sampling.

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