The Palaeomagnetism of Late Cenozoic Volcanic Rocks from Kenya and Tanzania

T. A. Reilly

Geological Survey of Ireland, Dublin

P. K. S. Raja

Department of Physics, University of Nairobi

A. E. Mussett

Sub-department of Geophysics, University of Liverpool

A. Brock

Department of Physics, National University of Lesotho, P.O. Roma, Lesotho, Africa

Summary

Palaeomagnetic results from 246 sites in the East African Cenozoic volcanics are reported. Palaeomagnetic pole positions are obtained for different age ranges as follows: 0–1·8 My, 104° E, 89° N, $A_{95} = 3°$ (54 sites); 1·8–7·0 My, 148° E, 87° N, $A_{95} = 2°$ (102 sites); around 12 My, 187° E, 87° N, $A_{95} = 6°$ (22 sites); around 17 My, 163° E, 85° N, $A_{95} = 2°$ (62 sites). Apart from the youngest these poles show a far-sided and right-handed tendency which is ascribed to a late Tertiary offset dipole field rather than to polar wander. For at least the past 7 My and possibly for the past 13 My, secular variation in East Africa has been large and in accord with model predictions for near equatorial sites. This contrasts with low secular variation observed in lavas younger than 5 My from the Hawaiian Islands.

Introduction

The Late Cenozoic volcanics of Kenya and Tanzania form a vast alkali igneous province which extends northwards into Ethiopia and which spans a time from Miocene to Recent. This paper describes the results of a large scale reconnaissance survey of the volcanics involving 184 sites mainly south of the equator. Preliminary results from some of these sites were reported by Mussett, Reilly & Raja (1964), and a detailed account is given in an unpublished thesis by Reilly (1970). A brief summary was given by Brock (1970), and the leading results were listed by McElhinny (1972) in ' Palaeomagnetic Directions and Pole Positions XII '. This is the first

published account to give more detail, and it incorporates a number of changes consequent upon improved geological information.

We also describe new results from 62 sites in the Miocene Turkana lavas west of Lake Rudolf. These results are fully discussed in another unpublished thesis (Raja 1968) and a preliminary account was given earlier by Raja, Reilly & Mussett (1966). There is a substantial gap in the coverage north of the equator in the Laikipia, Baringo, Kamasia and Elgeyo areas, but large collections have since been made in these areas by workers from Nairobi and Liverpool Universities, and will be the subject of further publications.

2. Geology and chronology

The geology of the East African rift system as a whole has been summarized by Baker, Mohr & Williams (1972) and the sequence and geochronology of the Kenya rift volcanics is discussed by Baker *et al.* (1971). This paper relies heavily upon the latter compilation, supplemented by a number of other age determinations reported by Evans, Fairhead & Mitchell (1971) and Fairhead, Mitchell & Williams (1972). In outline the sequence of events, as recognized by Baker *et al.* was as follows:

An upwarped region on the Kenya, Uganda border was the site of Miocene central volcanism accompanied by flood basalt eruptions in the Turkana depression of northern Kenya. Later an extensive phase of plateau phonolite eruptions occurred, mainly in central Kenya, but with a south-eastern branch forming the Kapiti–Yatta phonolites, and with ages in the range 13–11 My. After a relatively quiescent interval faulting developed forming an asymmetric trough followed by extensive flood basalts in the trough, and accompanied by the building of the basaltic Aberdare range (6·5–5 My). A phase of trachytic ignimbrite eruptions followed (5–3 My) partly filling the rift trough and locally oveflowing its flanks. At about this time uplift of the trough flanks and phases of graben-faulting began to form the symmetrical rift valley as we know it today, and a series of central volcanoes were built up in the rift—Olorgesaille, Ol Eseyati, Shombole and Ngong. This was followed by extensive flood trachyte volcanism in the floor of the central and southern rift valley (1·7–0·6 My). Baker *et al.* (1971) refer to the whole of the trachytic activity as the Plio-Pleistocene trachytic group but it is possible to distinguish an earlier ignimbritic phase and a later plateau trachyte phase. In the Quaternary a number of mainly trachytic central volcanoes were built up on the floor of the rift valley, whilst well to the east the Nyambeni, Thiba and Chyulu multi-centre basaltic chains were formed. The two largest volcanoes of East Africa, Mount Kenya and Kilimanjaro are both to the east of the rift valley and both have complex volcanic histories, the main phase of eruptive activity being Late Pliocene for Kenya and Pleistocene for Kilimanjaro. Fig. 1 is a simplified geological map showing the main groups described above.

Palaeomagnetic samples were taken from these volcanics in two main areas. One was the Turkana area which yielded 62 sites in the Miocene Turkana basalts. A number of ages have been reported for these lavas ranging from 32 to 14 My (Baker *et al.* 1971) but most lie in the range 23–14 My with a concentration at about 17 My, and the Turkana basalts are here assumed to have an age of about 17 My. They are the oldest of the East African Tertiary volcanics to have been sampled.

The other area was mainly in Southern Kenya and Northern Tanzania. Many different volcanic units were sampled with a wide spread both in space and in time with ages ranging from Miocene to recent. It became necessary to organize the sampled units in some suitable way, and a three-fold time division was used corresponding roughly to Miocene, Pliocene and Pleistocene. Assignation to the oldest division (Group A) was relatively easy since most of the relevant rock units were
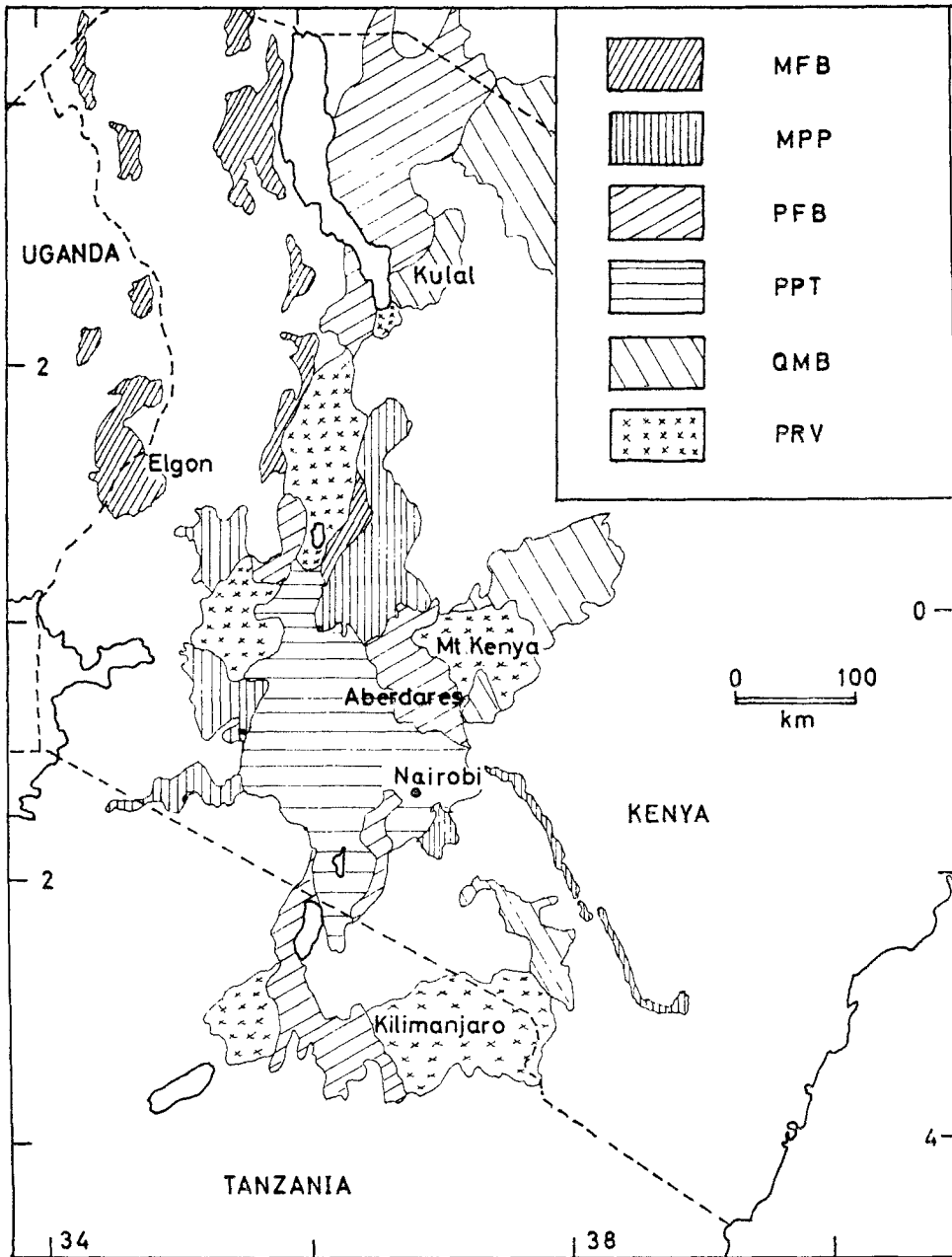
FIG. 1. Simplified geological sketch map (after Baker *et al.* 1971). Key: MFB, Miocene flood basalts and central volcanoes; MPP, Plateau phonolites; PFB, Pliocene flood basalts and Aberdare range; PPT, Plio-Pleistocene trachytic group; QMB, Quaternary multi-centre basalt chains; PRV, Pliocene to Recent central volcanoes.

from the plateau phonolite group with a tight cluster of ages in the 13–11 My range. A quiet period from 11 to 7 My enables the division between Group A and Group B to be made with ease, but the division between Group B and Group C (the youngest group) was more difficult. The boundary was eventually chosen within the Plio-Pleistocene trachytic group, by assigning the plateau trachytes and all younger units to Group C, and the remainder to Group B. On this basis, and using the ages listed by Baker *et al.* (1971), the Group B/Group C boundary has an age of about 1·8 My, which corresponds to the Plio-Pleistocene boundary of Berggren (1969). Thus a time sequence is formed as follows:

Group C	1·8 My–present
Group B	7 My–1·8 My
Group A	mainly 13–11 My

Turkana basalts about 17 My

The main sampled rock units and their age groupings are given in Table 1. The placements shown there rely heavily upon the chronology of Baker *et al.* (1971), but it should be remembered that not all the units have been dated, and their stratigraphic relationships are not always clear. The chronology is therefore not final, and further work may modify it. It differs slightly from that used by Reilly (1970) to whom fewer dates were available.

Table 1

Main rock units and age groupings

The letter codes are those used in Fig. 1, and the numbers in parentheses indicate the number of sites.

Group C (1·8–0 My)

Plateau trachyte group (PPT)

Gilgil trachyte (4), Karura trachyte (1), Kabete trachyte (1), Tigoni trachyte (1), Limuru trachyte (4), Plateau trachyte (6).

Quaternary multi-centre basalt chains (QMB)

Simba basalt (3), Thiba basalt (4).

Pliocene to recent central volcanoes (PRV)

Amboseli basalt (5), Central rift volcanoes (5), Hajaro basalt (8), Kilimanjaro rhombporphyry (3), Mawenzi trachybasalt (1), Suswa volcanics (5), Menengai trachyte (2).

Other

Olduvai basalt (2), Peninj basalt (1).

Group B (7–1·8 My)

Pliocene trachytic ignimbritic group and intercalated units (PPT)

Athi tuffs (4), Kinangop tuff (3), Nyeri tuff (1), Thika building stone (2), Upper Kerichwa valley series (3), Lower Kerichwa valley series (5), Kinangop-Naivasha trachyte (5), Londiani basalt (2), Mbaruk basalt (3).

Pliocene flood basalts, central volcanoes and Aberdare range (PFB)

Laikipia basalt (3), Lenderut volcanics (4), Mozonik nephelinite (2), Ngong basalt (4), Olorgesaile trachyte (4), Olorgesaile phonolitic nephelinite (2), Ol Esayeti volcanics (5), Simbara basalt (4), Shombole volcanics (4), Kandizi phonolite (3), Kirikiti basalt (6), Mbagathi trachyte (5), Nairobi phonolite (5), Nairobi trachyte (3), Older extrusives (5), Ol Keju Neru basalt (5) Singeraini basalt (2), Sambu basalt (10).

Group A (mainly 13–11 My)

Plateau phonolite group and other (MPP)

Kapiti phonolite (12), Kisumu phonolite (6), Kericho phonolite (3), Uasin Gishu phonolite (1), Shirere nephelinite (2).

Table 2

Site mean directions, poles, and statistical parameters

	Polarity			N*	Directions						Poles		
	N	R	I		D	I	K	α_{95}	s	Long °E	Lat °N	K	A_{95}
Group C	31	23	2	54	1·3	−2·4	18·3	4·7	19·0	104·0	88·7	37·8	3·2
Group B	48	54	2	102	3·3	−4·8	22·0	3·1	17·3	147·6	86·5	37·8	2·3
Group A	11	11	2	22	1·7	−4·2	13·4	8·8	22·1	186·6	86·5	28·8	6·1
Turkana	30	32	0	62	4·1	1·7	35·0	3·1	13·7	163·3	84·6	69·9	2·3
Ethiopia*	19	1	0	20	7·2	7·2	34·9	5·6	13·7	167·7	80·8	59·3	4·3
Group C, Brunhes	24	0	0	24	2·5	−1·7	14·9	7·9	21·0	107·1	87·6	32·6	5·3
Group C, Matuyama	0	23	0	23	359·1	−1·0	19·7	7·0	18·2	353·8	88·4	38·5	4·9

N, R, I, Number of sites with the designated polarity; N^*, Number of sites used to compute the mean; D, I, Declination and Inclination in degrees; k, K, Precision estimates; α_{95}, A_{95}, semi-angles of cones of 95 per cent confidence in degrees; s, angular standard deviation in degrees.
* Brock, Gibson & Gacii (1970).

3. Sampling and measurement

In the area south of the equator the sampling was on a reconnaissance basis with only a few sites in each rock unit but with a wide spread of units in space and time. The aim of sampling was to ensure that each site represents a separate flow, but field conditions are such that flows are not always distinguishable. Only in the Turkana lavas which form a thick sequence were a large number of sites collected, but even here individual flows could not always be recognized. In order to make the coverage more complete a number of sites reported by other workers are included. These include the Olduvai lavas (Grommé & Hay 1963), some lavas from the central part of the rift valley (Nairn 1964), and 12 sites from the Kapiti phonolite described by Patel & Gacii (1972). A grand total of 246 sites (694 samples) is involved, and the tabulation of the palaeomagnetic data at the site level is too lengthy for publication in a summary paper such as this. A copy of this primary data has been lodged with the Editors of *Geophysical Journal*, and further copies may be obtained from Dr A. E. Mussett at the University of Liverpool.

At each site a number of separately oriented samples were collected either as blocks or cores. In the laboratory several specimens were prepared from each sample for measurement under an astatic magnetometer with a maximum sensitivity of 9×10^{-6} emu of moment per mm deflection. Trial specimens were subjected to the usual step-wise partial demagnetization procedure, and a best field selected for AF cleaning of the remaining specimens from each site. In general, soft secondary components were removed in peak fields of 100–200 Oe. The site mean directions after cleaning were calculated giving unit weight to samples. A number of sites were discarded because cleaning was ineffective judged by a random distribution of sample directions after cleaning. Others were discarded because they showed unusually large intensities due to suspected lightning strikes. The remaining cleaned mean site directions were classified into normal (N), reversed (R) and intermediate (I). A number of arbitrary classification schemes have been suggested in the past, usually involving the deviation of the site direction from the dipole field direction. Wilson, Dagley & McCormack (1972) have suggested that the use of poles rather than directions provides a more natural definition of I. We here adopt their criterion that a site whose virtual geomagnetic pole has a co-latitude between 40° and 140° be designated I. On this basis the classification of sites is summarized in Table 2. The proportion of I directions is just under 3 per cent which is similar to the figures of between 3 and 4 per cent observed by other workers for Plio-Pleistocene volcanic sequences in Iceland and Hawaii, but contrasts with figures of between 11 and 15 per cent observed for older Tertiary lavas in Australia (McElhinny, Embleton & Wellman 1974).

In order to calculate the overall mean directions, it is necessary to combine the N and R sites. This was done by reversing the reversed site directions and combining them as if they all had normal polarity. The corresponding poles are then all in the Northern Hemisphere and can also be combined. There is no full justification for this procedure although it is widely followed, but in all cases the difference between the mean directions for the normal and reversed groups calculated separately was not significantly different from 180°. The resulting group mean directions and poles were calculated directly from the site means, and are shown in Table 2.

4. Magnetic properties

Measurements were also carried out on bulk magnetic properties, the following being determined routinely: intensity, susceptibility, saturation remanence, Curie point, and degree of oxidation. In addition selected samples were studied for information about low field hysteresis, and these more specialized studies are reported else-

where (Radhakrishnamurty *et al.* 1972; Radhakrishnamurty, Sahasrabudhe & Raja 1968).

The main findings can be summarized as follows:

(i) The distributions of NRM intensity and low field susceptibility were more nearly log-normal than normal, in agreement with the findings of Tarling (1966) and Irving, Molyneux & Runcorn (1966) for a wide variety of rock types. In our study the logarithmic mean values for intensity and susceptibility were $7 \cdot 39 \times 10^{-4}$ emu g^{-1} (266 samples) and $2 \cdot 80 \times 10^{-4}$ emu g^{-1} Oe^{-1} (141 samples) respectively.

(ii) The distribution of susceptibility values showed no significant difference between normal and reversed groups, but that for NRM intensity showed a slight bias toward higher values in the normal group. This is attributed to the presence of soft secondary normal components.

(iii) A total of 144 specimens was exposed to a field of 3000 Oe, and the resulting saturation remanence was measured. No difference was observed between the distributions of saturation remanence for specimens whose NRM was normal and those whose NRM was reversed.

(iv) The Curie points of 150 specimens were measured using a simple bifilar suspension type of Curie balance. A wide range of values was found from 100 °C to over 600 °C with the bulk of the specimens having values in the range 500–600 °C. No significant difference was observed in the Curie point distribution of the normal and reversed groups.

(v) The degree of oxidation of the titanomagnetites of 93 specimens from 93 different lava flows spread throughout the rift valley was determined by the methods of Wilson & Watkins (1967). No correlation with polarity was found. This is in agreement with the findings of Ade-Hall & Watkins (1970) for lavas from the Canary Islands, but in contrast to those of Ade-Hall & Wilson (1969), Watkins & Haggerty 1968), and Wilson & Watkins (1967) for lavas from Mull, Iceland and elsewhere.

(vi) The above data were used to compare Curie points and degree of oxidation for 50 specimens. A strong correlation was found between high Curie points and a high state of oxidation of the titano-magnetites, in agreement with the results of Ade-Hall, Wilson & Smith (1965).

The main aim of these measurements was to determine whether there was any correlation between bulk magnetic properties and polarity, but no such correlation was found. Minor differences in intensity are attributed to soft secondary components.

5. Palaeomagnetic results: pole positions

The overall means of site directions and of site poles are shown in Table 2 for each of the main groups. There are slight differences from the figures reported earlier by Brock (1970) for essentially the same rock units. These arise from different assignations to the age groups based upon more recent age data. The differences are small, and do not affect the general pattern of the results in which there appears to be a movement of the palaeomagnetic pole away from the geographic pole with increasing age (see Fig. 2). Unfortunately one of these changes is to reduce the number of sites in the older Group A to such an extent that although it is still displaced from the pole by about 4°, it no longer has a statistically significant displacement due to the larger A_{95}. This apart, only the youngest group (C) is close to the pole, and the 5° displacement of the pole for the Turkana lavas increases to 8° for the older (Oligocene?) Ethiopian

　　　　　　　　　　　　T. A. Reilly *et al.*

flood basalts described earlier by Brock, Gibson and Gacii (1970). In a comparison with Australian Cenozoic results, McElhinny & Wellman (1969) and later Brock *et al.* (1970) ascribed these small pole movements to true polar wander. More recently McElhinny (1973) has pointed out that when late Tertiary data from other parts of the world are considered, polar wander must be ruled out; the error lay in using data from only two places, Australia and Africa.

The pole displacement shown in Fig. 2 is, however, both far-sided and right-handed to use Wilson's terminology (1972) and it may therefore be no more than a reflection of the late Tertiary distortion of the time-average geomagnetic field so well documented by Wilson in a recent series of papers (1970, 1971, 1972). The difficulty in explaining the East African Tertiary results in terms of Wilson's offset dipole hypothesis was that the East African results showed a time trend, whereas Wilson regarded the offset dipole as a permanent feature of the late Tertiary field. Recently, however, McElhinny has suggested that the degree of dipole offset has changed with time through the late Tertiary, and in a re-analysis of the data Wilson & McElhinny (1974) show that the effect is near zero in the Quaternary but increases in magnitude in older
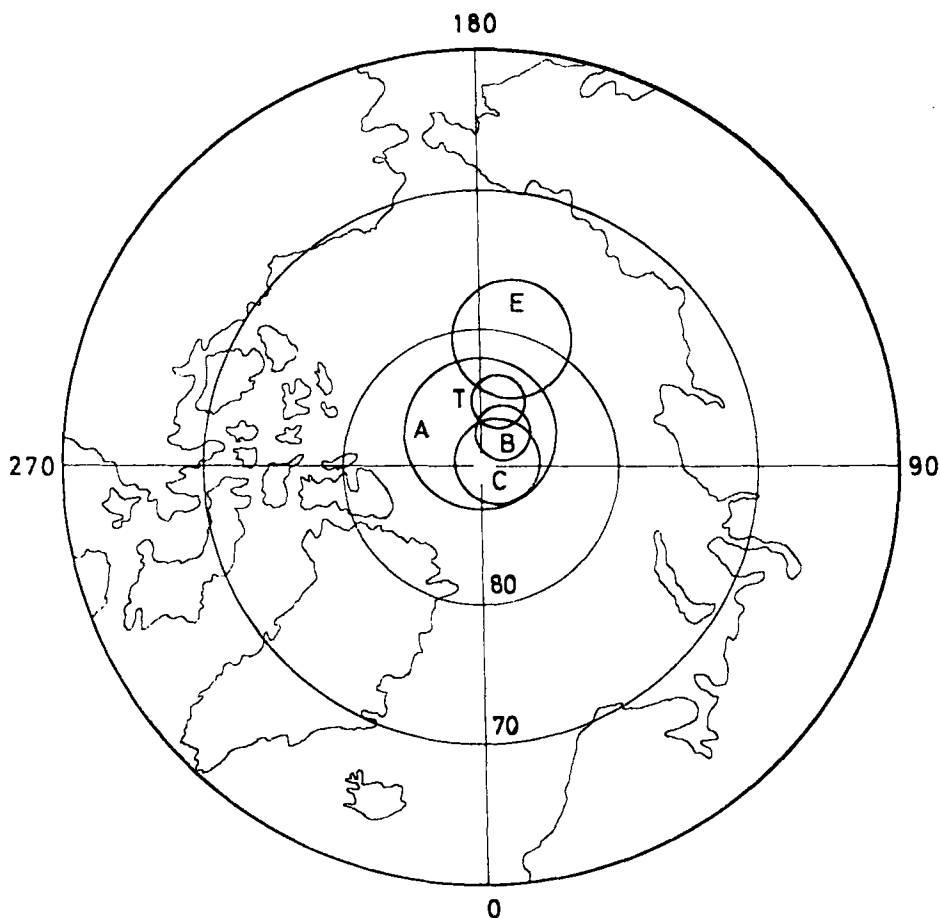
FIG. 2. Palaeomagnetic poles and circles of confidence for the main groups. Terminology as in Table 2: C, Group C (1·8 My–0 My); B, Group B (7 My–1·8 My); A, Group A (Mainly 13 My–11 My); T, Turkana lavas; E, Ethiopian flood basalts.

age groups. The East African results are entirely consistent with this (it is instructive to compare our Fig. 2 with Wilson & McElhinny's Fig. 3) and we now believe that the small pole movements shown in Fig. 2 are due to Wilson's offset dipole.

Table 2 also shows mean directions and poles for an important subdivision of Group C into Brunhes and Matuyama. The Matuyama sites are all post-Olduvai event, since it is not possible to separate the pre-Olduvai Matuyama sites in Group B from the many other older reversed sites in that group. The Brunhes sites are those which are certainly younger than 0·7 My, and thus Olduvai and possibly Jaramillo sites are excluded. As for the whole Group, both the Brunhes and Matuyama subgroups yield poles which are indistinguishable from the present, and which are certainly not far-sided. Indeed there is a hint of near-sidedness in these Group C poles (although it is below the significance level), and it is interesting to note that Watkins (1972) also reported a near-sided element in Brunhes age poles from sites in the Indian Ocean area.

Though the small late Tertiary pole shifts are due to distortions of the dipolar field, the much larger pole displacements shown by older rocks must be due to drift of the African plate. In the Mesozoic, a number of different studies give a group of poles at about 216° E 65° N (the ' mean Mesozoic pole ' of McElhinny et al. 1968). The youngest of these has an age of about 110 My, and there is clearly a large gap between this and the oldest of the East African Tertiary poles. Several attempts have been made to fill this gap. One successful one was reported by Raja & Vise (1973) who found an intermediate pole position for the Tororo ring complex in Uganda. Unfortunately the age of this formation is very poorly known, and little can be said about the timing of the pole movement. An unsuccessful attempt was made by Brock and Vise to find a pole position for the Jombo ring complex in SE Kenya which is dated at about 70 My. The material collected proved to be too unstable to yield a reliable palaeomagnetic direction. Palaeomagnetism can therefore say little about the post-Cretaceous movement of the African plate.

6. Palaeomagnetic results: secular variation

It is becoming common to analyse palaeomagnetic results for information about secular variation and the results reported here are of interest in this connection because they are from an equatorial region well removed from the well documented Pacific secular variation anomaly (Doell & Cox 1972). Doell and Cox describe an area of very low secular variation in the central Pacific which has existed not only for the past few thousand years, but which can be extended back for 5 My (Doell 1972). Doell has used a number of measures for describing secular variations but for our purpose it is sufficient to use the simple angular standard deviation s, given approximately by $(81/k^{\frac{1}{2}})°$ where k is the best estimate of the precision parameter for site mean directions. Table 2 lists the s values for each group, and it will be seen that for Groups A, B and C, the s values lie between 17° and 22°. A number of different models have been proposed for secular variation but when fitted to world wide data all predict equatorial values for s of about 18° or 19° (Brock 1971). The rift valley lavas in Group A, B and C yield s values of the same order, and it therefore appears that they record ' normal ' secular variation. They are in strong contrast to lavas in the age range 0–5 My from the Hawaiian Islands which are also low latitude but which yield values of s in the range 10°–14° (Doell 1972).

The two older groups of results, however, both show lower values for s, and the question arises whether these reflect less vigorous secular variation in Africa in Miocene–Oligocene time, or whether secular variation has not been properly averaged. If the time span represented by the lavas is too short, secular variation will be underestimated. In the field one attempts to avoid this by sampling from a large

number of lavas, and whilst the 20 sites from the Ethiopian basalts may be held to
be too few, the 62 sites from the Turkana lavas should be sufficient. Unfortunately,
it is not always possible to distinguish individual flows in the Turkana lavas, and the
62 sites may in fact represent fewer flows. In addition, the individual directions
contributing to the overall mean must be independent, if the statistical parameters
(k and s) are to be meaningful. If serial correlation is present, secular variation will
again be underestimated. Watson & Beran (1967) have described a test for serial
correlation between a set of unit vectors and Doell has used it most effectively in his
secular variation studies of Hawaiian Island lava flows. The use of the test, however,
requires that one knows the sequence of the directions being tested. Field conditions
were such that this was not possible in the Turkana lavas. Thus we cannot be sure
that the rather lower values for s found in the Turkana and Ethiopian lavas are real.

In the lavas from south of the equator (Groups A, B and C) it is impossible to
apply the serial correlation test since they nowhere involve single long sequences. But
this in itself implies that correlation is less likely. Moreover the time ranges used to
construct the groups are relatively long. It is perhaps a fortuitous advantage of the
reconnaissance style of sampling employed in this region that it yields good time
average collections. These collections enable us to conclude with some confidence
that in East Africa secular variation has had a value of around 18° for at least the past
7 My, and probably for the past 12 or 13 My. Our lava collections do not, however,
bear upon the past few hundred or the past few thousand years, and we cannot there-
fore make comparison with the younger and historical Hawaiian lava flows.

7. Other considerations

Out of the 246 sites, only six have intermediate directions. These presumably
represent the geomagnetic field in the process of reversing, but nowhere in this
collection can the reversal process be traced out. In the East African volcanic material
the only identified reversal that can be traced through a sequence of lava flows is that
corresponding to the Gauss–Matuyama boundary. It is found in the caldera wall of
Ngorongoro crater, Tanzania, and is fully described by Grommé *et al.* (1971).

The remaining 240 sites are either normal or reversed, and for those younger than
5 My the question arises whether they can be used to provide information about the
geomagnetic polarity time scale. In fact, long sequences of flows are almost entirely
absent. The collection is largely composed of many short sequences, in many of
which the stratigraphic order is not clear. There is, therefore, no opportunity for
matching polarity sequences observed in the field with that known from the time
scale. Locally, polarity information can be used to distinguish lava flows. It can also
be used to check the isotopic ages. Thus the plateau trachyte group contains both
reversed and normal sites, and has a range of ages from 1·7 to 0·6 My which is consis-
tent with the time scale. Again the Amboseli basalts are all normal but ages have
been cited ranging from 1·1 to 0·42 My (Baker *et al.* 1971). The polarity information
then suggests that these rocks are either of Brunhes age or that they represent the
Jaramillo event. Arguments such as these can be employed to supplement the other
ages, and can often put tighter bounds on possible age ranges. These considerations
were of help in deciding the assignations of sites to the three main age groups. Thus
in this study, the polarity time scale has been used to assist in the dating of the
formations, rather than having the dated rock units assist in refining the time scale.

The relatively restricted use to which polarity information has been put in this
study should not be used to suggest that polarity has no place in volcanic studies.
Wherever collections are made in which there is tight stratigraphic control, or in
which long sequences of lava flows can be identified, polarity information can be of
great importance. In East Africa there are currently a number of detailed projects

in which polarity is being determined routinely for both stratigraphic and dating purposes. In this study, however, the mode of sampling and the limited stratigraphic information makes polarity work less useful.

References

Ade-Hall, J. M. & Watkins, N. D., 1970. Absence of correlations between opaque petrology and natural remanence polarity in the Canary Island lavas, *Geophys. J. R. astr. Soc.*, **19**, 351–360.

Ade-Hall, J. M. & Wilson, R. L., 1969. Opaque petrology and natural remanence of the Mull lavas, *Geophys. J. R. astr. Soc.*, **18**, 333–352.

Ade-Hall, J. M., Wilson, R. L. & Smith, P. J., 1965. The petrology, Curie points and natural magnetizations of basic lavas, *Geophys. J. R. astr. Soc.*, **9**, 323–336.

Baker, B. H., Mohr, P. A. & Williams, L. A. J., 1972. Geology of the Eastern Rift System of Africa, *Geol. Soc. Am. Special Paper*, **136**.

Baker, B. H., Williams, L. A. J., Miller, J. A. & Fitch, F. J., 1971. Sequence and geochronology of the Kenya rift volcanics, *Tectonophys.*, **11**, 191–215.

Berggren, W. A., 1969. Cenozoic chronostratigraphy, planktonic foraminiferal zonation and the radiometric time scale, *Nature*, **224**, 1072–1075.

Brock, A., 1970. A survey of palaeomagnetic results from the Tertiary of East Africa, *Proc. E. Afr. Acad.*, **8**, 49–54.

Brock, A., 1971. An experimental study of palaeosecular variation, *Geophys. J. R. astr. Soc.*, **24**, 303–317.

Brock, A., Gibson, I. L. & Gacii, P., 1970. The palaeomagnetism of the Ethiopian flood basalt succession near Addis Ababa, *Geophys. J. R. astr. Soc.*, **19**, 485–497.

Doell, R. R., 1972. Palaeomagnetism of lava flows from Kauai, Hawaii, *J. geophys. Res.*, **77**, 862–876.

Doell, R. R. & Cox, A., 1972. The Pacific geomagnetic secular variation anomaly and the question of lateral uniformity in the lower mantle, in *The nature of the solid earth*, ed. E. C. Robertson, McGraw–Hill, New York.

Evans, A. L., Fairhead, J. D. & Mitchell, J. G., 1971. Potassium-argon ages from the volcanic province of northern Tanzania, *Nature Phys. Sci.*, **229**, 19–20.

Fairhead, J. D., Mitchell, J. G. & Williams, L. A. J., 1972. New K/Ar determinations on rift volcanics of S. Kenya and their bearing on age of rift faulting, *Nature*, **238**, 66–69.

Grommé, C. S. & Hay, R. H., 1963. Magnetization of Bed I Olduvai Gorge, Tanganyika, *Nature*, **200**, 560–561.

Grommé, C. S., Reilly, T. A., Mussett, A. E. & Hay, R. H., 1971. Palaeomagnetism and potassium-argon ages of Pleistocene volcanic rocks of Ngorongoro caldera, *Geophys. J. R. astr. Soc.*, **22**, 101–105.

Irving, E., Molyneux, L. & Runcorn, S. K., 1966. The analysis of remanent intensities and susceptibilities of rocks, *Geophys. J. R. astr. Soc.*, **10**, 451–464.

McElhinny, M. W., 1972. Palaeomagnetic directions and pole positions XII *Geophys. J. R. astr. Soc.*, **27**, 237–257.

McElhinny, M. W., 1973. *Palaeomagnetism and plate tectonics*, Cambridge University Press, Cambridge.

D

McElhinny, M. W., Briden, J. C., Jones, D. L. & Brock, A., 1968. Geological and geophysical implications of palaeomagnetic results from Africa, *Rev. Geophys.*, **6**, 201–238.

McElhinny, M. W., Embleton, B. J. J. & Wellman, P., 1974. A synthesis of Australian Cenozoic palaeomagnetic results, *Geophys. J. R. astr. Soc.*, **36**, 141–151.

McElhinny, M. W. & Wellman, P., 1969. Polar wandering and seafloor spreading in the southern Indian Ocean, *Earth Planet. Sci. Lett.*, **6**, 198–204.

Mussett, A. E., Reilly, T. A. & Raja, P. K. S., 1964. Palaeomagnetism in East Africa—a progress report, *Proc. E. Afr. Acad.*, **2**, 27–35.

Nairn, A. E. M., 1964. Palaeomagnetic measurements on Karroo and post Karroo rocks: a second progress report, *Overseas Geol. Min. Res. Gt. Brit.*, **9**, 302–320.

Patel, J. P. & Gacii, P., 1972. Palaeomagnetic studies of the Kapiti phonolite of Kenya, *Earth Planet Sci. Lett.*, **16**, 213–218.

Radhakrishnamurty, C., Sahasrabudhe, P. W. & Raja, P. K. S., 1968. On the magnetic memory phenomenon in rocks and its bearing on palaeomagnetic measurements, *Pure appl. Geophysics*, **70**, 94–104.

Radhakrishnamurty, C., Raja, P. K. S., Likhite, S. D. & Sahasrabudhe, P. W., 1972. Problems concerning the magnetic behaviour and determination of Curie points of certain basalts, *Pure appl. Geophysics*, **93**, 129–140.

Raja, P. K. S., 1968, *A Palaeomagnetic study of some East African rocks*, PhD Thesis, University of London.

Raja, P. K. S., Reilly, T. A. & Mussett, A. E., 1966, Palaeomagnetism of the Turkana lavas, *J. geophys. Res.*, **71**, 1217–1222.

Raja, P. K. S. & Vise, J. B., 1973. Palaeomagnetism of the Tororo Ring Complex, S. E. Uganda, *Earth Planet Sci. Lett.*, **19**, 438–442.

Reilly, T. A., 1970. *Some palaeomagnetic results from central East Africa and the Seychelles Islands*, PhD Thesis, University of London.

Tarling, D. H., 1966. The magnetic intensity and susceptibility distribution in some Cenozoic and Jurassic basalts, *Geophys. J. R. astr. Soc.*, **11**, 423–432.

Watkins, N. D., 1972. Hemispherical contrasts in support for the offset dipole hypothesis during the Brunhes epoch; the case for an unequal co-axial dipole pair as a possible geomagnetic field source, *Geophys. J. R. astr. Soc.*, **28**, 193–212.

Watkins, N. D. & Haggerty, S. E., 1968. Oxidation and magnetic polarity in single Icelandic lavas and dykes, *Geophys. J. R. astr. Soc.*, **15**, 305–315.

Watson, G. S. & Beran, R. J., 1967. Testing a sequence of unit vectors for serial correlation, *J. geophys. Res.*, **72**, 5655–5659.

Wilson, R. L., 1970. Permanent aspects of the Earth's non-dipole magnetic field over Upper Tertiary times, *Geophys. J. R. astr. Soc.*, **19**, 417–438.

Wilson, R. L., 1971. Dipole offset—the time average palaeomagnetic field over the past 25 million years, *Geophys. J. R. astr. Soc.*, **22**, 491–504.

Wilson, R. L., 1972. Palaeomagnetic differences between normal and reversed field sources, and the problem of far-sided and right-handed pole positions, *Geophys. J. R. astr. Soc.*, **28**, 295–304.

Wilson, R. L., Dagley, P. & McCormack, A. G., 1972. Palaeomagnetic evidence about the source of the geomagnetic field, *Geophys. J. R. astr. Soc.*, **28**, 213–224.

Wilson, R. L. & McElhinny, M. W., 1974. Investigation of the large scale palaeomagnetic field over the past 25 million years. Eastward shift of the Icelandic spreading ridge, *Geophys. J. R. astr. Soc.*, **39**, 571–586.

Wilson, R. L. & Watkins, N. D., 1967. Correlation of magnetic polarity and petrological properties in Columbia Plateau basalts, *Geophys. J. R. astr. Soc.*, **12**, 404–424.