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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

# Volcanism of the Kenya Rift Valley [and Discussion]

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*Phil. Trans. R. Soc. Lond. A* 1972 **271**, 185-208
doi: 10.1098/rsta.1972.0006

*Phil. Trans. R. Soc. Lond.* A. **271**, 185–208 (1972) [ 185 ]
*Printed in Great Britain*

# Volcanism of the Kenya rift valley

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The Kenya rift valley is a sector of the rift system of eastern Africa which is marked by volcanic activity throughout its history from Miocene times to the present day. Activity is not confined to the rift zone but extends for distances of 200 km or more both to the west and east and is broadly centred on the Kenya 'dome', a topographic culmination in the course of the rift.

The volcanic rocks show a considerable diversity of compositions ranging from basic to acid, but all are characteristically alkaline varying, however, from a mildly alkaline, alkali basalt–trachyte series, to strongly alkaline and undersaturated nephelinites and phonolites. The mode of extrusion and form of the volcanic accumulations are also very varied, evidently dependent in part on composition. There are thus the widespread 'plateau' phonolites of central and southern Kenya, possibly fissure eruptions; the large nephelinite central volcanoes of eastern Uganda, including Mt Elgon, and western Kenya; and the giant phonolite–trachyte or basalt–phonolite–trachyte volcanoes of Mts Kenya and Kilimanjaro. Extensive basalt fields were variously the products of fissure eruption, such as those of Samburu, or derived from numerous small centres as in the Nyambeni area or the Chyulu Hills. Large low-angle cones in the northern part of the rift are formed mostly of trachyte flows, whereas the axis of the rift is marked by a series of conspicuous trachyte–basalt volcanoes, often with spectacular calderas.

The composition of the volcanic rocks shows variations with time, possibly indicating a dependence on the structural evolution of the rift, but sequences are not simple and cannot be easily defined. The nephelinite volcanoes of eastern Uganda are of Miocene age, but this composition also characterizes recent volcanoes of northern Tanzania. The basalt–basanite association dominates the earliest volcanic rocks of the rift zone itself, but has been repeatedly represented to the present. The flood phonolites were, however, largely confined to the upper Miocene; the Pliocene and earlier Pleistocene were marked by great eruptions of trachyte lavas and ignimbrite, whereas acid volcanic rocks, comendites and pantellarites, of Quaternary age are limited to a small area in the central part of the rift.

The total volume of volcanic rocks cannot be estimated with any accuracy, but may be of the order of several 100000 $km^3$.

The second part of this account presents in preliminary form the results of field mapping and chemical analytical programmes on the Cainozoic volcanics of the northern Kenya rift. It is shown that in this sector there is a distinct petrochemical evolution from the Miocene to the Pleistocene, the general trend being a decrease in silica undersaturation in both mafic and felsic rocks. The succession of lavas and sediments has a maximum thickness of 3 km and the main unconformities, indicating the major faulting episodes, coincide with the petrochemical changes.

In this contribution the first part consists of a general synthesis by the first-named author (B. C. K.) of the volcanic history of the Kenya rift, necessarily largely based on a wide range of source material, while the second is a preliminary account by the other author (G. R. C.) of a region in the northern part of the rift valley which has recently been closely investigated and is thus well documented in stratigraphic, petrological and chemical terms.

## PART I

### Introduction

The Kenya (or Gregory) rift valley is a sector of the rift system of eastern Africa which has been marked by continuous volcanic activity from Miocene times to the present day. The volcanic region is broadly centred on the Kenya 'dome', a topographic culmination in the course of the rift; it passes southwards into northern Tanzania and northwards is continuous with the margin of the comparable, but even more extensive volcanic region of the Ethiopian 'dome'. The volcanic rocks extend for more than 1000 km along the Gregory rift, but are by no means confined to the rift itself and have a maximum width of 500 km across the Kenya 'dome'.

## General nature of the Kenya rift

The rift approximates along much of its course to a graben, 50 to 90 km across, with aggregate displacements amounting to 2 km or more, although in detail the structures are always more

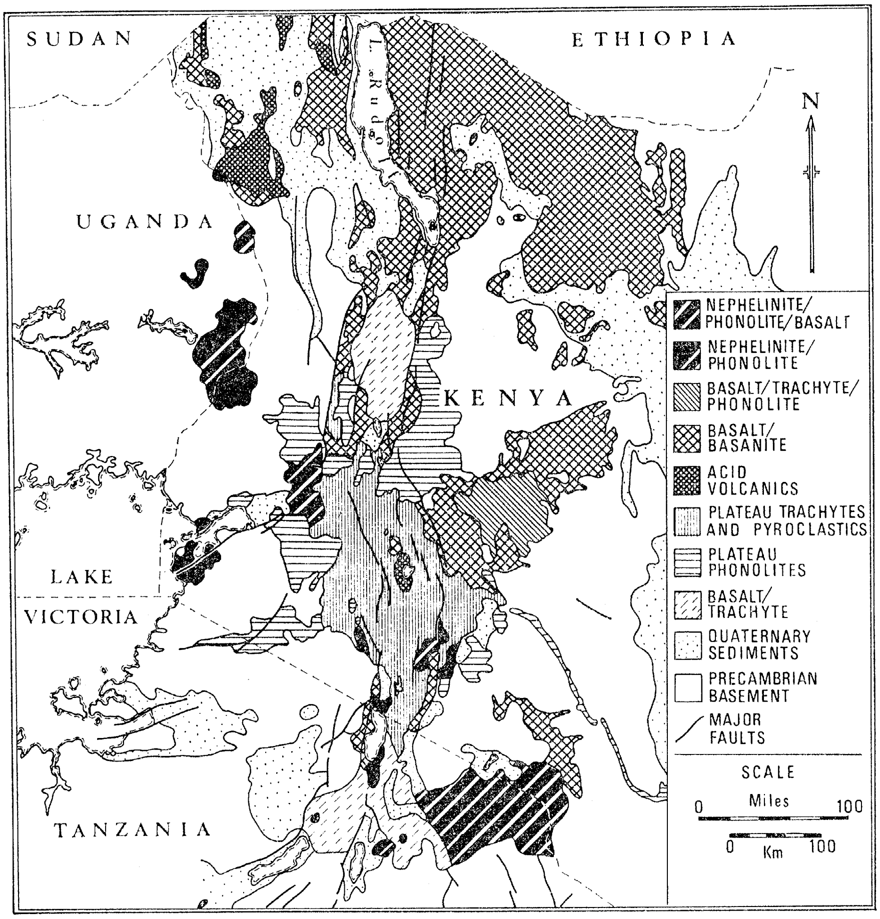


Figure 1. The distribution of the principal types and associations of volcanic rocks in the Kenya–Tanzania sector of the eastern rift. (Map compiled by L. A. J. Williams, whose permission to use it is gratefully acknowledged.)

complicated; only rarely has most of the movement occurred along a single bounding fault; more often there are step faults of varying magnitude, and subsidiary horsts and graben are not uncommon, while in some places the rift is bounded by monoclinal downwarps. Characteristically the rift zone is one of intense faulting, with individual displacements varying from metres to thousands of metres; the faults are normal and hading steeply, so that total extensions of no more than a few kilometres may be inferred. Typically there is a 'rise to the rift' and indeed in many places uplift of the shoulders has been more significant than subsidence of the floor. Structural and stratigraphic data also show that much of the present topographic relief was a comparatively late feature in the development of the rift, mostly dating from the Pleistocene,


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and that at earlier stages accumulation of volcanics and sediments largely or even wholly infilled the depression despite repeated rift movements.

Northwards around Lake Rudolf by a succession of splay faults and downwarps the rift zone widens to an ill-defined feature some 200 km across and only the narrow 'axial' trough passes via Lake Stephanie into the main Ethiopian rift, which again is essentially a typical graben, extraordinarily reminiscent of that of central Kenya. Southwards, too, in Tanzania the rift widens by splay faulting and merges into a broad zone of tilted blocks.

Both structurally and petrographically, the volcanic rocks associated with the Kenya rift show great variety (figure 1), in marked contrast to the comparative uniformity of the volcanic rocks of the Baikal rift system (Logachev 1968). All are, however, alkaline and typically soda-rich, but two genetic series have been distinguished; one strongly alkaline and nepheline-bearing (melanephelinite–nephelinite); the other mildly alkaline and without modal nepheline (alkali basalt–trachybasalt–trachyte–soda rhyolite) (Saggerson & Williams 1964; King & Sutherland 1960; Wright 1965, 1970). The series show extensive ranges in composition from melanocratic to leucocratic or basic to acid. With increase in available chemical data the contrast between the two series is becoming less apparent and it is possible that there are a number of intermediate trends more or less strongly alkaline in character. Again although continuous ranges in composition are shown by variation diagrams, some compositions are sparingly represented; there are in effect compositional hiatuses. Correspondingly certain groups of volcanic rocks show a remarkable uniformity of composition; particularly notable in this respect are the very voluminous 'plateau' phonolites.

The volcanic rocks assume a great diversity of form and include central volcanoes of a variety of dimensions and structures as well as 'flood' eruptions, both of multicentre and fissure types. Their eruption shows no very close connexion with actual faults or tectonic events, although the most continuous volcanic sequences and greatest thicknesses are confined to the rift itself. The largest of the central volcanoes are indeed on the flanks of the rift, but whereas those to the west are Miocene in age, those to the east are mainly Pleistocene to Recent.

## History of development

The evolution of the Kenya rift valley is becoming increasingly fully documented by means of well-established stratigraphic successions and faunal evidence from numerous occurrences of sediments, as well as isotopic data enabling wider correlations to be attempted. Structural and geomorphological information is also of considerable significance.

The pattern of the early drainage in East Africa suggests that it must have originated on a well-planed erosion surface on which the major continental divide lay roughly along the line of the present Kenya rift. A zone of deep weathering accompanied by lateritization was formed during the reduction of this surface, which is especially well preserved throughout central, western and southwestern Uganda, as the 'Buganda Peneplain' (Wayland 1930), a surface which is rarely flat, but undulates over more resistant formations. It evidently represents the effects of prolonged chemical weathering under stable tectonic conditions. Present evidence suggests that this surface is not younger than end-Mesozoic (cf. Bishop & Trendall 1967; King 1970). Residual hills and bevels in Kenya have long been ascribed to a Cretaceous erosion surface (Saggerson & Baker 1965) which is the probable correlative of the Buganda Surface (King 1970).

Arching over the sites of the future western and eastern rifts during the early Tertiary, accompanied by local faulting and warping, led to active erosion especially in eastern Uganda and western Kenya, the products of which include the Miocene sediments that are widely distributed in depressions and valleys of the varied landscape and are mainly preserved beneath later volcanic rocks. Although at this stage the older drainage pattern was not disrupted, accelerated erosion in the vicinity of the rift arch in Kenya led to the rapid dissection and removal of most of the early erosion surface, in contrast to its more extensive preservation where it was uptilted towards the western rift (King 1970, p. 269).

The earliest igneous activity which may be regarded as associated with the development of the Kenya rift is represented by a number of small alkaline complexes, typically of ijolite and carbonatite, which occur along a NNE–SSW line about 100 km in length in southeastern Uganda (Davies 1956; King & Sutherland 1966). Although available isotopic data show a considerable scatter, an Oligocene age appears probable (N. J. Snelling, personal communication). They formed sharply defined domes in the 'basement', and whether or not extrusive rocks were originally present, the intrusive members had already been exposed by erosion before the build-up of the Miocene volcanoes.

### *Miocene volcanoes of eastern Uganda and western Kenya*
(King, Le Bas & Sutherland 1971)

A series of large dissected volcanoes extends southwards through eastern Uganda into western Kenya (figure 2). All form very low angle cones, whether, like Elgon, Kadam and Napak they consist predominantly of pyroclastics, or like Moroto and Kisingiri of lavas. Mt Elgon is the largest: it rises about 3000 m above the surrounding plains and must originally have had a basal diameter of about 100 km. All the volcanoes are of simple central-type and their very uniform structures suggest virtually continuous eruption with few intermissions of erosion. The lavas were evidently very mobile, while the pyroclastics are often in very thick units. Elgon, Kadam and Napak consist chiefly of nephelinites and melanephelinites, including olivine- and melilite-bearing varieties; phonolites and trachybasalts also occur. Kisingiri is formed wholly of melanephelinites and nephelinites, often with melilite. On Moroto (Macdonald 1961; Varne 1966) nephelinites are subordinate to olivine basalt and trachybasalt, while phonolites, basanites and tephrites are recorded. Yelele (Nixon & Clark 1967) again shows nephelinite most abundantly, but in addition phonolite, tephrite, basanite and trachyte occur. Dissection has revealed a central mass of ijolite and carbonatite at Napak and the same association, together with uncompahgrite, occurs at Kisingiri, while ijolite is also seen in the central erosion 'caldera' of Moroto. Toror (Dubois 1959; Sutherland 1965) is inferred to be the remains of a volcano of the same series from which all extrusive formations have been removed by erosion, but the predominant intrusives are carbonatite and phonolite breccia, with only minor nephelinite.

From basal sediments or tuffs associated with many of these volcanoes prolific mammalian faunas have been collected, indicating a Miocene age (cf. Bishop 1967). Large numbers of isotopic age determinations have been made on lavas and minerals from intrusive rocks (Bishop, Miller & Fitch 1969; Baker, Williams, Miller & Fitch 1971; N. J. Snelling, personal communication 1971). The results show such wide discrepancies that undue reliance cannot be placed on any conclusions that have been drawn; Bishop *et al.* infer ages of basal formations of about 22 Ma for Elgon, 19 to 22 Ma for Kisingiri, 19 Ma for Napak and no more than 12.5 Ma for Moroto. Baker *et al.* suggest a range of activity for Elgon and Kisingiri of between 15 and

22 Ma. The complex volcano of Tinderet at the eastern end of the Kavirondo trough commenced as a pyroclastic nephelinite-melanephelinite volcano. Accepted ages of tuffs of 19.5 Ma associated with basal fossiliferous formations, containing Miocene faunas, are in the same general range (Bishop *et al.* 1969).

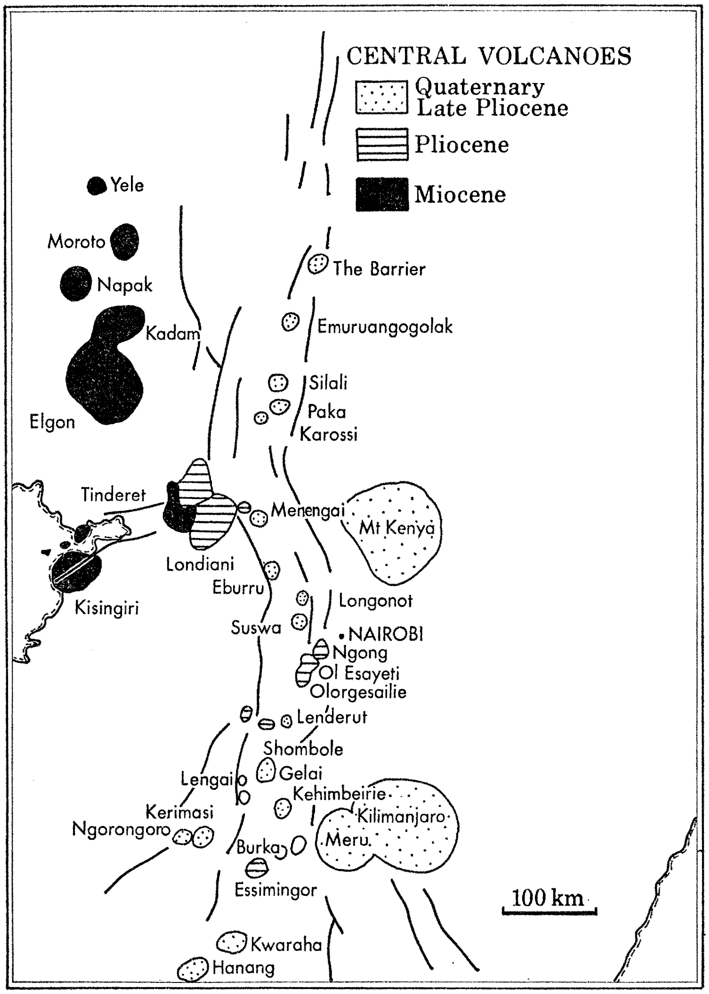


FIGURE 2

*Miocene basalts* (group I, p. 200)

These are the oldest volcanic rocks of the Kenya rift, but are confined to the northern part, extending little farther south than Lake Hannington (figure 3). It is possible that their distribution is largely coextensive with the earliest areas of relative subsidence in the rift zone. In many places their base is unexposed; in others they are seen to rest directly on basement, but particularly in western Turkana, where they are especially extensive, they overlie a sedimentary formation, often of considerable thickness, which reflects the result of vigorous erosion consequent upon the downwarp of the Turkana escarpment and initiation of the Elgeyo fault.

West of Lakes Baringo and Hannington basalts formerly included in this group have been shown to be considerably younger (Martyn 1969; S. J. Lippard, unpublished report), but the Elgeyo basalts (Walsh 1969) which have a restricted outcrop at the head of the Kerio valley can be ascribed to this group since they overlie the basement and are overlain by the 'plateau' phonolites.

On the eastern side of the rift the Samburu basalts also underlie the 'plateau' phonolites and the same relationship obtains southwards in Laikipia and to the east of Lake Hannington, but it is clear than considerable faulting and erosion intervened between these two volcanic groups (J. N. Carney, M. Golden, unpublished reports). In this region there is evidence that

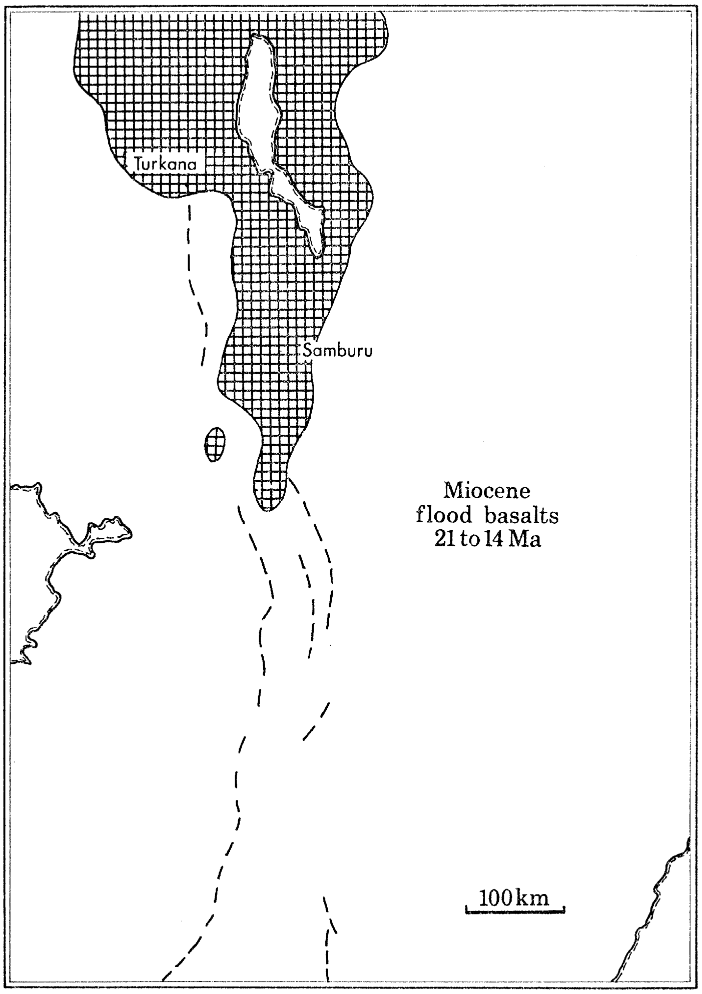


FIGURE 3

the basalts were erupted from a great number of limited areas of closely spaced dyke swarms around which the greatest aggregate thicknesses of flows were developed, while individual flows are not traceable over long distances.

No direct connexion exists between the basalts of Samburu and those of Turkana, although a correlation has been assumed (Joubert 1966; Walsh & Dodson 1969). The isotopic age determinations make this a plausible assumption, except that the time ranges are extremely wide. For the Turkana basalts ages from 32 to 14 Ma have been determined; for the Samburu basalts 23 to 18.8 Ma, and for the Elgeyo basalts about 15 Ma. An additional value for the Turkana basalts resting on Turkana grits at Kapchererat of 15.7 ± 0.6 Ma which occur below Kawun trachytes dated at 15.2 ± 0.5 Ma is acceptable within this range (N. J. Snelling, personal communication).


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There is no doubt that the isotopic dating of basalts in particular often yields discrepant results, the reasons for which are not understood. Thus the range of the Turkana–Samburu basalts accepted by Baker *et al.* of 14 to 23 Ma as plausible overlaps very widely with the stratigraphic and geomorphological events established for the Miocene central volcanoes and those in the Kamasia Range in Baringo.

Associated with or later than the basalts, but earlier than the 'plateau' phonolites, are a group of older phonolitic volcanoes below the Laikipia escarpment, to the north of Tangulbei, and the dissected phonolitic volcano of Murgomul farther to the north, with a central intrusive mass of syenite and microsyenite (J. S. C. Sceal, M. Golden, unpublished reports). Nephelinite dykes, microfoyaite intrusions and phonolite flows are emplaced in the Miocene basalts at a number of localities to the southwest of Lake Rudolf (Williams 1969).

*Plateau phonolites* (group II, p. 200)

Extensive plateau areas extending for considerable distances on either side of the rift and roughly coextensive with the central part of the Kenya dome, are covered by phonolites (figure 4). These evidently originated within the rift zone but flooded over the shoulders after the early rift depression had been infilled by the older volcanic rocks and sediments. They spread widely as thin flows after submerging most of the irregularities of the subvolcanic basement surface. Although there are some variations, they are rather uniform in type and are mostly dark flinty rocks in which occur more or less conspicuous phenocrysts of alkali feldspar and nepheline. They were evidently extremely mobile lavas, but may well have been erupted very rapidly and voluminously from a small number of central sources, rather than from numerous fissures as has commonly been postulated (see also p. 201).

The Mau phonolites extend for more than 150 km to the west, while the Yatta lava, only 10 to 15 m thick, flowed over 300 km down a former valley towards the coast.

Isotopic ages of the plateau phonolites mostly fall within a very restricted range from 12 to 13.5 Ma, but values down to $10.7 \pm 0.3$ Ma have been obtained for Rumuruti phonolites (N. J. Snelling, personal communication). The phonolite succession here differs greatly from that in the Elgeyo escarpment, so that variations in age among the plateau phonolites are not unexpected. In the Kamasia Range, within the rift, a succession 2300 m in thickness, of which phonolites make up 1600 m, is seen to rest on basement. Isotopic dates, which correlate well with the stratigraphic sequence, range from about 16 to 7 Ma. Thus flows which correspond to those of the Uasin Gishu plateau occur in the middle of the Kamasia sequence testifying to the continued subsidence of the rift floor after the extrusion of the main 'flood' phonolites (figure 10).

The plateau phonolites are characteristically mantled by a zone of deep weathering passing upwards into lateritic soil and laterite, which also extends over adjacent areas of basement, as between Eldoret and Kitale and from Kericho southwards. This appears to be traceable into the 'end-Tertiary' lateritized surface of western Kenya and Uganda where it planes basal volcanic rocks and forms valley floors within the dissected Miocene volcanoes. Eastwards it can be followed from the neighbourhood of Nairobi to the coast. In many places it has been removed by subsequent dissection (see also later, p. 201).

An important period of rift faulting succeeded the eruption of the phonolites, the relations being especially clear in the Kamasia Range and in Laikipia. South of Lake Hannington the phonolites are traceable almost continuously in horst strips across the rift.



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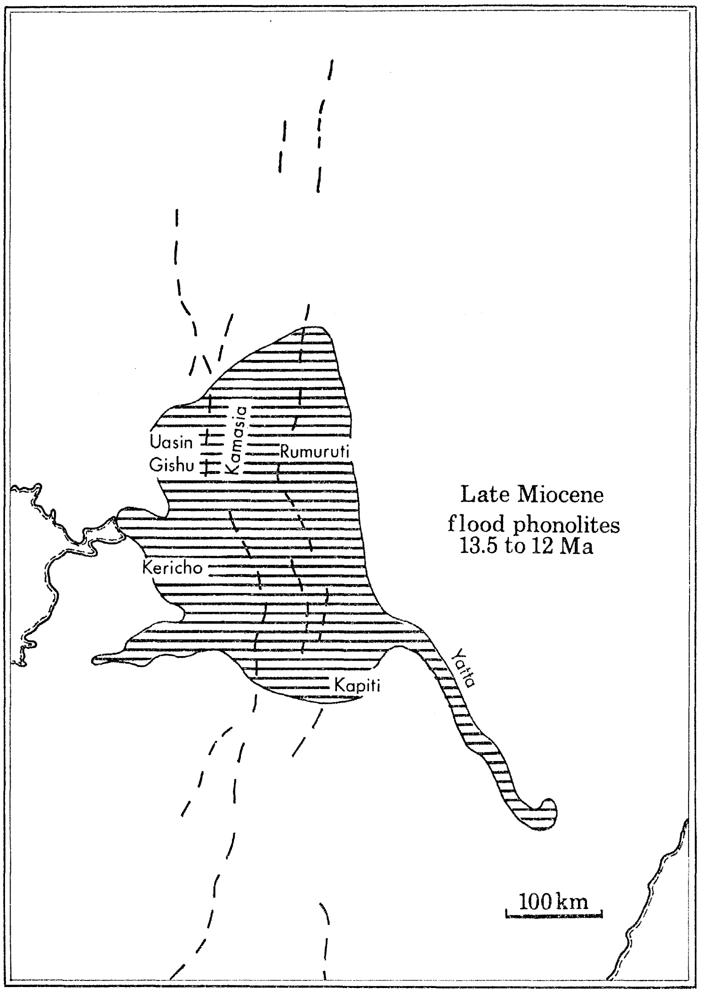


FIGURE 4

*Pliocene 'flood' trachytes and basalts* (group III, p. 201)

The Kabarnet trachytes (see later, p. 201) to the west of Lake Baringo rest unconformably on the faulted and eroded phonolites of the Kamasia range and are dated at 6.7 to 7 Ma (Baker *et al.* 1971; Snelling, personal communication) (figure 5). In the area of the Amaya river on the eastern side of the rift, trachytes infill valleys deeply dissected into the older phonolites and basalts. Similar ages are given by the Thomson's Falls phonolite, while by inference the earlier volcanic rocks of the Nairobi area are included in this group (Williams 1967) (figure 5).

Pliocene basalts are among the earliest volcanic rocks of the southern parts of the rift where they are mostly preserved in marginal fault steps and directly overlying basement across the rift in Tanzania (figure 6). Here basanites, tephrites, nephelinites and phonolites are also associated. The Kirikiti basalts which overlie nephelinites yield isotopic ages of around 5 Ma (Baker *et al.* 1971; Evans, Fairhead & Mitchell 1971). Inferentially they underlie much of the central rift, but the Aberdare volcanics on the eastern flanks, rising to a height of over 4000 m consisting largely of basalts with overlying phonolites, basalts and mugearites, on the basis of one isotopic date of about 5.5 Ma also belong to this period of activity (Baker *et al.* 1971). The main part of the Aberdare range appears to be a broad volcanic pile of central type. In the northern part of the rift the extensive Kaparaina basalts, stratigraphically well established as overlying Kabarnet trachytes, yield an age of 5.3 Ma from an intercalated trachyte (N. J. Snelling, personal communication). There is evidence that their greatest development is associated with close concentrations of dykes (Martyn 1969), so that there is no clear distinction between 'central' and 'plateau' or 'flood' type eruptions. Other areas of basalts, such as that in eastern Turkana are tentatively correlated with this group (Baker *et al.* 1971).

*Pliocene central volcanoes*

The Tinderet–Timboroa–Londiani complex of volcanoes at the junction of the Kavirondo trough with the main rift has not as yet been fully investigated, but it is clear that the earliest

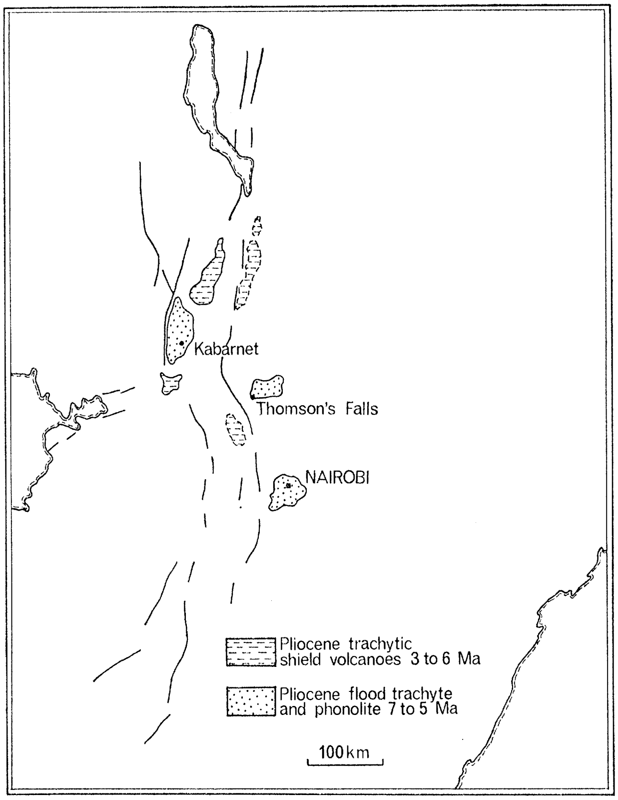


FIGURE 5

elements of the Tinderet volcano predated the plateau phonolites, while its final build-up and the formation of the other two centres was largely if not entirely later (figure 2). A great range of compositions is represented: nephelinites, phonolites, basanites and trachytes. Dates of around 5.6 Ma have been obtained from the terminal basanites of Tinderet (Baker *et al.* 1971). An observation of significance is that the mantle of deep lateritic weathering passes across the low-angle Timboroa and Tinderet volcanoes and is only absent where dissection has occurred towards the head of the Kavirondo trough.

In the northern part of the rift the discovery of large, low-angle trachytic volcanoes has again


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emphasized the difficulty of drawing a clear distinction between 'plateau' and 'central-type' volcanics (figure 5). These range in composition from slightly undersaturated to significantly oversaturated and it is possible that further detailed investigation northwards into Turkana would show that many areas of 'rhyolites' and 'trachyandesites' are of similar type and structure (Baker *et al.* 1971; S. D. Weaver, personal communication). These volcanoes were built up on

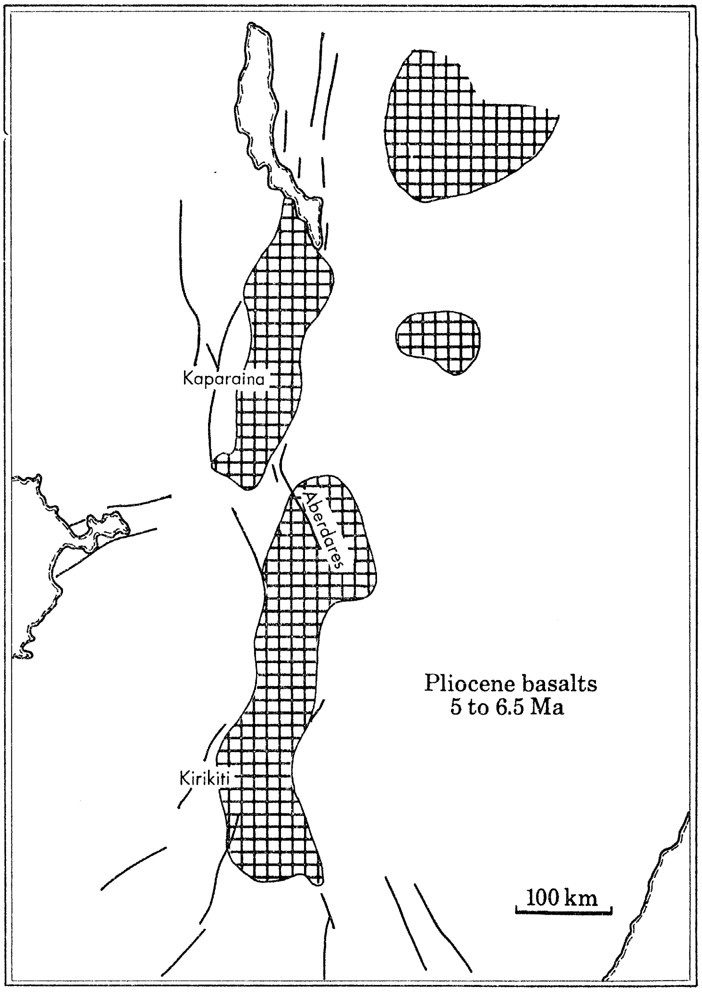


FIGURE 6

the down-faulted older volcanic rocks and a sequence among them is demonstrable (M. P. McClenaghan, P. K. Webb, S. D. Weaver, S. Rhemtulla, unpublished reports). They are largely later than the Kaparaina basalts, but basalts and trachybasalts often occur, mostly as initial or terminal phases, aiding in the distinction between particular volcanoes. An age range for these volcanoes from about 6 to 3 Ma has been established (N. J. Snelling, personal communication). Very similar is the recently discovered Kapkut trachytic volcano, also later than the Kaparaina basalts, to the south of the Kamasia Range (S. J. Lippard, unpublished report), while a Pliocene age is inferred for the trachytic caldera volcano of Kilombe to the east of Londiani (Baker *et al.*).

The dissected volcanoes of Olorgesailie, Ol Esayeiti, Ol Esakut and Ngong on the floor or


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eastern flanks of the rift to the southwest of Nairobi predate the Pleistocene flood trachytes (figure 2). They consist of varying proportions of basalts, nephelinites, phonolites and trachytes. Available isotopic dates suggest a range of 5 to 7 Ma (Baker *et al.*). Numerous similar volcanoes extend across the Kenya border into northern Tanzania and have been recognized as falling into an older and younger group from their relations to faulting, but recent isotopic data suggest a more continuous range of ages from about 5 Ma to less than 1 Ma, several being younger than was formerly thought; thus Lenderut, Gelai, Ketumbeine and Buiko yield ages of no more than 1 to 1.5 Ma (Evans *et al.* 1971). The volcanoes vary considerably in size, but are typically steep-sided cones rising to heights of 1000 m or more from their bases (figure 2).

### *Plio-Pleistocene trachytes*

Most of the floor of the central and southern parts of the rift is occupied by lavas and tuffs, often welded, of trachytic composition (figure 7). Tuffs and, locally, lavas occur sporadically on the flanking plateaux. Their wide distribution and general similarity throughout the region has led to their being regarded as of equivalent ages and, indeed, as an important horizon for correlation between the eastern and western sides of the rift (Williams 1965). Broadly a twofold

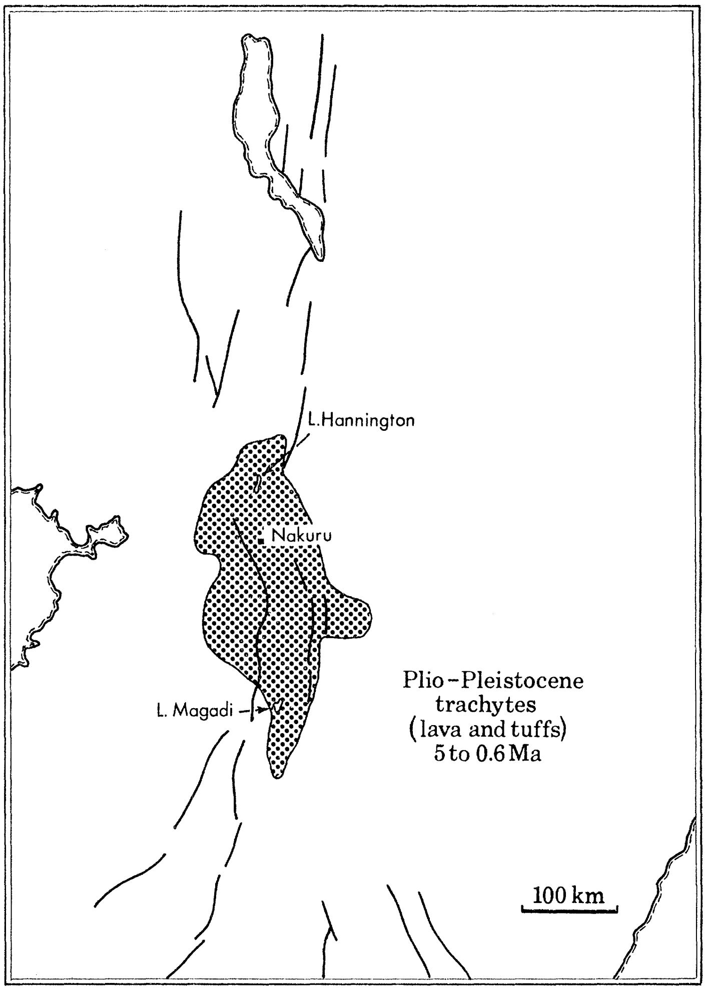


FIGURE 7

division into a lower part chiefly formed of tuffs and an upper part composed of trachyte lavas has been recognized (Williams 1969; Baker *et al.* 1971). Doubt as to the correlation of the widely scattered occurrences of tuffs is suggested by the fact that those of the Kedowa and Eldama Ravine area in the northwest and those around Nyeri, Fort Hall and Thika in the east are mantled by lateritic soil profiles, whereas those around Mau and Narok, on the Kinangop plateau and in the Bahati area, as well as those occurring on the floor of the rift, do not show such weathering and, indeed, can in places be seen to overlie lateritic soils which have developed from the older volcanic rocks and basement. The age range provisionally established as wide as from 2 to 5 Ma is therefore not surprising, but data are scant (Baker *et al.* 1971).

In the Lake Baringo–Lake Hannington area the Eldama Ravine tuffs infill a dissected topography in the Kaparaina basalts and older phonolites and are overlain by the Lower Pleistocene Chemeron beds, which in turn underlie members of the Dispei–Lake Hannington phonolites. The last named are widespread in this part of the rift and extend towards Laikipia in the east and towards Nakuru in the south (McCall 1967). They are better termed trachyphonolites (p. 201). A single isotopic age of $0.6 \pm 0.1$ Ma is currently available (N. J. Snelling, personal communication).

Trachytes also overlie the tuff sequence in the Gilgil–Nakuru area, but they are most extensively developed as the 'plateau trachyte series' of the Magadi area, whence they can be traced into a number of trachyte members to the west of Nairobi. Isotopic ages of the plateau trachytes are in the range 1.7 to 0.6 Ma.

## Quaternary volcanism

As indicated above, many of the volcanoes of northern Tanzania range into the Pleistocene. Some, including volcanoes of both later Pliocene and Pleistocene to Recent ages, such as Essimingor, Mosonik, Kerimasi and Oldoinyo Lengai are notable for their strongly alkaline and undersaturated character, with nephelinites and melanephelinites. Pyroclastics rather than lavas build the steep-sided cones. Extrusive carbonatites characterize the last three named and Lengai has erupted carbonatite ash and natro-carbonatite flows in recent years. Blocks of ijolite and related alkaline plutonic rocks are brought up as pyroclasts. In the Kavirondo trough some of the carbonatite centres, including Homa Mountain, have been shown to have been active during the Pleistocene (King *et al.* 1971).

Of the two giant volcanoes to the east of the rift, Mt Kenya, built of phonolites and trachytes with late basalts, appears to be mostly late Pliocene in age (2 to 3.5 Ma) but activity probably extended into the Pleistocene, whereas the complex Kilimanjaro volcano, formed mainly of basalts, bananites, phonolites and trachytes, was wholly built up during the Pleistocene (1 Ma and less) (figure 2).

Most distinctive of the Quaternary activity in the rift is the series of trachytic (more rarely phonolitic) volcanoes, often with spectacular calderas, alined along the central trough or graben. These from south to north are Suswa, Longonot, Eburru, Menengai, Karossi, Pakka, Silali, Emuruangogolak and the 'Barrier' at the south end of Lake Rudolf. All of these also erupted basalts, often as late phases; Teleki's volcano, a basalt cone, on the flanks of the Barrier erupted at the end of the last century (figure 2).

Also of Quaternary age are the soda-rhyolites and tuffs which occupy a small area near Naivasha in the central part of the rift (figure 1).

Three extensive fields of basalts, erupted from numerous cones occur at distances of around 200 km to the east of the rift (figure 8). They are the Hurri hills in northern Kenya, the Nyambeni hills, to the northeast of Mt Kenya, and the Chyulu hills to the southeast of Nairobi. Some of the cones in the Chyulu hills, as judged from their perfect preservation, are very recent. The basalts clearly rest on the lateritic soil mantling the basement.

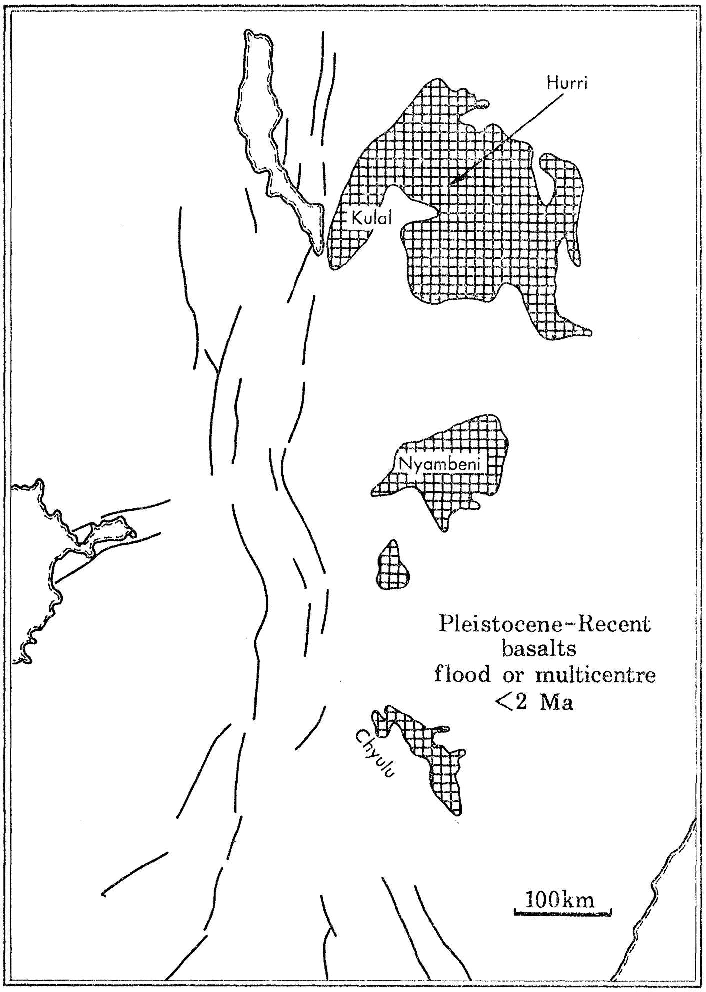


FIGURE 8

## LATER STRUCTURAL AND GEOMORPHOLOGICAL HISTORY

Although rift faulting has occurred from the Miocene onwards, in the central and southern parts of the rift there is evidence that much of the faulting that formed the present high relief is no older than the Pleistocene. The uplift of the shoulders of the rift is similarly largely a late feature.

Lateritic soil profiles occur on volcanic rocks no older than 4 to 5 Ma, although the deepest weathering mantles are on the plateau phonolites. An extensive period of formation is implied, and correspondingly prolonged periods when even within the rift zone relief was relatively low. Lateritic soils are elevated to 3000 m above the Elgeyo escarpment and to over 4000 m over the





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Aberdares, altitudes at which they are very unlikely to have formed originally. Such profiles are entirely absent from the Pleistocene volcanic rocks of the central and southern rift.

## Conclusions and summary

An effective account of volcanic events in the Kenya rift zone currently being presented (Baker *et al.* 1971) is largely a commentary based on the many new isotopic data that are now available. Other general statements are those by Williams (1969) and King (1970). The present account includes much that depends on currently unpublished work by members of the East African Geological Research Unit, and is greatly indebted to isotopic age determinations carried out by N. J. Snelling.

The main conclusions are:

(*a*) The earliest events related to the rift are the Miocene central volcanoes, mostly extremely alkaline, undersaturated and basic in composition, in eastern Uganda and western Kenya. The main age range is from 15 to 22 Ma.

(*b*) Volcanic events in the Kenya rift itself appear to have been initiated in the northern sector by alkali–basalt extrusion from central fissure activity. An overlap in time between these and the later phases of the eastern Uganda activity is inferred, notably that of Moroto Mountain, where the compositions of the volcanic rocks are similar. An age range of from 14 to around 20 Ma seems probable.

(*c*) Phonolites were erupted at least as early as 16 Ma in the Kamasia area of the northern part of the rift, but the main plateau phonolites were extruded during a relatively short range from 12 to 13.5 Ma over an area around the central to northern parts of the rift. The early rift at this stage appears to have been entirely infilled (figure 10).

(*d*) Active faulting and erosion followed a period of stability and the succeeding volcanic rocks of the Pliocene and Pleistocene show a significant change in composition in the northern rift, trachytes, often oversaturated, being characteristic, but there were important phases of basalt eruption (p. 201).

(*e*) Activity in the central part of the rift commenced with the main plateau phonolites, but in the southern sector it was even later, Plio–Pleistocene trachytes succeeding an initial phase of Pliocene basalt eruption.

(*f*) The development of peralkaline silicic volcanic rocks occurred in the Pliocene in the northern part of the rift, but not until the later Pleistocene in the central part.

(*g*) The numerous Plio-Pleistocene–Recent central volcanoes of southern Kenya and northern Tanzania show an extreme diversity of composition, often within a single volcano and the nephelinite–carbonatite association is seen even among the latest cones.

(*h*) In the northern and central parts of the rift both faulting and volcanic activity tend to become confined to a progressively narrower zone following the axis of the rift. This is most clearly shown by the series of late Quaternary volcanoes and the most recent grid faulting.

(*i*) Among the latest events were the multicentre basalts and the giant volcanoes well to the east of the rift zone.

Thus in general terms the earliest and latest volcanic activity occurred respectively on the western and eastern flanks of the rift; tectonic and volcanic events were initiated earlier in the northern part of the rift and progressed southwards; flood eruptions were characterized by great volumes of uniform compositions, but show a trend from undersaturated to


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oversaturated types in the course of time; many of the central volcanoes show great diversities of composition, suggesting differentiation in local reservoirs; both tectonic and volcanic events ultimately tended to be restricted to a narrow axial zone; and the development of the Kenya dome with uplift of the rift shoulders and the formation of the present rift valley landscape were largely related to events in the latest Pliocene and Pleistocene.

Estimates of the total volume of volcanic rocks are of the order of a few 100 000 km$^3$ (King 1970; Baker *et al.* 1971).

## PART II

### Introduction

The mapping programme carried out by the East African Geological Research Unit in the Baringo and south Turkana areas of the Kenya rift has to date covered an area of some 10 000 km$^2$ and a detailed reconstruction of the later Cainozoic history of this part of the rift can now be made. The results presented here include much unpublished information contributed by the writer's colleagues, in particular, Dr J. E. Martyn, J. N. Carney, Dr M. P. McClenaghan, J. S. C. Sceal, S. D. Weaver and Dr P. K. Webb.

### Stratigraphy

The Cainozoic succession attains a maximum observed thickness of 3 km, including 900 m of sediments, in the area to the west of Lake Baringo and from the areas as a whole it is proposed to erect a lithostratigraphic division into five major groups defined on the predominant petrology of the lavas (figure 9). Each group is composed of a number of provisionally named formations but for the sake of simplicity unpublished formation names are not used in the present account.

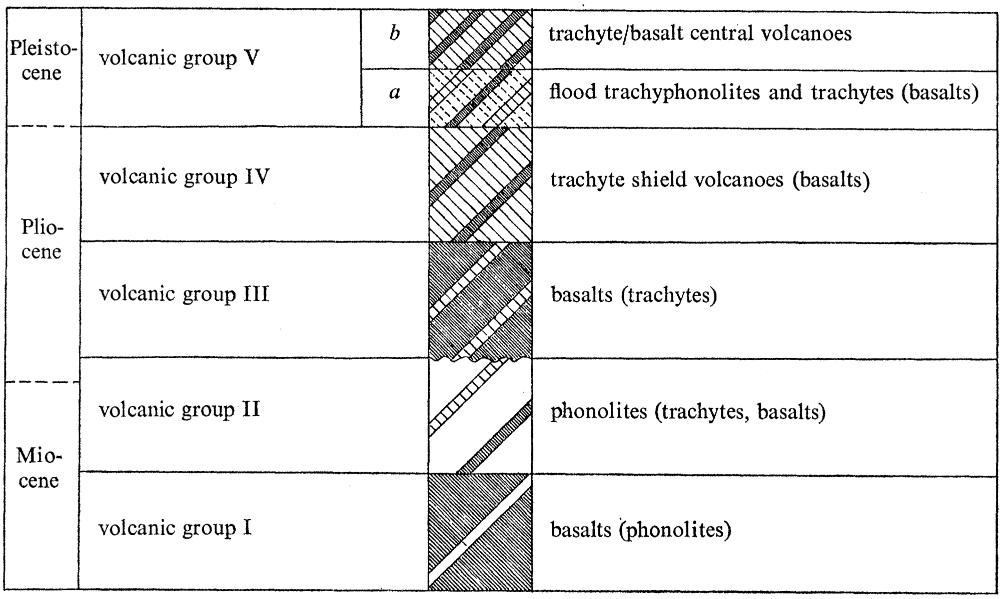


Figure 9. Stratigraphy of the northern Kenya rift volcanic rocks. Subordinate rock-types in parentheses.

*Group I*

This is composed chiefly of basaltic, basanitic and undersaturated intermediate lavas which crop out extensively in the north of the volcanic area. These include the 'Samburu basalts' of Shackleton (1946) and widespread basalts in Turkana (Baker 1963; Joubert 1966). The absence of group I basalts from most of the Elgeyo Escarpment and Kamasia Range (figure 10) can probably be related to the fact that those areas were almost certainly regions of early rift faulting and stood above the level of the flood basalts. A thick basaltic sequence, the base of which is not seen, occurs on the Laikipia Escarpment on the eastern side of the rift; in that area small elongate shield volcanoes with local dyke-swarms indicate some of the sources of the basalts.

*Group II*

This group comprises the 'plateau phonolites' which occur so extensively on the flanks of the rift. On the Kamasia Range (figure 10) these phonolite lavas alone have a total thickness of 1600 m which is far in excess of any sequence seen elsewhere in the province. This great thickness on the Kamasia, together with the presence of phonolitic pyroclastic centres and many syenitic plugs in the north of the area, suggests that the sources of the lavas may have included

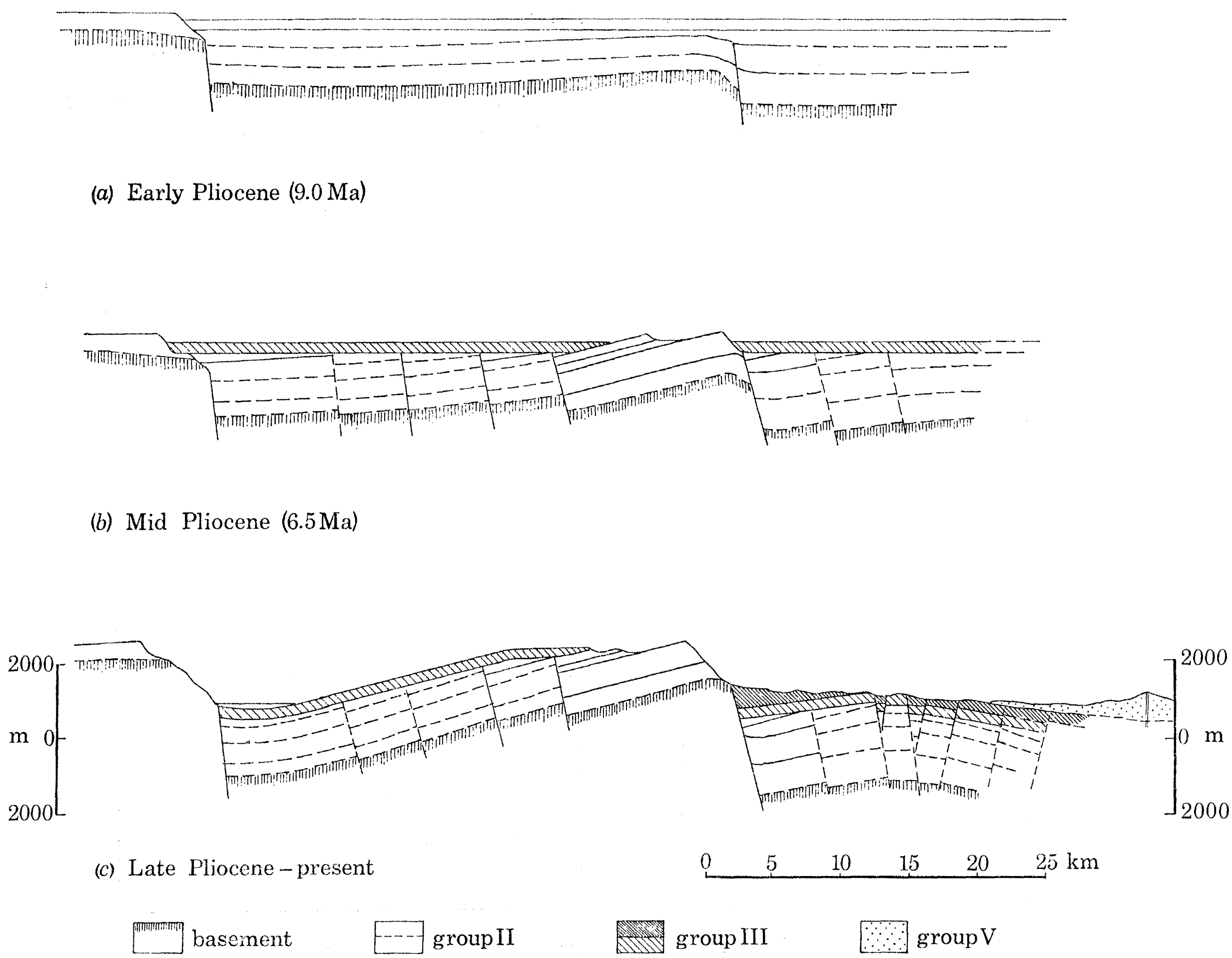


FIGURE 10. Development of the northern Kamasia range.

central or multicentre complexes well within the rift boundaries and now largely concealed by later volcanic rocks. Rift-shoulder fissure sources are usually postulated but have never been demonstrated despite the deep erosion of the phonolite succession on the rift shoulders.

Aphanitic phonolites, with abundant groundmass nepheline and, commonly, large feldspar and nepheline phenocrysts are not found in the rift volcanic rocks above this group.

While it is apparent that minor faulting occurred throughout the history of group II the accumulation of the group was terminated by a major faulting episode (figure 10*b*) amounting, on the largest faults, to nearly 1 km of near-vertical displacement. The faulting was followed by a considerable period of erosion which effected widespread planation of the faulted sequence and deep weathering of the phonolites before the eruption of the group III volcanic rocks.

### *Group III*

On the Kamasia the basal group III lavas are very extensive flood trachytes—the 'Kabarnet trachytes' of Walsh (1969); these are holocrystalline lavas with no indication of ignimbritic affinities. However, the most typical lavas of the group are olivine-basalts, with smaller amounts of hawaiites and mugearites, totalling up to 600 m in thickness. It is in general a 'flood' sequence but, as in the older basalt group, local multicentre foci with linear dyke-swarms have been located.

### *Group IV*

This is the most local of the groups (it is absent at the latitude of figure 10), but is impressively developed in southern Turkana to the east and northeast of the Tiati mountain mass (figure 5). It is composed of large complex shield-volcanoes, almost entirely of trachytic composition, varying from slightly undersaturated to moderately oversaturated. In each volcano a central area with pyroclastics, minor intrusions and short thick flows, is flanked by thin extensive and regular trachyte lavas and trachytic tuff-flows. The five large overlapping volcanoes mapped in the north of the area cover about 1000 km² and another isolated trachytic pile in the equivalent stratigraphic position occurs at the southern end of the Kerio Valley, north of Eldama Ravine.

### *Group V*

The initial Quaternary volcanic rocks are flood lavas (group V*a*), dominantly trachytic or trachyphonolitic (see below), but with many intermediate and basic types. They commonly lie unconformably on older volcanic rocks and this feature, together with sedimentary and geomorphological evidence, indicates a second major faulting and tilting episode (figure 10*c*).

In the northern rift the most extensive formation in the group is the Dispei–Lake Hannington phonolites (McCall 1967). These are distinctly different petrographically from the group II phonolites and have much closer affinities with trachytes. They correspond, in fact, to the 'Kenya-type phonolites' of Prior (1903) and other authors; the writer would rather propose for these lavas the name 'trachyphonolite' defined by the presence of between 10 and 15% nepheline in the mode. In this volcanic province generally the use of the name 'phonolite' for all felsic lavas with abundant (10%+) nepheline and the proliferation of geographically named 'types' seems to have effectively concealed the significant difference between the strongly undersaturated phonolites typical of group II and these other less undersaturated lavas. The latter are characterized by their coarser 'trachytic' texture and the occurrence of nepheline, or other feldspathoid, only as microphenocrysts. The point is strongly emphasized by the chemistry of the lavas, discussed below.

The trachyte/basalt central volcanoes in the rift centre, Karossi, Pakka, Silali and Emuruangogolak (Rhemtulla 1970) are separated as group V*b*. These volcanoes are roughly contemporaneous with the southern group: Menengai, Eburru, Longonot and Suswa from which they differ in the presence of considerable amounts of basalt and, by comparison with Suswa at least (Nash, Carmichael & Johnson 1969), a greater scarcity of undersaturated felsic lavas.

A very distinctive diktytaxitic type of basalt peculiar to group V is the only immediate suggestion of any petrologic difference between this group and the older groups and chemical analyses (below) appear to confirm the indication.

## Petrochemistry

A total of 162 wet chemical major element analyses are presented on variation diagrams. On the diagrams the analyses are plotted as three types of symbol representing groups I plus II, II plus III, and V respectively and the result clearly illustrates the relationship of chemical composition to stratigraphy. Representative rock analyses are given in tables 1 and 2.

The distinction between the early strongly undersaturated nephelinitic central volcanic rocks of eastern Kenya and western Uganda and the basalt–mugearite–trachyte/phonolite association

Table 1. Older suite lavas

| | 1/609v | 2/239 | 10/95 | 2/325 |
|---|---|---|---|---|
| $SiO_2$ | 43.90 | 49.88 | 50.85 | 55.22 |
| $TiO_2$ | 2.79 | 1.73 | 1.51 | 0.77 |
| $Al_2O_3$ | 14.38 | 19.14 | 19.69 | 21.09 |
| $Fe_2O_3$ | 4.58 | 2.37 | 3.01 | 2.02 |
| FeO | 7.68 | 4.55 | 3.17 | 2.19 |
| MnO | 0.23 | 0.13 | 0.20 | 0.26 |
| MgO | 6.10 | 2.19 | 1.96 | 0.48 |
| CaO | 10.48 | 5.63 | 5.86 | 2.21 |
| $Na_2O$ | 4.55 | 6.54 | 6.16 | 9.57 |
| $K_2O$ | 1.56 | 2.91 | 3.69 | 4.56 |
| $H_2O+$ | 2.42 | 2.43 | 1.81 | 1.41 |
| $H_2O-$ | 0.35 | 0.55 | 1.18 | 0.23 |
| $P_2O_5$ | 0.54 | 0.46 | 0.44 | 0.06 |
| $CO_2$ | — | 1.19 | 0.37 | — |
| | 99.56 | 99.70 | 99.90 | 100.07 |
| CIPW norms | | | | |
| or | 9.22 | 17.20 | 21.81 | 26.97 |
| ab | 12.93 | 30.45 | 29.85 | 33.47 |
| an | 14.21 | 14.28 | 15.18 | 1.08 |
| ne | 13.85 | 13.49 | 12.07 | 25.12 |
| di | 27.58 | 8.70 | 6.91 | 4.79 |
| wo | — | — | — | 1.23 |
| ol | 5.81 | 3.63 | 2.01 | — |
| mt | 6.64 | 3.44 | 4.36 | 2.93 |
| il | 5.30 | 3.29 | 2.87 | 1.47 |
| ap | 1.27 | 1.09 | 1.01 | 0.14 |

group II

1/609v Analcime–basanite, Saimo (Kamasia Range)
2/239 Analcime–mugearite, group II, Kamasia Range
10/95 Analcime–mugearite, group I, 'Samburu basalts', Laikipia
2/325 Phonolite, group II, Kamasia Range

was remarked by King & Sutherland (1960), but very few chemical data (apart from specialized studies) have hitherto been available for the latter association. Wright (1965) distinguished within the Kenya rift volcanic rocks a 'Miocene phonolite subprovince' and a 'Plio–Pleistocene rift valley subprovince', suggesting that the Miocene nephelinitic central volcanoes should be included in the phonolitic subprovince. Apart from the different geographical

TABLE 2. YOUNGER SUITE LAVAS

| | A | 2/156b | 10/322 | 1/125 | 1/51 | 2/22 |
|---|---|---|---|---|---|---|
| $SiO_2$ | 46.5 | 44.47 | 47.70 | 54.06 | 58.03 | 61.12 |
| $TiO_2$ | 2.3 | 2.64 | 1.73 | 1.45 | 0.69 | 0.67 |
| $Al_2O_3$ | 16.1 | 17.11 | 18.29 | 16.39 | 16.22 | 13.88 |
| $Fe_2O_3$ | 3.5 | 2.97 | 3.07 | 3.87 | 4.68 | 4.55 |
| FeO | 7.5 | 9.10 | 7.45 | 6.38 | 3.20 | 4.44 |
| MnO | 0.2 | 0.18 | 0.16 | 0.27 | 0.36 | 0.24 |
| MgO | 7.4 | 7.25 | 5.96 | 1.88 | 0.44 | 0.33 |
| CaO | 10.9 | 11.09 | 11.45 | 4.97 | 1.52 | 1.62 |
| $Na_2O$ | 3.1 | 2.74 | 3.12 | 5.58 | 7.26 | 6.13 |
| $K_2O$ | 1.1 | 0.98 | 0.37 | 2.84 | 5.92 | 4.84 |
| $H_2O+$ | — | 1.11 | 0.54 | 1.37 | 1.67 | 1.26 |
| $H_2O-$ | — | 0.44 | 0.26 | 0.61 | 0.84 | 1.07 |
| $P_2O_5$ | 0.4 | 0.35 | 0.07 | 0.39 | 0.05 | 0.03 |
| $CO_2$ | — | — | — | — | — | — |
| | | 100.43 | 100.17 | 100.06 | 100.88 | 100.18 |
| CIPW norms | | | | | | |
| q | — | — | — | 1.48 | — | 4.08 |
| or | 5.7 | 5.79 | 2.19 | 17.00 | 34.99 | 28.62 |
| ab | 21.0 | 14.07 | 25.81 | 50.70 | 33.04 | 44.33 |
| an | 26.7 | 31.44 | 34.81 | 13.73 | — | — |
| ne | 2.8 | 4.92 | — | — | 9.45 | — |
| ac | — | — | — | — | 9.65 | 6.59 |
| di | 19.9 | 19.15 | 17.51 | — | 6.23 | 6.64 |
| hy | — | — | — | 8.20 | — | 2.08 |
| ol | 11.5 | 13.83 | 10.84 | — | 1.65 | — |
| mt | 5.1 | 4.31 | 4.45 | 5.46 | 1.95 | 3.29 |
| il | 4.4 | 5.02 | 3.29 | 2.04 | 1.31 | 1.20 |
| ap | 0.9 | 0.83 | 0.16 | 0.63 | 0.12 | 0.03 |

A — Average of eight olivine-basalt analyses from groups III and V in the Kamasia Range. (Chemical screen of Manson 1967)
2/156b — Olivine–basalt, group III, Kamasia eastern foothills
10/322 — Olivine–basalt, group V, lower Mukutan River
1/125 — Mugearite, group III, Kamsoror
1/51 — Trachyphonolite, group Va, Loruk
2/22 — Trachyte, group IV, Ribon

distribution, the thickest phonolite sequence being within the rift where the strongly undersaturated suite is absent, recent isotopic age determinations (Bishop *et al.* 1969) also show that the latter suite is generally much earlier than the main plateau flood phonolites. Wright also considered the Miocene basalts to be part of a separate northern subprovince and, in company with several workers, underestimated the proportion of basalt in the younger 'subprovince'. A more recent paper by Wright (1970) adds little to the earlier synthesis and, in the complete absence of any chemical data, perpetuates the same errors.

Saggerson & Williams (1964) recognized two trends, distinguished on a compositional basis alone, in the northern Tanzania 'alkalic district' where the 'mildly alkaline' trend is comparable to the younger suite described in the present contribution; the 'strongly alkaline' trend of northern Tanzania is more undersaturated than most of the older suite from the northern Kenya rift but is comparable to the nephelinitic suite of the Miocene central volcanoes. In a complete reversal of the situation in the central and northern Kenya rift a major faulting episode in northern Tanzania corresponds to a change from mildly alkaline to strongly alkaline volcanism.

The chemistry of the Rungwe volcanic rocks in southern Tanzania (Harkin 1960) is similar to that of the northern Kenya rift volcanic rocks as a whole, but a conspicuous difference is the absence from the Rungwe association of the large volume of nepheline-free felsic lavas found in the Kenya rift.

The Aden Volcanic Series (Cox, Gass & Mallick 1970) shows a differentiation trend which is markedly less 'alkaline' than the younger suite of the Kenya rift and is considered to be transitional between an alkaline and a tholeiitic trend. An observation of considerable relevance to the present contribution is that the Aden volcanic rocks are also intermediate in space and time between the 'alkalic' Yemen trap series (which become less alkaline with time) and the tholeiitic volcanic rocks of the centre of the Gulf of Aden.

Cardinal features of the northern rift petrochemistry unremarked by previous authors are:

(i) The fact that basaltic (*sensu lato*) magma has been available throughout the volcanic history of the area but shows a decrease in silica undersaturation with time.

(ii) The distinct chemical hiatus within the group of lavas usually described as 'phonolite', the more undersaturated type being completely unknown in rift lavas younger than the 'plateau phonolites'.

## Variation diagrams

On the alkalis/silica diagram (figure 11) the difference between the moderately undersaturated suite of the lower groups and the well defined basalt–mugearite–trachyte trend of the upper groups is clearly illustrated. The twenty-three tightly clustered group II phonolite analyses are a conspicuous feature at the top centre of the diagram; there is a clear gap between that group and the 'trachyphonolites' represented by all three types of symbol just above the upper dotted line at between 55 and 59 % silica. No discernible gap occurs between the 'trachyphonolites' and the trachytes. The single solid circle on the extreme right of the diagram is an intrusive comendite from the Kamasia Range.

The Kuno solidification index variation diagrams (figure 12) for $SiO_2$ and $Al_2O_3$ also illustrate the two main associations and their differentiation trends. The division of the felsic lavas into two separate groups is again clear. These diagrams also show that it is possible to identify yet another trend in the few available group V analyses (asterisks): group V basalts of the diktytaxitic type described above have slightly higher $SiO_2$ and $Al_2O_3$ than the older types, whereas certain trachytes of the group are lower in alkalis and alumina than older trachytes. However, as observed, this youngest group also contains a relatively high proportion of 'trachyphonolites'.

On a solidification index/total iron diagram (not illustrated) the two main trends diverge from the basic types and the felsic rocks of the older suite are distinctly lower in total iron than those of the younger suite.

In nearly all the analysed rocks $Na_2O$ exceeds $K_2O$ but potash increases towards the felsic end of the trends, as in most associations of this type. While the younger suites show a distinct trend on this plot of rocks the older suites have a more scattered distribution.

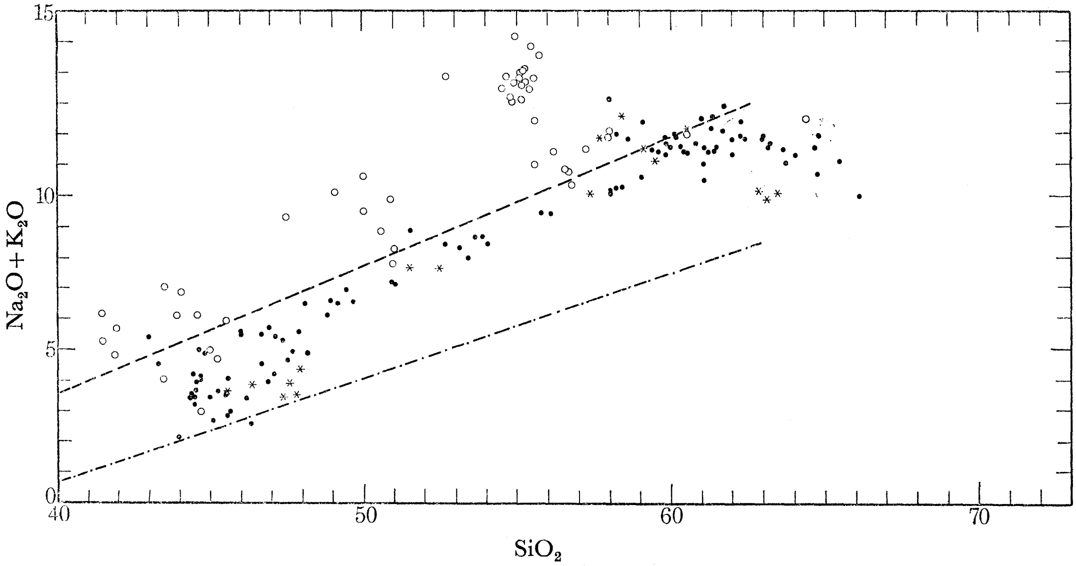


FIGURE 11. Alkalis: silica diagram of the northern Kenya rift volcanic rocks. ○, groups I and II; ●, groups III and IV; ✶, group V; – –, separates nepheline-bearing and nepheline-free rocks in northern Tanzania (Saggerson & Williams 1964); – · –, separates alkalic and tholeiitic suites in Hawaii (Macdonald & Katsura 1964).

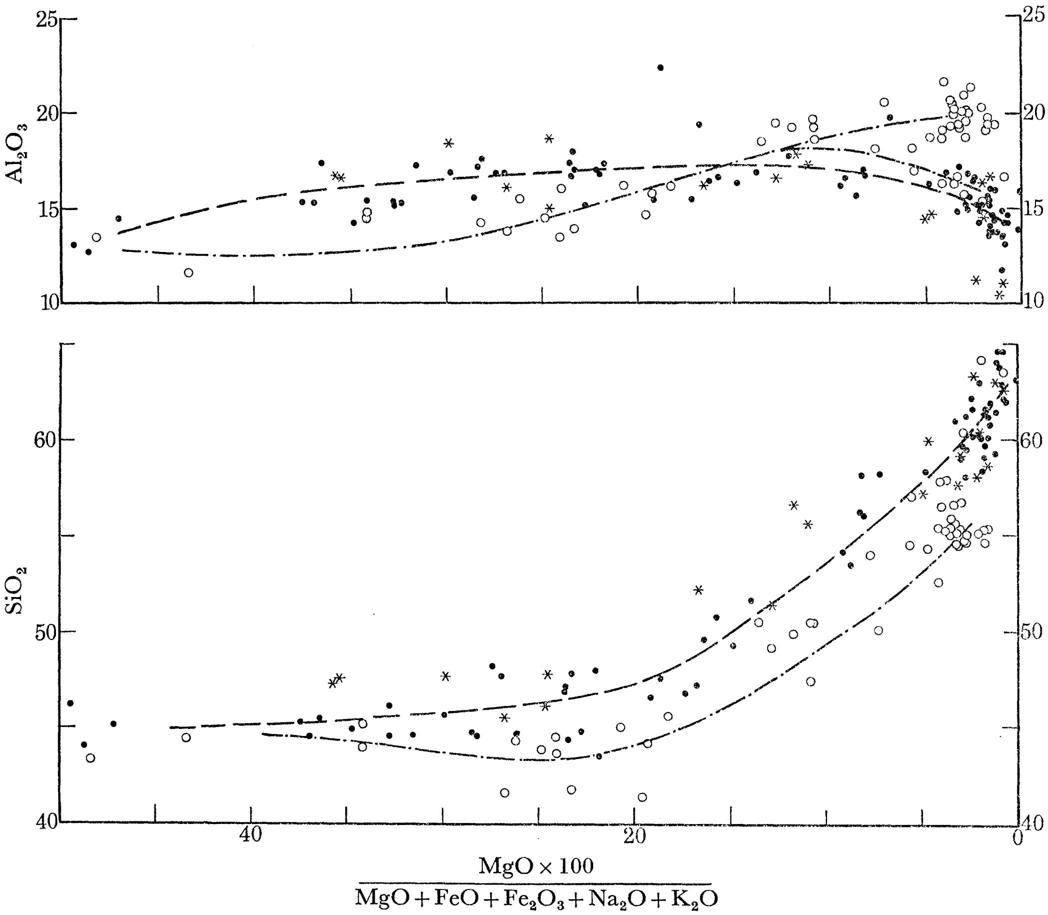


FIGURE 12. Oxide: solidification index diagrams of the northern Kenya rift volcanic rocks. ○, groups I and II; ●, groups III and IV; ✶, group V; – –, differentiation trends.


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## Normative analyses

In standard CIPW normative analyses, normative nepheline in the basic and intermediate rocks of the older suite varies between 7.2 and 22.5 % but there is no obvious pattern. The group II phonolites average over 20 % normative nepheline with none less than 14 %, whereas no 'trachyphonolite' from any group has more than 10 % ne.

In the basaltic rocks of the younger suite normative nepheline is, with two exceptions, always less than 5 % and decreases along the differentiation trend. The trachytes vary from 1.4 ne to 6.1 q and the exceptional comendite has 22 % q.

Most of the felsic lavas have acmite in the norm but a number of the group II phonolites are in fact metaluminous.

## Differentiation process

The preliminary results suggest that crystal fractionation cannot be readily dismissed as the main genetic process in the province. Subtraction calculations show that in the younger suite at least it is feasible to derive mugearite, trachymugearite (benmoreite), trachyte and quartz-trachyte from a calculated 'average olivine–basalt' by fractionation. Macdonald, Bailey & Sutherland (1970), however, demonstrate that differentiation from trachyte to peralkaline rhyolite cannot be explained by a simple crystal $\rightleftharpoons$ liquid equilibrium process and that the role of an alkali-rich vapour phase must also be considered.

The differentiation trend in the older suite is less obvious but a series: tephrite–feldspathoidal mugearite–phonolite can be tentatively postulated. The remarkable homogeneity of the phonolites compared to the variation among the trachytes is interesting. The distribution is the succession of the trachyphonolites suggests that they may perhaps be produced from either of the two main trends.

The very high proportion of felsic differentiates in both suites still presents a major problem. Bailey (1964) has suggested that partial melting of mantle material could account for the felsic proportion and has provided the experimental background (Bailey & Schairer 1966). Unfortunately, Bailey's mechanism for the necessary lowering of subcrustal pressure, that is, raising of the 'Kenya dome' by lateral compression is unacceptable on tectonic grounds, and the theory also appears to underestimate the volume of basaltic lava and the fact of its availability throughout the history of the province.

Apart from the different felsic:mafic proportions the younger suite is chemically very similar to the 'alkalic' trend in Hawaii (Macdonald & Katsura 1964); Williams (1970) has made the same comparison with regard to the 'mildly' alkaline association of northern Tanzania.



## Summary

It appears that any petrogenetic theory for the northern Kenya rift volcanic rocks must account for the following salient facts:

(1) There is a distinct bimodality in the frequency of rock types, with felsic lavas as abundant as basalts, but intermediate rocks are probably more abundant than has hitherto been supposed.

(2) Basaltic lavas of varying silica-saturation compose two major stratigraphic groups but also occur throughout the succession.

(3) Although trachytic eruptions have dominated the later history of the area, the more

significant compositional change with time is a decrease in silica-undersaturation in both mafic and felsic types.

(4) The petrochemical changes coincide with major episodes of rift faulting, indicating a connexion between tectonism and magma evolution.

(5) There have not yet been found in the rift any rocks with definite tholeiitic or calc-alkaline affinities, but the group V basalts with relatively high $Al_2O_3$ may indicate further evolution in that direction. The 'rhyolites' and 'andesites' of Turkana are in fact peralkaline rhyolites ('pantellerites' and 'comendites') and mugearites respectively (Walsh & Dodson 1969; Williams 1969).

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## *Discussion*

Dr D. A. Robson (*Ardrigg, Leazes Lane, Hexham, Northumberland*). The speaker has stated that volcanism is not a universal accompaniment of rift faulting, and that parts of the Kenya rift show no evidence of associated igneous activity. This is certainly true of the Suez arm of the Red Sea rift, where igneous activity ceased before Miocene times, though the rift faulting continued right through the Miocene period. It is conceivable that changes in stress directions which must have accompanied the development of lateral movement along the Gulf of Akaba–Jordan Valley in Miocene times may have caused cessation of igneous activity in the Gulf of Suez region. Is there any evidence in the Kenya rift which might suggest that a change of stress direction (within or outside the rift itself) could be responsible for absence or cessation of volcanic activity?

Dr R. B. McConnell (*Streatwick, Streat near Hassocks, Sussex*). King & Chapman have described a volcanic succession in the Kenya rift valley extending from Miocene times to the present day. Although there is a considerable overlap in composition it does seem that basaltic types predominate in the early stages of the volcanism whereas acid types, such as trachyte and ignimbrite, characterize the later stages. Does this development not appear to indicate the closing of a cycle of volcanism?