Petrogenetic significance of some new xenolithic alkaline rocks from East Africa

N. M. S. ROCK with chemical analysis by J. H. SCOON

Department of Mineralogy and Petrology, University, Cambridge, CB2 3EW

SUMMARY. New occurrences of xenolithic alkaline rocks from three East African volcanoes are described. Micro-ijolites and alkali pyroxenites occur in the carbonate-rich tuffs and lavas of Mount Elgon; kaersutite-rich pyroxenites and a suite of fenitized basement rocks in the caldera flows of Mount Meru, and apparently unique melanocratic hortonolite nepheline syenites in the central foyaite plug of Mount Kenya. The $^{87}Sr/^{86}Sr$ ratios indicate mantle origin, and all are enriched in trace elements such as Sr, Nb, and Zr. The xenoliths from Mount Kenya are cumulate equivalents of the glassy kenyte lavas of the mountain; the pyroxenites of Mount Elgon are also cumulates whose predominant titanaugite is of identical composition to that of the host lavas. The contrast between the 'dry' Elgon pyroxenites and the 'wet' amphibole-rich types from Mount Meru is believed to reflect different CO_2/H_2O ratios in the volatile phase accompanying the alkaline vulcanicity. Strongly alkaline, carbonate-rich suites such as that of Mount Elgon derive from fairly dry alkali-basaltic magma under high CO_2 activity by dominant pyroxene fractionation, whereas the mildly alkaline lineage seen in some areas of Mount Meru forms under more hydrous conditions in which amphibole fractionation is important. Mount Meru in addition shows a transition to rock-types typical of the strongly alkaline lineage, and this is reflected in the occurrence of relatively amphibole-poor pyroxenites with the amphibole-rich types.

THE volcanic and plutonic suites of the East African Rift alkaline volcanoes have been divided into 'strongly' and 'mildly' alkaline types, the first consisting of nephelinites, ijolites, phonolites, and carbonatites, the latter of basalts, phonolites, and trachytes (Saggerson, 1970, Williams, 1970). The significance of this division, and of its implied antipathy between basic plagioclase-bearing rocks (such as basalts) and carbonatites, has been explored in Rock (1975). It was concluded that the two series might result from a single basaltic parental magma whose course of crystallization differs according to the CO_2/H_2O ratio of the volatile phase. Under CO_2-rich dry conditions, fractionation is dominated by olivine and, or, pyroxene, without plagioclase, whereas under hydrous conditions amphibole and plagioclase dominate. The present communication reports the occurrence of several unusual xenolithic rock-types in three of these volcanoes, some of which have a bearing on the application of this model to the African Rift. One volcano exhibits the 'mildly' alkaline lineage, termed 'gabbroic' in Rock (1975), the second the 'strongly', or 'carbonatitic' lineage, and the third contains rock-types belonging to both lineages erupted at different periods. Locations of the volcanoes are shown in fig. 1.

Xenoliths from Mount Kenya

Baker (1967) provided the most recent summary of the geology of this volcano. Although an age range of 2·6–3·1 Myr has been obtained using the K–Ar method by

Baker *et al.* (1971), recent determinations (Rock, 1976) yield an isochron of age 4·5 Myr with an initial $^{87}Sr/^{86}Sr$ ratio of 0·7042.

Baker (1967) gave the lava sequence as:

Mount Kenya Suite (Pleistocene) ⎰ Pumice cones, agglomerates, etc.
Riebeckite trachyte, olivine basalts, mugearites, olivine trachytes
Nepheline syenite plug, kenytes, rhomb porphyries
Lower basalts.

Pliocene   Lakapian basalts.

This is an excellent example of the 'gabbroic' alkaline lineage from basalt to trachyte and phonolite, plagioclase being well represented and carbonatites absent. This particular suite is characterized by the occurrence of iron-rich olivine in the felsic members and by over-all scarcity of pyroxenes relative to other gabbroic suites. The nepheline syenite of the central plug (fig. 2), the phonolite surrounding it, and the glassy kenyte lavas appear to represent different manifestations of a single magma-type (Baker, 1967) as they have very similar chemistry (Table I). They are all foyaites with the peralkaline index, $(Na+K)/Al$, close to unity.[1]

The new rock-types were discovered during a traverse between Polish Man's and Emerald Tarns, in the summit area of the mountain, at the head of the Mackinder Valley (fig. 2). They occurred mainly as loose blocks on steep, ice-shattered slopes below the precipice
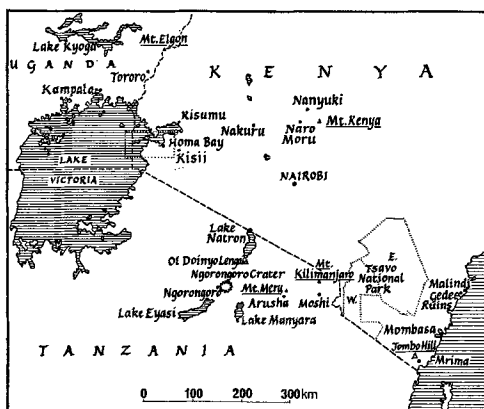

FIG. 1. Location of Mts. Elgon, Kenya, and Meru in E. Africa, together with localities mentioned in the text.

of Western Terminal, but a few *in situ* examples showed the host rock to be the central foyaite plug. Owing to the difficult nature of the terrain, only an approximate estimate of the geographical extent of the xenoliths was possible but no examples were discovered elsewhere.

The xenoliths, which may be designated 'cumulo-kenytes', are mesotype to melanocratic coarse-grained rocks, with a grain-size of 2 to 6 mm, although larger poikilitic amphiboles occur in some samples, measuring up to 1·2 cm. The masses encountered ranged from 4 to 50 cm in diameter.

In thin section the rocks are very fresh apart from minor clouding of feldspar. Nepheline is extremely fresh, and olivine oxidized rather than weathered. The texture is subequigranular, with a tendency towards idiomorphism in the nepheline and apatite. The minerals present are:

[1] The CIPW norm calculations given by Baker (1967), p. 28 are incorrect. They have been recalculated by computer and are given revised in Table I.

Olivine forms anhedral, slightly pleochroic, crystals charged with minute opaque grains, which are unresolvable in the electron-probe. Clouded, pleochroic olivines are known in some high-grade metamorphic rocks (Pitt and Tozer, 1970), and may reflect oxidation during reheating. This explanation is clearly applicable in the case of xenoliths incorporated in foyaite magma. The optical properties ($2V_\alpha = 70°$) were
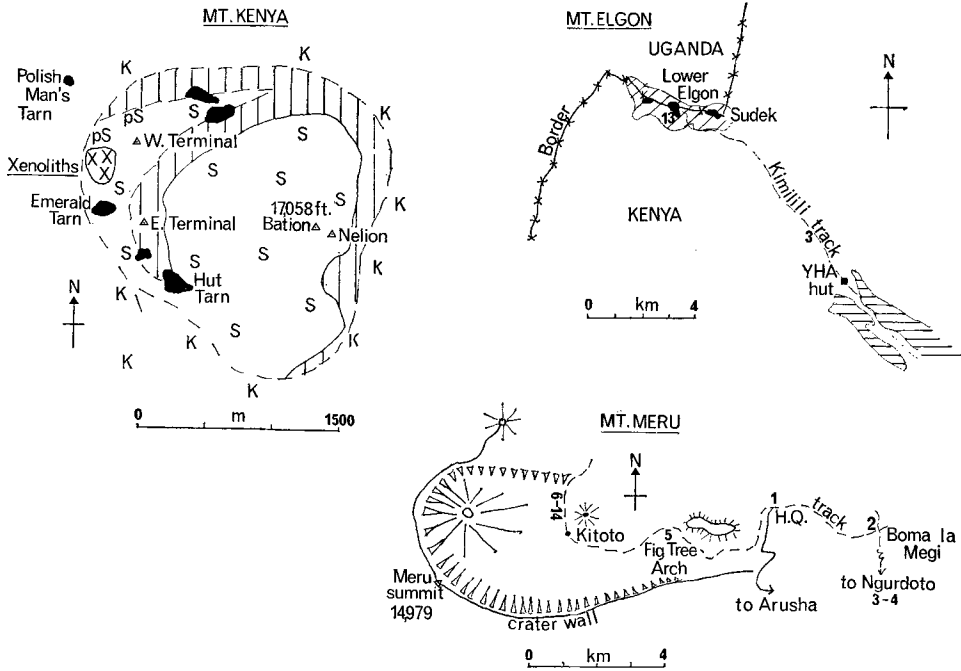

FIG. 2. Location of the specimens from Mt. Kenya (K, kenyte; S, nepheline syenite; vertical lines, phonolite), Mt. Meru, and Mt. Elgon. (Shading, lavas; unshaded, pyroclastics)

constant in the six samples studied in detail, although the modal proportion of olivine varied markedly (Table III). The olivine composition (Table II, 1) is $Fo_{38}Fa_{57}Te_5$ (Te = tephroite), which lies in the hortonolite range, unusual in rocks with such a high colour index (Table III).

Amphibole closely corresponds to the composition of richterite as listed by Deer *et al.* (1967), and provides another interesting occurrence of this rare amphibole in alkaline rocks. The pleochroism is not marked, varying slightly in shades of brown, without any trace of blue. The mineral occurs poikilitically, and is unevenly distributed in individual xenoliths. The average composition (Table II, 2) corresponds to $(Na,K)_2Ca(Mg,Mn,Fe)_5Si_{7.5}(Al,Ti)_{0.5}O_{22}(OH)_2$ that is, essentially a soda-tremolite with minor substitution of Ti and Al.

Feldspar: only homogeneous, untwinned, and practically unzoned orthoclase is present in the xenoliths. Its average composition is almost constant, and even in larger crystals the degree of zoning is slight (Table II, 3 and 4) with the cores averaging $Ab_{49}Or_{50}An_1$ and the margins $Ab_{47}Or_{53}$. Two single-crystal X-ray photographs showed

TABLE I. *Chemical analyses and norms of cumulo-kenytes and related rocks*

	1	2	3	4	5	6	7
SiO_2	38·72	34·90	53·80	53·98	51·64	46·73	47·85
TiO_2	2·20	3·70	0·31	0·57	1·58	0·78	—
Al_2O_3	11·95	11·16	18·46	19·43	19·12	10·05	13·24
Fe_2O_3	7·10	8·20	6·22	4·39	3·03	3·53	2·74
FeO	14·34	17·74	0·40	2·05	4·20	8·20	2·65
MnO	1·40	1·30	0·33	0·26	0·19	0·28	—
MgO	5·84	6·51	1·05	1·07	1·29	9·27	5·68
CaO	5·65	5·38	2·53	2·04	2·94	13·22	14·36
Na_2O	5·70	4·96	7·09	8·81	9·46	1·81	3·72
K_2O	2·65	2·32	5·46	5·27	4·37	3·76	5·25
P_2O_5	3·26	2·93	0·53	0·30	0·33	1·51	2·42
H_2O+	0·77	0·82	3·54	1·66	1·63		
H_2O^-	0·25	0·19					
Sum	99·83	100·11	100·57	99·96	100·26		

C.I.P.W. norms

	1	2	3	4	5	6	7
Ab	15·1	10·0	32·5	26·5	35·6		
Or	16·1	11·0	32·8	31·1	27·6		
An	—	1·4	2·0	—	7·7		
Ac	1·3	—	—	3·7	—		
Lc	—	—	—	—	—		
Ne	17·8	17·9	15·1	23·7	16·2		
Di	5·8	5·3	5·4	6·6	1·8		
Ol	22·0	25·3	—	0·1	1·6		
Mt	9·6	11·8	1·6	4·6	4·3		
Il	4·1	7·0	0·6	1·1	1·9		
Hm	—	—	5·1	—	1·8		
Ap	7·5	6·7	1·3	0·7	1·0		

Modes

	1	2	3	4	5	6	7
Alk. fels.	36	29				20	21
Ne	14	9				5	20
Sodalite	—	—				1	—
Biotite	—	—				8	2
Cpx	—	—				46	48
Olivine	23	20				10	—
Ore	8	17				6	—
Apatite	13	9				4	6
Sphene	—	—				—	1
Amphibole	5	15				—	—
Col. index	49	62				74	57

1. Most leucocratic cumulo-kenyte, Mt. Kenya (sample 119184, MK12B).
2. Most melanocratic cumulo-kenyte (sample 119189, MK13B), Mt. Kenya.
3. Kenyte, lava flow from Castle hill, Mt. Kenya (Baker, 1967).
4. Porphyritic phonolite, central plug of Mt. Kenya (Baker, 1967).
5. Nepheline syenite, snout of Lewis Glacier, Mt. Kenya (Baker, 1967).
6. Type shonkinite, Shonkin Sag laccolith (Johannsen, 1938).
7. Type malignite, Maligna River (Johannsen, 1938).
Analyst of 1 and 2: J. H. Scoon.

TABLE II. *Microprobe analyses of minerals in cumulo-kenyte, 119189*

	1	2	3	4	5	6	7	8
SiO_2	34·16	51·66	66·80	67·11	47·72	0·39	1·19	0·63
TiO_2	0·00	2·54	0·13	0·00	0·00	0·00	19·63	50·82
Al_2O_3	0·00	1·94	18·31	18·22	31·15	0·00	0·56	0·00
FeO*	46·30	11·35	0·48	0·65	1·28	0·00	71·57	44·18
CoO	0·36	0·13	0·00	0·00	0·00	0·00	0·73	0·28
MnO	4·19	0·60	0·00	0·00	0·00	0·00	2·32	4·99
MgO	16·19	15·38	0·00	0·00	0·00	0·00	0·86	1·31
CaO	0·00	6·75	0·07	0·00	0·03	54·10	0·00	0·00
Na_2O	0·00	5·84	5·61	5·17	15·54	0·00	0·00	0·00
K_2O	0·00	1·29	8·21	9·50	4·16	0·00	0·00	0·00
P_2O_5	0·00	0·00	0·00	0·00	0·00	42·49	0·00	0·00
V_2O_5	0·00	0·00	0·00	0·00	0·00	0·00	0·23	0·00
Sum	101·20	97·48	99·61	100·65	99·85	96·98	97·09	102·23

Ions per fixed number of oxygen atoms

	1	2	3	4	5	6	7	8
O =	4	23	8	8	32	12	32	32
Si	1·004	7·553	3·013	3·015	9·015	0·32	0·391	0·168
Ti	0·000	0·280	0·000	0·000	0·000		0·218	
Al	0·000	0·334	0·974	0·965	6·941		4·873	10·100
Fe	1·137	1·388	0·018	0·024	0·203		19·754	9·765
Co	0·009	0·016	0·000	0·000	0·000		0·193	0·060
Mn	0·104	0·074	0·000	0·000	0·000		0·651	1·119
Mg	0·741	3·421	0·000	0·000	0·000		0·340	0·518
Ca		1·057	0·003	0·000	0·000	4·678		
Na		1·655	0·491	0·450	5·738			
K		0·242	0·472	0·545	1·001			
P						2·903		
V							0·049	

* Total iron as FeO

1. Hortonolite (average of 4 analyses).
2. Amphibole (4 analyses).
3. Core of alkali felspar (2 analyses).
4. Edge of alkali felspar (2 analyses).
5. Nepheline (4 analyses).
6. Apatite (1 analysis).
7. Host of ore-phase (1 analysis).
8. Lamella in ore-phase (1 analysis).

TABLE III. *Modal analyses of igneous rocks*

	Mt. Kenya						Mt. Elgon		Mt. Meru	
	119183	119184	119185	119186	119187	119189	119218	119228	119208	119209
Olivine	24	23	20	27	23	20	—	—	—	—
Pyroxene	—	—	—	—	—	—	32	90	37	50
Amphibole	4	5	8	3	2	15	—	—	42	15
Nepheline	20	14	10	13	23	9	63	—	—	—
Felspar	45	36	36	30	40	29	—	—	—	—
Mesostasis	—	—	—	—	—	—	—	—	9	5
Apatite	14	13	10	11	9	9	4	4	2	3
Opaque phase	19	8	14	16	15	17	1	6	9	27
Col. index	61	49	54	57	49	62	36	100	91	95
Density	3·15	3·09	3·12	3·14	3·11	3·22	n.d.	n.d.	n.d.	n.d.

119218 Micro-ijolite
119208 Amphibole-rich pyroxenite
119183–9 Cumulo-kenytes
119228 Pyroxenite
119209 Amphibole-poor pyroxenite

the structure to be orthoclase cryptoperthite with spacings consistent with the micro-probe compositions.

Nepheline: the average composition (Table II, 5) is $Na_6K_1\square_1(Al,Fe)_7Si_9O_{32}$ or $6NaAlSiO_4 . KAlSiO_4 . 2SiO_2$ corresponding to 22 mol. % 'omission' solid solution of silica. The composition is typical of equilibrium plutonic nephelines, with the six smaller Na sites completely filled and omission solid solution being accommodated by loss of K only.

Apatite: Chlorine was absent from the microprobe spectrum and the remaining 3 % of the analysis (Table II, 6) is presumably F or (OH). The total is reasonable in the light of F contents of apatites given by Deer *et al.* (1967).

Opaque phase: under reflected light, very fine lamellae can be seen in this phase. One grain possessed sufficiently wide lamellae for separate analysis of host and lamella in the microprobe beam, and the results are given in Table II. The host is ulvöspinel, the lamella ilmenite, and the compositions are consistent with the formulae $Usp_{64}Mt_{36}$ for the host and $Ilm_{95}Hm_5$ for the lamella, when Co and Mn are included with FeO. Fe_2O_3 was calculated assuming ideal compositional solid solution in both cases. From the curves of Buddington and Lindsley (1964) these compositions give a tem-perature of equilibration of 930 °C, under an oxygen fugacity of 10^{-13} atm, values that seem reasonable given the differentiated mineralogy but mafic composition of the xenoliths (Tables I, II, III). The low value of P_{O_2} derived from low P_{H_2O} is reflected in relatively anhydrous and unoxidized mineralogy.

Affinities of the xenoliths. Modes of six xenoliths, all of hand-specimen size, are given in Table III, and chemical analyses of the most leucocratic and melanocratic xenoliths 119188 and 119189 in Table I, together with a series of comparative analyses.

There can be little doubt that these rocks are cumulates from the magma that also formed the kenytes, nepheline syenites, and phonolites of the Mount Kenya suite. Although chemically they are ultrabasic, the absence of plagioclase and abundance of Fe-rich olivine and alkaline amphibole places the xenoliths in the category of melano-cratic nepheline syenites, while the mineralogy of the kenytes (anorthoclase, nepheline, and fayalitic olivine in a glassy groundmass), closely corresponds with that of the xenoliths. Although the xenoliths are not porphyritic, it is most unlikely that there ever existed a liquid corresponding to their composition, combining as it would have to a high Fe/Mg ratio with very low SiO_2 content. There are no known lavas of such a composition in the Mount Kenya suite and it is therefore most unlikely that the xenoliths correspond to any form of basic parental magma, particularly as a much more reasonable parental magma is suggested by the presence of substantial flows of alkaline basalt.

The xenoliths are therefore best designated 'cumulo-kenytes' to indicate both their petrological affinity to the unusual kenytes and their unique character with respect to other mafic-rich nepheline syenites. Thus the alkaline rock shonkinite, closest in modal composition to cumulo-kenyte, still shows differences too large for cumulo-kenyte to be accommodated in the same class. Shonkinite is composed of 60 % mafic minerals (olivine, biotite, and pyroxene) but the abundance of clinopyroxene and lack of amphibole contrast strongly with cumulo-kenyte (Table I). Moreover,

shonkinite is a potassic alkaline rock ($K_2O > Na_2O$) typically associated with the 'shoshonite' suite (Joplin, 1968), whereas cumulo-kenyte is sodic ($Na_2O > K_2O$). Sr isotopes reveal that sodic and potassic alkaline rocks are likely to have entirely separate origins (Faure and Powell, 1972). There is thus neither a petrographic nor petrogenetic basis for equating cumulo-kenyte with shonkinite. The other similar rock-type is malignite (Table I); this again is potassic, however, and the predominance of clinopyroxene in the mode separates the type from the cumulo-kenytes.

These xenoliths therefore seem to be unique, since no other plutonic rock-type excepting nepheline syenite has previously been described from Mount Kenya, while olivine-rich cumulates at other alkaline complexes are typically true Mg-rich ultra-mafic rocks such as peridotites. Indeed, these xenoliths correspond in their dry reduced character more to differentiated tholeiitic rocks (e.g. ferrohortonolite diorites), than to the wet and more oxidized mineralogies typical of many alkaline sequences; nepheline syenites, for example, normally contain aegirine and, or, biotite, possibly with alkali amphibole. The low oxygen fugacity prevailing during the formation of the cumulo-kenytes is reflected in the low content of ferric iron, and hence absence of aegirine, while the low P_{H_2O} responsible for such a low P_{O_2} is reflected in the occurrence of olivine rather than biotite.

Xenoliths from Mount Meru, Tanzania

The geology of this volcano has been described very briefly by Oates (1934) and Guest and Leedal (1953), but no analytical data or geological maps appear to have been published. Wilkinson (1966) believed that the volcano showed two major sequences of lavas: nephelinite–basalt and phonolite–trachyte. When regrouped as nephelinite–phonolite and basalt–trachyte these correspond to the gabbroic and carbonatitic lineages, described above. Carbonatites *per se* have not yet been discovered, but carbonate-rich tuffs are present.

Brief petrographic descriptions of a series of samples collected from Mount Meru are given in Table IV, and their localities are shown in fig. 2. Some are types similar to those mentioned in the collection of Oates (1934) but not specifically described. Among those listed in Table IV, the following are new occurrences:

Pyroxenites. On the track almost due west of Kitoto Hill (fig. 2), large coal-like lumps of alkali pyroxenite, up to 25 cm in diameter, are abundant in phonolitic nephelinite lavas. Although extremely friable in hand specimen they proved to be fresh in thin section. Two major groups may be recognized, *amphibole-rich* and *amphibole-poor*. The former are relatively coal-black and coarse-grained the latter brown and finer-grained. Compositions are given in Table V (1 and 2), and modal analyses in Table III. The constituent minerals from both types (Table VI, 1–8) are very similar in composition, and the coexistence of the two types of xenolith in a single host lava suggests closely similar petrogenetic evolution.

The amphibole (Table VI, 1 and 2) is kaersutite approximately $Ca_2(Na, K)$ $(Mg,Mn,Fe)_{4.4}Ti_{0.6}Si_6Al_2O_{22}(OH)_2$ (Fe is total iron). The analyses given are averages of cores and rims; the crystals exhibit minor zoning, with $Mg/(Mg+Fe)$ varying from

63 to 65 %. *The pyroxene* (Table VI, 3 and 4) is essentially titanaugite in composition, approximately $Ca(Mg,Mn,Fe,Ti)Al_{0.2}Si_{1.8}O_6$ (Fe is total iron) with $Mg/(Mg+Fe)$ varying from 75 to 79 % from margin to core. *The opaque phase* (Table VI, 5 and 6); with Fe calculated as both FeO and Fe_2O_3 this has a peculiar composition—$Spinel_{3.2}$

TABLE IV. *Petrography of samples from Mt. Meru*

Sample no. in Harker collection, Cambridge.	Field no.	Rock-type	Locality	Petrography
119201	ME1	Nephelinite	Momela Gate	Euhedral titanaugite and nepheline phenocrysts in black glass.
119202	ME2	Phonolitic nephelinite	Boma la Megi	Euhedral titanaugite and alkali feldspar phenocrysts in black glass.
119204	ME4	Phonolitic nephelinite	Ngurdoto	Euhedral titanaugite, nepheline, and anorthoclase phenocrysts in black glass.
119205	ME5	Trachyte	Fig Tree Arch	Anorthoclase phenocrysts in trachytoidal groundmass of alkali feldspar, aegirine, and nepheline.
119212	ME11	Nephelinite	Kitoto track	Host to xenoliths described in text and below. Nepheline, titanaugite, and rare alkali feldspar phenocrysts with broken-off kaersutites in black glass.
119208/9	ME8	Kaersutite pyroxenite	Kitoto track	Kaersutite, titanaugite, apatite, magnetite, mesostasis.
119206	ME6	Quartz fenite (leucocratic)	Kitoto track	Quartz (10 %), microcline (65 %), and albite (25 %) with very minor aegirine.
119210	ME9	Mesotype fenite	Kitoto track	Hornblende (7 %), biotite (9 %), aegirine (12 %), microcline (60 %), albite (9 %), and opaques (3 %).
119214	ME13	Fenite (leucocratic)	Kitoto track	Microcline (85 %), quartz (4 %), aegirine (10 %), opaques (1 %).
119215	ME14	Fenite (leucocratic to mesotype)	Kitoto track	Composed of two portions. One very similar to ME13, one to ME9, with 30 % hornblende, 1 % biotite, 4 % aegirine, 54 % microcline, 5 % apatite, and 6 % opaques.
119211	ME10	Porphyritic phonolite	Kitoto track	Nepheline in groundmass of feldspar/nepheline and aegirine-augite.

$Magnesioferrite_{6.5}Ulvöspinel_{29}Wüstite_{64.3}$ (in molecular per cent), although the total does imply that the iron is mainly ferrous. *Apatite* is Cl-poor (Table VI, 8) and the analysis total correspondingly low. *The mesostasis* has almost zero relief and almost negligible birefringence, with a similar appearance to analcime. The analysis (Table VI, 7) shows it to be highly substituted analcime of formula (Na,K,Ca) (Al,Fe) $(Si,Ti)_2O_6$ indicating considerable solid solution of the wairakite molecule (Deer *et al.*, 1963).

The mineralogical composition of the xenoliths is rather variable, particularly in the amphibole-poor varieties, owing to clustering of the apatite and opaque phase into areas composed almost entirely of these two minerals.

TABLE V. *Chemical analyses of xenolithic alkaline rocks from Mt. Meru*

	1	2	3	4			1′	2′	3′
SiO_2	28·56	40·19	53·59	41·85		Ab	—	—	42·6
TiO_2	7·93	4·16	1·28	2·36		Or	—	—	14·4
Al_2O_3	7·06	5·67	17·40	10·35		An	13·3	9·9	12·7
Fe_2O_3	15·13	8·19	4·67	6·89		Ne	4·6	5·0	5·0
FeO	18·03	9·64	4·02	6·23		*Ks	1·3	0·8	—
MnO	0·36	0·24	0·12	—		La	7·5	2·7	—
MgO	8·49	10·19	2·69	10·13		Di	20·6	57·1	10·1
CaO	12·05	18·74	6·05	14·03		Ol	14·9	2·1	2·5
Na_2O	1·01	1·09	6·15	3·55		Mt	21·9	11·9	6·8
K_2O	0·40	0·23	2·44	1·44		Il	15·0	7·9	2·6
P_2O_5	0·18	0·33	0·71	0·71		Ap	0·4	0·7	1·6
H_2O+	0·46	0·46	0·63	—					
H_2O^-	—	0·08	0·18	—					
Sum	99·66	99·93	99·93						

1. Kaersutite-rich pyroxenite xenolith ME8, Kitoto track, Mt. Meru.
2. Kaersutite-poor pyroxenite xenolith ME8B, Kitoto track, Mt. Meru.
3. Hornblende-rich aegirine fenite xenolith ME9, Kitoto track, Mt. Meru.
4. Average East African olivine-poor nephelinite (Wood, 1968).
1′, 2′, 3′. C.I.P.W. Norms
*Ks calculated in preference to La.
Analyst of 1, 2, and 3: J. H. Scoon.

Fenites. These peculiar rocks, variable in colour and extremely friable in texture, occurred more extensively but in the same general area as the pyroxenites. Table IV shows the variation of mineralogical composition. The mesotype examples are composed of hornblende, biotite, aegirine-augite, and microcline, with or without albite, but are traversed by veins with mineralogy similar to that of the leucocratic examples, namely aegirine, microcline, and strained albite. The albite is approximately Ab_{95} and the aegirine-augite has $2V_\alpha = 65°$, $\alpha: [001] = 30°$. Quartz is present only in the more leucocratic types. The feldspars show peculiar yellow patches of higher birefringence that may represent incipient transformation to aegirine. They are clearly basement rocks that have been caught in the explosive nephelinitic vulcanicity and thoroughly fenitized, and they resemble the fenites of the Oldoinyo Dili carbonatite complex some 84 km to the west (McKie, 1966). Specimen 119210 (Table III, 3) is slightly undersaturated in composition, indicating the extent of fenitization, although it lacks modal Ne.

Mount Elgon

The geology of this pile of nephelinite lavas, carbonate-rich pyroclastics, melilitites, phonolites, and phonolitic nephelinites has been described by Odman (1930), Davies (1952), and Searle (1952). The geological map published with the latter account seems to overestimate the proportion of pyroclastics relative to lavas in the summit region

of the mountain. Thus nephelinite lavas are extremely abundant on the SE (Kenyan) slopes between the 11 000-ft hut and the summit of Lower Elgon, and the exposures along the Kimilili track show abundant pyroclastics only in the lower reaches (fig. 2).

Ijolites were briefly reported by Odman (1930) and Davies (1952) noted the presence of ijolite pegmatite dykes. Micro-ijolite xenoliths were collected during the present

TABLE VI. *Average analyses of minerals from pyroxenites*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	40·44	39·77	49·41	48·66	0·57	0·60	50·65	0·41	49·88	49·06	0·64	51·33	52·41	40·59
TiO_2	5·23	5·29	1·92	2·69	17·23	18·15	1·92	—	1·63	1·81	14·90	1·20	0·71	0·00
Al_2O_3	10·56	11·25	3·31	4·23	2·40	1·63	19·04	—	2·52	2·67	1·84	0·63	0·37	31·52
FeO^*	14·66	12·62	7·33	7·07	75·88	75·34	6·72	—	8·13	8·48	76·56	10·38	7·34	2·23
MnO	0·18	0·18	0·15	0·19	0·96	1·19	0·29	—	0·17	0·23	0·82	11·57	13·36	0·00
MgO	10·95	12·44	12·99	13·04	3·06	0·00	0·43	—	12·46	12·02	2·89	0·33	0·33	0·00
CaO	11·84	12·16	23·45	23·97	0·21	0·15	3·66	54·49	23·43	23·30		22·23	23·93	0·37
Na_2O	2·53	2·27	0·49	0·40	0·00	0·00	5·08	—	0·68	0·76		1·63	0·95	15·47
K_2O	1·48	1·72	0·00	0·00	0·00	0·00	6·05	—	0·00	0·00		0·00	0·00	7·26
Cl	0·00	0·00	0·00	0·00	0·00	0·00	0·38	0·08	—	—		—	—	—
P_2O_5	0·00	0·00	0·00	0·00	0·00	0·00	0·00	41·18	—	—		—	—	—
Sum	97·87	97·70	99·05	100·25	100·70	98·03	94·22	96·15	98·90	98·33	98·27	99·30	99·41	97·43

Ions per fixed number of oxygen atoms

O=	23	23	6	36	32	32	12	12	6	6	32	6	6	32
Si	6·109	5·960	1·869	1·821	0·181	0·199	3·870	0·033	1·894	1·867	0·203	1·959	1·972	8·179
Ti	0·596	0·598	0·055	0·076	4·102	4·532	0·111	—	0·047	0·052	3·684	0·035	0·020	0·000
Al	1·881	1·992	0·147	0·187	0·898	0·638	1·715	—	0·113	0·149	0·715	0·028	0·016	7·487
Fe	1·853	1·586	0·232	0·221	20·104	20·924	0·429	—	0·258	0·270	21·114	0·331	0·231	0·381
Mn	0·023	0·022	0·006	0·006	0·258	0·334	0·019	—	0·006	0·007	0·235	0·011	0·011	0·000
Mg	2·464	2·784	0·732	0·727	1·440	0·000	0·049	—	0·706	0·682	1·427	0·658	0·749	0·000
Ca	1·917	1·957	0·950	0·961	0·070	0·054	0·300	4·787	0·953	0·946	—	0·909	0·965	0·079
Na	0·740	0·661	0·036	0·036	0·000	0·000	0·752	—	0·050	0·056	—	0·120	0·070	6·046
K	0·284	0·309	0·000	0·000	0·000	0·000	0·590	—	—	—	—	0·000	0·000	1·864
Cl	—	—	—	—	—	—	0·049	0·011	—	—	—	—	—	—
P	—	—	—	—	—	—	—	2·858	—	Co =	0·199	—	—	—
V	—	—	—	—	—	0·107	—	—	—	—	—	—	—	—

* Total iron as FeO.

1. Kaersutite, amphibole-poor pyroxenite, 119209, Mt. Meru (ME8b) (2 analyses).
2. Kaersutite, amphibole-rich pyroxenite, 119208 (ME8) (5 analyses).
3. Titanaugite, amphibole-poor pyroxenite, 119209 (ME8b) (4 analyses).
4. Titanaugite, amphibole-rich pyroxenite, 119208 (ME8) (5 analyses).
5. Ore-phase in amphibole-poor pyroxenite (2 analyses).
6. Ore-phase in amphibole-rich pyroxenite (2 analyses). Includes $V_2O_5 = 0·49$ %.
7. Analcitic mesostasis in amphibole-poor pyroxenite (2 analyses).
8. Apatite in amphibole-poor pyroxenite (1 analysis).
9. Titanaugite in pyroxenite, Mt. Elgon, specimen No. 119228 (EL13) (5 analyses).
10. Titanaugite phenocrysts in host nephelinite, Mt. Elgon (3 analyses).
11. Ore-phase in pyroxenite, Mt. Elgon (2 analyses). Includes CoO = 0·73 %.
12. Rim of clinopyroxene in micro-ijolite, Mt. Elgon (EL3), 119218.
13. Core of clinopyroxene in micro-ijolite, Mt. Elgon (EL3), 119218.
14. Average of 2 nephelines, micro-ijolite, Mt. Elgon (EL3), 119218.

work from tuffs about a kilometre from the 11 000-ft YHA hut, exposed in the summit track. One measured some 20 cm in diameter. The mineralogy is typical of ijolites with sodic pyroxene $2V_\alpha = 75°$, α: [001] = small (Table VI, 12, 13), nepheline of plutonic equilibrium composition (Table VI, 14) and some wollastonite.

Pyroxenites have not been previously recorded. Small nodules of somewhat fibrous appearance were discovered just below the summit of Lower Elgon (14 010 ft) in

olivine-poor nephelinite lavas. They appeared to be abundant locally, but were not seen elsewhere on a traverse around the Kenyan part of the caldera (fig. 2). They are completely fresh, but contain very little mesostasis and no amphibole, in contrast to the pyroxenites of Mount Meru. Pyroxene constitutes 90 % of the rock, and the bulk composition is therefore taken to be close to that of the pyroxene, which is essentially unzoned titanaugite (Table VI, 9). This composition is almost identical to that of the euhedral phenocrysts of pyroxene in the enclosing nephelinite lava (Table VI, 10), which are also of very similar size to the grains of the pyroxenite itself. The opaque-phase (Table VI, 11) is a titaniferous magnetite with a small amount of spinel solid solution.

TABLE VII. *Trace-element compositions of new rock-types (ppm)*

| | Mt. Kenya | | | | | | Mt. Meru | Mt. Elgon | |
	119185	119183	119189	Basalt	Foyaite	Kenyte	119208	119218	119228
Zn	347	324	356	127	124	108	84	16	99
Nb	231	226	224	117	287	295	32	51	24
Yt	160	148	150	48	60	35	29	19	32
Sr	445	457	387	1118	691	329	368	1409	613
Rb	86	78	72	44	145	156	4	64	10
Zr	544	446	534	312	992	555	146	113	126

119183/5/9 Cumulo-kenytes.   119228 Pyroxenite.
119218 Micro-ijolite.   119208 Amphibole-rich pyroxenite.

Strontium isotopic and trace-element data

$^{87}Sr/^{86}Sr$ ratios have been measured (Rock, 1976) by standard methods and the initial ratios are equal to measured values owing to the very young age of the rocks. Although not identical, all the initial values lie well within the range typical of oceanic basalts (Faure and Powell, 1972), and support the mantle derivation of all the xeno-lithic types: 119183 (MK12) 0·7035; 119208 (ME8) 0·7055; 119218 (EL3) 0·7049; 119188 (MK13) 0·7044; and 119228 (EL13) 0·7058.

Determinations of six trace elements by the X-ray fluorescence method, on discs of pressed powder, are given in Table VII. The cumulo-kenytes are strongly enriched in Zn, Nb, Yt, Sr, and Zr with respect to 'non-alkaline' igneous rocks, and show values comparable with other members of the Mount Kenya suite. The pyroxenites are, as might be expected, impoverished in the incompatible elements Zr, Nb, and Rb, about normal in Zn and Yt, but enriched in Sr, presumably owing to their high content of alkali pyroxene and, or, amphibole.

Petrogenetic significance of the pyroxenites

The possible role of pyroxenite in alkali rock suites was considered recently (Rock, 1975). In the proposed model, fractionation of alkali-basaltic parental magma under conditions of low H_2O but high CO_2 fugacity leads to suppression of plagioclase crystallization, enhanced fractionation of clinopyroxene, and to the formation of

carbonates. This leads further to the generation of olivine-poor nephelinite magmas, together with carbonatites and pyroxene cumulates. The interpretation of pyroxenites in carbonatite complexes as cumulates is in keeping with previous accounts (e.g. Upton, 1967; Aoki, 1970; Dawson and Smith, 1973) and with field evidence. The identity of the pyroxenes in the Elgon pyroxenites and the host lavas, and the fact that these compositions lie in the range typical of pyroxenes in normal alkali-basaltic magmas (titanaugites), act as support for the model. The titanaugites from other East African nephelinites analysed by Wood (1968) are also similar to those from alkaline olivine basalts.

The proposed model derived from the observation that plagioclase-bearing alkali rocks are incompatible with carbonatites in alkaline complexes, suggesting that large quantities of CO_2 prevent the formation of the anorthite molecule. The Mount Elgon suite is also a good example of this antipathy in operation, since calcic plagioclase is entirely absent from the rocks of the suite, but the availability of vast quantities of CO_2 is confirmed by the abundance of calcite in the tuffs that form a substantial proportion of the volcanic pile (Sutherland, 1966).

The occurrence of amphibole-rich cumulates in nephelinite lavas on Mount Meru requires closer scrutiny. Xenoliths with major or predominant kaersutite have not previously been described from other East African volcanoes, although xenocrysts of pargasite have been noted at Moroto mountain, Uganda (Varne, 1968) and alkalic pyroxenites with interstitial pargasite described from the ankaramitic scoria and carbonatitic tuffs of the Lashaine cone, only a few miles south of Mount Meru (Dawson and Smith, 1973). In both of these instances, the amphibole is less Ti-rich and less abundant than in the Meru examples. Occurrences of kaersutite-rich pyroxenites are well known elsewhere, but they tend to be associated with alkali-basaltic rather than nephelinitic activity. Aoki (1970) described kaersutite peridotites, pyroxenites, gabbros, and hornblendites in the alkali-basaltic scoria of the Iki islands, Japan, and considered them to represent crystallization products of alkali-basaltic magma at depths of 25 to 35 km under hydrous conditions. Borley et. al. (1971) described similar xenoliths from the alkali-basalt–phonolite lavas of Tenerife. The summary of amphibole pyroxenite occurrences given by Dawson and Smith (1973) leaves little doubt that the more strongly alkaline (nephelinitic) the activity, the less hydrous do the accompanying xenoliths become until, with the strongest alkaline activity of carbonatite complexes, only completely anhydrous pyroxenite cumulates are normally present (Upton, 1967) as at Elgon. The Meru xenoliths are unlikely to be cumulates from the nephelinite magma that solidified round them, since there is no evidence, experimental or otherwise, that such magmas are capable of crystallizing abundant kaersutite. Dawson and Smith (1973) concluded that the pargasite of the Lashaine xenoliths represented hydrous residual nephelinite magma that had crystallized interstitially between the cumulus olivine and pyroxene grains. This explanation is clearly untenable for the Meru examples since the kaersutite is not interstitial but forms a major proportion of the xenoliths, even though its composition remains similar to that of the average East African olivine-poor nephelinites given by Wood (1968) (c.f. Tables V, 4 and VI, 1 and 2). These xenoliths are thus likely to be accidental.

The mineralogy of world-wide alkaline suites implies that the gas phase accompanying carbonatitic alkaline activity is richer in CO_2 and poorer in H_2O than that accompanying gabbroic activity. Thus hydrous minerals in carbonatite suites are generally restricted to late-stage rocks such as biotite sovites, to phenocrysts in differentiated phonolitic nephelinites (e.g. Ruri, Kenya), or to true metasomatic rocks formed by the agency of a water-rich fluid, such as the biotite uncompahgrite of Rangwa, Kenya. Because of the general scarcity of H_2O relative to CO_2, the majority of rock-types in carbonatite suites consist of pyroxenes, alkali feldspars, and feldspathoids, with or without olivine, melilite, and garnet. Cumulate rocks, therefore, are also anhydrous, and are typically pyroxenites or dunites (Upton, 1967). However, under wetter conditions, plagioclase can crystallize because CO_2 is concomitantly less abundant, and amphibole and micas also make their appearance. Even in the Mt. Kenya suite, which is an unusually dry gabbroic example, amphibole and mica are well represented in the more felsic members such as nepheline syenites, while the majority of large gabbroic intrusions such as Monchique, Ditro, and the Monteregian hills contain abundant examples of kaersutite-rich gabbros and lamprophyres, together with amphibole or biotite-rich nepheline syenites.

At Meru, therefore, it is possible to envisage a situation in which a single basaltic parental magma gave rise to the varied lava sequence and accompanying xenoliths owing simply to a changing gas-phase composition. An initial water-rich gas allowed the generation of the normal alkali-basalt–trachyte lineage and the accumulation of kaersutite-rich assemblages in the manners suggested by Aoki (1970) and Borley *et al.* (1971); then a gradual increase in the CO_2/H_2O ratio suppressed both plagioclase and hydrous minerals, leading to the more anhydrous xenoliths and the nephelinitic phase, in the manner discussed previously. The whole range of xenoliths became incorporated in the nephelinites because of the more explosive nature of the nephelinitic vulcanicity, which is repeatedly shown in East Africa by the predominance of tuffs in the nephelinite volcanoes such as Elgon, Meru, and Kisingiri, and their scarcity in the basaltic volcanoes such as Kilimanjaro and Kenya.

It is perhaps surprising that such plagioclase-free xenoliths should be genetically related to basaltic magma, which normally crystallizes abundant plagioclase, and not to nephelinite magma, which solidifies to a plagioclase-free assemblage. However, nephelinites are absent on Tristan da Cunha, the Iki islands, and Tenerife, so that kaersutite-bearing pyroxenite xenoliths on these islands can only be related to alkali basaltic activity. Borley *et al.* (1971) discussed in detail the origins of the Tenerife examples, and concluded from previous experimental work that kaersutite–clinopyroxene assemblages could be produced by accumulation from basaltic magmas under 9 to 10kb P_{H_2O} between 1015 and 960 °C, under which conditions plagioclase does not separate until below 900 °C. The associated plagioclase-bearing xenoliths were consequently deemed to form below 900 °, while kaersutite-free pyroxenites formed above 1015 °, where amphibole is unstable with respect to pyroxene. These conclusions were in fact only extrapolations from experimental results obtained with tholeiitic basalts and pargasitic amphiboles, rather than with alkali basalts and kaersutites; nevertheless there seems little reason to doubt the general conclusions reached.

However, because the effect of CO_2 offers a rather simpler, and equally well-substantiated explanation for the examples from Meru, it is preferred for this volcano. It may conceivably be applicable to Tenerife as well, for the island consists predominantly of alkali-basaltic vulcanism but there is also recent evidence for the occurrence of carbonatites.

There are, moreover, a number of other alkaline provinces for which the role of CO_2 offers ready explanation. In the Monteregian Province, Quebec (Philpotts, 1974) a changeover occurs in progressing westwards from gabbroic activity with abundant amphibole-rich cumulate rock-types, to the Oka carbonatite complex, where the cumulates consist predominantly of pyroxene. The intrusion of a single parental magma, subsequently affected by a varying gaseous composition, offers an alternative explanation to Philpotts's suggestion that parental magmas in the east and west were of differing composition. In a number of other alkaline provinces, gabbroic and carbonatitic complexes are rather irregularly distributed in space, but in each case the cumulates accompanying gabbroic complexes are more hydrous than those accompanying carbonatites; examples are the Kapuskasing Arch, Ontario (Allen and Gittins, 1974), and the Damaraland province, SW Africa (Martin et al., 1960). This effect extends to the dyke-rocks as well as to the plutonic intrusions (Rock, 1975), and variations in gaseous composition offer a simple explanation that is believed to deserve as serious consideration as more conventional theories, which rely on compositional variations in the magmas intruded. It is perhaps easier to envisage a situation in which gas composition varies irregularly, than one in which the degree or depth of partial melting of mantle material does so.

REFERENCES

ALLEN (C. R.) and GITTINS (J.), 1974. *Abstracts GAC-MAC conference* (3rd circular), St. Johns, Newfoundland.
AOKI (K.), 1970. *Contr. Min. Petr.* **25**, 270.
BAKER (B. H.), 1967. *Bull. Geol. Surv. Kenya*, no. **79**.
—— WILLIAMS (L. A. J.), MILLER (J. A.), and FITCH (F. J.), 1971. *Tectonophysics*, **11**, 191.
BORLEY (G. D.), SUDDABY (P.), and SCOTT (P.), 1971. *Contr. Min. Petr.* **31**, 102.
BUDDINGTON (A. F.), and LINDSLEY (D. A.), 1964. *Journ. Petrology*, **5**, 310.
DAVIES (K. A.), 1952. *Mem. Geol. Surv. Uganda*, **8**.
DAWSON (J. B.) and SMITH (J. V.), 1973. *Journ. Petrology*, **14**, 113.
DEER (W. A.), HOWIE (R. A.), and ZUSSMAN (J.), 1963. *Rock-forming Minerals*. London (Longmans).
FAURE (G.) and POWELL (J. L.), 1972. *Strontium Isotope Geology*. New York (Springer-Verlag).
GUEST (N. J.) and LEEDAL (G. P.), 1953. *Rec. Geol. Surv. Tanganyika*, **3**, 140.

JOHANNSEN (A.), 1938. *Descriptive Petrography of the Igneous Rocks*, vol. **4**, University of Chicago Press, Chicago.
JOPLIN (G. A.), 1968. *Journ. Geol. Soc. Aust.*, **15**, 275.
MARTIN (H.), MATHIAS (M.), and SIMPSON (E. S. W.), 1960. *Int. Geol. Congr., 21st sess.*, pt. **13**, 156.
McKIE (D.), 1966. In *Carbonatites*, New York (Wiley & Sons), 261.
OATES (F.), 1934. *Tang. Geol. Surv. Report for 1933*.
ODMAN (O. H.), 1930. *Geol. Fören. Förh.*, **52**, 455.
PHILPOTTS (R. A.), 1974. The Monteregian Province, in *The Alkaline Rocks*, ed. Sorensen, New York (Wiley & Sons), 293.
PITT (G. D.) and TOZER (D. C.), 1970. *Phys. Earth Planet. Interiors*, **2**, 179.
ROCK (N. M. S.), 1975. *Geol. Mag.*, in press.
—— 1976. *Contr. Min. Petr.*, in press.
SAGGERSON (E. P.), 1970. *Bull. Volc.* **34**, 38.
SEARLE (D. L.), 1952. *Geol. Surv. Kenya Report*, **19**.
SUTHERLAND (D. S.), 1966. Ph.D. thesis, Bedford College, University of London.
UPTON (B. C. J.), 1967. In *The Ultramafic Rocks*, ed. Wyllie, New York (Wiley & Sons), 281.
VARNE (R.), 1968. *Journ. Petrology*, **9**, 169.
WILKINSON (P.), 1966. *Proc. Geol. Soc. Lond., 1929*, 28.
WILLIAMS (L. A. J.), 1970. *Bull. Volc.* **34**, 439.
WOOD (C. P.), 1968. Ph.D. thesis, University of Leeds.