Potash-trachytes and ultra-potassic rocks associated with the carbonatite complex of the Toror Hills, Uganda

By D. S. SUTHERLAND, B.Sc., L.R.I.C., F.G.S.

Department of Geology, The University, Leicester

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Summary. Rocks containing a high percentage of potash feldspar are described for the first time from the Toror Hills in the Karamoja district of eastern Uganda. They include feldspathic fenites, intrusive feldspathic fenite–breccias, potash-trachytes, and orthoclasites. Petrographic data and chemical analyses show the close similarity in composition of these rocks despite their widely differing textures and modes of occurrence. The potash metasomatism associated with the emplacement of carbonatite, and the subsequent mobilization of these feldspathic fenites are compared with similar phenomena observed at other carbonatite centres. The problem of the mechanism of mobilization is discussed.

THE Toror Hills lie approximately thirty-five miles north-west of Moroto town in the Karamoja district of eastern Uganda and represent the most northerly of the group of dissected Tertiary volcanoes, Elgon, Kadam, Napak, and Moroto. At Toror the volcanics have been removed by erosion and the intrusive complex, over two miles in diameter, is formed of carbonatite surrounded by altered gneisses of the Basement Complex in which are emplaced dykes and plugs of trachytic rocks. The marginal zone of the carbonatite and its surrounding breccia forms a circular group of hills rising to 2000 feet above the level of the surrounding plain and within the inner bowl-shaped depression the carbonatite is cut by a central mass of phonolitic agglomerate. All of these rocks are extensively invaded by dykes, sheets and plugs of phonolite, which by their relative resistance form features of varying prominence, including the highest point, Toror Peak itself (6380 ft).

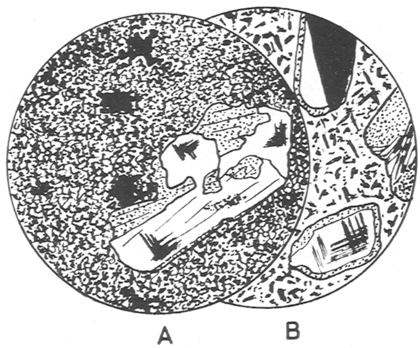
The geology of the Toror Hills was studied by DuBois (1956, 1959), and an account in the course of publication (King and Sutherland) embodies further work by the present writer.

DuBois recorded a small number of trachyte dykes from the southern part of the complex, but the more recent work has shown that trachytes are in fact widely developed and constitute an important phase in the history of the complex. They are of particular interest owing to their unusually high content of potash, and can be shown to be closely related to potash-rich rocks derived by metasomatic alteration of the Basement Complex adjacent to the carbonatite. The group of related rocks includes feldspathic fenites, intrusive feldspathic fenite–breccias, xenolithic trachytes, and porphyritic trachytes. The trachytes constitute the main subject of the present account, but the related rocks will be described in so far as they are relevant to a discussion of the derivation of the trachytes.

Feldspathic fenites. The predominant rock-type of the Basement Complex in the area is a foliated gneiss consisting of microcline, subordinate plagioclase, abundant quartz, and biotite, pleochroic from greenish-brown to pale yellow. Around the complex, for a distance varying up to 600 yards from the carbonatite boundary, the gneiss is fenitized. Two processes of alteration can be recognized: the development of Na–Fe mafic minerals, and potash-feldspathization. Although locally one process seems to have affected the gneiss more than the other, in general the two cannot be distinguished as separate phases (as is possible at many carbonatite centres) and appear to have been simultaneous.

The rock appears initially to have been shattered and, along a close network of channels, feldspar is recrystallized either to a fine granular texture or to an intergrowth of small parallel laths. At the same time, plagioclase and microcline are partly replaced by anhedral plates of cloudy, untwinned potash feldspar, and biotite shows alteration to laths of potash feldspar aligned parallel with the original cleavage, and granular blebs of black ore and limonite. Veinlets of mafic minerals (aegirine, soda-amphibole, yellow-brown biotite, and chlorite) are developed along the feldspar channels and across the rock between channels, replacing quartz, in particular around the crystal boundaries. The dark minerals show partial alteration to limonite.

Where the channels of feldspar or veinlets of mafic minerals become more than a few millimetres in width the rock assumes the appearance of a breccia (e.g. SUT 233, table II, 16). Fenitization at Toror at the level of exposure is slight by comparison with other carbonatite centres and the complete elimination of quartz and biotite is only sporadic. SUT 242 (table II, no. 15) represents a feldspathic fenite some 300 yards distant from the carbonatite, east of Toror Peak. It consists of a coarse textured intergrowth of turbid untwinned orthoclase ($2V_\alpha$ 54°), and subordinate microcline ($2V_\alpha$ 83°); original biotite is replaced by parallel laths of potash feldspar (orthoclase ? $2V_\alpha$ 46°) associated with limonite, and quartz is absent, as are the mafic minerals generally associated with fenitization (fig. 1). On the northern flanks of the complex, the gneiss has a brecciated appearance, feldspar is developed extensively in fine-grained channels together with the coarser crystalline replacement comparable with SUT 242, and mafic minerals, possibly the result of fenitization, are represented only by limonite. Quartz disappears only in the immediate vicinity of the carbonatite.



FIGS. 1 and 2: FIG. 1 (left). Feldspathic fenite consisting almost entirely of potash feldspar. Microcline (clear with cross-hatching) and orthoclase (stipple); lath-textured orthoclase and iron oxides (black) replace original biotite (SUT 242). Field of view 1 mm. FIG 2 (right). A. Feldspathic fenite–breccia, SUT 192. Fragments of feldspathic fenite (microline and orthoclase) in fine-grained groundmass of feldspar and limonite. Field of view 1 mm. B. Xenolithic potash–trachyte, SUT 155A. Twinned phenocryst of sanidine, rimmed with orthoclase (stipple), together with fragments of feldspathic fenite (microline and orthoclase) in fine-grained felsitic groundmass. Same magnification.

On the western side of the complex the development of sodic pyroxenes and amphiboles predominates over feldspathization (e.g. SUT 228, table II, no. 17), and quartz is present in these fenites even at the contact with the carbonatite.

Intrusive feldspathic fenite–breccia. Several types of breccia are recognizable at Toror and they may be assigned to a number of episodes of brecciation. Many of the breccias have a ferruginous or carbonate-rich matrix, but a distinctive type consists of fragments of feldspathic fenite, with occasional fragments of porphyritic trachytes, contained in a buff-coloured feldspathic matrix. Such breccias are dyke-like, up to 30 feet in width, and their fragments range from 15 cm down to fractions of a millimetre in diameter, although 2 or 3 cm size is common in the field.

Alongside the dykes of breccia, the adjacent Basement gneiss retains an undisturbed foliation and consists of quartz-bearing fenite. Several dykes of this breccia occur on the lower slopes of the western hills, about 500 yards from the carbonatite. In thin section the fragments consist of feldspathic fenite of varying texture, including aggregates of anhedral turbid potash feldspar, fragments with channels of fine-grained feldspar or parallel laths, and fragments of crystals of microcline. Often the microcline is narrowly rimmed by untwinned potash feldspar, but there is no further evidence of alteration of the fragments. Occasionally fine-grained trachytic rock containing euhedral phenocrysts of feldspar forms fragments in the breccias (e.g. SUT 193, table II, no. 7). Dark minerals are not abundant in the fragments, and comprise tufts and granules of limonite, with occasional aegirine.

The groundmass of the breccias consists of potash feldspar with a fine-grained felsitic texture, speckled with clumps of limonite, and occasionally containing quite large grains of apatite (fig. 2A). A pale greenish-yellow granular mineral is abundant in the groundmass of several of the breccias; it has high relief and very low birefringence, with oblique extinction. It is particularly abundant in SUT 192, and in view of the high P_2O_5 percentage in the rock (table II, no. 14) may be a phosphate mineral. The intrusive feldspathic breccias grade, by increase in the proportion of fine-grained groundmass to fragments, into rocks with the appearance and character of xenolithic trachytes (e.g. SUT 113, table II, no. 13). The fragments are not conspicuously corroded, and quite angular chips of microcline are common in these rocks. Some of these intermediate types contain both xenoliths and occasional phenocrysts (SUT 155A, fig. 2B).

Porphyritic trachytes. Dykes of trachyte occur in the Basement gneiss all round the complex, but are particularly abundant on the northern flanks where locally they form a complex mesh, the dykes ranging in width to up to forty feet. An early series, which trends mainly 80°, is transected by later dykes with a predominant trend of 160°, parallel with the foliation of the gneiss. Around the northern half of the complex where the dykes have been studied in detail, this later series shows a distinct radial arrangement (fig. 3).

In addition to the dykes, many areas of trachyte, often affected by later shattering and brecciation, have a patchy distribution in the Basement rocks and are not dyke-like in form. An approximately oval area of trachyte some 400 yards across occurs in the lower part of the northern valley. Exposures here are rare, although loose debris is plentiful, and the contact with Basement rocks is not seen; it is probable from its shape that it represents a plug, although it is not marked by a topographic feature. Five other bodies of similar shape and comparable size previously mapped, along with this area, as altered Basement are considered by analogy also to be trachytic vents. The group is centred around the main vent occupied by phonolitic agglomerate (fig. 3).

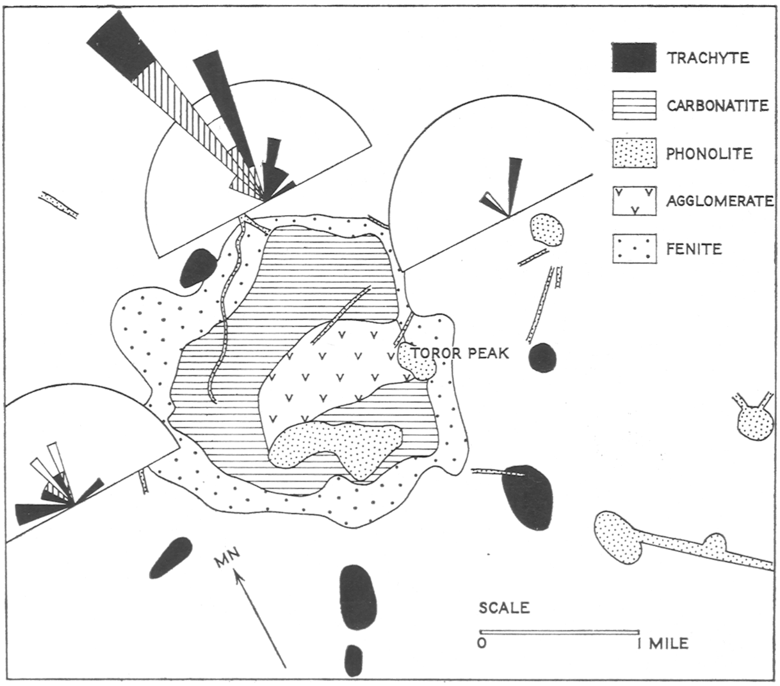
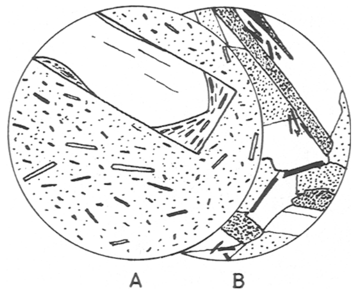


FIG. 3. Simplified geological map of the Toror Hills, and diagrams showing trends of trachyte dykes (black), with foliation of Basement gneiss (no ornament; where both are superimposed, diagonal stripes). Smallest unit of length in the segments of semicircles represents one measurement. Semicircles are located on western, northern, and eastern spurs where the respective measurements were taken. (Diagram drawn by Mrs. E. K. Harris.)

Although it is readily established that the trachytes are earlier than the phonolites, their relations with the carbonatite are often obscure. Some sheets of trachyte (SUT 167 and SUT 136) certainly cut the carbonatite (fig. 4). Along its northern boundary the carbonatite, in the form of discontinuous dykes, is transected by trachyte dykes forming conspicuous wall-like features. Many of the trachytes in this part of the complex, however, appear to be cut off by the carbonatite dykes, and locally xenoliths of trachyte occur in the carbonatite (SUT 35). The relationships are frequently obscured by the intensive limonite-veining and local brecciation, which affected many of the rocks, including the late trachytes such as SUT 136, but it is concluded that trachytes were emplaced both before and after the intrusion of the carbonatites.



FIGS. 4 and 5: FIG. 4 (left). Field outcrop, drawn from a photograph, of sheet of porphyritic trachyte, SUT 136, (upper part of diagram) cutting carbonatite, which shows vague vertical banding. (Top, centre is hammer). The area sketched is 4 ft wide. FIG. 5 (right). A. Porphyritic trachyte, SUT 103. Phenocryst of orthoclase partly resorbed, with outgrowth of sanidine enclosing groundmass laths. Final stage of crystallization of groundmass is very fine-grained and speckled with limonite. Field of view 0·8 mm. B. Orthoclasite, SUT 134. Shown as with crossed nicols, stipple indicating various shades of interference colours. Black: acicular crystals of aegirine (?) replaced by limonite. Diameter of circle 1 mm.

The trachytes are fine grained and 'chalky' rather than crystalline in aspect; they are buff coloured, often speckled with limonite or ochre, and may be closely jointed. Small tabular phenocrysts of feldspar frequently show a parallel orientation. At the contacts, the trachyte, the Basement gneiss, or both of these rocks, may be involved in local brecciation, but normal contacts also occur, where the trachyte is finer grained along a selvedge only 0·2 mm in thickness, and the gneiss is slightly feldspathized.

The tabular phenocrysts of feldspar are generally small, less than 2 mm in length, and sparsely distributed. They are invariably elongate parallel to [001], and sometimes twinned on the Carlsbad law. In many trachytes the phenocrysts consist of turbid orthoclase, with $2V_\alpha$ varying from 40° (SUT 136) to 52° (SUT 29). In other cases they are formed of clear sanidine, with $2V_\alpha$ less than 20° (SUT 114) and the optic axial plane perpendicular to (010). In SUT 103 partly resorbed phenocrysts of orthoclase, $2V_\alpha$ 45°, show an extended growth of sanidine ($2V_\alpha < 20°$) with the optic axial plane perpendicular to that of the main crystal; the outgrowth encloses microlites of feldspar aligned by flow around the main crystal (fig. 5*a*).

The groundmass of the trachytes varies from very finely granular or felsitic with an intergrowth of feathery lath-like crystals to trachytoid; sometimes aligned laths are dispersed in a felsitic groundmass, but occasionally the whole groundmass, which is less fine grained, consists of a close intergrowth of laths aligned in small-scale sweeping structures.

Minerals of the feldspathoid and zeolite groups are not abundant. Sometimes granular aggregates of zeolite (natrolite?) occur, and may be replacements, but oval areas with fine-grained rims and inner rosettes of natrolite (?) resemble amygdales.

The amount of mafic material is generally small, and is represented mainly by limonite in the form of small granules of gœthite and amorphous material. Aegirine is rare, but has been recognized in thin section or separated from the crushed rock in small amounts. Much of the limonite in these rocks is associated with later veining. Few other minerals are found in the trachytes, although apatite and the pale green mineral found in the breccias also occur in some of the trachytes. Fluorite forms occasional patches and veinlets, associated with apatite. It forms a major constituent of SUT 167, where it occurs in purple-coloured patches associated with baryte (?) and chlorite; this trachyte is comparable with borengite, a dyke rock found at Alnö (von Eckermann, 1960).

Orthoclasites. In many of the trachytic intrusions there are transitions into a medium-grained rock consisting entirely of potash feldspar. This rock-type predominates near the carbonatite boundary in the north and north-west, but it also occurs sporadically in some of the trachyte dykes up to 800 yards from the carbonatite. SUT 101 from such a dyke consists of a medium grained intergrowth of orthoclase laths 1 to 2 mm in length, often twinned, and grouped in stellate clusters. In SUT 139, from a dyke at the summit of the northern ridge, the texture shows a strong parallel orientation of laths, with interstitial tufts of limonite. The feldspar of these rocks is orthoclase, with $2V_\alpha$ varying between 40° and 60° in different examples (fig. 5*b*). Occasional phenocrysts of turbid orthoclase, similar to those in the trachytes, are encountered in the feldspar-rock.

Chemical composition. The results of complete and partial analyses of the various rocks are given in tables I and II; the unusually potassic

TABLE I

	1	2	3	4	5	6
SiO_2	58·84	54·69	58·43	58·98	50·53	60·57
Al_2O_3	17·48	21·02	17·84	18·69	17·84	15·60
Fe_2O_3	5·33	6·38	5·09	2·72	2·38	7·20
FeO	0·07	0·10	0·00	2·20	1·46	0·00
MgO	0·24	0·00	0·43	0·36	0·79	0·00
CaO	0·30	2·01	0·80	2·37	8·60	0·11
Na_2O	0·40	0·62	0·38	0·75	0·90	0·49
K_2O	14·96	13·34	13·90	12·49	10·40	13·71
TiO_2	0·37	0·30	0·34	0·42	0·39	0·46
P_2O_5	0·26	0·28	0·35	0·24	0·07	0·09
F	n. d.	n. d.	n. d.	n. d.	6·47	n. d.
MnO	0·30	0·13	0·42	0·23	0·11	0·14
H_2O^+	1·17	1·60	1·05	n. d.	1·36	2·00
H_2O^-	0·13	0·19	0·11	0·26	0·63	
BaO	n. d.	n. d.	0·18	n. d.	1·01	0·08
	99·85	100·66	99·32	99·71	102·94	100·45
Less O for F					2·72	
					100·22	
C.I.P.W. norms						
qz	—	—	1·39	1·06	4·19	5·27
or	88·50	73·45	82·23	73·89	61·49	81·12
ab	1·31	—	3·20	6·34	7·60	3·77
an	—	8·31	2·22	10·34	—	—
lc	—	4·27	—	—	—	—
ne	1·13	2·84	—	—	—	—
c	0·59	2·48	1·41	0·10	5·08	—
ac	—	—	—	—	—	0·32
wo	—	—	—	—	—	0·02
hy $MgSiO_3$	—	—	1·07	0·89	1·97	—
hy $FeSiO_3$	—	—	—	1·58	0·28	—
ol Mg_2SiO_4	0·42	—	—	—	—	—
ol Fe_2SiO_4	—	—	—	—	—	—
mt	0·14	—	0·37	3·94	3·46	—
hm	5·26	6·38	4·85	—	—	7·10
il	0·70	0·49	0·65	0·81	0·74	0·30
ap	0·60	0·67	0·84	0·57	0·17	0·20
fl	—	—	—	—	12·39	—
ru	—	0·05	—	—	—	0·30

1. SUT 197 Trachytic orthoclasite, summit W. Ridge, Toror Hills. Anal. A. Mayer.
2. SUT 134 Orthoclasite dyke, N. Ridge, Toror Hills. Anal. J. M. Bartle.
3. SUT 213 Potash–trachyte, W. side, Toror Hills. Anal. D. S. S.
4. SUT 137 Potash–trachyte, NNE. spur, Toror Hills. Anal. A. Mayer.
5. SUT 167 Fluorite–potash–trachyte, N. Ridge, Toror Hills. Anal. D. S. S.
6. SUTo 512 Potash–trachyte, East Road, Tororo Complex (S.E. Uganda). Anal. D. S. S.

nature of these rocks is evident. Their normative compositions, shown diagrammatically in fig. 6, illustrate their high content of orthoclase. The remaining constituents, apart from the normative minerals shown, consist chiefly of iron and manganese oxides and water, present in the mode as limonite. In calculations based on the partial analyses, silica has been allotted to the salic minerals only; on this basis most of the

TABLE II. Partial analyses of rocks from Toror Hills

	7	8	9	10	11	12
SiO_2	59·4	59·9	57·4	56·3	56·14	52·65
Al_2O_3						
Na_2O	0·30	0·42	0·47	0·46	0·25	0·20
K_2O	14·58	14·38	14·03	13·45	14·57	14·55
P_2O_5	—	—	—	—	0·47	2·06
	13	14	15	16	17	18
SiO_2	51·77	48·69	62·73	55·50	54·95	63·39
Al_2O_3	—	—	—	13·77	13·57	20·25
Na_2O	0·32	0·31	0·38	3·61	3·50	3·22
K_2O	14·15	12·23	14·97	9·20	8·24	6·08
P_2O_5	2·44	6·85	—	0·16	0·09	0·02

7. SUT 193 Porphyritic potash–trachyte fragment in breccia, W. side, Toror Hills. Anal. A. Mayer.
8. SUT 102 } Potash–trachyte, N. side, Toror Hills. Anal. J. M. Bartle.
9. SUT 120 }
10. SUT 114 ditto, spherulitic-weathering.
11. SUT 17 } Xenolithic non-porphyritic pseudotrachyte, N. side, Toror Hills. Anal. A. Mayer.
12. SUT 18 }
13. SUT 113 }
14. SUT 192 Intrusive feldspathic fenite–breccia, W. side, Toror Hills. Anal. A. Mayer.
15. SUT 242 Feldspathic fenite, E. side, Toror Hills. Anal. A. Mayer.
16. SUT 233 Fenitized granitic Basement, E. side, Toror Hills. Anal. A. Mayer.
17. SUT 228 Fenitized granitic Basement, W. side, Toror Hills. Anal. A. Mayer.
18. SUT 230 Granitic Basement, hardly fenitized, W. side, Toror Hills. Anal. J. M. Bartle.

rocks are at least saturated. The very high proportion of ferric iron in the complete analyses confirms that the samples are mostly altered, probably by weathering; the limonite seen in thin section in some cases represents original aegirine. It is to be inferred, therefore, that some Na_2O and SiO_2 have been removed by leaching.

In fig. 7, in which the analyses have been recalculated in terms of $NaAlSiO_4$–$KAlSiO_4$–SiO_2, the plots lie close to the composition $KAlSi_3O_8$ and form a belt straddling the saturation boundary. It may be noted that the trachytes containing xenoliths of feldspathized Basement are undersaturated (nos. 11, 12, 13), whereas the feldspathic fenite-breccia (no. 14) is just saturated. Normal trachytes become progressively richer

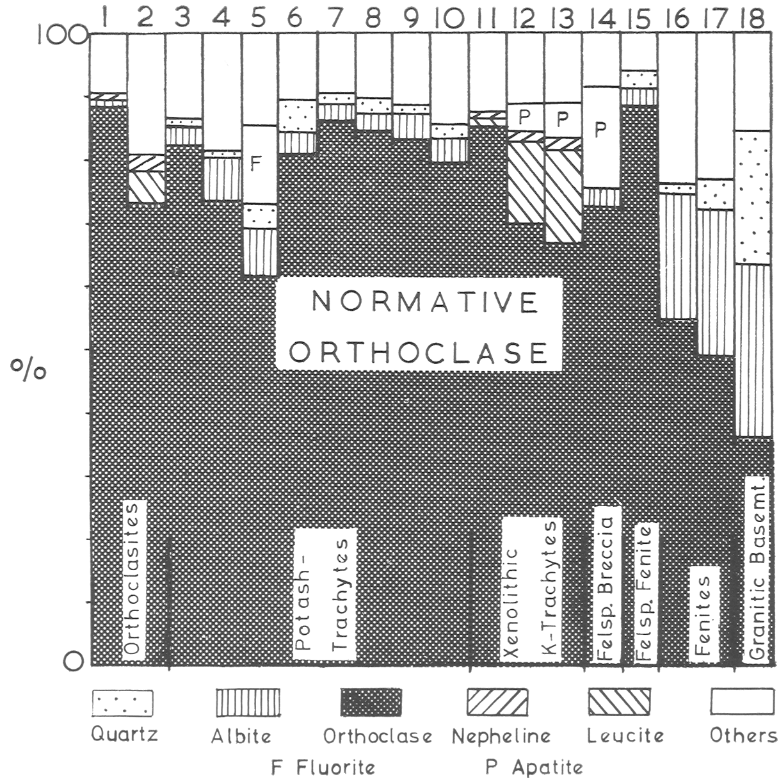


FIG. 6. Diagrammatic representation of normative constituents calculated according to the system of C.I.P.W. Nos. 1–6 from complete analyses, the rest from partial analyses. The bulk of the remaining dark minerals is represented by iron ores, present in the mode as limonite.

in silica (and Na_2O) towards no. 5, which from its field relations represents one of the latest trachytes. The silica content of the rocks appears to be unrelated to the distance from the carbonatite.

Values for trace elements in the trachytes so far determined are given in table III together with those of other feldspathic rocks from the Tundulu complex in Nyasaland. Whereas Garson (1962, p. 189) noted a decrease in the amount of Ba and Sr acompanying the mobilization of the feldspathized rocks, the trachytes of Toror contain abundant Ba, and SUT 114 is especially high in Sr; both elements may be regarded as substituting for K in the potash feldspar, and the extent of this substitution may reflect in some measure the temperatures attained in the formation of the trachytes. The indication is that the trachytes of Toror

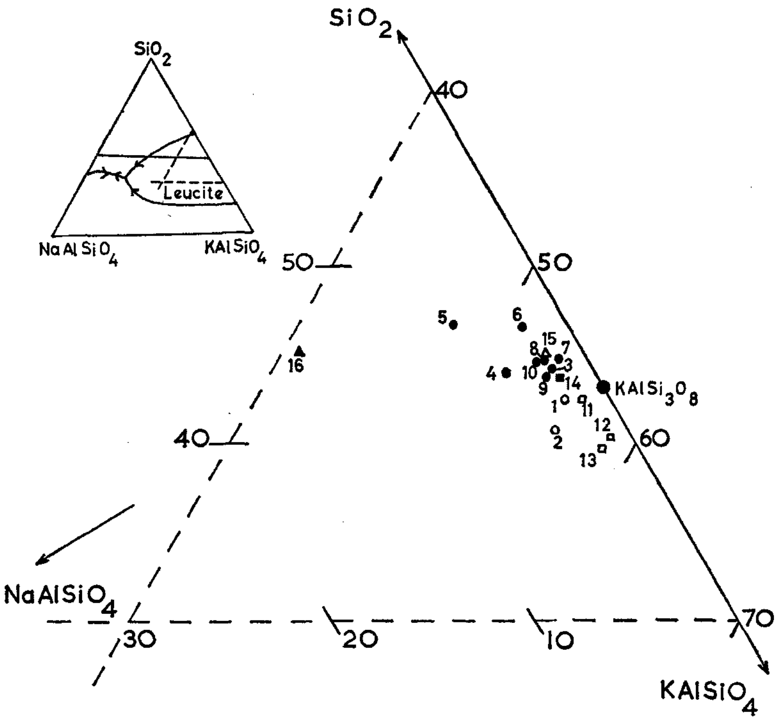


FIG. 7. Chemical composition of the feldspathic rocks in terms of $NaAlSiO_4$–$KAlSiO_4$–SiO_2. ○, orthoclasites; ●, potash-trachyte; □, xenolithic trachytes; ■, feldspathic fenite-breccia; △, feldspathic fenite; ▲, fenitized Basement.

formed at higher temperatures than those of Tundulu (cf. Rankama and Sahama, 1950, p. 472). Variations in the other trace elements are irregular, but comparable with the Tundulu rocks. The actual concentration of elements such as Nb and Zr, La and Y, Ga and Be is characteristic of carbonatites and associated rocks (cf. Garson, 1962, p. 192) and is regarded as diagnostic of the late-stage differentiates of igneous melts that contain a high proportion of volatile components including P and F.

Derivation of the ultra-potassic rocks. Petrographic and chemical data suggest a genetic connexion between the various types of feldspathic rocks. The development of potash-feldspar in the Basement gneiss is recognized as the first stage; at many alkaline centres the potash-metasomatism that occurs adjacent to the carbonatite produces a coarse-textured rock composed of conspicuous laths of orthoclase (e.g. at Tororo,

TABLE III. Trace-elements of Toror Hills rocks compared with rocks of the Tundulu complex, Nyasaland. Parts per million.

	G1344*	N1380b*	G1449*	N1528*	SUT 114	SUT 213	SUT 167
Ba	>1000	>1000	350	500	3800	3200	9000
Sr	900	800	55	125	2300	<100	—
Ga	25	35	30	30	50	50	—
La	120	120	400	225	<100	<100	—
Mo	250	<3	8	<5	<5	<5	—
Nb	>1000	120	600	300	300	400	—
Y	35	40	130	40	100	30	30
Zr	30	>1000	>1000	1000	100	100	—
Be	<10	<10	<10	<10	40	20	6

G 1344 Feldspathic breccia, Nathace Hill, Nyasaland.
N 1380b Orthoclase-rock, Nyasaland.
G 1449 Pseudotrachyte, Kalicelo Hill, Nyasaland.
N 1528 Trachyte, Chuara, P.E.A.
SUT 114 Trachyte, northern slopes Toror Hills, Uganda. Anal. Miss D. E. M. Hosking.
SUT 213 Trachyte, north-western slopes, Toror Hills, Uganda. Anal. Miss D. E. M. Hosking.
SUT 167 Trachyte, summit north ridge, Toror Hills, Uganda. Y and Be anal. Miss D. E. M. Hosking.

* Analyses reproduced from Garson's account of the Tundulu complex, 1962, p. 187.

Davies, 1956, and King and Sutherland), but at Toror the texture produced is a variable one, consisting of aggregates of anhedral plates of orthoclase and microcline separated by channels of fine-grained granular feldspar or sheaves of feldspar laths. This feldspathized rock subsequently became brecciated, as shown by the occurrence of fragments of it in the feldspathic fenite breccias. The breccias are evidently intrusive, and are derived from deeper levels, for the fragments are varied and are of more highly feldspathized rock than the surrounding quartz-bearing gneiss.

The xenolithic trachytes are considered to be the products of more intense brecciation, with the development of a greater proportion of comminuted groundmass. In all these rocks, however, the texture of the groundmass is crystalline and not fragmental.

Garson (1962, p. 78) has traced the development of trachytic rocks in successive stages by the recrystallization of feldspathic breccia at Tundulu. Although the sequence at Toror appears to be similar, the writer's interpretation of the initial stages differs: at Tundulu (and other Chilwa vents) Garson describes the feldspathization of a breccia, whereas at

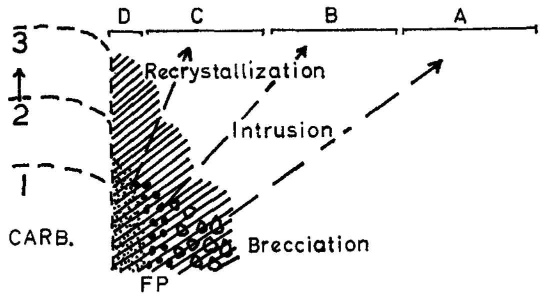


Fig. 8. Derivation of the feldspathic rocks. *FP*, feldspathic fenite; *A*, zone of intrusive feldspathic fenite–breccia; *B*, zone of xenolithic trachyte; *C*, zone of trachyte; *D*, zone of orthoclasite and successive phases of feldspathic fenite accompanying the rise of carbonatite.

Toror the development of trachyte begins with the brecciation of an already feldspathic rock. Garson observes that phenocrysts of sanidine develop from aggregates of orthoclase in the breccia, but no conclusive evidence of this is found at Toror.

The orthoclasites that occur as dykes and as phases of the trachytes are regarded as the coarser-grained equivalents. It may be noted that, with some exceptions, there is a tendency for the intrusive breccias to occur farthest from the carbonatite, followed successively by xenolithic trachytes, porphyritic trachytes, and orthoclasite as the carbonatite is approached. Fig. 8 shows diagrammatically the relationships envisaged between the rock types.

The problem of mobilization. The trachytes, which can be traced to derive from the brecciated feldspathic fenites, have, nevertheless, all the characters of normal magmatic trachytes: intrusive, sheeted habit, euhedral phenocrysts, and fine-grained groundmass with flow-texture. The rocks were certainly mobile; but were they molten?

One of the most important factors in this discussion is the absence of leucite from the trachytes, despite their chemical composition, which falls in the field of primary crystallization of leucite under anhydrous conditions. A few of the trachytes contain spherical structures of various kinds, but they are doubtful evidence of the existence of leucite. Theoretical considerations based on the work of Bowen and Tuttle (1950) lead to the conclusion that the water-vapour pressure would have exceeded 2000 kg/cm^2 if melting took place without the appearance of leucite. The temperature of melting would then lie around 800° C.

In several of the trachytes and related rocks, however, more than one type of potash feldspar occurs. In SUT 155A, for example, phenocrysts of sanidine and orthoclase coexist with angular chips of microcline narrowly rimmed by untwinned (?) orthoclase. Experiments have shown that microcline, if heated for a matter of hours, assumes a monoclinic structure; and sanidine is reputed to form at temperatures above 850° C. It remains a problem to explain the survival of small chips of microcline at the same time as the formation of sanidine. The paragenesis clearly indicates that the mineral assemblage was not in equilibrium. There appears to be a possibility that sanidine may form metastably at temperatures below 850° C.

It seems that the nature of the process of mobilization is not sufficiently understood. There are obvious difficulties in the way of actual melting. Garson does not appear to discuss the mechanism of mobilization, although he uses the term 'rheomorphic feldspathic breccia' (1958, p. 29) and refers to 'partial mobilization' of the fenites (1962, p. 78). The original use of the term 'rheomorphic' by Backlund, and subsequently by many authors, implied the presence of a magmatic phase (cf. Goodspeed, 1953). It is possible, however, in the case of the feldspathic breccias and trachytes, that mobilization was effected by a gaseous rather than a liquid medium in which the solid fragments were carried. Such a concept is already acceptable in application to the emplacement of agglomerates and breccias, and a similar mode of emplacement has been claimed for the intrusive granophyres of Slieve Gullion (Reynolds, 1954). At present, not enough is known of the crystallizing behaviour of gas/solid systems. Is it possible, for instance, that an active gaseous medium might produce at lower temperatures a disordered distribution of Al and Si in the lattice of precipitated feldspars, while existing fragments remain unaltered?

In the absence of further evidence, no conclusions are drawn, and both melting under high pressure and transportation as a 'fluidized' system remain possibilities.

Source of potash. From the numerous examples of potash feldspathization adjacent to carbonatite masses[1] it is evident that carbonatite itself is a carrier of potash and the source of potassic emanations. In many cases the potash metasomatism is seen to be later than an earlier phase of Na–Fe fenitization, and is usually closely followed by the emplacement of carbonatite (Chilwa — Garson and Campbell Smith, 1958; Tororo — King and Sutherland). Whereas the potash metasomatism is evidently associated with the emplacement of carbonatite, the earlier Na–Fe metasomatism may be more closely related to a silicate magma of alkaline character prior to the derivation of the carbonatite itself. Nevertheless, it has been shown recently, by the discovery of fresh carbonatite lava in the crater of Oldoinyo L'Engai, Tanganyika (Guest, 1963, and DuBois *et al.*, 1963) that both soda (in particular) and potash are abundant in the molten extrusive carbonatite. Indeed, the presence of these constituents is probably as essential as that of water vapour in maintaining carbonatites as melts at relatively low temperatures. Intermittent plugging of the vent by solidified volcanic material, followed by build-up of pressure below, may have been the cause of the escape of alkalis from the carbonatite into the surrounding rocks, eventually leaving residual Ca, Mg, and Fe carbonates to crystallize.

Although some of the soda and potash present in the carbonatite magma may have been derived from wall rocks by reaction, these alkalis are present in greater abundance than can be accounted for in this way, and they are regarded as predominantly juvenile.

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References

Bailey (D. K.), 1960. Bull. Geol. Surv. Northern Rhodesia, no. 5.
Bowen (N. L.) and Tuttle (O. F.), 1950. Journ. Geol., Chicago, vol. 58, p. 497.
Brown (P. E.), 1964. Quart. Journ. Geol. Soc., vol. 120, p. 223.
Davies (K. A.), 1956. Mem. Geol. Surv. Uganda, no. 8.
Dixey (F.), Campbell Smith (W.), and Bisset (C. B.), 1937 (revised 1955). Bull. Geol. Surv. Nyasaland, no. 5.

[1] e.g. Chilwa centres (Dixey *et al.*, 1937; Garson and Campbell Smith, 1958; Garson, 1961, 1962); Rufunsa Valley, Northern Rhodesia (Bailey, 1960); Mbeya, Tanganyika (Brown, 1964); Uganda centres (King and Sutherland).

DuBois (C. G. B.), 1956. Ph.D. thesis, Univ. London.
——, 1959. Internat. Geol. Congr., Mexico, p. 303.
——, Furst (J.), Guest (N. J.), and Jennings (D. J.), 1963. Nature, vol. 197, p. 445.
von Eckermann (H.), 1960. Arkiv. Min. Geol., vol. 2, no. 39, p. 519.
Garson (M. S.), 1961. Rec. Geol. Surv. Nyasaland, 1959, p. 51.
——, 1962. Mem. Geol. Surv. Nyasaland, no. 2.
——and Campbell Smith (W.), 1958. Mem. Geol. Surv. Nyasaland, no. 1.
Goodspeed (G. E.), 1953. Amer. Journ. Sci., vol. 251, p. 453.
Guest (N. J.), 1963. Proc. Geol. Soc., no. 1606, p. 54.
King (B. C.) and Sutherland (D. S.), in The Carbonatites, edit. Tuttle (O. F.), and Gittins (J.), in course of publication, John Wiley, New York.
Rankama (K.) and Sahama (Th. G.), 1950. Geochemistry. Univ. Chicago Press.
Reynolds (D. L.), 1954. Amer. Journ. Sci., vol. 252, p. 577.

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