PETROGENESIS OF KATUNGITE AND ITS ASSOCIATES

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ABSTRACT

The young volcanic fields near Ruwenzori are characterised by ultrabasic potassic volcanic rocks made up of various combinations of melilite and/or augite; kalsilite and/or leucite and/or potash-rich glass; and, with few exceptions, olivine; invariable accessories are perovskite and black ores. The types include *katungite* (olivine+melilite+potash-rich glass), *mafurite* (olivine+augite+kalsilite), and *ugandite* (olivine+augite+leucite) and all possible transitions are represented. The activity was intensely explosive. The pyroclasts invariably contain fragments both of basement rocks and of a cognate sub-volcanic suite composed of pyroxene and/or biotite and/or olivine (O.B.P. series). The rocks and minerals of the latter appear simultaneously with the volcanic types as fragments in the tuffs and inclusions in the lapilli, etc. It is shown that the series proto-katungite (olivine-free)—katungite—alnöite—olivine-ouachitite is a genetic one that could have been formed from O.B.P. by magmatic material even more ultrabasic than proto-katungite. In an earlier hypothesis this magmatic material was regarded as "emanations" (E) of alk-aluminous and cafemic composition, but the sources of the "emanations" and of the O.B.P. rocks were then left unexplained. It is now suggested that the alk-aluminous material (and all the SiO_2 of the resulting rocks) came from granite (G) and its derivatives, and that the cafemic material came from "magmatic carbonatite" (C). For katungite (K) the hypothesis can be expressed in the form C+G=O.B.P.+K. Additional potash, (e.g. in mafurite) is accounted for by the demonstrated fact that biotite formed at greater depths became altered and gave up part of its potash to the liquid phase. Brief reference is made to the possible application of the "magmatic carbonatite" hypothesis (*a*) to the petrogenesis of soda-rich alkali rocks; and (*b*) to the long-continued uplift of the rift valley regions of Africa and the origin of the rifts themselves.

DEDICATION

Nearly twenty years ago, during a memorable visit to Harvard, I first had the privilege of discussing with Professor Larsen some of the interests we share in common, including the petrogenesis of biotite-pyroxenites and melilite-rocks. Since then I have turned again and again to his stimulating publications on the Iron Hill (Uncompaghre) complex for guidance in my efforts to solve the related problems raised by the pyroclasts and lavas of the volcanic fields near Ruwenzori. I have long suspected that the most significant clue to their origin lay in the carbonatite core of the Uncompaghre complex—and, of course, in the analogous occurrences of carbonatites in so many other complexes of alkali rocks. But only recently have I found a way to follow up the clue, as I hope, successfully. It therefore seems appropriate to select this new development as the subject of my contribution to the *Festschrift* organised in honour of Professor Larsen. If, in advocating the active role played by carbonatite regarded as a magma, instead of considering carbonatite as the material assimilated by some other magma, I have, so to speak, turned inside out

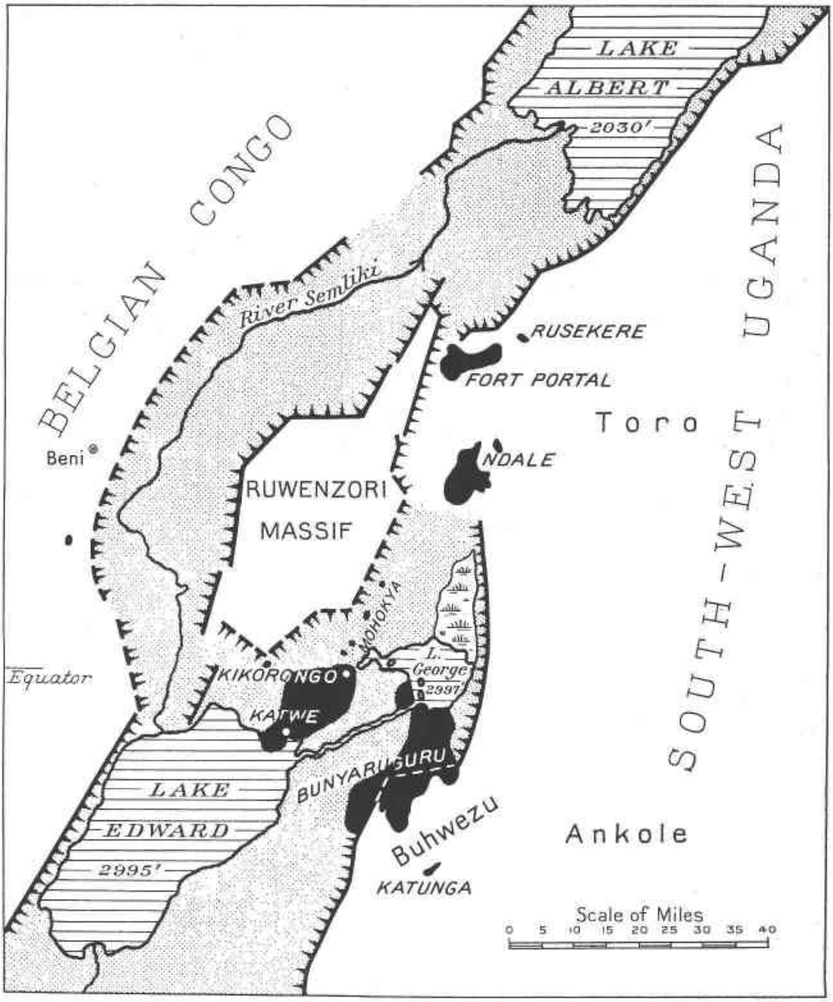

FIG. 1. Sketch map of part of the Western Rift Valley of Africa showing the horst of Ruwenzori and (in black) the neighbouring volcanic fields. The Bukangara field is indicated by the black spot above the 'OR' of KIKORONGO.

the hypothesis favoured by Professor Larsen, he himself will be the last to object on any grounds other than those based on factual evidence. It is a genuine pleasure to dedicate to him this token of friendship and admiration.

THE VOLCANIC FIELDS NEAR RUWENZORI AND THEIR MATERIALS

Half encircling the imposing horst of Ruwenzori, in and adjoining the

Western Rift of Central Africa, there are several areas of tuffs and explosion craters accompanied, in some of the areas, by lava flows or near-surface plugs and sheets. The various fields (Fig. 1) are distinguished under the following names: (*a*) *Katunga*, in the plateau country in the south of the province; (*b*) *Bunyaruguru*, lying athwart the eastern wall of the rift depression; (*c*) *Katwe-Kikorongo*, in the rift, between L. Edward and L. George; (*d*) *Bukangara*, on the slopes leading up to the southern foot of Ruwenzori (possibly an extension of (*c*) to the north-west); (*e*) an isolated *unnamed* explosion crater lying well to the west of Ruwenzori on the Butembo Road, 14 miles south of Beni in the Belgian Congo; (*f*) a line of craters on the *Mohokya* bench extending N.N.E. from Kikorongo towards Ndale; (*g*) *Ndale*, where the low wall of the L. George depression dies out to the north; (*h*) *Fort Portal*, where the eastern wall of the L. Albert rift dies out to the south; and (*j*) *Rusekere*, on the plateau to the north-east.

Although each of these areas has its own local characteristics, the group as a whole constitutes a highly distinctive petrographic province, the leading features of which were first recorded in a preliminary contribution (Holmes and Harwood, 1932) based mainly on the reconnaissance collections made in the early days of the Uganda Survey. Subsequently my old friend and collaborator, the late Mr. A. D. Combe, began a systematic survey of the province which he completed only a few months before his lamented death in 1949 (see Holmes, 1949). At intervals the specimens collected by him, amounting in all to well over a thousand, have been sent to me for petrological study. It is expected that a joint memoir—which will be a lasting monument to Combe's insight as a vulcanologist—will eventually be published (see Combe, 1930–1944).

Apart from the Pleistocene lacustrine and fluviatile deposits of the Kaiso Series, which occupied much of the floor of the rift depression, the underlying rocks are of Pre-Cambrian age, the sequence being:

Post-K.A. Granites
Karagwe-Ankolean (K.A.) System: mainly argillites, phyllites and quartzites

Toro System: mainly schists, quartzites, amphibolites, gneisses and granites.

The upper part of the Kaiso Series is of Middle Pleistocene age. In the Bunyaruguru and Katwe-Kikorongo fields it grades upwards into subaqueous volcanic tuffs which are themselves perforated by a succession of later vents. Some of the younger crater-rims are so little affected by erosion that they cannot be very old. Moreover, there are native traditions of volcanic activity (Wayland, 1934), some of which are preserved

TABLE 1. CHEMICAL ANALYSIS OF MEMBERS OF THE O.B.P. SERIES

	1	2	3	4	5	6	7
SiO_2	50.39	43.35	44.39	33.99	38.18	42.59	47.33
Al_2O_3	3.04	9.67	6.37	5.86	16.52	3.82	6.84
Fe_2O_3	2.61	5.26	5.11	9.35	2.90	2.55	.02
FeO	5.42	2.65	4.86	8.54	5.24	4.96	5.62
MgO	13.14	15.74	14.20	7.53	19.32	33.84	19.31
CaO	22.57	12.20	17.02	18.23	1.16	2.84	16.99
Na_2O	.56	.44	.50	.69	.56	.26	.41
K_2O	.08	4.74	2.35	2.38	9.01	2.58	.88
H_2O+	.14	.59	.35	.96	1.22	2.96	.55
H_2O-	none	.07	.05	.18	.58	.63	.21
CO_2	none	.04	.04	.30	none	.25	.02
TiO_2	1.96	4.38	3.91	8.65	5.18	1.60	1.26
ZrO_2	—	none	—	none	—	—	none
P_2O_5	tr.	tr.	.26	2.80	—	.22	.21
Cl	—	tr.	.04	.02	—	.05	tr.
F	—	.11	.04	.09	—	.12	.01
S	—	tr.	.02	.03	—	.18	.01
Cr_2O_3	—	.05	.03	none	.14	.23	.32
V_2O_3	—	.04	.05	.07	—	.01	.04
NiO	—	.04	.01	none	—	.21	.04
MnO	.05	.09	.10	.15	tr.	.10	.12
BaO	tr.	.30	.16	.13	.16	.13	.03
SrO	.12	none	.03	.05	.22	.02	none
Li_2O	—	tr.	tr.	none	—	tr.	tr.
	100.08	99.79	99.89	100.00	100.17	100.15	100.22
Less O	—	.04	.03	.05	—	.11	.01
	100.08	99.75	99.86	99.95	100.17	100.04	100.21

1. Pyroxenite. Xenolith from ejected block of olivine-rich ugandite, C.4035, Kakunyu crater, Bunyaruguru (Combe and Holmes, 1945, p. 377). *Analyst:* W. H. Herdsman.
2. Biotite-pyroxenite. Ejected block, C.2786, vent on S.S.W. end of Lutale Ridge, Bufumbira (Holmes and Harwood, 1937, p. 29). *Analyst:* H. F. Harwood. Total includes CuO = .03.
3. Biotite-pyroxenite. Ejected block, G.20, Katwe crater (Holmes and Harwood, 1937, p. 30). *Analyst:* H. F. Harwood.
4. Sphene-rich biotite-pyroxenite. Ejected block, K.4, Katwe crater (Holmes and Harwood, 1937, p. 30). *Analyst:* H. F. Harwood.
5. Glimmerite. Xenolith from ejected block of olivine-rich ugandite, C.4034, Kakunyu crater, Bunyaruguru (Combe and Holmes, 1945, p. 377). *Analyst:* W. H. Herdsman.
6. Biotite-peridotite. Xenolith from ejected block of olivine-rich ugandite, C.4034, Kakunyu crater, Bunyaruguru (Holmes, 1945, p. 377). *Analyst:* H. F. Harwood.
7. Biotite-bearing augite-peridotite. Ejected block, C.1963, Mabungo crater, Bufumbira (Holmes and Harwood, 1937, p. 23). *Analyst:* H. F. Harwood.

in the names of the craters: e.g. Kasesankaranga (in the Fort Portal area) means "spewer of roasted material." The volcanic activity thus seems to have continued intermittently from late Middle Pleistocene to comparatively recent times.

The tuffs and other pyroclasts contain fragmental materials consisting of:

(1) The underlying rocks and their minerals.

(2) The rocks and minerals of a sub-volcanic suite of biotite-pyroxenite and related types, including pyroxenite, glimmerite and peridotites. The suite will be referred to collectively as the "O.B.P." series, after the dominant minerals olivine, biotite and pyroxene. Common but variably developed minerals in the biotite-pyroxenites are melanite, ilmenite, sphene, apatite and calcite, usually replacing the earlier minerals in the order stated. Perovskite and potash nepheline are also occasionally present. The rocks range in grain size from extremely coarse to very fine and are often patchy, exhibiting sudden changes of texture and composition. The types and their associations can be closely matched by the corresponding rocks described from the Libby Stock (Larsen and Pardee, 1929) and the Iron Hill complex (Larsen, 1942). Representative samples of the O.B.P. series have been analysed and the results are listed in Table 1, together with those for two examples from the Bufumbira field (North Kivu) to the south.

(3) Lapilli, bombs and ejected blocks of *katungite* and other ultrabasic potash-rich volcanic types, the assemblage of which for the whole province is schematically summarised in Fig. 2. Apart from xenocrysts, not a trace of feldspar or hornblende

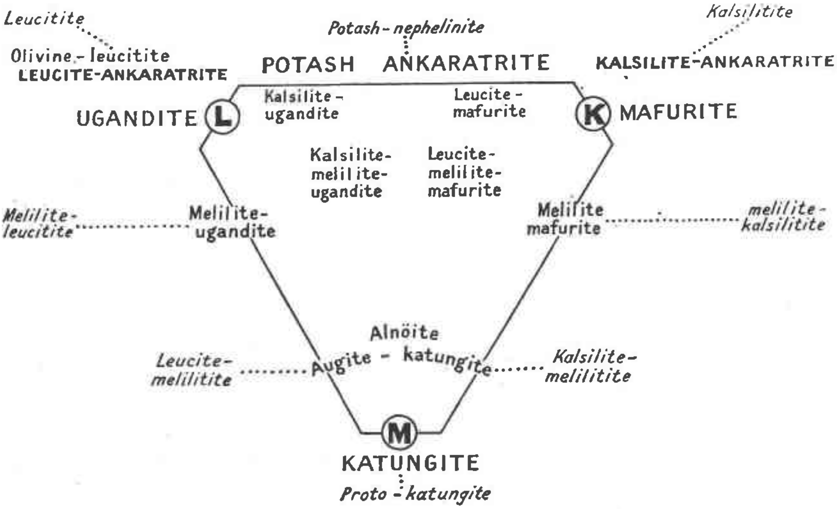

FIG. 2. Triangular classification of the rock-types occurring in the volcanic fields near Ruwenzori. L = Leucite and augite; K = Kalsilite and augite; M = Melilite and potash-rich glass, occasionally with kalsilite or leucite. All the types contain olivine, except those named in italics. Biotite varieties (including heteromorphs such as olivine-ouachitite) of some of the types are known, but are not named except in the case of alnöite. The ankaratrite series differs from the mafurite-ugandite series in being conspicuously rich in augite and relatively poor in olivine.

has been detected in any of the volcanic rocks examined. The critical minerals of the suite are melilite and/or augite, and kalsilite and/or leucite, together with olivine in all the types except those—mostly very rare—named in italics in the outer part of Fig. 2; biotite occurs in some varieties and accessories common to all are perovskite and opaque ores, often accompanied by apatite. In katungite, however, which is ubiquitous and generally by far the most abundant type, the potash is mainly present in a glassy base from which kalsilite, leucite or biotite have crystallised in only a few of the many occurrences studied; phillipsite, however, is commonly present in veinlets and as a lining to vesicles. Because of the paucity of kalsilite and leucite, katungite is placed at one of the corners, M, of Fig. 2, the others being L, occupied by *ugandite* or *leucite-ankaratrite* (melanocratic types of olivine-leucitite which are respectively rich in olivine and augite); and K, occupied by *mafurite* or *kalsilite-ankaratrite*, the corresponding types with kalsilite in place of leucite. The diagram itself makes clear the composition of the many transitional varieties.

Lava flows are rare, except in the Fort Portal area, where highly carbonated melilite-nepheline-leucitite occurs as numerous small outpourings (Holmes and Harwood, 1932, p. 379). Flows of katungite are known only from Katunga itself (Combe, 1937). In Bunyaruguru, mafurite, the rock in which kalsilite was first discovered (Bannister and Hey, 1942; Holmes, 1942), occurs in a lava sheet truncated by the wall of a crater adjoining Lake Mafuru. In the same field there are other flows and a lava-dome or plug consisting of mafurite and related types (Combe and Holmes, 1945), and also flows of ugandite and melilite-ugandite—from Kazimiro—not yet described. The Katwe-Kikorongo field is noteworthy for the abundance of various members of the potash-ankaratrite series, mostly occurring as ejected blocks, but also as lava-sheets and plugs in the craters of Mbuga and Nyabugando.

One of the most significant features of the province is the fact that in the earliest tuffs minerals of the O.B.P. series and lapilli of katungite (see Table 2, 8) invariably appear together. Since an overwhelming proportion of the lapilli contain xenocrysts of augite and biotite, and sometimes of olivine, all obviously derived from the O.B.P. series, it is clear that the latter crystallised before the consolidation of the associated katungite. In this sense the oldest O.B.P. rocks are older than the oldest katungite, but it is also clear that the O.B.P. series and the associated katungite magma originated contemporaneously. The same relationships occur throughout the province. The lapilli, bombs and blocks of katungite—and also those of all the other volcanic types, including the flows—contain xenocrysts, and often aggregates, of the O.B.P. minerals. While katungite contains mainly biotite and augite, ugandite carries a higher proportion of olivine and potash-ankaratrite of augite; mafurite contains variable amounts of all three minerals, often with a conspicuous abundance of biotite, much of which has been severely altered, as described on p. 789. There is, of course, no reason to suppose that all the O.B.P.

rocks and minerals are older than all the volcanic types. The two sets of materials may have continued to form contemporaneously throughout the period of activity. No standard sequence of volcanic types can be established, but in many of the crater walls a record of several eruptions of katungite can be recognised, with intervening appearances of members of the ugandite, potash-ankaratrite or mafurite series.

THE KATUNGITE SERIES: PETROGENETIC CONSIDERATIONS

The rock now known as katungite was originally described as melilite-basalt or olivine-melilitite. Detailed investigation of the specimens from the two Katunga flows showed, however, that they differ from olivine-melilite in being both potash-rich and free from augite; hence a new name was felt to be justified. As usual, leucite can only rarely be detected, but kalsilite has now been found in a number of the specimens. Both minerals are restricted to the lower parts of the flows, where the lavas are richer in potash than nearer their sources. Natrolite is a common zeolite near the source but lower down phillipsite increases in amount and natrolite dies out. The later parts of the lava to be extruded were evidently progressively poorer in potash and relatively richer in soda. Confirmation is provided by the following analyses (W. H. Herdsman), listed in order of time of emergence of the analysed materials:

		K_2O	Na_2O	K_2O/Na_2O
C.4418	Bomb, outer face of crater	4.21	1.34	3.2
C.4407	Lava, near end of western flow*	4.09	1.32	3.1
C.4411	Lava, 50 feet below source of flow	3.84	2.91	1.3
C.4412	Lava, near source of flow	3.55	2.96	1.2

* For complete analysis see Table 2, 9.

This evidence illustrates a characteristic feature of the rocks of the province—the compositional variability of the volcanic rocks—observed not only in the lava flows, but even in single ejected blocks. It also exemplifies a general tendency, shared with the Birunga or North Kivu field, for the later products of an eruption to be relatively less potassic than the earlier. It seems likely that soda was partly removed from the upper part of the magma column, possibly as carbonate or some other volatile compound. Oldonyo l'Engai (south of Lake Natron in the Eastern Rift) erupted soda-rich vapours, mainly carbonate, in 1917, as recorded by Hobley (1918). That an immense concentration of gas had risen to the head of the magma column at Katunga before the outbreak occurred may be inferred from the visible indications of a powerful explosive phase. The vent, 800 feet in diameter, was drilled through Toro schists and a vast accumulation of blocks and slabs of these rocks form the cone and the crater rim. Tuffs with katungite lapilli came next, followed in turn by bombs and finally, extruded from the slopes of the cone, by the eastern and western flows.

Kalsilite-katungite has now been recognised in the tuffs from a dozen different localities in Bunyaruguru. Only one band has been found, however, in which all the lapilli consist of this type and so could be separated for analysis (Table 2, 10). The analysed type-material has been already figured and described (Holmes, 1942; Combe and Holmes, 1945). In other occurrences it has been noticed that wherever xenocrysts derived from quartz-bearing basement rocks are present—as they often are—kalsilite has failed to develop in their vicinity. Similarly in the mafurite-ugandite and potash-ankaratrite series it is found that development of leucite instead of kalsilite (and also of augite instead of melilite) is often demonstrably due to the incorporation of sialic material. It therefore seems probable that kalsilite-katungite would be much more plentiful, were it not for siliceous contamination.

Confirming this inference is the fact that xenocrysts of quartz in the katungite bomb C.4418, referred to above, have been transfused into glass having the composition of a potassic obsidian (for analysis see Holmes, 1936, p. 415). Before parting with Al, K and H in exchange for Si, the molten lava must evidently have been even more ultrabasic and potassic than the resulting solid katungite. Innumerable other examples of the same phenomenon are widespread, but much more spectacular is the discovery that granitic xenoliths and xenocrysts derived from them or from other sialic rocks have been transformed into leucite or leucite glass and eventually, in some cases, into leucitite and olivine-leucitite (Holmes, 1945). So far examples of leucitization have not been found in katungite, but they are by no means rare in members of the mafurite-ugandite series.

The katungite from Chamakumba crater (Table 2, 11) illustrates another common type of transformation which is of great significance. The rock has an extremely dark groundmass and contains two varieties of melilite: one, clear and beautifully fresh, giving inky blue interference colours; the other showing low normal colours and sometimes having a patchy isotropic core. The change from one variety to the other occurs suddently and crystals can be found which are 'normal' at one end and 'inky blue' at the other. The 'normal' variety has clearly been derived from xenocrysts of augite, for most of these have corroded and embayed margins which have been replaced by this variety of melilite. The rims consist of a coarse felt of melilite laths which are separated from the unaltered augite by a continuous peripheral band of melilite with the same optical properties as the laths. Xenocrysts of biotite have also contributed to the resulting katungite, for they are marginally trans-

TABLE 2. ANALYSES OF KATUNGITE, ALNÖITE AND OLIVINE-OUACHITITE

	8	9	10	11	12	13	14
SiO_2	34.23	35.37	33.52	33.22	35.51	37.93	38.94
Al_2O_3	8.02	6.50	8.04	9.71	6.83	6.59	6.92
Fe_2O_3	6.62	7.23	5.88	6.68	9.68	6.81	5.27
FeO	5.34	5.00	5.50	5.30	2.70	4.37	5.09
MgO	9.92	14.08	13.54	12.12	11.67	14.54	11.58
CaO	16.54	16.79	15.22	15.64	16.00	15.23	15.95
Na_2O	1.20	1.32	1.42	1.51	1.56	.88	1.01
K_2O	3.39	4.09	4.26	3.54	3.30	2.65	3.96
H_2O+	2.80	2.78	2.34	3.28	3.11	3.38	2.26
H_2O-	1.72	1.15	1.68	.80	1.31	1.42	1.20
CO_2	4.02	.09	.96	.42	1.47	.50	2.12
TiO_2	4.56	3.87	6.04	6.08	4.88	4.12	3.88
ZrO_2	—	none	—	—	none	—	—
P_2O_5	.96	.74	.82	1.12	1.18	1.03	.91
Cl	—	.02	—	—	tr.	—	—
F	.14	.16	—	.08	.27	.16	.13
S	.12	.35	—	—	—	—	.14
SO_3	—	—	—	—	.13	.06	—
Cr_2O_3	—	.01	—	—	.02	—	—
V_2O_3	—	.03	—	—	.04	—	—
NiO	—	.19	—	—	.02	.03	.09
MnO	.22	.24	.15	.52	.22	.18	.23
BaO	.20	.25	.15	.17	.27	.30	.18
SrO	.23	.04	.44	.05	.24	.25	.19
Li_2O	—	none	—	—	tr.	—	—
	100.23	100.36	99.96	100.24	100.41	100.51	100.05
Less O	.09	.15	—	.02	.11	.07	.09
	100.14	100.21	99.96	100.22	100.30	100.44	99.96

8. Katungite. Lapilli separated from the first volcanic horizon of the Upper Kaiso Series, C.5945, near M.P.75 on the Fort Portal Road, N.W. edge of the Bunyaruguru field. *Analyst:* W. H. Herdsman.
9. Katungite. Western flow of Katunga volcano, C.4407 (Holmes, 1937, p. 205). *Analyst:* A. W. Groves. Total includes CuO 0.06.
10. Kalsilite-katungite. Lapilli separated from tuff, C.4012, N.W. rim of Changabe crater, Bunyaruguru (Combe and Holmes, 1945, p. 367). *Analyst:* W. H. Herdsman.
11. Katungite. Ejected block, C.3509, Chamakumba crater, Bunyaruguru. *Analyst:* W. H. Herdsman.
12. Katungite. Lapilli from tuff, G.21, Katwe crater. *Analyst:* H. F. Harwood.
13. Alnöite. Ejected block, G.56, Katwe crater. Another sample gave Na_2O 1.07; K_2O 3.63 (Holmes and Harwood, 1932, p. 405). *Analyst:* H. F. Harwood.
14. Olivine-ouachitite. Ejected block, C.5844, from 20 feet below the rim of Katwe crater. *Analyst:* W. H. Herdsman.

formed to a cloud of black-ore specks in an obscure residuum. Alteration of biotite, of which there is ample evidence throughout the area, would obviously provide some of the potential leucite or kalsilite required for katungite, besides some of its olivine and black ores.

These observations indicate that katungite has originated, at least in part, from biotite-pyroxenite, or, more generally (remembering that corroded xenocrysts of olivine are also occasionally present), from the materials of the O.B.P. series. Theoretically, at any rate, katungite could be formed from the O.B.P. series by the desilicating action either of a magma much more ultrabasic than itself or, at the limiting extreme of ultrabasicity, of "emanations" of cafemic (including TiO_2, P_2O_5, etc.) and alk-aluminous composition. If this concept in either form has any basis in fact it should be possible to recognise (*a*) a series of types bridging the gap between katungite and the O.B.P. series; and, in the other direction, (*b*) types having a composition more ultrabasic than normal katungite. Both expectations have been realised.

The series (*a*) is illustrated by katungite, alnöite and olivine-ouachitite from the tuffs and agglomerates of the walls of Katwe crater. The micrometric measurements given below (including two other measured katungites) indicate the range of the melilite proportions:

Rock and Locality			Melilite (Vol. per cent)
Katungite, Katunga,	C.4407	(*An.* 9)	40
Chamakumba,	C.3509	(*An.* 11)	38
Katwe,	G.21	(*An.* 12)	37
Alnöite, Katwe,	C.5775		26
	C.5778		21
	G.56	(*An.* 13)	18
	C.5779		5
Olivine-ouachitite, Katwe,	C.5884	(*An.* 14)	0

Katungite contains abundant melilite and no augite other than sparse xenocrysts and minute amounts formed by reaction against transfused quartz. Olivine-ouachitite has abundant augite and no melilite. The various specimens of alnöite fall between. In these the augite is mostly too fine grained for accurate measurement, but it is clear from inspection that there is a rough complementary relationship between melilite and augite.

The more ultrabasic type (*b*) referred to above is the rock for which the name *proto-katungite* has already been suggested (Holmes, 1942, p. 199; 1945, p. 317). The name implies the supposition that it represents the earliest known stage in the magmatic ancestry of katungite. Somewhat paradoxially—though emphasizing the extreme basicity—proto-katungite differs mineralogically from katungite in being free from olivine. Occurrences of lapilli and ejected blocks of this type turn up sporadically in the tuffs and agglomerates of Bunyaruguru and Katwe-Kikorongo, their most abundant development being in some of the oldest of the pyroclasts. Without exception the rocks are crowded with xenolithic biotite and augite (rarely olivine) and most of them are highly charged with carbonates.

The analysed example (Table 3, 15 *a*) is the freshest part of an eight-inch block of fine-grained gray lava, mottled with minute calcite-lined vesicles and conspicuously sprinkled with xenolithic material. Apart from very rare relics of phyllite and quartzite, the xenolithic material consists of fragments of biotite-pyroxenite and its minerals, the biotite being margined and veined by clouds of black ores and perovskite in an obscure background, while the augite is margined with reaction rims of melilite. Only a trace of xenocrystic olivine is present. In the lava itself, small laths of melilite are very abundant, together with grains, octahedra and clusters of magnetite and golden brown or clove-coloured perovskite, all embedded in a greenish grey to brownish base which is isotropic or feebly cryptocrystalline and copiously dusted with specks of black ore and perovskite.

The bulk composition of the material is that of a typical katungite, from which it follows that in this particular case, which is typical, katungite = proto-katungite + biotite-pyroxenite (+ a very little olivine). A closer approach to the composition of proto-katungite is given in Table 3, 15*b*.

Between proto-katungite and katungite with abundant olivine there is every gradation, olivine-poor varieties being very common. Taking the series as a whole, a rough complementary relationship can often be noticed between the respective abundances of phenocrysts of olivine and xenocrysts of biotite and augite. At one extreme are the holo-magmatic lavas of Katunga with well developed olivine and no xenolithic relics. At the other are the occurrences of proto-katungite, invariably rich in xenolithic relics and free from authigenic olivine. Plotting the analyses of Table 2, and either average biotite-pyroxenite or average O.B.P. (Table 3, 17), on a silica basis, results in an approximately straight-line variation diagram. The proto-katungite analysis, 15*a*, fits well into the series and so, obviously, must 15*b*. The series proto-katungite—katungite—alnöite—olivine-ouachitite—biotite-pyroxenite (or O.B.P. for the more olivine-rich varieties) is therefore a genetic one, in the sense that it can be completely accounted for in terms of its end-members.

In looking through a comprehensive suite of specimens of katungite-bearing tuff, one cannot avoid noticing that sialic basement rocks, often including granite, contribute a very high proportion of the accidental fragments, whereas such debris is rare within the katungite lapilli, the dominant xenolithic material being derived from biotite-pyroxenite. This generalisation is also true of the occurrences of proto-katungite. Moreover, olivine and olivine aggregates from biotite-peridotite are much more abundant in the non-volcanic materials of the tuffs than in the volcanic lapilli. It may therefore be inferred that at the time of explosive eruptivity the katungite and proto-katungite magmas existed in an environment of biotite-pyroxenite, which was probably ensheathed by peridotite or olivine-rich members of the O.B.P. series, the latter being covered, or perhaps in part intercalated with, the sialic rocks above the explosion level. This inference is consistent not only with the conclusions already reached, but also with the possibility later to be discussed that both magma and O.B.P. may in part have been derived from granitic and other sialic rocks. Some support for this, until recently, unfamiliar idea is provided (*a*) by the observation that biotite and augite of O.B.P. types have been found as replacement minerals in a few of the ejected blocks of basement rocks; and (*b*) by the evidence that the biotite-pyroxenite and -peridotite of the Newry Complex (Northern Ireland) represent part of a basic front which developed by replacement of country rocks as a complementary product of underlying granitization (Reynolds, 1944, pp. 234–236).

PETROGENESIS: A SUGGESTED HYPOTHESIS

In the first paper on katungite, being already impressed with the evidence of transfusion and metasomatism brought about by migrating "emanations" (gaseous transfer, or diffusion), I proposed the hypothesis that katungite, K, might be a rheomorphic product of the action of essentially silica-free emanations, E, on biotite-pyroxenite (Holmes, 1937, p. 216). Briefly, and more generally, this idea can be qualitatively expressed in the form

$$K = O.B.P. + E.$$

Graphically, the same idea is represented in Fig. 3, where the point E on the base of the triangle indicates the composition of the emanations required to transform average O.B.P. (the point m) to katungite, the field of which is shown in black. The line Em, prolonged upwards, passes through biotite-pyroxenite, which for all the olivine-poor varieties of

Table 3

	Proto-katungite		K. Av. Katungite	Average O.B.P.	G. Av. Granite	C	Alteration of Biotite	
	15*a*	15*b*	16	17	18	19	20	21
SiO_2	33.89	31.91	34.54	42.89	72.51	—	37.05	42.77
Al_2O_3	8.27	8.45	7.77	7.45	14.73	—	15.04	9.02
Fe_2O_3	7.03	7.71	7.17	3.97	.69	11.56	4.12	5.09
FeO	5.21	5.18	4.74	5.33	.79	9.48	5.10	4.18
MgO	10.93	9.48	12.18	17.58	.49	29.18	19.74	13.48
CaO	16.98	17.85	15.94	13.00	1.06	29.61	.33	12.21
Na_2O	1.42	1.62	1.39	.49	2.79	−.85	.23	1.42
K_2O	3.65	3.76	3.70	3.15	5.28	1.55	9.55	5.05
H_2O+	2.08	2.33	2.83	.97	.72	3.59	4.15	1.39
H_2O-	1.19	1.39	1.32	.25	.18	1.68	.30	.82
CO_2	3.27	3.96	1.38	.09	.23	1.57	—	.40
TiO_2	4.43	4.56	5.05	3.85	.20	9.31	2.81	3.61
ZrO_2	—	—	—	none	.02	—	—	—
P_2O_5	.97	1.06	.95	.58	.13	1.54	—	—
Cl	—	—	.01	.02	.03	−tr.	—	—
F	.18	.21	.16	.07	.07	.18	.40	—
S	.14	.16	.19	.05	.03	.25	—	—
Cr_2O_3	—	—	.02	.13	none	.13	—	—
V_2O_3	—	—	.04	.04	tr.	.08	—	—
NiO	—	—	.10	.05	none	.17	—	—
MnO	.26	.29	.27	.09	.03	.38	.28	.15
BaO	.21	.23	.21	.13	.09	.27	1.26	.15
SrO	.29	.34	.20	.06	none	.30	none	.11
Li_2O	—	—	tr.	tr.	tr.	—	—	—
	100.40	100.49	100.16	100.24	100.07	99.98	100.36	99.85
Less O	.11	.13	.16	.05	.04	.15	.17	—
	100.29	100.36	100.00	100.19	100.03	99.83	100.19	99.85

15*a*. Proto-katungite (including xenocrysts: approximately, augite, 12%; biotite, 5%; olivine and black ore, 1%). Ejected block, C.6065, from the rim of one of the oldest craters, Lugazi, Bunyaruguru. *Analyst:* W. H. Herdsman.

15*b*. Proto-katungite. Estimated composition after subtracting 18% average O.B.P. column 17) from the all-over analysis, 15*a*. Subtracting biotite-pyroxenite corresponding to the xenocrysts actually present yields essentially the same result.

16. Average of five analyses (Table 2, 8–12) of katungite.

17. Average of seven analyses (Table 1, 1–7) of the O.B.P. series. Plotted as "*m*" on Fig. 3.

18. Average of six analyses of Post-K.A. granites (King, 1939, p. 138). Plotted as 'Granite' on Fig. 3.

19. Calculated composition of "C," the carbonatite material (less liberated CO_2) re-

katungite would serve as well as average O.B.P. Proto-katungite is represented by the white dot in the katungite field nearest to E and is probably a close approach to the most ultrabasic silicate rock that could exist. The hypothesis would now take the form

$$\text{PK} = \text{O.B.P.} + \text{E}.$$

This hypothesis, however, is no more than a half-way stage, since it leaves both O.B.P. and E unaccounted for. And even if O.B.P. be regarded, as it was in 1937, as primary peridotite metasomatically modified by emanations rich in Ca, Fe, Ti, K, Al, etc., the source of the various emanations still remains unknown. Moreover, the hypothesis fails to account for the mafurite series, except by involving the action of emanations even richer in potash. Despite the obviously close relationship between katungite and mafurite, neither can be derived from the other by addition or subtraction of crystalline phases, whether magmatic or xenolithic.

The combination of high potash with cafemic constituents is the geochemical peculiarity that especially challenges explanation. It would be a purely *ad hoc* assumption to regard primary peridotite or the material of the substratum as a potential source for the potash of either potash-rich rocks or the alk-aluminous emanations necessary to generate such rocks. Supporting this rejection of primary peridotite is the very low radium content of rocks of the latter type (Davis, 1947). Members of the O.B.P. series and the comparable xenoliths of the kimberlite pipes contain 50–280 times as much radium as primary peridotite (Holmes and Paneth, 1936). Basaltic materials cannot be regarded as a promising source for potash and in any case they are out of the question, since they play no part in the province under discussion. The only obvious source of potash would appear to be granitic rocks and their pelitic derivatives: let us say granite, for short. This possibility, however, implies that granite supplied not only potash, but also alumina and silica, and that the cafemic materials must have come from an essentially silica-free source, such as carbonates.

Theoretically, reaction of high-temperature granite magma with carbonate rocks of appropriate composition would solve the problem. But there are fatal objections to this variant of the limestone-assimilation hypothesis. There was no granite magma to incorporate carbonate rocks.

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quired to generate katungite (16) and O.B.P. (17) from granite (18). Iron oxides expressed as total FeO = 19.88.

20. Biotite. Core of xenocryst in kalsilite-ugandite, C.4788, Upper Kabirenge lava, Bunyaruguru (Combe and Holmes, 1945, p. 377). *Analyst:* H. F. Harwood.
21. Alteration product of biotite. Rim of same xenocryst as No. 20 (*Ibid.*). *Analyst:* H. F. Harwood.

Apart from the carbonate deposits representing, e.g. the hot-spring phase of the volcanic activity itself, the only known carbonate rocks are thin intercalations of limestone locally present in the Karagwe-Ankolean System. Blocks of these have been ejected from some of the vents of Bunyaruguru but, unlike the overwhelmingly more abundant sialic rocks, they show no signs of alteration or incorporation. Moreover, they are geochemically of inadequate composition. What is required would have to be a mixture of dolomite, siderite and magnesite (in proportions such as 65:25:10 respectively) with a good deal of TiO_2, H_2O and P_2O_5 and notable amounts of other minor ingredients: a most improbable sediment.

The only remaining alternative which would not be altogether fantastic is to postulate reaction of "magmatic carbonatite" with granitic rocks. This idea has several advantages. The temperature would be adequate for the work to be done. There would be ample supplies of high-pressure gas available for the drilling of vents, for the production of widespread tuffs and the ubiquitous development of drop-like lapilli, and for the transport of "emanations." Known carbonatites in Africa (Dixey, Campbell Smith and Bisset, 1937; Pulfrey, 1944; Davies, 1947; King, 1949), Iron Hill (Larsen, 1942), Fen (Brögger, 1921), Alnö (von Eckermann, 1948) and many other localities are often dolomitic and ferruginous and are geochemically characterised by the appropriate assemblage of other elements necessary to the hypothesis. In this respect the only unusual feature about the Uganda rocks is their very high content of TiO_2, but even this can be matched elsewhere. Since $MgCO_3$* would be the first to give up CO_2 and react with granite, it is only to be expected that the carbonatites actually exposed (whether magmatic or hydrothermal) should be richer in $CaCO_3$ than the original materials. Carbonatites are naturally not to be found in comparatively recent vents, but there is ample evidence in Uganda of a source of carbonate in depth. Many of the tuffs, and especially the older ones, are saturated with $CaCO_3$, which occurs both as cement and as a replacement mineral. The lavas of the Fort Portal and neighbouring areas are so highly carbonated that in many cases they have almost lost their identity. Travertine deposits of hot-spring origin are developed on a considerable scale along the outer slopes and foot of the Mohokyo bench, and pinnacles of travertine have been built up in Katwe and other craters (Combe, 1944, p. 14).

The hypothesis is now proposed that magmatic carbonatite, presumably derived from the substratum, ascended through fractures into the sialic layer where it reacted with, say, granite, G, to form crystalline O.B.P. and molten proto-katungite or katungite, K, with eventual loss

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* Probably $FeCO_3$ would give up CO_2 even earlier than $MgCO_3$.

of most of the liberated CO_2. Qualitatively we can write

$$\mathrm{C + G = O.P.B. + K}$$

where C represents the composition of the carbonatite, less all the liberated CO_2 except that fixed in katungite and O.B.P. It is easy to show that this hypothesis is only a genetic development of the old one, qualitatively expressed as

$$\mathrm{K = O.B.P. + E.}$$

Let us now make the symbols quantitative by using italics. Suppose that an amount $(C+G)$ of the carbonatite and granite yields an amount *O.B.P.* of crystalline phases and an amount E of residual material, i.e.

$$(C + G) = O.B.P. + E. \qquad (1)$$

In the limiting case, where all the SiO_2 of G has been used up, E becomes the "emanations" of the old hypothesis (cf. Fig. 3). Let E react with an amount a *O.B.P.* to produce an amount K of katungite. Then

$$K = a\, O.P.B. + E \qquad (2)$$

which expresses the old hypothesis. Eliminating E from (1) and (2), we have

$$(C + G) = O.B.P. + K - a\, O.B.P. = (1 - a)\, O.B.P. + K \qquad (3)$$

which expressed the new hypothesis.

It is, of course, impossible to say to what extent the two stages (1) and (2) represent the real facts of the very complex processes that must actually have been involved. On Fig. 3 the line CG represents all possible mixtures of C and G, and m represents average O.B.P. The residual material could theoretically lie anywhere on the part of the line mE below its intersection with the line CG. Katungite lies on this part of the line, proto-katungite being nearer E and alnöite being nearer m. Olivine-ouachitite falls on the O.B.P. side of the intersection, this representing the rare case where the proportion of O.B.P. to E has been higher than in equation (2)

It is interesting to notice that E (on Fig. 3) also represents the composition of the "emanations" required to transform granite into leucitite. The base-line of the triangle (Fig. 3) represents all the possible compositions of "emanations" from the alk-aluminous material of the corner A to the essentially cafemic material of the corner C. The material required to transform granite into leucite is represented by a point that closely approaches A.

It is now possible to estimate, at least roughly, the composition of C in equation (3). Adopting the figures in analyses 16, 17 and 18, we can

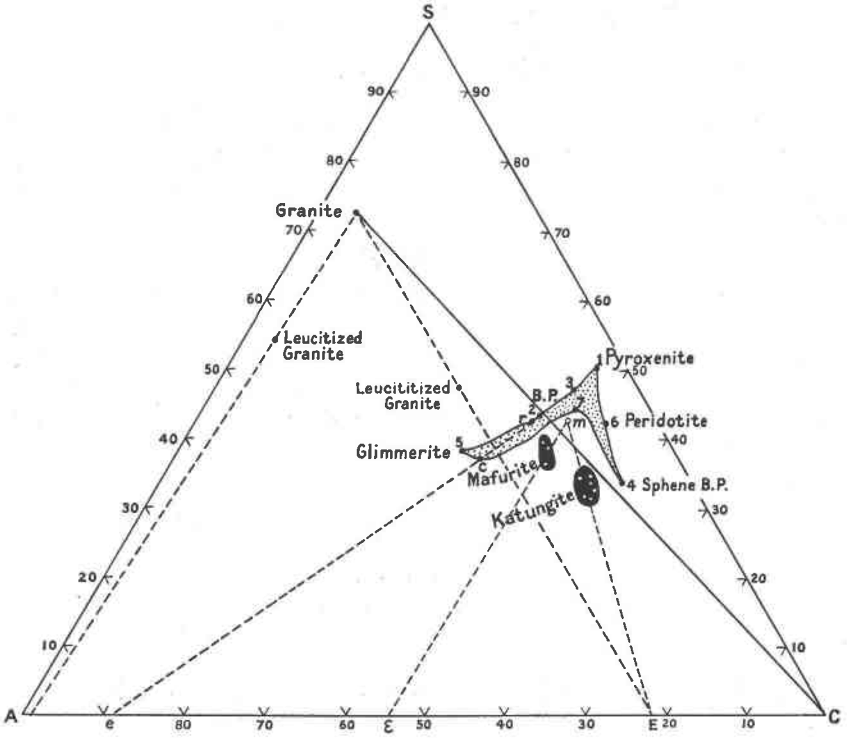

FIG. 3. Triangular diagram to illustrate the chemical relationships of some of the chief rocks under discussion. $S = SiO_2$; $A = Al_2O_3 + K_2O$ and Na_2O; C = the sum of all the remaining constituents (mainly cafemic oxides). m = average composition of the O.B.P. group (dotted), the numbers referring to the analyses of Table 1. c and r = the core and rim of an altered biotite xenocryst (Table 2, 20 and 21). e represents the composition of the material liberated by the alteration of biotite from c to r; E that of the material required to transform m into katungite; and ϵ that of the material required to transform m into mafurite.

write for any given constituent

$$x\,\mathrm{K} + (100 - x)\ \mathrm{O.B.P.} = y\,\mathrm{G} + (100 - y)\ \mathrm{C}. \qquad (4)$$

SiO_2 and Al_2O_3 give two equations which can be solved for x and y, assuming that these two constituents are ideally absent from C. Inserting the values so found, equation (4) can now be written.

$$60.9\ \mathrm{K} + 39.1\ \mathrm{O.B.P.} = 51.9\ \mathrm{G} + 48.1\ \mathrm{C}. \qquad (5)$$

Solving for the remaining constituents, the composition of C is found to be as listed in Table 3, 19. If the same procedure is carried out for proto-katungite, 15*b*, equation (5) becomes

$$39.5\ \text{PK} + 60.5\ \text{O.B.P.} = 53.2\ \text{G} + 46.8\ \text{C}$$

indicating that much less PK has been generated, as would be expected. The composition of C in this case is nearly the same as before.

Inspection of column 19 in Table 3 shows that C is essentially cafemic oxides, with high TiO_2 and considerable H_2O and P_2O_5, together with notable amounts of all the characteristic minor constituents of the province. Na_2O is negative, implying a loss which is probably to be referred to gaseous transport, as already suggested. The presence of K_2O is less easily disposed of, since it suggests that granite may not be capable of producing all the K_2O required. This would not disturb von Eckermann, however, who writes, in postulating a carbonate magma to account for the rocks of the Alnö complex (1948, p. 161): "The magmatic melt, or rather liquid, is suggested to have been a high tensioned one . . . , consisting of mainly carbonates, predominatingly potassic. . . . " It is not surprising, therefore, that he also writes (p. 157): "No explanation, however, has been offered as to the origin of this liquid and none will be given in this memoir." Since my own main purpose in this paper is particularly to try to account for the potash of the rocks under discussion, the appearance of even a little K_2O in the composition of C calls for further discussion. This is the more necessary because mafurite contains up to 7% K_2O(Holmes, 1942) and the composition of C required to generate this type of lava would have to be correspondingly richer in K_2O.

Fortunately this excess potash can be readily accounted for without assuming abnormally potash-rich granites and without arbitrarily taking it for granted in C. Reference has already been made to the marginal alteration of the biotite relics in katungite. More conspicuous relics, with dull stony rims surrounding fresh cores, are especially common in the members of the mafurite-ugandite series. Analyses of an investigated example from kalsilite-ugandite show that the composition of the rim (analysis 21) approximates to biotite-pyroxenite and that the biotite (analysis 20) lost mainly Al_2O_3, MgO, K_2O and H_2O during its alteration. Obviously, biotite formed at greater depths and higher pressures, gave up part of its potash, etc. to the liquid phase, and so provided the material required for mafurite. In Fig. 3 the composition of the rim is represented by r (near B.P.) and that of the core by c (near Glimmerite). The line through r c meets the base of the triangle at e, which represents the liberated material. A combination of e and C, or of e and E, gives ϵ, representing the "emanations" required to generate mafurite from average O.B.P. The slight excess of K_2O required for katungite is, of course, similarly accounted for.

Lack of space forbids discussion of the many side issues that arise from this preliminary outline of the hypothesis here proposed. It should, however, be kept in mind that for simplicity of exposition only the limiting silica-free compositions of carbonatite and emanations have been considered. The actual compositions need not have been entirely silica-free. The liquid carbonatite may, for example, have been associated with normal periodotite magma, in which case it would only be necessary to add the constituents of peridotite in equal amounts to each side of equation (4). This would, of course, not affect the arithmetical solution of the problem. It should also be remembered that various compositions could be used for O.B.P. in place of the average here adopted. The sequence of crystallisation and metasomatism and the effects of migration of volatiles are other features that call for subsequent discussion.

Before concluding, however, two other points deserve brief mention. The first is that the same kind of hypothesis, suitably modified, should be applicable to the soda-rich alkali rocks of Africa, particularly on the eastern side, many of which are associated with plug-like carbonatites (see King, 1949). Here the difficulty is to get rid of the potash which has been the special problem of the Western Rift. The only conjecture that can be offered is that the reactions may have occurred at a high crustal level in the Western Rift (and other potassic provinces), but at a much lower level in the east (and other sodic provinces). The granitic rocks of the lower levels of the "granite layer" are likely to be richer in soda than potash, not only because granodiorite is more abundant than potassic granite, but also because granitization seems everywhere to have involved a late upward migration of potash. Moreover, reaction with the materials of the "basaltic layer" is likely to be common and there again soda is strongly favoured. Another probability is that biotite formed in depth would remain stable and so would drain off potash from the primary reacting materials. The residual magma and volatiles that ascended to higher levels would thus become increasingly enriched in soda. It is hoped that a satisfactory extension of the hypothesis to embrace a wide variety of alkali complexes may eventually be developed along these lines.

The second point refers to the origin of the rift valleys. One of the most striking features of many parts of Africa, including the rift-valley regions, is the cumulative uplift that has taken place since at least the early Cretaceous. How is this to be accounted for? From an isostatic point of view it can only mean that changes have taken place in the substratum whereby the density of the material of the latter, especially near the base of the crust, was reduced. Thermal expansion might do a little in this way, but it would surely be far from sufficient to meet the requirements. The only remaining possibility would seem to be an appropriate change of composition. Ascent of carbonate-carrying material, and its gradual concentration beneath the crust, would not only provide for the eventual development of carbonatites and alkali rocks in the parts of the crust now exposed to view; it would also inevitably lead to the uplift of the overlying country. Rift valleys may well have been formed, in the manner experimentally investigated by Cloos (1939), where the upper parts of the substratum became particularly enriched in carbonate material. If so, the negative anomalies of gravity could be readily accounted for, without recourse to the otherwise unsatisfactory compression hypothesis. The cause of the great uplift of Ruwenzori would also cease to be a tantalising mystery. The "magmatic carbonatite" hypothesis thus promises to co-ordinate a variety of enigmatic phenomena which have hitherto defied explanation.

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