

NOT AVAILABLE FOR SCAN

THE SUKULU COMPLEX, EASTERN UGANDA  
AND  
THE ORIGIN OF THE AFRICAN CARBONATITES.

C.E. Williams.

A Thesis submitted in fulfilment of the requirements for the  
degree of Doctor of Philosophy at the University of Cape Town.

May, 1959.

The copyright of this thesis vests in the author. No quotation from it or information derived from it is to be published without full acknowledgement of the source. The thesis is to be used for private study or non-commercial research purposes only.

Published by the University of Cape Town (UCT) in terms of the non-exclusive license granted to UCT by the author.

PART I.

THE SUKULU COMPLEX, EASTERN UGANDA.

## CONTENTS.

### PART I. The Sukulu Complex, Eastern Uganda.

INTRODUCTION	.. .. .	1
LOCALITY & PHYSICAL FEATURES	.. .. .	2
CLIMATE & RAINFALL	.. .. .	2

#### STRUCTURE.

Mapping Method	.. .. .	3
Regional Structure	.. .. .	3
Surface Structure	.. .. .	5
Structure of Carbonate Core	.. .. .	6
Description of Tororo Hill Structure	.. .. .	10
Description of Sukulu Hills Structure	.. .. .	11
Structure of Outer Zones	.. .. .	20
Conclusion	.. .. .	24

#### PETROGRAPHY.

Introduction	.. .. .	26
Rock types	.. .. .	26
Carbonatites	.. .. .	26
Accessory Minerals	.. .. .	28
Nepheline Syenites within the Carbonatite	.. .. .	31
Flows in vicinity of Sukulu	.. .. .	32
Nepheline Syenites of Perimeter	.. .. .	33
Ijolite and Melteigite	.. .. .	34
Nepheline-pyroxene agglomerates	.. .. .	34
Pyroxenites	.. .. .	34
Fenites	.. .. .	35

ECONOMIC GEOLOGY

Introduction .. .. .	37
The Sukulu Soil Deposit .. .. .	38
Description of Ore Minerals .. .. .	43
Proving the Deposit .. .. .	48
Vermiculite .. .. .	50
The Uganda Cement Industry .. .. .	51
Working the Deposit .. .. .	52
Classification of Carbonatite Mineral Deposits ..	53
Conclusion .. .. .	55

## INTRODUCTION.

The vexed problem of the origin of alkaline rock types has for many years engaged the minds of some of the world's foremost geologists. Little need be said here of the many arguments for and against Daly's classic "Limestone Syntexis Theory" which is well known to all who interest themselves in this intriguing problem.

The publication of the work by von Eckerman in Sweden, Larsen in the U.S.A., Dixey, Campbell-Smith and Bisset in Nyasaland and Davies in Uganda has lent impetus to the concept to the formation of alkaline rock types in close association with limestones of igneous origin.

In spite of the wealth of data accumulated few criteria have been laid down for the positive identification of sövitic types as opposed to limestones of sedimentary origin. It is hoped, therefore, that an approach from a structural point of view may assist in the elucidation of these phenomena.

In August, 1949, the author was sent to the Tororo area to assist in the search for raw materials for the manufacture of cement. For the following two years and nine months he remained in the area, engaged in the proving of limestone and clay deposits and of the Sukulu soil deposit, discovered shortly after his arrival there.

In October, 1951, at the close of the first stage of prospection of the economic mineral deposits, permission was obtained to carry out detailed structure mapping in the carbonatites of Tororo and Sukulu complexes. For the next four months, the author was engaged in this work.

### LOCALITY AND PHYSICAL FEATURES.

The Sukulu hills are situated two and a half miles to the south west of Tororo township, in the Mbale district of eastern Uganda. The hills take their name from the highest member of the group which lies in the southern portion of the main mass of hills. Tororo is located on the main Mombasa-Kampala road and railway system and is a junction for the Soroti branch line. Tororo is the focal point of a well-developed system of roads linking the eastern and northern provinces and Buganda with Kenya.

The general elevation of the district is in the neighbourhood of 4,000 ft. above sea level but is overshadowed to the north east by the massive bulk of Mt. Elgon (14,300 ft.).

The Sukulu and Tororo hills form marked eminences of up to 800 ft. above the plain. To the east across the Kenya-Uganda border are the low granite hills of western Kenya.

The area is drained by the Malawa river, which at this point marks the inter-territorial boundary.

### CLIMATE AND RAINFALL.

The rainfall is confined to two periods during the year, the main precipitation occurring in the period March to June, with a second, short rains following in September to November. No detailed records are available but it is estimated that the total annual rainfall is approximately sixty inches. During both the "long" and the "short" rains malaria is prevalent, being mainly of the malignant tertian type. It is necessary, however, to make use of

prophylactic drugs throughout the year. The climate is generally drier than that of the central and western provinces of Uganda.

### STRUCTURE.

#### Mapping Method.

A set of aerial photographs taken in 1947 and covering the whole of the Tororo and Sukulu area was available for the work. These photographs were enlarged to a scale of 1:5,000, corrected by Multiplex and a topographical map produced by Messrs. Harward, McLouglin and Co., Nairobi, using ground control supplied by the Uganda Survey Dept. A set of oblique aerial photographs was also taken at the author's request.

Plane-table and telescopic-alidade methods were used throughout; but, owing to the large amounts of magnetite present, the use of a magnetic compass was precluded. Position was determined by resection from known points. The trend of the various structural components was traced out by this method and plotted on the topographical map. These trends were constantly checked by reference to the aerial photographs, using a wide-field stereoscope.

#### Regional Structure.

In considering the structure of carbonatites one of the most striking features is the regional aspect of the distribution of these volcanoes.

In East Africa, the tract of country extending from Homa Bay on the eastern shore of Lake Victoria through the Mbale and Karamoja districts of Uganda and into the Southern Sudan, is penetrated by a series of volcanic centres of the Elgon type. The volcanoes so far recognised are (from south to north):-

Homa Mountain, Tororo, Sukulu, Bukusu, Sekululu, Elgon, Aliket, Kadam, Napak, Moroto, Toror and at least one occurrence north of the Uganda-Sudan border.

The country rock in the area consists of Basement Complex, granites, gneisses and schists. The general grain of the country is north-south, the rocks being folded and sheared along this major axis. South of Mt. Elgon, younger granites have to some extent obliterated this trend.

The age of Mt. Elgon, which is considered to be the youngest member of the group, has been fixed within reasonably narrow limits as late Miocene. While it has not yet been possible to date accurately any of the others, it is clear that the Tororo, Sukulu, Bukusu and Sekululu complexes are older than Elgon and have only recently emerged from a cover of Elgon pyroclastics.

All stages of denudation are represented, from the almost perfectly preserved cone of Elgon to the deeply eroded and calcrete-covered area of Homa Bay. At Elgon, Kadam, Napak and Toror, the lavas and pyroclastic rocks of the cone remain to show the former presence of large volcanoes of the central type. On the other hand, at Tororo, Sukulu, Bukusu, Sekululu and Aliket, only the carbonatite plug and fenite areas remain. The connecting link is provided by Napak and Toror where, owing to the deep dissection of parts of the pyroclastic cone, the carbonatite plug and fenite zone are revealed.

The materials of the cone are dominantly agglomerates and tuffs with only minor intercalations of lavas. Coarse lacustrine sediments known as the Bugishu series have been observed at the base of Elgon and Napak, underlying the agglomerates.

### Surface Structures.

Napak provides the best example of the structures to be found on the old land surface through which the diatrema made its way. According to B.C. King (10, 1951) the first sign of the impending volcanic action, both here and at Elgon, was the depression of the surface of the peneplain resulting in the formation of a series of shallow lakes in which the prevolcanic sediments accumulated.

This was followed by the gradual flexuring of the basement complex, leading to the development of a broad dome structure, ten miles in diameter and dipping outwards at angles of up to 25°. This feature is believed to have resulted from the strong upward pressure which must have existed prior to eruption from the central vent. This vent was drilled through the highest point of the dome.

The present writer is of the opinion that the pre-volcanic sediments may be explained as resulting from the erosion of the rising dome. It is felt that this elevation would cause the deposition of coarse grits around the outer edge of the dome. Typically, the Bugishu series attain maximum development beneath the outer edge of the agglomerates of Elgon and are not recorded closer to the centre.

During and after the formation of the volcanic cone, faulting occurred which tended to be both radial and concentric in relation to the volcanic centre. Radial faulting resulted in the relative uplift or depression of blocks or wedge-shaped sectors of the volcano, while concentric faulting relatively depressed blocks of the volcanics and tilted them towards the centre. There is often a marked coincidence between the areas of faulting and the occurrence of parasitic vents and cones.

The tilting of sectors of the volcanic cone has been observed in the area on the north side of Kadam,

recently mapped by the author, where a block of country extending for twelve miles outwards from the volcanic centre has been tilted inwards carrying with it the earlier agglomerates and lava flows, while the later ejectamenta lies in a normal attitude above the discontinuity.

At Napak and Toror, the carbonatite occupies the central vent and it is clear that the sövite represents the final phase of the extrusive stage. The sövite solidified in the vent at a stage when the activity of the volcano had waned to such an extent that it was unable to remove an obstruction of any great dimension. It is probable, however, that the carbonatite stage had been reached on earlier occasions during the life of the volcano but that sufficient pressure remained to brecciate and remove the plug. This may account for the fragments of carbonatite recorded in some of the agglomerates of Elgon.

It is important to note that the carbonatite plug represents only a minute portion of the rocks related to the volcanoes of this type.

#### Structure of the Carbonate Core.

At Tororo and Sukulu the carbonate cores are well exposed and for this reason a detailed structural analysis has been made.

Several types of structural features have been observed:-

1. The massive structural components which are visible at a distance. These are composite sheeted bodies which, owing to their relatively uniform chemical and physical characters, tend to stand out as individual units from neighbouring carbonate sheets of slightly different composition. On the ground, these units are not easily differentiated from the adjacent bodies since they are

seldom marked by any definite boundaries, except where they impinge upon cross-cutting structures. They are clearly seen on the vertical and oblique aerial photographs, where, in many instances, they have the appearance of sedimentary strata dipping towards the centre.

The main volcanic neck at Tororo is encircled by one of these bodies which is in turn circumscribed by a further ring structure of greater diameter. It is suggested that the term "collar structure" might usefully be applied.

The primary foliations or flow lamellae are invariably parallel to the general direction of elongation of the massive features.

2. The lamellar flow structure is characterised by mineral banding, the darker minerals being segregated into separate sheets generally approaching the vertical in attitude. The presence of these mineral bands assists in the interpretation of displacing structures such as faults and shears, and in the determination of strike over considerable distances. The sheets are seldom sufficiently constant to give accurate indication of dip which is generally determined when collar sheets pass across a valley.

Turbulent flow is recorded around wall-rock inclusions and is general in the fenite areas.

3. Accompanying each phase of the emplacement of the carbonatite and probably representing a period of tension at the end of each phase are numerous dyke-sets of fine-grained carbonatite. These, in general, lack the darker minerals of the main sövite mass and particularly at Sukulu contain considerable amounts of ankeritic carbonate. Sets belonging to the earlier phases are

faulted and displaced by those of later phases.

It is important to note that these dykelets occur at the end of any particular phase and are found cutting nearly all the other rock types within the aureole. They are generally small, ranging in size from a fraction of an inch to a maximum of just over three feet. They are stained a dark yellow-brown colour on outcrop but at depth are white and interspersed with minute crystals of pyrite or fluorite. Fresh rock of this type when left out in the open rapidly becomes stained a rusty red. The orientation of these dykelets is generally parallel to the direction of lamellar flow as well as at right angles to this direction. They also occur in the same direction as the major fault lines.

4. Originating at the centre of the complex and passing outwards through some or all of the collar sheets are a series of radial faults which are probably related to the tilted wedges of the cone. These faults are characterised by considerable displacement and intense brecciation, giving rise to sovite-breccias and fenite-breccia-dykes.

5. It has been noted that, while the major faulting radiates from the intrusion centre, very few of the sovite "dykes" are true radials. They are almost invariably tangential. Close examination indicates that these "dykes" originate as part of the ring structure but tend to straighten out particularly along the grain of the country rock. This tangential aberration of ring structure which has an important bearing on economic considerations, has been observed only in the high angle sheets fairly close to the centre of the plug. In general they tend to retain something of their inward dip until the sphere of influence of the centre is escaped when the primary foliation becomes vertical. It is believed that these features run out laterally and

do not necessarily arrive in their present position from directly below. This is certainly the case on Lime Kiln Hill, Tororo, where diamond drilling shows that the limestone body is floored by syenitic material.

Since these tangential "dykes" may arise from points on either side of the plug, a pattern of intersecting lamellae is often to be found in the direction of maximum eccentricity of the complex.

6. The jointing in the sövite is generally of the ex-foliation type, the wide joints being filled with coarsely crystalline calcite. As this jointing is parallel to the surface it is only seen in the recently opened excavations. A further joint system is orientated parallel to the lineation.

7. The weathering of the carbonate rock tends to accentuate the structural features. The massive components stand out owing to their greater resistance to weathering than the adjacent sheets. The foliation is brought into sharp relief through fluting and dyke-swarms made conspicuous by their discoloration on weathering. Dolomitic segregations are obvious owing to their typical weathering. A curious feature of the carbonate rock is its ability to resist weathering to the extent that it stands three hundred to eight hundred feet above the fenite pediment. The answer probably lies in the fact that while the sövites are reasonably homogeneous, the fenites are complex mixtures of the various rock types, with minerals more liable to hydration and oxidation than those of the carbonatite.

It may be mentioned here that extremely high yields are obtained from water boreholes sited in the mixed rock zone surrounding the carbonatite.

Description of Tororo Hill Structure.

The central part of the Tororo plug is a small structureless mass, about ten feet across, of medium-grained, red-stained sovite. This is cut through the centre by a small calcitic dyke. Immediately surrounding the inner body is a series of rings of fine-grained, limonite-stained sovite displaying vertical lineation. This occupies most of the top of the hill.

With the step down onto the first of the collars, the sovite becomes coarse-grained and the sheets are inclined very slightly towards the centre. As the collars are traversed outwards from the centre there is a gradual increase in the angle of dip until, at the foot of the rock, a dip of  $73^{\circ}$  is recorded.

From the foot of Tororo Rock, the complex develops an eccentricity towards the south, in which direction are three very much smaller hills.

The trend of tangential aberration of ring structure at both Sukulu and Tororo follows an anti-cyclonic pattern with departure from the ring structure generally taking place in an anti-clockwise manner. The two hills, known as Reservoir Hill and Cave Hill respectively, show the result to be expected when clockwise and anti-clockwise features converge.

The structure on Reservoir Hill is that of a tangential dyke arising from the eastern foot of Tororo Rock, while the Cave Hill structure is that of a tangential dyke originating on the western foot. The outbreak of the two components was clearly simultaneous, for the foliation of each cuts the other indiscriminately. A series of collar sheets dipping inwards at  $57^{\circ}$  forms the basis of the outward termination of both Reservoir Hill and Cave Hill. These are older than the tangential dykes which pass through them.

The Lime Kiln Hill may be divided into two separate parts, the North Kiln Hill, which is an extension of the tangential dyke from Reservoir Hill and the South Kiln Hill which, although originating from the same source as the former, is separated from it by the strongly cross-cutting components from the Cave Hill dyke.

The North Kiln Hill is composed of alvikitic sövite contaminated by fragments of syenitic material, while the South Kiln Hill, where the carbonate is of the same composition, has fewer xenoliths.

The Lime Kiln Hill carbonatite is contained within a narrow trough, the walls of which are composed of shattered fenites in process of digestion by sövite. As already mentioned, the intrusion is floored by syenite. This floor is inclined towards the point of aberration of the western tangential dyke. The primary foliation of the dyke is vertical and parallel to the side of the trough except where the xenoliths have caused turbulent flow. The dyke is modified by the later collar sheets which have been intruded at a low angle, parallel to the syenite floor. Once again the axis of intrusion is directed towards a point west of Tororo Rock, external to the centre. From the intense brecciation of the walls and distal end of the trough, it is clear that this body became emplaced under explosive conditions. Parallel to the flow lamellae is a series of narrow pyroxene-nepheline breccia dykes which are younger than the collars.

#### Description of Structure of Sukulu Hills.

The central portion of the sövite of the main centre at Sukulu has for the most part been removed by erosion and is now covered by magnetite-apatite soil. Only a small portion of Hill L which forms the northern

rim of the inner ring, remains to indicate the presence in the centre of a large, apparently structureless mass which formed the original obstruction in the vent.

Immediately after the emplacement of the central plug, a series of vertical collars were intruded between the plug and the wall rock. This is evidenced by the numerous small fragments of fenitised material incorporated in these sheets. The collars in the initial stage must have been almost perfectly concentric except on Hills P and T where tangential aberration commenced at an early stage.

As collar sheet injection proceeded further outwards, larger bodies of wall rock were incorporated in the sovite, causing the development of a slight eccentricity in the sheets crossing Hill J. Up to this point the sheets remained vertical or had a slight inward dip.

Following this stage came the subsidence of the wedge formed by the faults cutting Hills V and H and Hills V and I. Owing to the vertical attitude of the sheets on the southern rim of the inner ring or Hill V, very little displacement of the sheets is observed. Development of an extensive shear zone, in the direction of the chord, obliterated the original attitude of the sheets in the Hill H area. The depression of this sector not only displaced the carbonatite but resulted in the incorporation of a large block of wall-rock which was shattered and partly digested by the sovite.

The next major episode was the injection of the massive features of the outer ring which extend from the outer portion of Hill K to the western end of Hill H. These collars increase in dip very rapidly towards the outside and form marked ridges often

characterised by sheer cliffs covered with secondary limestone and stained with limonite. A considerable amount of wall rock was incorporated as each component forced its way between the last collar emplaced and the wall. The collars traversing Hill C are believed to belong to this episode.

On the northern and western portions of the inner ring, the outer massive features are not present. Instead, a series of tangential dykes arose in both clockwise and anti-clockwise fashion to form a criss-cross fabric of lamellae which constitutes the body of rock running out towards Hill M. At this point, tangential dykes arising from Hill T intersect those arising from Hill L. Accompanying the injection of these tangential dykes was a gradual change of centre associated with intense explosive activity and resulting in the large area of sovite breccia on Hill M and the two breccia plugs of Hills O and N. These latter two hills are composed entirely of angular fragments of sovite, set in a fine-grained, limonite-stained, calcitic matrix. The new centre was finally established at the small hill north east of the Hill D beacon.

At the end of this phase, a series of radial faults originating at the main centre of the complex developed. The most important of these was the major fault of the complex which cuts diametrically across the centre, from the western end of Hill H through the western tip of Hill V and out through the valley between Hills A and B. This fault, which was accompanied by intense brecciation, displaced the northern rim of the inner ring towards the south west. While the rocks in the fault zone on Hills H and V are sovite-breccias, those in the A - B valley are fenite-breccias. It is significant that the fault line when produced passes

through the central plug of the Tororo complex, two and a half miles to the north east. It is, therefore, believed that the establishment of the Tororo centre of activity followed upon the establishment of this major fault, which must certainly have affected the surrounding country rock and the cone of the volcano.

The main sheets on Hill D are believed to be tangential dykes arising from the western edge of the inner ring. With the establishment of the Hill D centre a series of sheets was emplaced radial to the new centre. This is the only case so far observed in the area, where carbonatite dykes occupy a true radial position and may have come into position along a series of radial faults. The other faults on Hill D, however, although radial, are accompanied by the emplacement of sovite-breccias. Also radial to the new centre are two dykes of tinguaitite.

At a period immediately prior to the displacement of the northern half of the complex by the main Sukulu-Tororo fault, a series of smaller but no less violent faults starred out from the centre to cut the northern part of the inner ring. These faults were again accompanied by intense brecciation and mylonitisation. Immediately following the major displacement by the main fault, intense explosive activity brecciated a considerable area of the rock on Hill P to the west of the main centre. Immediately there were emplaced, probably simultaneously, two series of sheets, those leaving the central plug at Hill A and traversing across Hill B, and the second passing across Hills P, Q, R and S. These series of intrusions have several properties in common. Firstly they were both accompanied by brecciation of the wall rock forming fenite-breccias. In both cases the flow lamellae are strongly marked by

segregations of magnetite and are straight and vertical in attitude. Finally, both series are abnormal in containing considerable amounts of brown pyrochlore visible in the hand specimen.

This was followed almost immediately by a recrudescence of activity related to the main centre. This took the form of the injection of a series of sövite ring-dykes around the circumference of the complex. For the most part these ring dykes have been removed by erosion but small segments remain on the outer edges of Hills H, I, J, B, C, E and on the northern tip of Hill D. Since most of the sheets on Hill E are vertical, they may belong to this period of ring-dyke emplacement.

The next major movement occurred at the establishment of the large fault, cutting the western edges of Hills H, T and S, which was accompanied by the emplacement of sövite-breccias. It is not possible to state definitely the relative direction in which the sövites to the west of this fault were displaced, but the author favours the view that the displacement of this segment was to the north-west.

The faulting of the Hill E sheets and the drilling of the sövite-breccia plugs on Hill E and in the neck separating Hill E from Hill F is probably related to the partial development of a new centre in the soil-filled valley between the arms of Hills E and F. This centre, however, failed to develop fully.

The final phase of activity is associated with the development of a small dyke of sövite on Hill A and the breaking out of a series of sheets on the western edge of the main centre. These traversed the western edge of the sövite-breccias of Hill P

and swung out to modify the tangential dykes of Hill T and the sövites of Hills F, U and G.

At both Tororo and Sukulu, it is clear that individual collars increase in angle as they approach the centre. This has also been noted by Strauss and Truter (1930) in Sekukuniland. The occurrence, therefore, takes the form, in the ideal case, of a funnel with a parabolic profile. In the field, the term "collar structure" is used to differentiate these bodies from true conesheets. The use of the latter term is liable to induce fallacious arguments as to the depth of the intrusion foci. In view of the tremendous "punch" known to be associated with these volcanoes, it is likely that a cone of percussion would be produced. The possibility of the existence therefore, of true conesheets is not excluded, but it is thought that these would be intruded earlier in the history of the volcano, during periods when the vent was choked with extrusive material and that the rock types in the true conesheets would be representative of the flow material of the earlier phases.

From the above structure mapping there emerges a concept of a centrally placed body growing in size by the emplacement of material between the core and wall rock. This is largely accomplished by the brecciation and digestion of the wall rocks. In view of the evidence offered by the fault cutting the inner ring at Hill V and displacing the collar sheets of Hill I, while in no way affecting the outer collar sheets and ring dykes of Hills H, I, K and J, it is difficult to subscribe to the normally

accepted view that the outer sheets were emplaced first and the central plug last of all.

Von Eckermann (S. 101) writes of the Alnō centre: "Another striking feature of the sövites of the central area is in many cases the strained appearance of their calcite while the normal texture of pure sövites is granular..... Evidently the internal CO<sub>2</sub> pressure at the time of the consolidation of the last central parts of the sövites must have been very high. This is confirmed by an elsewhere unknown lateral displacement of dikes within the central sövitic cone".

The Alnō centre, therefore, shows a marked resemblance to that of Sukulu. It is felt that lateral displacement within the centre would have affected the outer sheets had they already been emplaced. It should be remembered however, that the major portion of the central sövites of Alnō lies below the water of Klingerfjarden and the complete picture of the structure could not be obtained.

It is believed, on evidence found at Tororo, Sukulu and other alkaline centres in Eastern Uganda, that the central portion of the carbonatite plug congealed in the volcanic conduit as a result of rapid escape of CO<sub>2</sub>, leading to a drop in both temperature and pressure. It is probable that this occurred more than once in the history of the volcano and may be regarded as the end of a single phase.

The plugs at present occupying the conduits represent a phase in the history of the volcano when insufficient explosive forces remained to enable the vent to clear itself of a large obstruction. Any remaining carbonate below the plug would then be intruded as ring features along the only possible zone of weakness, that existing between the congealing mass and the wall-rock.

Should any of the earlier collar sheets actually pass the obstructing mass, they would tend to flow inwards over it. This might explain the outward dipping primary foliation recorded by Strauss and Truter at Spitskop (1933).

It is thought that the major processes of fenitisation took place after the obstruction of the conduit and that the fenite aureole was enlarged by the penetration of sövite collars deep into the country rock. Any mobilisation of fenite material would occur later than this stage.

The hypothesis, that the innermost mass is the youngest, presupposes that the vent was occupied by congealed lavas, for without some obstruction or constriction there would be no impetus to ring intrusion. It would, therefore, be expected that xenoliths in the carbonatite would represent lava types. This is, however, not the case and all inclusions so far observed are fragments of rocks normally found in the area surrounding the carbonate.

Several other features contribute to the hypothesis that sövite ring structure is the result of carbonatite obstruction of the vent.

Firstly, the central sövites are generally of finer grain than the outer sövites which would indicate rapid cooling of the central mass and a more leisurely emplacement of the outer rings.

Secondly, the tangential aberration of ring structure follows an anti-cyclonic pattern, indicating a rotatory outward flow from a centre of pressure. The tangential dykes originate at a point away from the centre, suggesting that the vent had already been plugged. A good example of a tangential dyke originating from the periphery of a volcanic plug may be seen in M.P. Billing's

"Structural Geology" Plate XVII, facing p.243. While it is not suggested that the feature shown here is an aberrant ring structure, it is thought likely that, as the conduit became plugged with volcanic materials, the dyke material was forced to take a path between the plug and the wall-rock.

Segregation of minerals of the carbonate core has been recognised in other complexes. T.W. Gevers (1911) discussing the "marble core" at Loolekop writes: "The rock throughout is massive, but a rude banding of the various mineral constituents is sometimes to be noted, as well as a vague indication of parallel structures in the purer limestones".

Of the "marble" at Iron Hill, Gunnison County, Colorado, E.S. Larsen (1902) writes: "The silicate minerals are distributed irregularly in the contact zone and occur partly in thin streaks or seams.....Seams of pyrite and other sulphides and of apatite and martite cut the main mass of limestone." While Larsen claims that the "marble" is a structureless body, it is, nevertheless, possible that detailed mapping of these "streaks and seams" might reveal a complex structure. At Sukulu the structure is not immediately apparent and appears, at first sight to be absent. Larsen has mapped many of the narrow dykelets, mainly in the fenite zone, and believes them to be of hydrothermal origin.

Strauss and Truter (1908) write of the limestone body at Spitskop: "The outer zone of the alvikite has a concentric structure and the banding is either vertical or has a steep outward dip. The inner mass of fine-grained beforsite is obviously dome-shaped, for the banding is concentric and dips outwards at angles which increase towards the outer margin, though it is vertical in places."

R.A.P. Fockema (1908) writes of the 'dolomite

xenoliths' at the confluence of the Elands and Crocodile rivers:"The rocks are medium to coarsely crystalline and often well banded. The individual bands vary in colour from white to shades of brown and blue and are from a few inches to several feet wide. The bands of more dolomitic limestone and marble are sometimes folded and broken up.... Apatite and magnetite are found in bands throughout the xenolith."

B.C. King, (1914) describing the central carbonate at Napak writes:"Structurally the rocks show a well marked vertical concentric jointing which corresponds with a distinct though less apparent, composition banding. Streaks and knots of fine-grained carbonatite, which are more resistant to weathering, show a sub-parallel alignment and give a "streaming" effect to the rock. The weathered surfaces of the steep cliffs by which the greater part of the hill is surrounded provide an excellent display of these structural features".

It appears, then, that segregations of minerals into sheets and a complex structure are to be found in the central carbonates of many complexes, in which are found a constant and probably diagnostic mineral and rock assemblage.

#### Structure of Outer Zones.

Surrounding the composite carbonate body has been recognised a series of partial or complete rings which divides the area between the carbonate and the unaltered country rock into rough zones.

Owing to the laterite pediment around the Sukulu Hills, it has not been possible to observe these zones in any detail, but their presence has been indicated, in a series of boreholes sited in the vicinity of the new cement factory and to the south of the main group of hills.

In order to obtain a complete picture of the structure, in the outer area, it is necessary to look to the neighbouring complexes of Tororo and Bukusu.

In each case the complex is surrounded by a circular fault zone, generally two or three miles from the centre. This zone is marked by intense vertical shearing and in the case of Bukusu a small segment of sövite ring-dyke. At Sukulu the zone is marked by a very leucocratic sheared granite. Faults radial to the carbonate centre are also seen in this zone.

Immediately surrounding the carbonate is a zone of brecciated and fenitised wall rock intruded by and in process of digestion by sövitic material, arising from the main limestone mass. Proceeding outwards there is a gradual diminution of brecciation and where, as at Tororo Lime Kiln Hill, the area of alteration is small, there is a gradation from syenitic fenite through quartz-syenitic fenite to the granite of the Basement Complex. In the larger complexes of Bukusu and Sukulu, the zone between the fenites and the boundary fault is occupied by a number of different alkaline and ultra-basic rock types. At Bukusu these are mainly biotite-pyroxenite, nepheline-syenite, urtite, ijolite, dunite and segregations of both high- and low-titanium iron ores. At Tororo nepheline-syenites are the main rock types, but a large body of apatite-pyroxenite was located in two water boreholes to the east of the Rock. The latter rock-type was composed of 50% apatite and 50% diopsidic pyroxene.

The fenite zone may be penetrated by bodies of sövite as at Busumbu Hill in the Bukusu complex. This is an apatite-sövite, containing approximately 15% apatite. In the upper portion of this body, the calcium-carbonate has been leached out, leaving a residual deposit rich in apatite and capped by a surface deposit of secondary phosphate composed of francolite and staffelite. Some

of the cracks in this capping are filled with the zeolite thompsonite.

In the Iron Hill area, Colorado, the 'marble core' is surrounded by a large mass of pyroxenite which is intrusive into the outer edge of the marble and the uncomphagrite to the south. This was followed in order, by a finer-grained pyroxenite, mica-rich and apatite-rich varieties, nepheline-bearing rocks, olivine-bearing rocks and finally fine-grained carbonate veins.

At Spitskop in Sekukuniland, ( ) "the complex is entirely surrounded by Bushveld granite and granophyre. The irregular zones of the complex consist, from the outside inwards, of alkali-granite, quartz-syenite, red umptekite and white umptekite, all of which are obviously fenitised Bushveld granite and granophyre. The granitic rocks and umptekites have a concentrically sheeted structure with centripetal dip. Nepheline appears in places in the inner umptekites, so that undoubted pulaskitic fenite also occurs.

The umptekite is followed inwards by fayalite-diorite and theralite.....The central mass of the complex consists mainly of red, coarse-grained ijolite, black, fine-grained ijolite and dark melteigite and jacupirangite,..... The coarse-grained red ijolite is intrusive into the other ijolites and may be a truly magmatic rock.

A poorly exposed, stocklike body of biotite-pyroxenite is clearly older than the pyroxenite but is intrusive into the theralite.

Inside the complex are two big ring dykes of foyaite intrusive into the ijolites and theralites and in the Bushveld granite outside the complex there are numerous conesheets of foyaite and tinguaitite. Inside and outside the complex are numerous radial dykes of foyaite, tinguaitite, dolerite and lestiwarite."

At Loolekop, Eastern Transvaal, the 'marble core' is surrounded by an extensive body composed essentially of diopside but often rich in vermiculite and apatite. The pyroxenite mass is surrounded by granite and syenite, "the two rock types being intricately intermingled in the contact area." (p. 46). The syenites are everywhere intrusive into the pyroxenite.

In spite of the complicated and often slightly differing field relationships these complexes show marked similarity.

The following sequence of events is suggested:-

1. . The explosive drilling of a diatreme and the up-doming of the country rock.
2. The building up of a volcanic cone composed mainly of agglomerates and tuffs, with subsidiary lava flows of basaltic, phonolitic and nephelinitic types.
3. The emplacement and ejection of carbonate bodies within the plug (it should be noted that fenitisation of the wall-rock may have commenced during periods when the vent was occupied by the earlier carbonate plugs.).
4. The solidification in the throat of the vent of the central core of the final carbonatite body.
5. The emplacement of collar sheets around the central plug, accompanied by the faulting of the plug, country rock and cone.

This marked the end of the major volcanic cycle and the first stage in the development of the hypabyssal alkaline complex.

6. The emplacement of further sheets between the last formed sheets and the country rock incorporating fragments of wall rock and digesting them.

7. The penetration, by sövite sheets, of the area surrounding the vent whose fabric had already been loosened by the initial punch of the volcano and subsequent radial and ring faulting. This materially assisted the metasomatic processes of fenitisation.
8. Ring subsidence, marked by intense shearing of the perimeter.
9. The intrusion of nepheline-syenitic types as ring dykes and cone or collar sheets, from below the carbonate centre.
10. The possibility is not excluded of the intrusion at depth of a basic or ultra-basic plutonic complex comprising the greater part of the gravitational differentiates.

It will be seen from the above that the order of intrusion in the hypabyssal complex is largely dependent upon the timing of the subsidence of the complex, the minor variations being explained on this basis. The early emplacement, for instance, of normally intrusive types might render them liable to fenitisation after reaching their final position. Depending upon their original composition and the degree of metasomatic action, a wide range of rock types might result.

#### Conclusion.

The sövites of Tororo and Sukulu Hills exhibit a detailed and intricate structure, the mapping of which suggests a mode of emplacement diametrically opposed to that which is normally accepted.

Structural components similar to those mapped in the Uganda complexes have been noted in the carbonate

centres of alkaline complexes in many parts of the world. It is suggested, therefore, that this structure, together with the mineral assemblage normally found associated with it, may be considered diagnostic of carbonatites. There can be little reason for alkaline complexes in which limestone has been assimilated, to assume the form shown by those known to be associated with volcanic action.

## PETROGRAPHY.

### Introduction.

The complex at Sukulu, while perhaps ideal for structural and economic investigation, is not well suited to petrological studies. The fact that it consists to a large extent of an eluvial and residual economic mineral deposit means that many of the rock types in the area surrounding the carbonate core have been deeply buried. Even where exploratory boreholes have penetrated the soils and laterites, the rocks are found to be weathered to a considerable depth and it has frequently been necessary to resort to partial chemical analysis in order to establish the identity of some of the minerals encountered.

### Rock Types.

Carbonatites form by far the greatest bulk of rocks at Sukulu. Actual exposure and information gained from boreholes and pits indicates that these rocks are present in an area of approximately six and a half square miles. They form a roughly circular group of hills reaching a maximum height of 4,648 ft. above a plain at 3,900 ft.

At Sukulu the carbonatites are mainly of calcitic type, showing a variable content of magnesium carbonate. They range in colour from pure white through grey to dark brown, limonite-stained varieties.

In texture they are usually granular and consist of equidimensional grains showing signs of magmatic abrasion and the development of glide planes. In size the plates vary from .05 mm to 5mm. They are usually equi-granular, but where inequigranular types exist, the matrix material is seldom very fine, being of the order of .2 mm.

The accessory mineral content of the carbonatites is extremely variable owing, in part, to the complicated, structurally controlled order of emplacement. The various structural components have "flowed" through each other, causing mineral contamination. It is clear that many of the sheets were emplaced while their immediate predecessors were still in a relatively plastic condition. Where the earlier components had already solidified, intense brecciation took place.

While partial analyses from many thousands of feet (36,000 ft.) of drill cores have shown the most

extreme chemical variation from foot to foot, it has nevertheless been possible to distinguish specific types of carbonate rock.

The Calcitic Group. These rocks consist of white to pink-stained granules of calcite, usually with some dolomitic carbonate within the lattice. Very few are pure and they frequently contain a scattering of other minerals. The most common accessories are apatite, magnetite and biotite. Each of these minerals assumes dominant proportions in various parts of the rock and occur as schlieren and flow lamellae imparting a strong foliation.

Dolomitic Carbonates. These range from white, fine-grained patches and blebs showing typical, reticulate, dolomitic weathering, and containing only apatite as an accessory, to iron-rich types with siderite and olivine.

The overall average magnesia content of the Sukulu group is of the order of 5%, while at Tororo, where dolomitic patches are less frequent, the magnesia averages 1.5%.

In this group are biotite-beforsites containing biotite, apatite, perovskite and pyrite. Magnesian olivines are present in small amounts at both Sukulu and Tororo, but no types comparable with the picrite-beforsites of the neighbouring Bukusu complex have been seen. The olivines appear to form by dedolomitisation of the host rock whenever the dolomitic carbonate has been emplaced close to the siliceous wall rock. Certainly in areas where large numbers of wall rock xenoliths are present the amount of dolomite is drastically reduced.

Ankeritic Carbonates. These occur in small dyke sets and veinlets which are emplaced after both calcitic and dolomitic phases.

The dark brown ankerite is often associated with small amounts of manganese carbonates.

Closely associated with the emplacement of the ankeritic group are small amounts of strontium and barium minerals. While strontianite has not yet been identified at Sukulu, its presence is indicated by several partial analyses.

Barytes and witherite have been noted in the Sukulu West Valley in association with wollastonite and a radio-active mineral containing thorium but too finely divided for accurate identification.

### Breccias.

The breccias may be divided into two main types:-

1. Sovite breccias. Quite large areas of the carbonate body are occupied by sovite breccias consisting of rounded and angular fragments of both calcitic and dolomitic types set in a fine-grained matrix of ankeritic carbonate. The breccia fragments range in size from just under half an inch to one foot in diameter. Sometimes the matrix itself is a micro-breccia.

It is of interest to note that niobium values are conspicuously higher in the breccias although pyrochlore has not been observed in situ there. Considerable enrichment in pyrochlore in the soil immediately adjacent to breccia zones has, however, been encountered.

2. Fenite Breccias. These are composed of fragments of fenitised silicate rock set in a matrix of calcitic or dolomitic carbonates. They occur generally in zones close to the original conduit wall. The fragments represent pieces of wall rock spalled off during the emplacement of the carbonatite and are usually angular though at the Tororo contact, similar fragments are rounded and partly digested by the carbonatite. Sections cut at the edge of these inclusions show plumes of fine-grained, dark silicate material migrating outwards into the carbonate.

### Description of Accessory Minerals.

The main accessory minerals of the carbonatites are:-

Apatite: Euhedral apatite is seldom seen in the main sovites and occurs invariably as rounded or egg-shaped grains. It is found as strings of rounded grains between the calcite granules. It is fluor-apatite and contains a fine dust of inclusions.

Magnetite: Magnetite occurs as irregular clusters and lenses consisting of euhedral crystals up to 1 cm, across. Tiny specks of apatite are common within the magnetite. Analyses show that the Sukulu magnetite contains less than 2%  $TiO_2$  and is consequently of value as an iron ore. It occurs in octahedra sometimes with dodecahedral modifications. Occasionally ilmenite occurs as small granules close to the magnetite.

Mica: The mica in the Sukulu carbonatite is of a bright green variety, though small fragments of red-brown biotite are sometimes present.

Analysis of green mica from Sukulu:-

SiO <sub>2</sub> .....	35.17
Al <sub>2</sub> O <sub>3</sub> .....	8.36
Fe <sub>2</sub> O <sub>3</sub> .....	10.15
FeO .....	1.50
MgO .....	20.99
CaO .....	2.12
Na <sub>2</sub> O.....	0.55
K <sub>2</sub> O .....	1.69
H <sub>2</sub> O+.....	18.62
TiO <sub>2</sub> .....	0.38
MnO .....	0.08
	<hr/>
Total.....	99.61
	<hr/>

(Analyst: J.B.Pollock)

This is a vermiculitic biotite very similar to some types recorded at Palabora (26) and Bukusu (3).

Pyrochlore: This mineral occurs in small quantities throughout the sovites but is often concentrated in tangential dykes of late formation. It occurs as honey yellow, grey and almost black vitreous octahedra, with slight dodecahedral modifications. It has clearly grown in situ at the same stage as the magnetite, and in some cases has used fragments of apatite as a nucleus around which to form. The growth of pyrochlore and magnetite occurred under hydrous conditions with the accompanying formation of radiating asbestiform fibres of tremolite and a small amount of zeolite. The very fine, orange-yellow octahedra sometimes found in magnetite lenses is probably pyrrhite.

Amphibole: Tremolite Z  $\wedge$  C 18° is the most common amphibole. It is rare in the carbonatite except in the Hill E area of Sukulu and at Tororo. A small amount of hornblende may be present near the contact with the wall rock. Tremolite N $\alpha$  1.596  $\gamma$  N = 1.625 is also found in the surrounding granites a considerable distance away from the Tororo occurrence.

Pyroxenes: These are generally rare in the carbonatite, except at Tororo, where there is a considerable development in the zone nearest the wall rock. Small fragments and microlites of diopside Z  $\wedge$  C 40° - 46° and acmite are sometimes seen. Wollastonite is of rare occurrence except in the West Valley at Sukulu.

Zircons: The zirconiferous minerals, while not seen in any of the rock slices available, are known to be present in the carbonatites from a detailed study of the soils at Sukulu and from residues obtained after digestion of the rock in acid. Zircon occurs as single crystals and twinned aggregates with well-developed terminal pyramids but with poorly developed prism faces, so that the crystals are easily mistaken for octahedra. X-ray photographs, however, show them to be definitely tetragonal. A second zirconiferous mineral, baddeleyite, is found in vitreous grey crystals up to 4 mm. in length. It has a pearly lustre and the following optical characters:- Negative,  $2V = 30^\circ$   
 $N = 2.11$   $N = 2.18$   $X \wedge c = 12^\circ$  .

Barite: In the West Valley of Sukulu this mineral is common. It is usually light brown in colour and has a dull surface. The crystals are usually from 3 - 5 mm. in length,  $N_\alpha = 1.641$   
 $N_\gamma = 1.655$ .

Olivine: Small yellow crystals of olivine are sometimes seen at Sukulu on the outer edge of the complex and near the fenite breccia zone.

Felspars: In some parts of the carbonatite orthoclase is seen, usually related to the late stage sheets and in felspathic breccias.

Quartz: The occurrence of small crystals of quartz has been noted in a few sections and are always to be seen in residues after digestion of the rock in acid. A few grains have been noted, in the silica fraction, of a mineral whose optical and physical properties suggest that it may be coesite, the high pressure form of quartz. Too little has been isolated so far to make the identification positive by chemical analysis.

Carbon dioxide: Small bubbles of  $CO_2$  have been noted in the calcite of some of the carbonatites at Sukulu and can be seen when the rock is crushed under petrol. This seems to indicate that the carbonatites crystallised under conditions providing an excess of  $CO_2$ .

Knopite: Brown or grey octahedra of knopite occur quite frequently in the Sukulu limestone where they are sometimes mistaken for pyrochlore.

Pyrolusite: At Sukulu small cavities in the carbonatite contain powdery manganese ore.

Anatase: This mineral occurs as tiny, dark blue bipyramids usually associated with visible pyrochlore.

Pyrite: Pyrite is most common in the South Kiln Hill at Tororo, where it occurs as scattered euhedra, while at Sukulu it is rare and occurs in minute veins.

Chalcopyrite: This mineral has only been found in the Hill C quarry at Sukulu and occurs as scattered specks.

Gold: A small amount of gold was found by K.A. Davies on his first visit to Sukulu but has not been recorded since.

Nepheline Syenites within the Carbonate Body.

Two narrow tinguaitite dykes are found to cut the syenites in the Hill D area. The dykes are 10 - 15 ft. in width, very fine-grained and grey-green in colour. They closely resemble the Elgon phonolites and are covered by a yellowish skin of weathered material. They are extremely tough and tend to break into sharp slivers.

Under the microscope they are seen to be xenomorphic granular in texture and to contain scattered phenocrysts of pyroxene up to 2 mm. in size, nepheline and a little orthoclase, seldom exceeding .1 mm. in size.

Nepheline is fringed by ragged cryptocrystalline pyroxene and occurs in the groundmass as tiny euhedra usually less than .1 mm. in size.

Pyroxene: The pyroxenes are aegirine-augite ZAC  $66^{\circ}$  -  $72^{\circ}$  and may be euhedral or apparently broken. Tiny needles of aegirine are also seen in the granular groundmass. In some slides a few small anhedral barkevikite are present.

Feldspars: Orthoclase showing Carlsbad twinning forms phenocrysts as well as some of the larger granules in the groundmass.

Zeolites: Analcite and natrolite are common in most slides and thomsonite is sometimes seen in small segregations of acicular crystals.

Biotite: No biotite was seen in the sections examined but was noted in hand specimens as large black books up to 1" in size, which on being split into fine sheets, was of a yellow-brown colour.

The tinguaites are the only silicate rocks seen to be cutting the carbonatite and clearly originate below the carbonate floor.

The following is an analysis of the most southerly dyke at Sukulu:-

	%	Normative	Composition %
SiO <sub>2</sub>	54.62	Or	20.54
Al <sub>2</sub> O <sub>3</sub>	20.95	ab	42.44
Fe <sub>2</sub> O <sub>3</sub>	3.39	an	0.56
FeO	0.84	ne	23.86
MgO	0.62	di	3.24
CaO	1.19	mt	2.55
Na <sub>2</sub> O	10.21	he	1.60
K <sub>2</sub> O	3.54	sp	0.34
TiO <sub>2</sub>	0.45	il	0.32
P <sub>2</sub> O <sub>5</sub>	0.04	Water	4.73
MnO	0.26	etc.	<hr/>
Loss on ignition	4.73		<hr/>
	<hr/>		<hr/>
	100.84		100.18

Specific Gravity 2.45

Analyst: P.G. Jeffery,  
G.S.D., Uganda.

Flows in the Vicinity of Sukulu.

Two lava flows and a group of pyroclastics are found in the vicinity of Sukulu, though it is not known whether they belong to the Elgon cone or to the Sukulu episode.

Nephelinite.

A small flow 35 ft. thick lies in the bed of the Osia river about 1 mile north east of the Sukulu carbonatite.

In the hand specimen the rock is fine-grained tough and grey-green with some phenocrysts of pyroxene 1 - 2 cms. in length. Occasional small nepheline euhedra are seen.

Nepheline occurs as euhedra up to 4 mm. in length, refractive indices determined on a crush of the rock are  $n_g$  1.538 and  $n_w$  1.543. Some zoning indicates the presence of kalio-

-phillite. The nephelines show clouding and the development of mica and cancrinite.

Pyroxenes occur as ragged clusters of zoned, light green to dark green crystals. The optical characters indicate a gradation from augite to aegirine-augite  $N_g$  1.690 - 1.710  $N_{\alpha}$  1.662 - 1.680,  $2v$   $40^{\circ}$  -  $68^{\circ}$ ,  $z \wedge C$   $40^{\circ}$  -  $66^{\circ}$ , but most commonly near  $50^{\circ}$ . The deepening colour appears to be directly related to an increase in the acmite molecule.

Biotite: A very few tiny flakes of brown biotite are seen but chlorite is more common.

Iron ores form the bulk of the accessory minerals, though rare prisms of apatite also occur. (C.E. 92).

#### Phonolite Flow.

Near the cement factory site a deeply weathered phonolite flow was encountered in several boreholes. The rock is yellow-green in colour and very fine-grained, with tiny laths of kaolinised feldspar. The whole rock resembles the weathered skin frequently found on Elgon phonolites.

It is of interest to record that this flow may be used as a low-iron, aluminous fraction in the manufacture of cement at Sukulu.

#### Syenites.

Between the carbonatites and the granites at Sukulu, a series of water-boreholes have yielded small fragments of syenitic rocks.

These may be divided into two types, though they may well grade into each other, as fragments of both types are found in a single hole. It is possible however, that they form a series of cone sheets, since the holes were constantly deflected toward the carbonatite on entering the relatively unweathered rock. It may be mentioned here that the depth of the weathered zone is always of the order of 100 - 110 ft. in this part of the complex.

1. Nepheline Syenites: These may be termed juvites and consist of anhedral orthoclase, nepheline, which has broken down to fine micaceous material and plates of dark green pyroxene. In a few fragments melanite and cancrinite are found.

The texture is usually xenomorphic granular but may be quite coarse in places.

2. Syenites: This group appears to be closely allied chemically to the trachytes.

They consist of intergrown orthoclase crystals with interstitial ferro-magnesians.

Felspars: These are dominantly orthoclase but rare fragments of albite are seen.

Pyroxene is dark green aegirine.

Accessories: Magnetite, apatite, sphene and zircon are the most common accessories.

Ijolite and Melteigite.

Members of this group have been found on the South Kiln Hill and Tororo. They are rather decomposed and consist of an inequigranular intergrowth of turbid nepheline and pyroxene in varying amounts. The nepheline is replaced by cancrinite and mica. The pyroxene is dark green aegirine and aegirine-augite. The accessories are sphene, apatite and magnetite. In places segregations of nepheline constitute the urtites.

Nepheline-pyroxene Agglomerates: Recent quarrying at Tororo Hill has revealed the presence of a series of agglomerate dykes, usually about one foot across, consisting of rounded fragments of nepheline and pyroxene ranging in size from  $\frac{1}{2}$ " to 3", set in a fine-grained matrix which is also made up of nepheline and pyroxene. These dykes are vertical cross-cutting structures and are the latest emplacements into the carbonatite.

Pyroxenites.

A shaft sunk at Sukulu near the cement factory penetrated a zone of rocks consisting of pyroxene, magnetite, apatite and phlogopite in varying amounts. The rocks were too weathered for reliable optical examination but in the hand specimen are seen to be a coarse intergrowth of these minerals. Similar, though fresher, rock from a borehole at Bukusu contains olivine Fa 25 - 30, magnetite, diopside and brown biotite. Titanium minerals are indicated by the presence of leucoxene. The olivines are cracked and serpentinised in part. Apatite is the most common accessory in this group.

At Tororo, a rock fragment from a waterborehole contained equal quantities of apatite and diopsidic pyroxene.

Fenites.

The country rock through which the two major diatremes in the Sukulu-Tororo area were cut is, as far as borehole information allows of assessment, mainly granitic. The granites observed are fairly coarse-grained with allotriomorphic inequigranular texture. The feldspars, which are dominantly potassic, show faint cross-hatching and in common with many other Uganda granites, perthite is conspicuous. A small amount of albite also occurs. In the plagioclase both albite and pericline twinning occur frequently. Muscovite and fine flecks of a russet biotite occur interstitially and the rock is generally extremely leucocratic. The quartz also occurs as small granules though larger grains are sometimes seen.

On the Lime Kiln Hill of the Tororo occurrence, the relatively simple relationship of the sövite intrusion to the wall rock is easily observed.

The sövites of the South Kiln Hill lie in a narrow trough bounded by vertical walls of now modified country rock. The effect of the intrusion is first marked at 200 - 300 ft. from the contact by the intense granulation of the quartz, in the introduction of marked strain and sometimes an almost mylonitic crushing of the quartz fragments into plates exhibiting an undulose extinction. Shattering of the feldspars is marked by bending and micro-faulting of the twin lamellae.

Closer to the sövite, distinct brecciation occurs and often large blocks of up to 20 ft. in diameter have been disorientated. The sövite has actively penetrated the interspaces between the breccia fragments and still closer to the main sövite mass the fragments have lost their angularity to form rounded xenoliths and "ghost" xenoliths. This brecciation and digestion is clearly seen on outcrop on the eastern slope of the South Kiln Hill.

A gradation from the very mixed rocks close to the hill through syenite and quartz-syenite to the intensely sheared granite is also visible in the hand specimen.

In thin section the most obvious feature is the penetration of calcite between and into the existing mineral grains of the wall rocks. This is accompanied by the growth of turbid nepheline, ragged hornblende, which in the later stages becomes euhedral, zoned melanite and sometimes small crystals of sphene, together with the disappearance of albite, perthite and quartz. Sometimes aegirine-augite grows at the expense of hornblende. The most prominent introduced accessory minerals are euhedral apatite and fine stringers of purple fluorite.

The main change in the sövite penetrating the breccia zones, is the incorporation of the minerals introduced from the wall rock fragments which then exhibit a fluidal arrangement. In some cases, fine crystals of melilite, now almost entirely replaced by calcite but still showing evidence of a median crack, are present. The dissipation of xenolithic material and its incorporation in the sövite is achieved by the loosening of the fabric of the included fragments by the continued penetration of the calcite and by the development of plumes of very fine grained silicate material migrating outwards into the sövite.

It should be noted that it is not necessary to postulate extensive ionic migration either to or from the main sövite body and the desilication is achieved by the admixture of calcite with the shattered silicate wall rocks. This effectively reduces the relative silica percentage in the mixed rocks and may be termed "silica dilution". Probably the most significant fenitisation effects are the formation by reaction of magnesian olivines, diopsidic pyroxenes and some nephelines.

The incorporation of silicate material in varying quantities in the sövite contributes to the evolution of members of the silicate-sövite series.

Where alkaline and ultrabasic types are brought into intimate contact with the sövite, physical admixture and fenitisation also occur. Fenitisation may therefore be described as the admixture of sövite with silicate rocks under such conditions of temperature and pressure that new minerals can form in equilibrium with the relatively reduced silica percentage.

From the foregoing descriptions it is clear that the Sukulu assemblage closely resembles a number of other, better exposed alkaline complexes such as Spitskop, Bukusu, Chilwa and Alnö Island.

ECONOMIC GEOLOGY.

Introduction.

Work in the alkaline areas in Eastern Uganda began in 1927 when K.A. Davies, in the course of routine mapping, discovered the phosphate deposits of the Bukusu complex. In addition to the phosphates on Busumbu and Nakupa hills, low titanium ore, incorporating small amounts of knopite, was found at Surumbusa, while deposits of vermiculite were located at Sukusi and Namakara hills.

A geological investigation, accompanied by a diamond drilling programme on the Tororo Limekiln Hill, was undertaken by K.A. Davies in 1947 in order to estimate the limestone reserves for the establishment of a cement industry.

In 1943, Dr. Davies visited the Sukulu hills and while examining the reject material from the lime kilns of the Uganda Lime Co., noticed small brown octahedra, which he later identified as koppite. Examination of the source rock confirmed the presence of this niobium-bearing mineral in the sovites of the Sukulu hills. A grab sample of the detritus was taken and examined in the laboratory.

In August, 1949, the author was sent to the Tororo area to site a quarry for the proposed cement works. It was hoped that a suitable site could be found in which the limestone would satisfy the necessary chemical conditions for the manufacture of cement, as well as containing a quantity of pyrochlore which could be extracted in the cement manufacturing process.

In addition, the author was to site a series of boreholes in a search for secondary limestone. This material had been observed coating the top of the laterites

around the base of the Sukulu hills. Drilling was commenced in the Sukulu south valley. In all instances the boreholes passed through varying thicknesses of red soil before reaching laterised material. Samples taken from the soil cores were washed and examined under a binocular microscope. The author found these samples to be composed of apatite and magnetite with small amounts of niobium-bearing material. This led him to the belief that the Sukulu soil might prove to be of economic importance and a report to this effect was submitted to headquarters, Subsequently, the mineral baddelyite was identified by K.A. Davies in a sample of soil from this area.

Early in 1950, a team was assembled under the leadership of Dr. K.A. Davies, to investigate more fully the economic potentialities of this field. The members of the team were drawn from both the Geological Survey Dept. and the Mineral Resources Research Committee. The author served in the capacity of resident geologist at Sukulu.

In a field laboratory maintained in the area, rough size analyses and mineral determinations were made, but for the purposes of this paper, the more accurate estimations made by members of the Mineral Resources Division of the Imperial Institute are given.

The author wishes to record his sincere appreciation of the assistance rendered by his wife, particularly in the preparation of the many hundreds of soil samples from the South Valley soil cores, the examination of which led directly to the discovery of the soil deposit.

#### The Sukulu Soil Deposit.

The sovites of the Sukulu Hills contain, as accessory minerals, varying amounts of magnetite, apatite

pyrochlore, zircon and baddeleyite. In most of the alkaline complexes of this type in Eastern Uganda, Nyasaland and Scandinavia, some or all of these minerals are known to occur.

In the course of normal processes of atmospheric weathering, the calcium carbonate of the sövite is removed, leaving the insoluble minerals as an eluvial residue. Under conditions of tropical denudation, there is a tendency for the carbonatite plug to remain standing above the fenite pediment. It is to be expected therefore, that a small deposit of resistant minerals should remain at the base of the limestone hills. In an area where a juvenile or even mature river system is in operation, it is unlikely that such a soil deposit would attain very large dimensions. In the Tororo area, however, conditions were imposed which led to the accumulation of considerable thicknesses of soil.

It is clear from the work of K.A. Davies that a youthful system of drainage was in operation before the eruption of Mt. Elgon. With the first flows of Mt. Elgon, the rivers became choked with lava and the area has only recently emerged from the cover provided by the pyroclastic cone.

The Osia river, which drains the northern part of the Sukulu area, still contains a thickness of over 30 ft. of nephelinitic lava in its bed. It has been unable, therefore, through the raising of its base level, to remove the increasing thicknesses of soil behind this barrier.

To the south and east, the main drainage falls directly into the Malawa river. This river, which originates in the southern foothills of Mt. Elgon, has clearly been constricted, probably by lavas which have only recently been removed

In plan, the Malawa exhibits all the features of a senile stream, with a wide flood plain, meandering course and the formation of small oxbow lakes and swamps. Within comparatively recent times, however, presumably with the cutting of the lava bars, rejuvenation has commenced. The river is now fast-flowing and deeply incised, while the old oxbows are stranded at twenty to thirty feet above the present stream level. On the south side of Sukulu, where rejuvenation is most marked, the soil deposit has already diminished considerably.

Evidence presented by extensive diamond-drilling and from the results of geophysical survey, indicates that in pre-Elgon times, the valleys which cut into the Sukulu hills to the north and south were of youthful profile and cross-section. Today these valleys are seen only as wide soil-filled embayments of relatively mature profile, where large thicknesses of up to ninety feet of soil have been allowed to accumulate. Diamond-drilling has revealed the presence of a horizontal body of francolite and staffelite, normally associated with the surface deposits of Busumbu, at a depth of over 90 ft near the mouth of the North Valley.

Along the outer perimeter of the sôvites is a laterite dipping gently away from the hills. On this laterite have accumulated varying thicknesses of magnetite-apatite soil, which occurs in outwash fans, valley accumulations and eluvial deposits at the foot of the sôvite cliffs. The soil, which attains a depth of up to 85 ft. at one place and a minimum of 20 ft. around the whole perimeter, gradually thins off away from the hill, until bare laterite is exposed.

The laterite forms a cellular body, believed by the author to be the iron-enriched upper portion of an older Sukulu-type soil deposit containing angular quartz fragments. This older soil rests on an old land surface

of weathered fenite rocks. The laterite becomes soft where large thicknesses of soil overlies it.

The Sukulu soil is a heavy red-brown loam, which, on drying, tends to harden rapidly. A rough analysis of the mineral composition of the soil, made at the Imperial Institute, was as follows:-

Apatite .. .. .	36%
Quartz .. .. .	12%
Silicates .. .. .	9%
Magnetite & hydrated $Fe_2O_3 - Al_2O_3$ .. .. .	43%

(Analyst: T. Deans).

This agrees closely with the original estimates made in the field laboratory during the early part of the work.

The great variety of particle sizes is shown in the following size analysis, which was made on a head sample of 20 Kg. of raw Sukulu earth. This was scrubbed and divided by screening into "sand" (plus 325 mesh) and "slime" (minus 325 mesh). All meshes are Tyler.

P.T.O.

<u>Mesh</u>	<u>Microns</u>	<u>%Weight</u>	<u>(NbTa)<sub>2</sub>O<sub>5</sub></u>	<u>%Distn. Nb</u>
-10	-1651	1.8	.220	1.10
-10-28	589	3.9	.486	5.35
-28-35	420	2.7	.433	3.30
-35-48	295	4.0	.395	4.46
-48-65	208	5.2	.264	3.86
-65-100	147	6.9	.364	7.06
-100-150	104	6.0	.375	6.34
-150-200	74	5.5	.511	7.92
-200-270	53	4.4	.695	8.63
	38	3.9	.696	7.66
	26	3.8	.898	9.64
	19	3.6	.984	9.96
	12	2.9	.562	4.42
	-12	<u>46.0</u>	.157	<u>20.30</u>
		<u>100.5</u>		<u>100.00</u>

(Messrs. Pryor & Fleming)

In the first instance, the ore-dressing of the sand fraction only is likely to be attempted and the slimes will be stockpiled pending the development of suitable chemical or metallurgical extraction processes. The head of potentially recoverable pyrochlore is, therefore, approximately fifty per cent of the amount contained in the soil.

The main investigation of the ore-dressing problems has been carried out by Messrs. Pryor and Fleming of the Royal School of Mines. Their main line of attack has been an attempt by flotation methods to depress the apatite from the pyrochlore after magnetic separation of the magnetite.

A rapid technique for the quantitative estimation of niobium has been developed by members of the Chemical Institute. This method will be of great assistance in the evaluation of pilot plant tests and in the final ore-dressing plant.

Description of the Ore Minerals.

Pyrochlore.

The pyrochlore found at Sukulu represents the niobium-bearing end member of the microlite-pyrochlore series.

The following analysis, carried out at the Imperial Institute in London, indicates a close resemblance to theoretically pure pyrochlore,  $\text{NaCaNb}_2\text{O}_6(\text{O},\text{OH},\text{F})$ :-

		<u>Per cent.</u>
Soda	$\text{Na}_2\text{O}$	7.24
Potash	$\text{K}_2\text{O}$	0.07
Lime	$\text{CaO}$	14.82
Magnesia	$\text{MgO}$	0.49
Thoria	$\text{ThO}_2$	0.37
Cerium group earths	( $\text{Ce}_2\text{O}_3$ $\text{La}_2\text{O}_3$ ) etc.	0.62 1.38
Yttrium group earths	$\text{Y}_2\text{O}_3$ etc.	not detected
Zirconia	$\text{ZrO}_2$	1.91
x Ferric oxide	$\text{Fe}_2\text{O}_3$	0.48
Alumina	$\text{Al}_2\text{O}_3$	0.20
Titania	$\text{TiO}_2$	0.56
Niobium pentoxide	$\text{Nb}_2\text{O}_5$	68.72
Tantalum pentoxide	$\text{Ta}_2\text{O}_5$	0.20
Fluorine	$\text{F}$	3.87
Combined water	$\text{H}_2\text{O}$ 105°C.	0.50
Moisture	$\text{H}_2\text{O}$ - 105°C.	0.14
		<hr/> 101.57
	Less O=F	1.63
		<hr/> 99.94

x Calculated from total Fe;  
FeO not determined.

(Analyst:- W.H. Bennet, M.Sc., F.R.I.C.)

The pyrochlore occurs as brown, dark brown, reddish brown, yellow and grey octahedra, frequently modified by the partial development of dodecahedral faces. It is brittle with a conchoidal fracture, a somewhat indistinct octahedral cleavage and a vitreous or resinous

lustre, the latter on fresh fracture surfaces.

Hardness 5 - 5.5

Specific Gravity 4.2 - 4.36

There are eight molecules in the elementary cell and the Sukulu mineral is not metamict, as is normal in pyrochlore. The crystals vary in size from three-eighths of an inch to less than ten microns.

The minute orange-yellow octahedra observed in the rock and soil are believed to be pyrrhite, a niobate related to pyrochlore.

The overall average for pyrochlore in the sovite is in the neighbourhood of .2% but in some instances, particularly in the Hill B area, small samples containing as much as 10% have been found. It occurs as disseminated grains throughout the sovite but small lenses of magnetite have been found containing four or five per cent  $Nb_2O_5$ .

The pyrochlore-sovite dyke on Hill B contains 5% pyrochlore and it is possible that the extraction by calcination and air separation may be attempted. This presumes a sufficient demand for the lime produced.

The total niobium in the soil is in the region of 0.3%  $Nb_2O_5$  but the amount contained in the coarser fraction is considerably lower.

### Magnetite.

Iron-rich minerals constitute the major portion of the soil and the magnetite may, later, be the basis of an iron and steel industry. The mineral occurs as small fragments and crystals of the cubic system. Octahedra are the most common form but dodecahedral modifications are frequent. Generally the faces are striated parallel to the edge between the dodeca- and octahedral faces. It has a subconchoidal to uneven fracture and a metallic lustre.

Two analyses of bulk samples of the Sukulu magnetite are as follows:-

Fe <sub>2</sub> O <sub>3</sub> (total iron)	87.13	88.67
Al <sub>2</sub> O <sub>3</sub>	2.90	2.93
P <sub>2</sub> O <sub>5</sub>	3.40	1.80
TiO <sub>2</sub>	0.94	1.67
MnO	1.03	1.71
SiO <sub>2</sub>	1.35	0.85
CaO	3.70	1.48
MgO	0.20	0.20
Moisture	0.92	1.13
	<hr/>	<hr/>
	101.57	100.45
Less O <sub>2</sub> -Equiv. of FeO	1.71	1.42
	<hr/>	<hr/>
	99.86	99.03
	<hr/>	<hr/>

It will, therefore, be seen that this magnetite is a potential high grade, low titanium iron ore, suitable for steel manufacture in the basic open-hearth furnace.

A complication arises out of the fact that occluded within the magnetite are crystals of pyrochlore ranging in size from five to more than fifty microns and a sample assayed by L.C. Chadwick of the Imperial Institute, showed a (NbTa)<sub>2</sub>O<sub>5</sub> content of 0.15%. Small inclusions of apatite are also known to occur and probably account for the above average P<sub>2</sub>O<sub>5</sub> percentage. It is thought that light grinding would release the pyrochlore for recovery and eliminate the apatite. In any event, the iron ore would require sintering before smelting.

A minimum of four million tons is required for the establishment of a small iron and steel works at Sukulu and this amount has already been proved.

The possibility of the manufacture of such alloys as ferro-silicon, ferro-tungsten, ferro-niobium

and ferro-zirconium should be borne in mind.

Apatite.

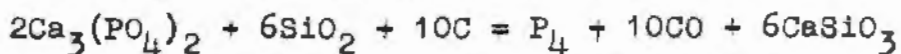
The phosphate-bearing mineral in the Sukulu soil is mainly fluor-apatite,  $(CaF)Ca_4(PO_4)_3$ . Even in the sövite the apatite occurs as anhedral egg-shaped grains. In the soil these oval or broken grains rarely attain a size greater than 60 mesh and are generally pitted and covered by a film of ferruginous material which can, however, easily be removed by light attrition scrubbing. A sample prepared in this fashion was analysed as follows:-

P <sub>2</sub> O <sub>5</sub>	.. .. .	39.85
CaO	.. .. .	53.82
F	.. .. .	3.08
Fe <sub>2</sub> O <sub>3</sub>	.. .. .	0.49
Al <sub>2</sub> O <sub>3</sub>	.. .. .	1.65
SiO <sub>2</sub>	.. .. .	1.37
Moisture	.. .. .	0.14
Ignition Loss	.. .. .	0.98
		<u>101.38</u>
Less O equiv. of F		<u>1.30</u>
		<u>100.08</u>

(Analyst:- L.C. Chadwick.)

This material is an extremely high-grade phosphate ore which, owing to its very low iron content, is well suited to the manufacture of super-phosphate by the sulphuric acid method. A complication arises out of the fact that this material has a limited solubility in sulphuric acid at normal operating temperatures, but in view of the vast amounts of cheap ore available this does not constitute a serious problem.

The apatite is also well suited to the manufacture of elemental phosphorus which is produced by the conversion of apatite in the presence of silica and carbon in an electric furnace. The essential reaction is:-



The reaction is completed at between  $1400^\circ\text{C}$ . and  $1500^\circ\text{C}$ ., the phosphorus distilling off and the calcium silicate forming a fluid slag.

Iron compounds present in the charge are converted to ferro-phosphorus containing about 70% iron and from 20% to 24% phosphorus. A minimum of three million tons of apatite is required for the establishment of this industry. This amount has already been proved in the North Valley where pyrochlore values are lower than elsewhere. Silica required for the charge is abundantly available, in the normal cotton soils of the area surrounding the Sukulu complex, in the sandstones of the Bulugwe series to the south east and in the bagasse ash from the sugar industry near Jinja.

#### Zirconiferous Minerals.

The presence of zircon in the heavy concentrates from the Sukulu soil was not suspected for some time after the discovery of the deposit, owing to the tendency for the prism faces to be absent or poorly developed. At first sight, this gives the zircon the appearance of being octahedral. The zircons occur as colourless, smoky or reddish crystals and are sometimes massed together as sugary aggregates of interpenetrating pyramids.

Baddeleyite,  $\text{ZrO}_2$ , first identified in the soil concentrates by Dr. Davies, is the more abundant zirconiferous mineral, particularly in the size grades less than 60 mesh. Baddeleyite occurs as tabular, monoclinic crystals, varying from colourless to yellow,

brown or black, with a high specific gravity of 5.5 - 5.6 . It is optically negative.

Baddeleyite constitutes the best known ore of zirconium and is in demand owing to its lower refining costs.

#### The Proving of the Deposit.

When once the decision had been made to proceed with the examination of the soil deposit, it fell to the author to design and execute a detailed programme of prospecting. This was carried out under the supervision of Dr. K.A. Davies.

The first stage in the proving of the deposit was the siting and drilling of four hundred Banka drill holes. The first line was sited with the holes 50 yds. apart around the perimeter of the limestone hills and into the soil filled embayments in the hills. A second line was sited in positions corresponding to those of the first but 50 yds further from the hills. In each case the boreholes were placed sufficiently far from the outcrop to ensure a minimum soil depth of 20 ft.

The holes were made with a 4" Banka set, using only the 4" spiral auger bit made up to 5 ft. in length with the short rod designed for this purpose. An additional three lengths of drilling rod of 5 ft. each were provided, thereby permitting the drilling of a 20 ft. borehole in four easily measured stages. Each drill was operated by a crew composed of four African porters and a drilling headman capable of keeping a written record.

Samples were taken at the end of each 5 ft. run. This produced a composite sample for the five feet of drilling, four such samples being taken in each borehole. The samples were placed in cotton sample bags which were indelibly labelled with the relevant data and despatched

to headquarters.

In Entebbe, the samples were carefully washed, the slimes removed and the clean residue subjected to magnetic separation. The non-magnetic fraction was then placed in hot aqua-regia and the final residue handed to the petrologist for examination and estimation of pyrochlore percentage after heavy media separation. This percentage was then re-calculated as pounds of pyrochlore per cubic yard. Throughout the headquarters procedure, accurate weighings were made at the end of each operation.

The figure of one ton, two hundred and sixteen pounds per cubic yard of soil was obtained by the removal and weighing of an accurately measured cubic yard.

The assay results of the first two lines of boreholes indicated an area of pyrochlore enrichment, often in excess of five pounds per cubic yard, extending from Hill C for two miles to the south. A further seven lines of boreholes were sited to cover this area. These holes were sited at 50 ft. centres.

Additional boreholes were sited in the South Valley bringing the total drilled to 1308.

In order to record permanently the position from which any particular sample was taken, each borehole was pinpointed individually on the 1:5,000 aerial photographs. A print laydown covering the whole of the area was made, using the enlarged air photographs and a tracing made of the sovite, soil, laterite and borehole positions. Prints made from this tracing serve as a useful background to the assay plan.

In all estimations of tonnage available, the soil lying in the West Valley has been neglected, owing to the occurrence there of radio-active minerals associated with barite. The presence of the latter mineral

involves a complication in ore-dressing technique which is considered to warrant a separate investigation. The radio-active deposit was located by the author, using a Cinema-Television rate-meter, Model No. 1011.

The soil deposit lies around the nine mile perimeter of the Sukulu Hills, with an average width of three hundred yards. The Banka borehole results show a minimum depth of 20 ft. throughout the major portion of this deposit, though in many places even on the perimeter, depths of from 60 ft. to 80 ft. have been recorded. A depth of seven yards may, therefore, be taken as a conservative estimate. The amount of soil contained in this strip is, thus, of the order of 36,500,000 long tons. Since the coarse sand fraction represents 37.3% of the total soil, there are estimated to be at least 13,600,000 long tons of this easily separated portion.

The coarse sand fraction is made up of 53.6% or 7,290,000 long tons of magnetite, 5,814,000 long tons of apatite and 0.5% or 68,000 long tons of pyrochlore. The remainder consists of baddeleyite, zircon and gangue minerals, mainly silica and feldspar.

#### Vermiculite.

The presence of vermiculite has been noted in a series of diamond drill holes in the fenite area. In radial borehole No. 3, a band of this material 45 ft. in width was traversed. The vermiculite is a weathered phlogopite occurring in small books which, on heating, exhibit a linear expansion of eight to ten times the original width along the C crystallographic axis. The mineral is associated with magnetite-apatite and unidentified weathered material.

In view of the extensive near-surface deposits of vermiculite of the Bukusu complex, it is unlikely

that the Sukulu material will be extracted in the near future.

### The Uganda Cement Industry.

A public utility company known as the Uganda Cement Industries has been established in order to manufacture cement from the sövites of Tororo and possibly Sukulu Hills. A £2,500,000 plant with an annual output of 60,000 tons has been erected at Sukulu.

The main difficulties to be overcome in the manufacture of cement from sövite are firstly, its normally high content of magnesia, phosphate and the iron oxides.

The sövites of the Tororo Lime Kiln Hill, however, have been found to carry 2%  $\text{mgO}$ , which is satisfactory for the manufacture of cement. The average for phosphorus-pentoxide content of the hill is 2%. In order to remove the phosphorus-bearing apatite, as well as the silicates, it has been necessary to incorporate in the cement factory a battery of kilns for the calcination of the limestone and a Sturtevant Cyclone air separator to extract the lime.

The presence of  $\text{P}_2\text{O}_5$  in the cement mix results in a lack of early strength in the finished product, owing to the formation of calcium-silico-phosphate, a compound with poor cementing qualities, in place of the normal calcium silicates which usually constitute the first formed compounds in setting cement. Even in cements with a high  $\text{P}_2\text{O}_5$  content, the cement gains in strength within the first ten days. The British Standard Specification for early strength cannot, however, be complied with unless the phosphate content of the raw material is less than 2%.

The argillaceous material also required for the cement process has been located close to the cement factory in the Malawa river basin.

Working the Deposit.

Since the deposit consists of an eluvial soil no great difficulty in mining is anticipated.

The main problem likely to arise is in the movement of heavy equipment during the periods of tropical rains. In order to keep the excavations in workable condition, it will be necessary to take advantage of the natural slope and drainage of the valleys.

A further complication affects the choice of excavating machinery. This arises from the fact that at various levels within the soil, laterites have been found by diamond drilling. The older laterites at deeper levels have to some extent been softened but some bands are quite hard and would form a serious obstacle to bucket-dredge equipment.

As the greater part of the deposit consists of valley-filling, it is likely that the heavier minerals such as pyrochlore and magnetite will be found in quantity nearest the hills forming their source, while the lighter apatite may well be more abundant in the deeper central parts. The breakdown of iron minerals and the dispersal of the fine limonitic material during deposition may well have enhanced the phosphate values at depth in the valley centres. This feature appears to be borne out by the preliminary assays.

Directly below the true soil is the residual material of the carbonate, weathered and leached in situ. This appears in drilling cores as a brownish yellow micaceous clay, rich in the accessory minerals of the

carbonatite. This is not likely to be workable and estimation of reserves should exclude this part of the deposit.

The disposal of slimes poses a further problem and it will be necessary to devise some means of damming these to prevent contamination of water supplies where these are drawn from local streams.

### Classification of Carbonatite Mineral Deposits.

The mineral deposits associated with carbonatite complexes may be classified briefly as follows:-

1. Ore minerals in the sövite. The sövite may be used as the source of CaO in the manufacture of cement, if satisfying the necessary conditions in respect of magnesia, phosphorus and iron.

At Alnö, the sövite is milled and used as a fertiliser rich in lime, iron and phosphate.

The dolomitic carbonates of Sukulu may later be used in the smelting of the magnetite.

In some cases, one of the normal accessory minerals of the sövite predominates to such an extent that its extraction proves to be an economic proposition.

At Sukulu, it may be possible to calcine the pyrochlore-bearing rock from Hill B and extract the niobium in an air separator. At Olefoss, Norway, sövites bearing 0.4% Nb<sub>2</sub>O<sub>5</sub> are dissolved in nitric acid, leaving a pyrochlore rich residue, the liquor being converted into a nitrogenous fertiliser.

At Alnö, plans are in hand for the separation of apatite from the sövite by a flotation technique.

Most of the complexes so far investigated in Africa, America and Scandinavia have been prospected for iron ore.

The carbonatites frequently contain small amounts of copper minerals. In some cases, as at Palabora, the concentration is such that the possibility of economic extraction has been considered. Urano-thorianite accompanies the copper at Palabora. In some complexes manganese minerals (Chilwa) and fluorite (Kalkveld) may form local segregations.

2. Ore minerals in the "fenite" area. Segregations of apatite, vermiculite, high- and low-titanium magnetic iron ore, perovskite and knopite are found to be associated with the pyroxenites of the Bukusu complex. Some or all of these minerals are found in the fenite areas at Sukulu, Tororo, Palabora, Iron Hill (Colorado) and Alnö.

The dunite found at Bukusu constitutes a possible source of MgO for the smelting of iron ore.

A strong possibility exists of the presence, in this part of the complexes, of the rare earth minerals.

3. The Basal and Lower Peripheral Zones of the Sövite.

In the more deeply eroded complexes the zone of carbonate close to the underlying nepheline syenite is revealed and a very considerable concentration of the rare earths is found. This is thought to be the case in the Mountain Pass occurrence where the Sulphide Queen ore-body (3116) may contain as much as 38% of rare earths. Bastnäsite and synchysite are the most likely minerals in this zone.

4. Eluvial Deposits. In addition to the large accumulation of magnetite, apatite, pyrochlore and baddeleyite at Sukulu, similar, though very much smaller, soil deposits have been recognised at Tororo, Napak, Toror and Chilwa.

5. Residual Deposits. Where calcium carbonate has been leached out of the sövites in situ, there is a corresponding accumulation above the unweathered carbonate, of the accessory minerals. At Busumbu Hill in the Bukusu complex, a series of ring dykes of apatite-sövite have been subjected to deep weathering, resulting in the removal of most of the calcium carbonate to a depth of nearly 200 ft.

Pits and adits at Busumbu show clearly the slump features to be expected in a residual deposit of this kind. The phosphate material may be ground and used as a fertiliser but owing to its low citric-solubility, is useful only for long term application. Its high iron content renders it unsuitable for the manufacture of sulphuric-superphosphate.

6. Secondary Deposits. Surface deposits of secondary phosphate rock, comprising frankelite and staffelite, have been recognised at Busumbu and Sukulu. At the former locality, the rock is quarried and transported to Kenya, where it is mixed with Magadi soda and fused to form soda-phosphate fertiliser.

7. Explosion Craters. The crater lakes of western Uganda and the Kenya Rift valleys constitute an important source of sodium salts which are extracted from a brine and sold locally.

8. Cone Materials. The weathering of the materials of the volcanic cones of Elgon, Kadam and Moroto produces a deep fertile soil rich in lime, iron and phosphate,

which is well suited to agricultural operations.

The weathered tuffs are cut as freestone blocks for use in building.

### Conclusion.

The Sukulu soil deposit constitutes a unique source of useful and strategic minerals and a major factor in the development of Uganda.

The increased use of niobium in jet and rocket engines and in surgical practice is likely to create a steady demand for pyrochlore and columbite. It is hoped that the Sukulu soil will materially assist in the satisfaction of this demand.

The establishment of an iron and steel industry will not only provide the East African territories with an independent source of pig-iron and steel products but should stimulate the development of secondary and light industries.

The production of cheap superphosphate fertilisers will permit the widespread improvement of Uganda's soils and crops, so necessary for the adequate nutrition of the rapidly expanding population.

It has been the responsibility of the Uganda Geological Survey Dept. and the Mineral Resources (Research) Committee to bring the investigation of the deposit to the pilot plant stage. Much work remains to be done, but it is with confidence that the deposit has been handed over to the operators.

While the author has been credited with the discovery of the Sukulu soil deposit (1953), he would like to stress that the individual minerals were found in the area by Dr. K.A. Davies several years earlier.

PART II

THE ORIGIN OF THE  
AFRICAN CARBONATITES.

PART II

TABLE OF CONTENTS.

INTRODUCTION .. .. .	56
ROCKS OF THE VOLCANIC CONE.. .. .	57
CLASSIFICATION OF COMPLEX TYPES .. .. .	68
<u>PETROGENESIS</u>	
Development of Ijolitic types .. .. .	71
Development of Melilite rocks .. .. .	73
Origin of Carbonatites.. .. .	74
The Mechanism of Carbonatite Formation..	76
The Source of Carbon dioxide .. .. .	82
The Geochemistry of Carbonatites .. .. .	84
Conclusions .. .. .	87
Acknowledgements .. .. .	93
References .. .. .	94

## INTRODUCTION.

The alkaline centres of eastern Africa constitute a distinct petrographic province and are clearly of similar origin, though they differ widely in age. The regional alignment of the various complexes from the Sudan to the Transvaal, closely approximates to the pattern of rifting, and it is probable that volcanic activity has accompanied the rifting and dates from the earliest movements. Du Toit (24, 1957) and Dixey (21, 1954) have stressed the periodic rejuvenation of rifting since the pre-Cambrian.

The petrographic unity of the various centres is maintained in spite of the diversity of the associated country rocks. The obvious consanguinity of the complexes renders it desirable that the members of the province should be considered as a whole rather than as separate entities, and any hypothesis put forward must be competent to explain all the observed phases.

Since the alkaline complexes differ considerably in age, they have been denuded to varying depths. This factor is of value in enabling the detailed examination, not only of the surface expression of the vulcanism, but also of deeper levels, extending to the roots of the associated hypabyssal complexes. The ages of the complexes vary from a dubious 1,400 million years for Palabora (35) to the present day at Ol Donyo L'Engai. In the east and central African zone most of the complexes are post-Karoo.

In any consideration of the nature and origin of the carbonatites, it is important to realise that the rocks exposed in a particular alkaline complex represent only part of the problem to be elucidated. The problem is essentially three-dimensional and the types present at various levels within the same complex are different, although linked both structurally and genetically.

The complexes in the following summaries occur in eastern and southern Africa.

	<u>Rock types present.</u>	<u>Structures.</u>
<u>Volcanics.</u>		
(1) Pyroclastics	Agglomerates predominant in volcanic succession. Fragments:- Nephelinites, ijolites Basement Complex. Crystal tuffs - augite & nepheline crystals Felspathic tuffs.	Partly eroded volcanic cone (3% left) on domed Basement platform dipping outward at 25°, dome 12 miles in diameter.  <u>Faulting</u> Radial & concentric <u>faulting</u> affecting cone.
(2) Lavas	<u>Lavas in their relative amounts.</u>	
	Phonolite	1
	Nephelinite (Leucocratic)	7
	Nephelinite (Mesocratic)	21
	Melanephelinite (Melanocratic)	30
	Olivine nephelinite	1
	Olivine melanephelinite	17
	Melilite-nephelinite	3
	Olivine-melilite-nephelinite	<u>1</u>
	Total	<u>81</u>
<u>Hypabyssal Zone.</u>		
Centre	Carbonatite comprising Calcitic } <u>Accessories</u> Dolomitic } types Apatite, magnetite Ankeritic } siderite, pyrochlore	Composite Stocklike body. Concentric cone & collar sheets with flow banding. Radial and arcuate faulting
Surrounded by	Composite ijolite rings.	
Other plugs and dykes.	Satellite agglomerate & lava plugs Dykes of melilite lamprophyres.	
<u>Country Rock.</u>	Basement Complex gneisses, schists and amphibolites.	<u>Age:</u> Late Tertiary

TOROR : EASTERN UGANDA. C. du Bois, Reconnaissance : B.C. King, C.E. Williams.

	<u>Rock types present.</u>	<u>Structures.</u>
<u>Volcanics.</u>		
(1) Pyroclastics	Cone remnants entirely agglomeratic Phonolitic & nephelinitic agglomerate fragments. Tuffs and ashes	Cone materials almost entirely removed.
(2) Lavas	No lavas have been found in the cone remnants	
<u>Hypsabyssal Zone.</u>		
	Central phonolitic agglomerate pierced by two pipes of tinguaitite. Centre surrounded by carbonatite ring dykes Nephelinite, trachyte & micro-foyaite dykes. Carbonatite consists of calcitic, dolomitic and ankeritic types.	Composite stock-like body    Radial faulting
<u>Satellite.</u>	Theno : carbonatite plug.	
<u>Wall Rock.</u>	Basement Complex, gneisses and schists.	

CHILWA ISLAND : NYASALAND. Dixey, Campbell-Smith & Bisset, Garson & Campbell-Smith.

Rock types present.

Structures.

Volcanics.

Absent

Erosion to below original land surface level.

Hypabyssal Zone.

Central carbonatites consisting of calcitic, dolomitic, ankeritic and sideritic types.

Flow structures in carbonatite.

Nepheline syenite, juvite, foyaite, phonolite, micro-foyaite.

Ring dykes, tangential dykes, cone & collar sheets

Trachyte, solvsbergite, felspathic breccias.

Radial & arcuate faulting

Ijolite, nephelinite, lamprophyre. Dolerite & basalt.

Carbonatite accessories: Siderite, apatite, feldspar, mica, pyrochlore, synchysite, fluorite, magnetite, pyrite, quartz, manganese, barium, and strontium carbonates, barite, acmite.

Satellite.

Marongwe Hill, Carbonatite, trachyte, microfoyaite, phonolite, dolerite.

Country Rock.

Gneisses, granulites, graphite-bearing limestones of Basement Complex.

Complexes in area.

Tundulu hill : Carbonatites, breccias, tinguaite, dolerites

Songwe hill : Carbonatites, breccias, nepheline syenites, Dolerites.

Age : Mesozoic

KALKVELD.

ONDURA KORUME. OTJIWARONGO, S.W.A.

C.A.Key (12)

Rock types present.

Structure.

Volcanics. Nil

Ring Complex.

Hypabyssal. Well exposed.

Centre carbonatite.

Carbonatites: Calcitic In order  
Dolomitic of  
Sideritic emplacement

Pronounced "flow" structure  
Ring dykes, tangential  
abberation.

Earliest carbonatite shows papillae  
indicating possible gas fluxion  
structures.

Accessories: Magnetite, apatite, mica,  
columbite, ilmeneo-rutile lens,  
sovite breccia, fenite breccia.

Radial tinguaitite dyke-  
vertical.

Limited zone of fenitisation, replacement of  
quartz by green amphibole.

Foyaite and tinguaitite.

Foyaite ring dyke, poss.  
cone sheets

Small olivine basalt dyke.

Dyke vertical, ring dyke  
segment.

Basaltic dyke radial.

Greater facility of intru-  
sion in marble zone than  
in gneisses, hence  
eccentricity.

Country Rock. Damara system : Schists, gneisses, graphite  
and marble

Study of trace elements  
shows no Ba, Sr in  
marbles.

Age: Post-Damara.

MT. ELGON : EASTERN UGANDA. H.Odman(17 ), K.A.Davies( 3 ), C.Williams (1949) : recon-  
aissance

<u>Volcanics.</u>	<u>Rock types present.</u>	<u>Structures.</u>
(1) Pyroclastics	Agglomerates constitute over	Low angle volcanic cone 60 miles in diameter. Radial fractures affecting cone. Evidence of caldera collapse.
(2) Lavas	Trachytes, trachyandesite. Phonolites Nephelinites dominant flow type. Melanephelinites, melilite nephelinites. Tannbuschites, ankaratrites. Melilite-ankaratrites, melilite- nepheline-basalt. Basaltic Group. (Odman).	
<u>Hypabyssal Zone</u>	Only partly exposed. Dykes of ijolite pegmatite, bergalite,alnoite.	Some evidence of prevolcanic doming and post-volcanic collapse.
<u>Satellite.</u>	Budeda complex - crush syenites, fenites, cancrinite syenite.	
<u>Country Rocks.</u>	Northern Part : Basement Complex. Gneisses, schists & amphibolites.	

Age : Miocene.

MBEYA CARBONATITE : PANDA HILL, Rukwa Trough, Tanganyika. Fawley & James (1955).

	<u>Rock types present.</u>	<u>Structures.</u>
<u>Volcanics.</u>	Tuffs & agglomerates (unnamed)	Complex poorly exposed.
<u>Hypabyssal Zone.</u>	Carbonatite rich in pyrochlore. Calcitic, dolomitic, ankeritic.	Central carbonate plug & outer ring of carbonatite surrounding it Flow structures indicate plastic deformation during emplacement. Large fault filled with travertine cuts central plug.
<u>Fenites.</u>	Explosion breccias with fragments of gneiss surrounded by ferruginous carbonatite. The gneisses & tuffs have suffered metasomatism & carbonitisation.	Breccias occur in small dykes & subcircular vents.
<u>Country Rock.</u>	Pre-Cambrian gneisses and Cretaceous sandstones.	

Age : Jurassic?

N.B. OLDONYO L'ENGAI : Eastern Rift, Tanganyika. Erdsmannsdorffer (1935), Hopley (1917), James (1956).

Rock types present.

Structure.

Volcanics.

Pyroclastics: Agglomerates & tuffs  
Ejected blocks: Biotite-hornblendite  
Olivine-biotite-pyroxenite  
Melteigite, ijolite, malignite  
Wollastonite-apatite-pyroxenite  
Direct emission of sodic vapours  
Calcium & sodium carbonate bombs  
ejected.

Intermittently active  
volcanic pile.

Lavas: Mainly nephelinite with  
subsidiary phonolites.

CHISHANYA: Sabi, S.Rhodesia. Swift (1952)

Hypabyssal Zone. Central carbonatite with concentrations  
of magnetite and apatite.  
Nepheline syenites.  
Mafic & felsic nepheline-bearing rock  
and carbonatites occur outside plug area.

Volcanic neck

Fenites. Altered pre-Cambrian granite.

Age : Post Karroo?

MUAMBE : Mozambique. Dixey, Campbell-Smith & Bisset (1935)

Hypabyssal Zone. Central carbonatite with local enrichment  
in iron and manganese.  
Agglomerate neck  
Younger dykes of nephelinite & phonolite

Basin-shaped craterlike  
depression with central  
plug

Country rock. Karroo sandstone

Age : Mesozoic?

NKUM BWA ISOKA : N. Rhodesia. Reeve & Deans (1954). Deans & McConnell (1955).

Rock types present.

Structure.

Volcanics.

Absent.

Poorly exposed ring structure.

Hypabyssal Zone.

Central carbonatite plug  
Mainly ankeritic dolomite  
with pyrochlore, monazite isokite  
Magnetite and apatite

Fenites.

Complex surrounded by fenitised  
Basement gneisses.

SHAWA, Sabi, S. Rhodesia.

Mennell (1946).

Volcanics.

Absent.

Hypabyssal Zone.

Central carbonatite with  
magnetite and apatite.  
Biotite-pyroxenite, jacupirangite  
ijolite, syenite.

Fenites.

Altered pre-Cambrian rocks

Age : Mesozoic?

DOROWA : Sabi.

Mennell (1946).

Hypabyssal Zone.

Central carbonatite

surrounded by

biotite-pyroxenite, shonkinite  
malignite.

Age : Mesozoic.

KALKVELD - EISENBERG. OTJIWARONGO South West Africa. From field notes E.S.W.Simpson(1953)

	<u>Rock types present</u>	<u>Structures.</u>
<u>Volcanics.</u>	Absent	
<u>Hypabyssal Zone.</u>	Central iron-rich core Surrounding carbonatite with iron ore Veins of iron ore & felspar "schlieren"  Carbonatite surrounded by syenite with acicular amphibole Porphyritic tinguaite occur near perimeter. Dolerite dyke.	Foliation visible
<u>Country Rock.</u>	Damara schist and marble	
<u>Other complexes in area.</u>	<u>Honerub</u> - cancrinite syenites, phonolite. <u>Paresis</u> - Agglomerates and lavas <u>Okurusu</u> - Carbonate rock, fluorite veins foyaite, syenite.	

Age : Post-Damara

SPITSKOP, Sekukuniland, Eastern Transvaal

A.L.Hall (1910), H.A.Brouwer (1917),  
S.J.Shand (1921), Strauss & Truter (1950)

Rock types present

Structures.

Volcanics.

Alkali basalt plugs are only clue to  
vulcanicity.

Hypabyssal Zone.

Eccentric carbonatite core, calcitic  
dolomitic & ankeritic types.  
Surrounded by: coarse carbonatite,  
melteigite, jacupirangite, ijolite,  
urtite, biotite-pyroxenite & theralite.

Carbonatite flow structures dip  
outwards. Coarse carbonatite  
ring dyke around central plug.  
Roughly concentric sheeted  
structure.

Two big ring dykes of foyaite and  
numerous cone sheets.

Foyaite ring dykes & cone sheets  
arise from below carbonatite  
plug.

Radial dykes of foyaite, tinguaitite,  
dolerite and lestiwarite.

Biotite-pyroxenite poorly  
exposed, interpreted as  
stocklike body.

Fenites.

Red & white umptekites & pulaskite.

Country rock.

Bushveld granite & granophyre.

Satellite.

Magnet Heights: Carbonatite, peridotite,  
ariegite, albitite.

Age: Post-Bushveld.

MESSUM IGNEOUS COMPLEX. South West Africa. Korn H. & Martin H. (1954); Mathias M. (1956)  
C. Williams : visit 1947.

	<u>Rock types present.</u>	<u>Structures.</u>
<u>Volcanics.</u>	<u>Basic lavas &amp; dykes.</u> (a) Non-phyric basalts (b) Felspar-phyric basalts. (c) Tholeiitic basalt (d) Bronzite basalts <u>Acid lavas &amp; pyroclasts</u> Altered microgranophyres & microgranites	Relict volcanic cone with cauldron subsidence and radial fractures. Interbedded sediments present.
<u>Hypabyssal Zone.</u>	Eucrites, anorthosites gabbros, pyroxene granulites. Microgranites & granophyres Aplogranites Alkaline phase: Tinguaites & Syenite- porphyries Foyaite. Nephelinites, olivine tephrites	Layered complex with centri- petal dip.  With inner fault ring
<u>Fenites.</u>	Melanocratic fenites : basaltic hybrids Leucocratic fenites : foyaite fenites & syenite fenites. Rheomorphic fenites Carbonatite vein	Zone surrounding foyaite body.
<u>Country Rock.</u>	Damara schists & marbles.	

Age of Complex - Post Damara. Karroo?



HOMA MOUNTAIN: KAVIRONDO GULF, Kenya. Pulfrey (1949), Shackleton (1951), Saggerson(1952).

Rock types present.

Structures.

Volcanics.

Pyroclastics : Tuffs & agglomerates  
Lavas : Nephelinites & phonolites

Remnants of volcanic cone.

Hypabyssal Zone.

Massive carbonatite & sovite breccia,  
several subsidiary vents with carbonate  
rock.  
Nepheline-rich plug rock contains  
dykes of sovite breccia.

Country Rock.

Precambrian

Age ; Late Tertiary.

RANGWE. KISINGIRI MOUNTAIN, Kavirondo Gulf, Kenya.

Pulfrey (1949), Shackleton (1951).

Volcanics.

Tuffs & agglomerates.  
Flows, dykes & plugs of  
nephelinite & phonolite.

Volcanic cone

Hypabyssal Zone.

Central carbonatite with  
breccias. (No details).

Age: Miocene (fossils)

RURI MOUNTAIN : KAVIRONDO GULF, Kenya.

Pulfrey,(1949), Shackleton (1917) .

Central Carbonatite (no detail)

Volcanic cone.

Age : Tertiary?

MOROTO MOUNTAIN: Karamoja, Uganda.

C.B. Bisset, C.E. Williams ; visits.

Volcanics.

Rock types present.

Mainly pyroclastics - tuffs and agglomerates. Pyroxene tuffs, Lavas . Nephelinites & phonolites.

Structures.

Remnant of volcanic cone

Age: Tertiary?

BUKUSU COMPLEX : Eastern Uganda.

K.A. Davies (1947, 1956).

Volcanics.

Not present.

Hypabyssal Zone.

Central Carbonatite  
Carbonatite ring dyke segments

Deeply weathered in parts  
Poorly exposed.  
Some flow structure recognised.  
Outer carbonatite in arcuate fault zone.  
Concentric ring structure

Centre surrounded by : Ijolite  
malignites, foyaites & Urtites  
Biotite-pyroxenites, pyroxenites  
hornblendites.  
Apatite-magnetite-vermiculite rock  
Dunite

Fenites.

Introduction of amphibole in shattered wall rock.

Country Rock.

Basement granites

Age : Late Tertiary.

KADAM MOUNTAIN: Karamoja, Uganda.

C.E. Williams : visit.

Volcanics. Rock types present.  
Mainly nephelinitic agglomerates  
and tuffs  
Lavas: Nephelinites, phonolites &  
some ankaratrites.  
Subsidiary nephelinite plugs

Structures.

Radial faults, collapse  
structures.  
On domed Basement platform

Age: Tertiary?

MRIMA HILL, Jombo, Kenya.

Baker (1953)

Volcanics. Agglomerate vents : mafic and  
felsic nepheline-bearing types.

Laterite cover in parts

Hypabyssal Zone Veinlike mass of pyrochlore-  
bearing carbonatite.

Related to Jombo alkaline complex

Country rock. Mesozoic sediments

Age : Tertiary?

KERIMASI : Gregory Rift Valley, Tanganyika.

James (1956).

Volcanics. Stratified tuffs and agglomerates  
mainly nephelinite.  
Carbonatite fragments  
Carbonatite exposed in crater  
Bedded limestone with angular  
carbonate fragments on slopes

Volcanic cone.

Age : Recent.

In considering the genesis of carbonatite complexes, it is necessary to study them against the broader background of the volcanoes in which they were produced and of which they form a relatively insignificant portion. The cones of these volcanoes provide the clues to the genesis of the carbonatites, and for this reason details of Napak and Elgon are given here. The data is drawn from the Elgon and Napak Memoirs of the Uganda Geological Survey and from the author's own examination of the rock collections and slides from these two complexes.

THE ROCKS OF THE VOLCANIC CONE.

NAPAK.

Classification of the Pyroclastic Rocks (After B.C.King).

	Composition	Occurrence
Agglomerates  and Breccias	Matrix of volcanic material including calcite & zeolite cement and veins.  Fragments of: (a) Lavas (b) Ijolites (c) Basement Complex (d) Earlier Tuffs & Agglomerates. (e) Sediments.	Ubiquitous; the predominant type in the volcanic succession.
Common Types:		
1. Lava Fragment type.		
2. Polygenetic type.		
Special Types:		
1. Ijolite type of Morualorogai		
2. Type with large boulders of Basement rocks of Moruita & Lotuk.		
Lava-Breccias	Angular fragments of lava closely cemented with zeolites and calcite	At various horizons; much as lava flows. Not common.

---

Ashes	Fine volcanic material, more or less cemented by calcites and zeolites.	Lower levels of volcanic succession; particularly the outer flanks of the volcano.
Tuffs		
and	Some sedimentary material in lower horizons	Interbedded with sediments.
Grits	Shards of lava, Basement Complex & crystal fragments (pyroxene): grading into agglomerate.	

---

Special Types:

1. Crystal Tuffs
  2. Felspathic ashes & Tuffs of Lokeru
- 

Petrography of the Napak Pyroclastics.

The matrix of the agglomerates, tuffs and ashes consists of fine volcanic dust assumed to be essentially the same as the larger fragments. Calcite, natrolite and other zeolites are present in varying amounts and in some cases the matrix has been impregnated or entirely replaced by calcite. The calcite occurs in two generations: a fine granular variety which replaces the matrix and forms zoned concentrations around small fragments of pyroxene, and a coarser, clearer calcite occurring in veins and amygdales.

The fragments in the agglomerates are characterised by considerable secondary replacement.

Nepheline is replaced by natrolite, chlorite and calcite. Limonitic staining is common.

Pyroxene is usually unaltered but sometimes changes to amphibole needles, chlorite, calcite and secondary ores.

Biotite alters to chlorite, calcite and epidote.

Melilite alters to chlorite or calcite.

Olivine alters to iddingsite or serpentine.

Ore Minerals are usually altered to limonite or leucoxene.

- (a) Lava Fragments. Representatives of all the principal lavas occurring as flows are found amongst the fragments in the agglomerates.
- (b) Ijolite Fragments. Fragments ranging from nepheline rock to aegirine-augite rock are found in the agglomerates.
- (c) Fragments of the Basement Complex. Felspathic granulites and granite gneiss composed of oligoclase, orthoclase and quartz with accessory garnet, biotite and diopside occur as fragments in the agglomerates.
- (d) Crystal Fragments. Angular crystal fragments including quartz, feldspars, biotite, hornblende, apatite and abundant pyroxene and nepheline also occur in the agglomerates.
- (e) Fragments of pre-existing agglomerates, ashes and sediments are numerous and widespread.

#### ELGON.

Pyroclastic materials form by far the greater proportion of the mountain and fall within three classes:-

(1) Felspar Tuffs. These occur mainly at an early stage in the volcanic history. They are usually micro-crystalline and often contain iron ore, apatite and ferro-magnesian minerals. They are cemented by a felspathic material and are often replaced by calcite and zeolites. The felspar is usually orthoclase, though sodic varieties are sometimes present.

(2) Tuffs and Agglomerates of the Undersaturated Rocks. These constitute by far the greater part of the mountain. Volcanic bombs and lapillae are common. The rock fragments and minerals are mainly derived from nephelinites, phonolites and, rarely, basic lava types. Ijolites, pyroxenites, biotite-pyroxenites, jacupirangite and carbonatite are also common in the agglomerates. Recently, pyrochlore-bearing carbonatite and calcareous tuffs have been found near the base of the succession.

(3) Crystal Tuffs. Rarely, crystal tuffs composed entirely of whole or broken crystals cemented by calcite or zeolite are found. Those recorded consist mainly of pyroxenes.

#### Mud Flows.

Beds containing boulders of up to 20 ft. or more across occur early in the succession. The boulders consist

mainly of granites with some crystalline limestone, schists and dolerites cemented by easily weathered volcanic material. These beds are considered to be mud flows of wet lahar and "Glutwolke" lahar types.

THE LAVAS.

NAPAK.

B.C. King estimates that of the total bulk of the volcanic material at Napak, not more than three per cent consists of lava flows.

A general classification of the lavas in the Napak area is given in the following table:-

<u>Saturated Lavas:</u>		<u>Characteristic Minerals:</u>	
<u>Group I:</u> "Andesite".		Plagioclase: non-porphyrific.	
<u>Undersaturated Lavas:</u>		<u>Characteristic Minerals:</u>	
	Nephelinite	Nepheline dominant	Olivine absent
<u>Group IIA.</u>	Melanephelinite	Pyroxene dominant	Olivine absent
Melilite	Olivine-nephelinite	Nepheline dominant	Olivine present.
absent	B. Olivine-melanephelinite.	Pyroxene dominant	
<u>Group IIIA.</u>	Melilite-Nephelinite	Melilite, nepheline	Olivine absent.
Melilite		pyroxene.	Olivine present.
present.	B. Olivine-melilite-nephelinite.	Ditto	

Relative Abundance & Distribution of the Various Lava Types.

Andesite ... ..	1
Nephelinite (leucocratic)... ..	7
Nephelinite (mesocratic) ... ..	21
Melanephelinite (melanocratic)... ..	30
Olivine-nephelinite ... ..	1
Olivine-melanephelinite ... ..	17
Melilite-nephelinite ... ..	3
Olivine-melilite-nephelinite ... ..	1
Total.....	<u>81</u>

Group I : "Andesite" (Napak type)

A single flow of rock of approximately andesitic composition has been observed as one of the first episodes in the history of Napak. It consists principally of plagioclase and iron ore, with some chlorite but no pyroxene. The plagioclase occurs as phenocrysts and as tiny laths in the matrix. It is a sodic andesine and the larger crystals commonly show zoning to more sodic margins. Amygdales are present containing a mosaic of quartz crystals showing strained extinction. The rock is notable for its high  $\text{Na}_2\text{O} : \text{K}_2\text{O}$  ratio, high iron and relatively high lime content.

Group II : A. Nephelinite and Melanephelinite.

These are extrusive rocks consisting of essential nepheline and pyroxene without olivine. They are characteristically felspar-free, but ore minerals are essential constituents. Nephelinite is defined as having dominant nepheline, and melanephelinite, dominant pyroxene.

Nepheline: In the nephelinites, nepheline forms almost perfect euhedral crystals. Even in the matrix, nepheline shows a strong tendency to assume regular outlines so that there is a wide range of sizes. The refractive indices indicate a content of up to 20% of the kaliophilite molecule.

Pyroxene: The pyroxene phenocrysts are stumpy subhedral crystals of a pale green, slightly pleochroic variety. Poikilitic crystals of pyroxene, enclosing nepheline and ores occur in the coarser-grained lavas. Pyroxene ranges from diopside to aegirine-augite. There is normally only a small percentage of the aegirine molecule. Zoning is a strong feature.

Iron Ores: Magnetite and ilmenite occur abundantly in the lavas, particularly in the melanephelinites.

Biotite: In only a few lavas does biotite appear to be a normal constituent, in others the biotite occurs in clumps, suggesting its derivation from xenolithic material.

Amphibole: In lavas showing deuteric alteration, actinolite appears as a secondary mineral after aegirine-augite.

Accessory Minerals: Apatite, calcite and perovskite occur in addition to the iron ores.

### Order of Crystallisation.

The pyroxene usually crystallised first, but the determining factor was the predominance in the magma at the time of crystallisation of the constituent of one or other of the two minerals. In a nepheline-rich fraction, nepheline starts crystallising at an early stage. In the matrix, except in those lavas which were nepheline-poor, both minerals crystallised together; iron ores formed fairly early.

### Group II : B. Olivine-nephelinite & Olivine-melanephelinite.

The rocks in this group are similar to those in the nephelinite and melanephelinite group, except for the presence of varying amounts of olivine. As pointed out by B.C. King, the two major points of difference between groups A. and B. are, firstly, that the pyroxenes in group B. are of the paler variety, in fact definitely diopsidic, and secondly that the olivine lavas, which also bear porphyritic nepheline, are extremely rare. The only olivine-nephelinite seen contained very little olivine.

It will be seen later that these points are of great importance in the elucidation of the genesis of these rocks.

### Group III : A. & B. Melilite-nephelinite & Olivine-melilite-nephelinite.

Melilite-bearing lavas are rather rare and are generally of fine grain or carry only sparse small phenocrysts.

#### A. Melilite-nephelinite: olivine absent.

- (i) Nephelinite and melilite with subordinate aegirine-augite. The phenocrysts are sparse aegirine-augite and small euhedra of nepheline. The matrix is composed of nepheline and numerous tiny laths of melilite in a dusty background of ores, nepheline and pyroxene.
- (ii) Pyroxene and melilite: porphyritic texture. Pale green diopside occurs as phenocrysts in a dusty matrix of ores, nepheline and pyroxene, amongst which are numerous tiny laths of melilite.

(iii) Melilite, pyroxene and nepheline : non-porphyrritic texture.

The melilite forms abundant laths of up to 2 mm. in length. Some euhedra of nepheline occur, and the interstices between these minerals are occupied by diopside, nepheline and ores.

B. Olivine-melilite-nephelinite. Olivine present. Pale green diopside forms the majority of the phenocrysts, together with sparing olivine in a dusty matrix of ores, pyroxene, nepheline and sparse melilite laths.

ELGON.

MOUNT ELGON : LAVA TYPES. (After K.A. Davies)

Feldspars +	Feldspar +	Nepheline +	Nepheline +	Nepheline +	Nepheline +
Pyroxene	Nepheline +	Pyroxene	Melilite +	Pyroxene +	Melilite +
	Pyroxene		Pyroxene	Olivine	Pyroxene +
					Olivine
Trachytes Trachy- andesites Trachyte- andesite (Johannsen)	Phonolites	Nephel- inites  Melaneph- elinites	Melilite- Nephelin- ites	(Nepheline- basalt, Johannsen) Olivine- nephelinite  Ankara- trite Tannbusch- ite	Melilite- nepheline- basalt. (Johannsen)  Melilite- Ankaratrite

Amongst the first lavas poured out from Elgon is a series of trachytic types. A fairly complete gradation from saturated to undersaturated types is also present.

The trachytic rocks are represented by:-

- (1) Anorthoclase Trachyte containing orthoclase rimmed by more potassic material. Albite occurs as phenocrysts as well as in the ground mass. Perthite occurs as phenocrysts in place of the other sodic varieties. A small percentage of ferro-magnesian is present consisting of chlorite, green-brown biotite and fine needles and prisms of pyroxene. A small amount of ilmenite is present.
- (1i) Trachyandesite. This rock consists of andesine-orthoclase and anorthoclase, hornblende, pyroxene and iron ore with accessory apatite, sphene and calcite.

The phonolitic-trachytes and related rocks form a link between the trachytes and the phonolites of Elgon proper.

- (a) Phonolitic trachytes. Sanidine phenocrysts occur in a felt of microlites, the interstices being filled with decomposition products and a cryptocrystalline feldspathic material. Chlorite and pyrite occur in the ground mass. Pyroxene occurs as needle-like inclusions in the feldspar and a little decomposed nepheline is present.
- (b) A second type is rather similar but shows a more marked fluxion structure and contains about 4% pyroxene.
- (c) Trachytoid Phonolite. This rock is similar to (b) but has a good deal more ferro-magnesian mineral and a fair amount of decomposed nepheline. The feldspars are soda-sanidine.
- (d) Phonolite. This rock is again similar to the previous varieties but contains 15% - 20% of broken-down nepheline. Biotite and a little analcite occur as well as needles and prisms of pyroxene. Pyrite is present.

Phonolites. (of Elgon proper).

Most of the phonolites are aphanitic rocks with only occasional phenocrysts of feldspar and nepheline. A

few of the melanocratic types carry phenocrysts of pyroxene. These rocks lie on and around the foot of the mountain and are confined mainly to the lower parts. They occur as flows of considerable size.

The transitional nature of the Elgon rocks is well exhibited in the phonolite and the rocks described include specimens which possess less than 5% of felspar as well as those containing up to 70% of this mineral.

The minerals of the phonolites are as follows:-

Nepheline: This mineral usually occurs as euhedra and is commonly zoned, suggesting a kaliophilite mixture in the outer zones. Inclusions of pyroxene and iron ore are seen within the nepheline.

Felspars: These are usually sanidine or orthoclase. It is important to note that in one instance a sodic rim was found to surround a more potassic centre, usually the position is reversed. Crypto-perthite and albite occur with a little anorthoclase.

Pyroxene: This mineral occurs as prisms, laths and plates, often with irregular terminations. It is usually a medium green in colour with lighter crystals sometimes occurring, and the depth of colour varying markedly in zoned crystals.

Biotite: This mineral occurs as single crystals surrounded by rims of pyroxene.

Barkevikite: Brown hornblende showing marked pleochroism occurs and has been identified as barkevikite.

Accessory Minerals: Sphene and apatite are of frequent occurrence and limonite and pyrite have been noted. A feature of these rocks is the occurrence of zircon.

#### The Nephelinites and Melanephelinites.

These rocks make up just half of the flows mapped by K.A. Davies. They vary widely and often grade into the phonolites. Over half the specimens collected were melanephelinites and the majority contain from 20% to 80% nepheline. The ferro-magnesian minerals vary from 10% - 90%. Odman (1970) has stressed the frequency of these types around the main vent in the Alpine region.

The following minerals are found in this group:-

Nepheline: The crystals are invariably euhedral except as the rock becomes coarser where the outlines are lost. Inclusions of magnetite and rimming by dusty magnetite

inclusions are common. Some included pyroxene also occurs and colours the nepheline. Occasional zoning is present.

Pyroxenes: These are mainly diopsidic in type, though occasionally aegirine-augite is present. Zoning is sometimes common and the tendency is for the colour to increase outwards, though occasionally the reverse is true. In some cases titaniferous augite is present. The pyroxene is seldom euhedral.

Barkevikite: This occurs as resorbed crystals or as euhedral crystals in biotite. It is often bordered by dark pyroxene.

Biotite: This mineral is present in small amounts generally secondary after pyroxene.

Apatite: This occurs in fair quantities and the crystals are invariably filled with inclusions of magnetite.

Iron Ores: These may constitute up to 15% of the rock in the melanocratic varieties. Magnetite and ilmenite are plentiful and pyrite has been seen.

Accessory Minerals: Perovskite is common and a little sphene occurs in some specimens. Titaniferous garnet is of rare occurrence.

Melilite, feldspar and olivine occur in varying proportions to form links with the melilite-nephelinites, phonolites and olivine-nephelinites.

#### The Melilite-Nephelinites.

These are transitional types showing wide variation in the amounts of the essential minerals. They are distinguished from the nephelinites by the presence of melilite and from the melilite-ankaratrites and the tannbuschites by the lack of olivine. The texture varies from porphyritic to aphanitic but sometimes fluidity is marked by the alignment of melilite.

Melilite: These crystals occur as rectangles up to 3.5 mm. in length, invariably possessing a median crack; peg structure is rare. Occasionally they contain rounded inclusions of nepheline and pyroxene.

Nepheline: Once again, crystals are invariably euhedral and show zoning and patches of inclusions such as perovskite, rutile and long, needle-like, transparent crystals.

Pyroxenes: The colour of the pyroxenes is usually pale yellow or grey-green, though sometimes blue-green aegirine occurs. The borders of the pyroxene are often picked out by lines of iron ore.

Biotite: This mineral may constitute up to 10% of the rock and sometimes gives place to chlorite.

Accessory Minerals: Iron ore is the most common of the remaining minerals and may form up to 15% of the rock. All specimens contain at least 5%.

Apatite with dusty inclusions of iron ore is abundant, as is perovskite.

### Tannbuschites and Ankaratrites.

These are very melanocratic lavas which vary in grain from those which are almost entirely aphanitic to those in which pyroxene especially and olivine rarely occur as phenocrysts. In no case do ferro-magnesian minerals form less than 50% of the whole. These rocks are of very limited occurrence.

Nepheline: This mineral is rarely prominent and is found as anhedral crystals in the interstices between the pyroxenes. It is sometimes present in two generations.

Pyroxene: In thin section this mineral is pale yellow-green or grey-green and occurs both as large euhedral phenocrysts and as fine micro-crystalline needles in the interstices. Oscillatory zoning is a common feature. Some crystals possess a pale centre passing to a darker rim, while in others the position is reversed.

Olivine: Large crystals of olivine are sometimes present and are usually magnesian. Sometimes crystals are zoned.

Biotite: This occasionally occurs after olivine.

Apatite: This usually forms inclusions in the pyroxene but perovskite is more frequent.

Iron Ore: Plentiful ilmenite and rarer magnetite may form up to 15% of the rock. They occur from a dust up to crystals 2 mm. across and are sometimes euhedral.

Melilite-Ankaratrite and Melilite-Nepheline-Basalt.

Several flows contain melilite in addition to nepheline, pyroxene and olivine and these have been called melilite-ankaratrite where ferro-magnesian minerals are dominant, and melilite-nepheline-basalt where nepheline and melilite form more than half the rock.

Nepheline: This mineral is rarely prominent and completed its crystallisation only slightly later than the pyroxene.

Melilite: The melilite is similar to that described earlier and sub-parallel laths give some of the rocks a fluidal texture.

Pyroxene: It is a pale, yellow-green magnesian diopside with occasional purple titaniferous borders. Where zoning and twinning are noticeable, pale cores are common. Inclusions of nepheline and olivine occur round the edges of the crystals.

Olivine: This is a magnesian olivine occurring in both euhedral and anhedral crystals, often replaced by biotite.

Biotite: This occurs occasionally and is of later formation than the nepheline.

Accessory Minerals: Small quantities of apatite are present while perovskite is common. Titaniferous iron ore may make up 7% - 10% of the rock.

The rocks of the cone form the major part of volcanoes producing carbonatite. Consequently it is of the greatest importance to explain the genesis of these rocks as well as that of the carbonatites.

The complexes in the foregoing summaries may be divided into several groups which are related both structurally and petrologically.

1. Elgon type volcanoes. These consist dominantly of an alkaline volcanic cone. The cone material is mainly agglomeratic and the most common lava is nephelinitic.

Elgon itself, being the youngest, is least dissected and very little evidence is available as to the nature of its hypabyssal complex. Some idea of this zone may be gained from a study of the materials ejected from the vent. Probably the most important is the fact that carbonatites have at various stages throughout the life of the volcano occupied the vent and been ejected.

Crystal tuffs consisting of pure pyroxene, feldspars or nephelines are also quite common.

The presence of rare peralkaline lavas is also recorded, and at Elgon dissection has also revealed the presence of a stock of peralkaline syenites within the cone.

Kadam and Moroto belong to this group. Of similar type too, are the volcanics of the Kavirondo Rift Valley in western Kenya (20.73), where a sequence of phonolites, nephelinites and trachytes are found in association with tuffs and agglomerates. The pyroclastic sediments include coarse pyroxenic tuffs and agglomerates containing nephelinite and angular carbonatite fragments. Bedded limestones consisting of finely comminuted carbonatite are ubiquitous. The vents in this province also produced augite-rich nephelinites, nepheline basalt, olivine basalt, tephrite and melillite-bearing types. The centres in this area are so close together that their cones appear to have overlapped.

2. The Napak type. This type consists of an Elgon type cone dissected sufficiently to reveal a central hypabyssal complex. The two members of this group are Napak (10.194) and Toror (2.173) but the group might be extended to include Sukulu if the volcanics there do in fact belong to that complex. This is, however, open to debate. The hypabyssal complexes at both Napak and Toror consist of carbonatite in association with alkaline or peralkaline rocks.

Fluxion structures indicate that the carbonatite was emplaced in a relatively plastic condition and was capable of invading and digesting the wall rock.

3. The Sukulu-Spitskop Type. This group embraces most of the complexes in which carbonatite occupies the central conduit. They are characterised by the presence of peralkaline types, dominantly foyaitic though sometimes trachytic. They invariably show signs of reaction with the wall rock and hydrothermal emplacement of coarse, hydrous minerals into the reaction zone. In this zone are found the olivine-biotite pyroxenites, apatite pyroxenites and phlogopite(vermiculite)-apatite-magnetite rocks.

The main differences between the members of this group appear to be directly related to the depth of the level of erosion below the original surface. It cannot be stressed too strongly that in no complex, either in Africa or in the rest of the world described to date, has the carbonatite been found to be capped by

country rocks. A number of investigators, when dealing with deeply eroded carbonatites, have envisaged the whole mechanism occurring without access to the surface. There is no support whatever for this concept. In the Kerimasi (1954) occurrence in Tanganyika, the head of the carbonatite column is exposed within the crater.

Carbonatite cores are invariably made up of carbonates of calcium, magnesium, iron, manganese, strontium and barium and these are emplaced in this order.

4. Messum type. In the coastal region of South West Africa two deeply eroded volcano roots have been described. These are the Messum (1954) and Okonjeje (1954) complexes and their relationship to the carbonatite complexes elsewhere is obscure. Both these ancient volcanoes are centred by foyaite surrounded by gabbros. At Messum the author has seen carbonatites and fenitisation effects have been noticed in the zone surrounding the foyaite plug. Since it is unlikely that the foyaite itself could have achieved this fenitisation, it is probable that the conduit originally contained carbonatite. In this connection it is interesting to note that Martin has recorded the presence of "kalkbomben" in agglomerates found in the region.

5. Katwe type. (1954) Surrounding the southern nose of the Ruwenzori in Uganda and the Belgian Congo are a group of explosion craters which produce small cones of nephelinitic agglomerate and tuff and subsidiary flows of potassic type. Carbonatite fragments are rare but in places the tuffs consist of calcitic dust and sodium salts. These salts have been leached and transported into the crater lakes. Fragments in the agglomerates include members of the olivine-biotite-pyroxenite series.

The Pretoria saltpan has recently been found to contain a small body of carbonatite breccia.

Direct field evidence is available to show that paroxysmal eruptions in volcanoes which normally produce nephelinitic types result in the withdrawal of carbonates and chlorides. Bombs seen to be ejected from the throat of the active volcano Ol Donyo l'Engai were found on analysis to consist of carbonates and soda salts.

While not strictly applicable to the African field it may be noted that the tuffs associated with the carbonatite complex at Kaiserstuhl (1954) show that paroxysmal eruptions were followed by the deposition of much calcite and soda zeolites. Rock types in the volcanic series there include nephelinite, olivine leucitite, tephrites and nepheline syenites.

## PETROGENESIS.

### The Development of Ijolitic Types. (Nephelinites.)

N.L. Bowen (1928) has shown that when a mineral crystallises from a magmatic liquid, it may be either segregated or at a later time react with the residual liquid to form another mineral in a reaction series. The permanent withdrawal of a mineral causes a relative increase or decrease in the percentage of any particular oxide in the residual magma, depending on whether the mineral contains less or more of that oxide than the parent magma. If olivine, which possesses a lower percentage of silica than the parent magma, is segregated, there is an enrichment in silica in the residual liquid. (Fig. 1.).

The nature of the residual magma during the crystallisation of olivine, pyroxene and plagioclase from basaltic liquid depends primarily on the degree of permanent segregation or fractionation of the oxides involved in the crystallisation. These trends are illustrated in Figs. 1, 2 and 3. The pyroxenes likely to separate from a basaltic magma contain more silica than the parent magma. In cases where reaction is prevented by segregation of these crystals, desilication of the residual magma results. In Fig. 2, an attempt has been made to demonstrate the trend of the residual magma during the segregation of pyroxene from a normal alkali basalt magma (olivine basalt). The choice of the pyroxenite in the diagram is open to debate since, in fact, the segregation appears to be achieved not so much by direct gravitational accumulation but by explosive expulsion of the crystals into the tuffs. The important point remains, however, that the removal of the pyroxene inevitably produces a desilicated residual liquid. Direct evidence is available to demonstrate that pyroxene crystals were explosively withdrawn from the magma at Elgon and Napak, with the formation of crystal tuffs.

Similarly in Fig. 3., the trend of the residual magma during the withdrawal of plagioclase from normal alkali basalt is demonstrated. Here, too, field evidence is available to show that this withdrawal did in fact occur to a limited extent with the formation of felspathic crystal tuffs at both Napak (1949) and Elgon (3,197).

In Elgon type volcanoes the segregation of pyroxene was clearly the more important, since the volume of pyroxene crystal tuffs by far exceeds that of the felspathic tuffs. When both pyroxene and plagioclase were withdrawn, a compromise was effected and the most important result remained the desilication of the residual liquid.

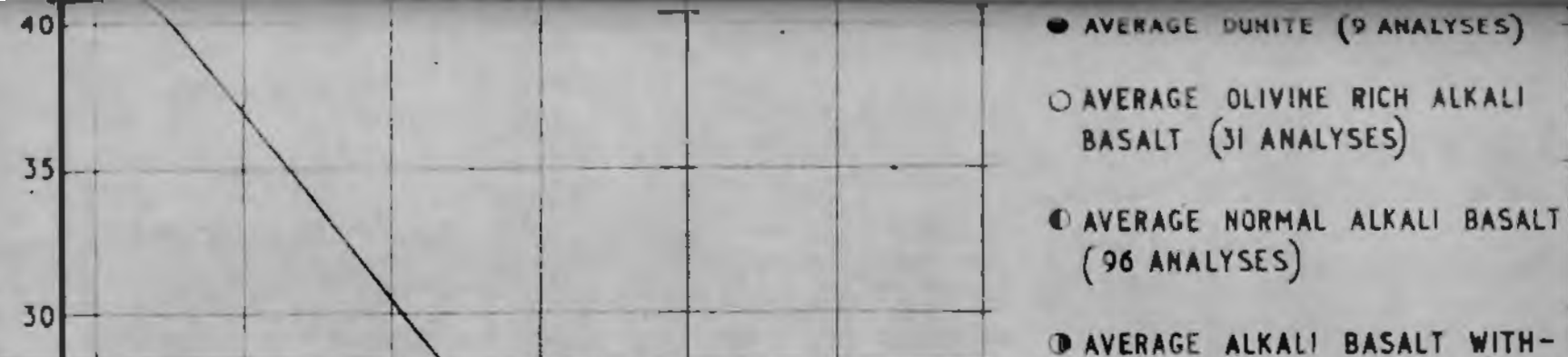
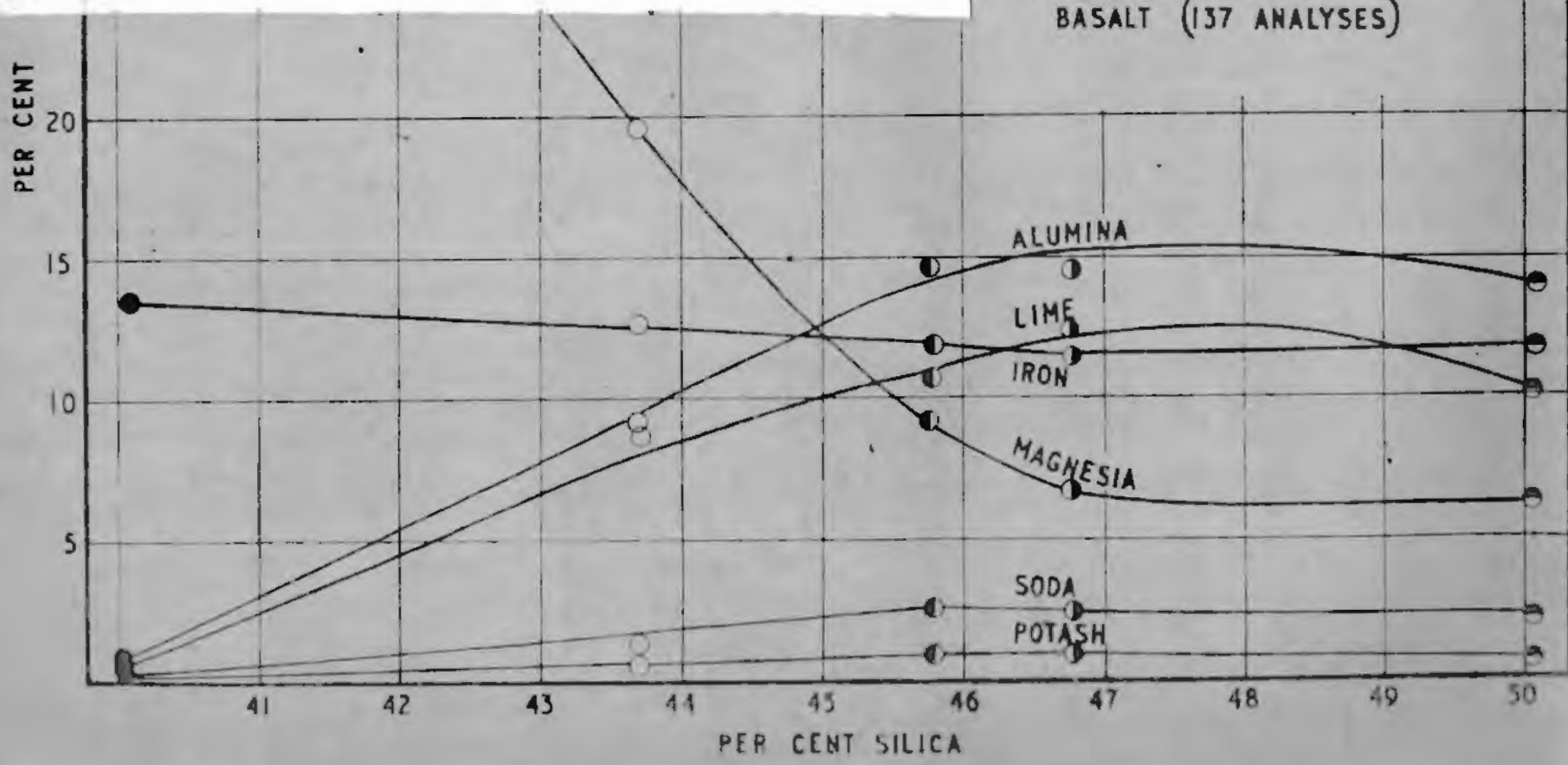
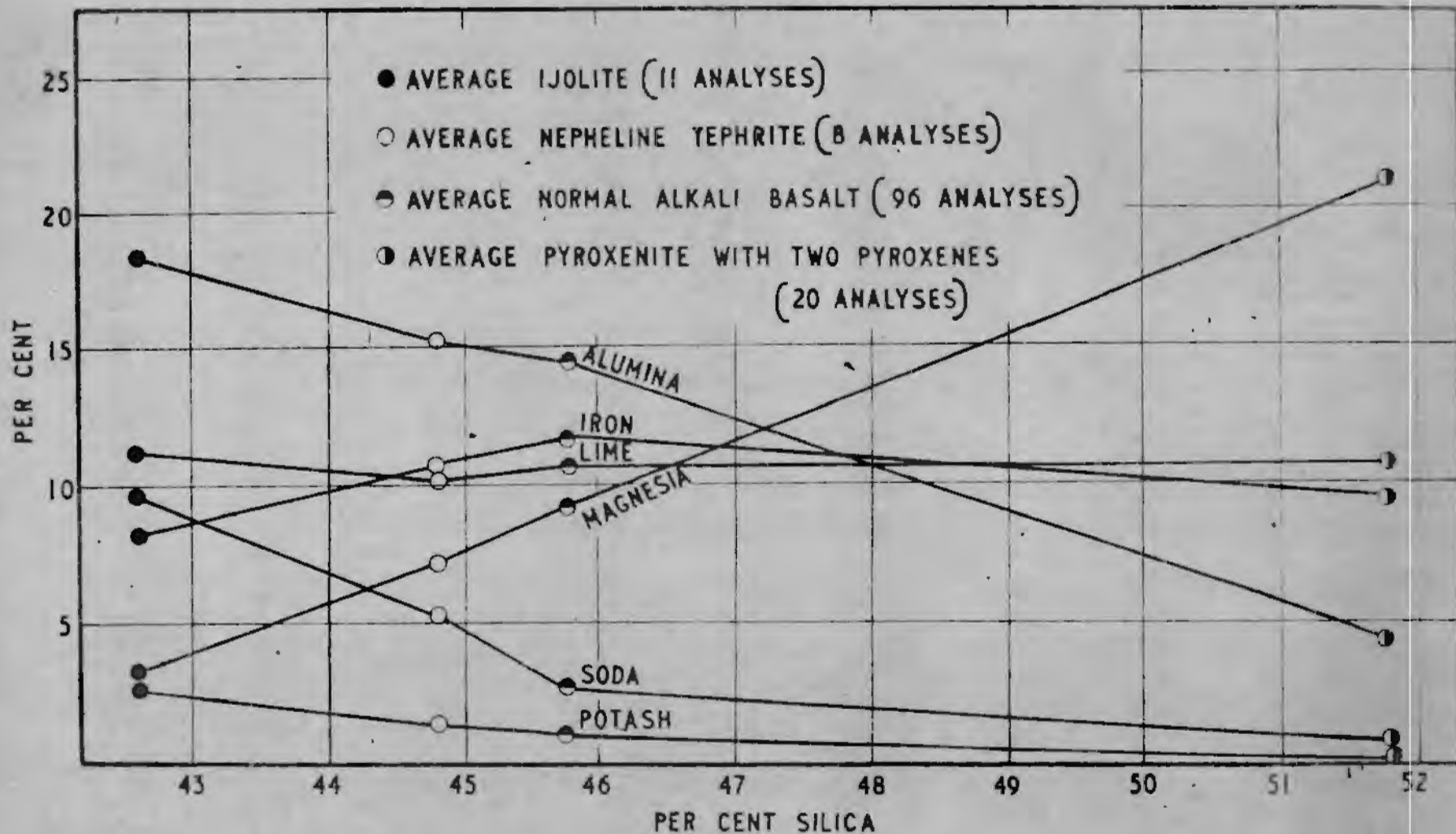


Figure 1. Variation diagram showing the effect of the segregation of olivine from normal alkali basalt magma. Average analyses after Nockolds (1954).

- AVERAGE DUNITE (9 ANALYSES)
- AVERAGE OLIVINE RICH ALKALI BASALT (31 ANALYSES)
- ⊙ AVERAGE NORMAL ALKALI BASALT (96 ANALYSES)
- ⊖ AVERAGE ALKALI BASALT WITHOUT OLIVINE (22 ANALYSES)
- AVERAGE NORMAL THOLEIITE BASALT (137 ANALYSES)





**Figure 2.** Variation diagram illustrating the desilication produced by the removal of pyroxenes from normal alkali basalt magma. Average analyses after Nockolds. (1954).

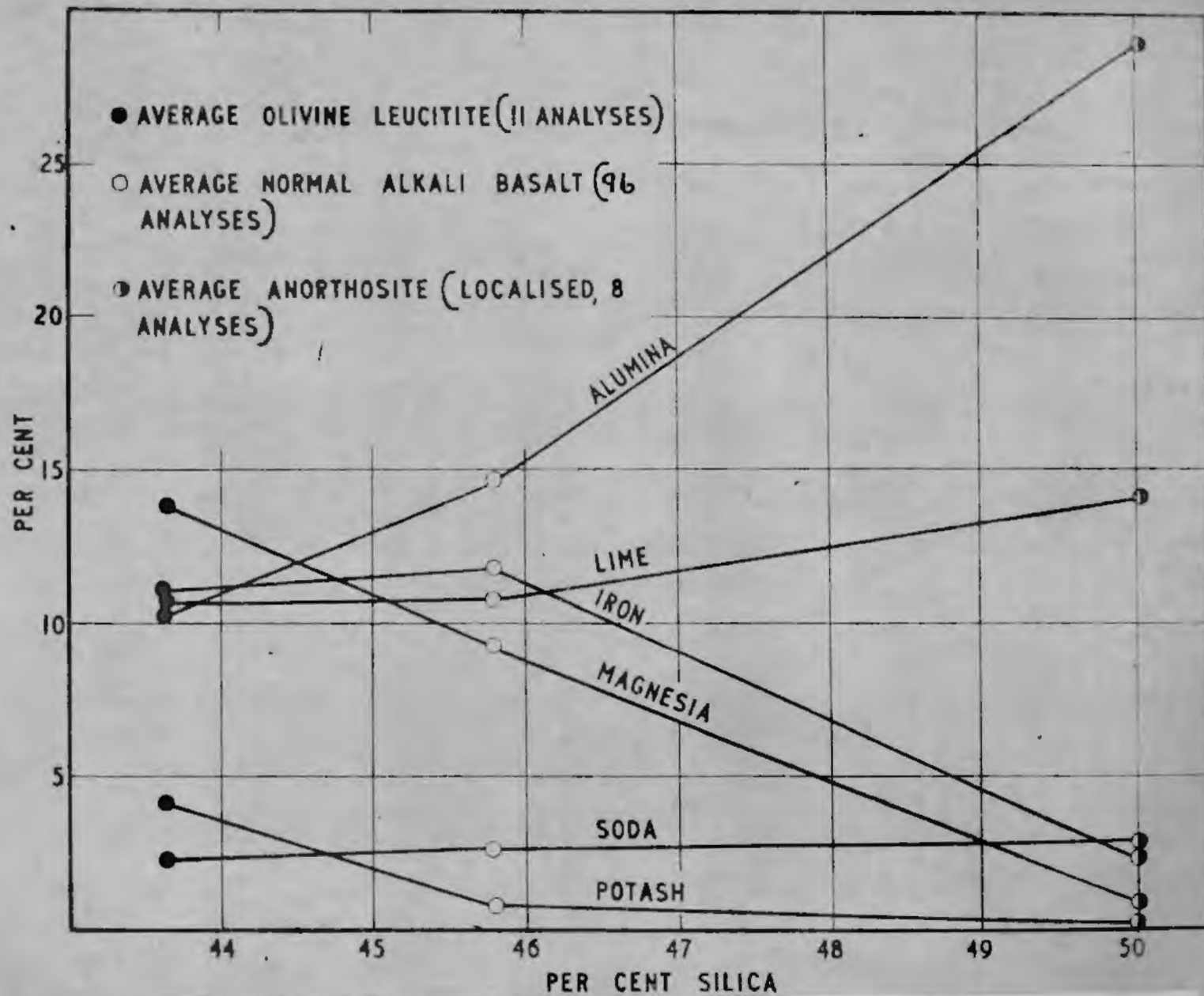


Figure 3. Variation diagram showing the trend of differentiation resulting from the removal of calcic plagioclase from a normal alkali basalt magma. Average analyses after Nockolds (1954).

While the removal of pyroxene tends to diminish the amount of magnesia in the residual liquid and relatively increases the amount of alumina, the removal of plagioclase achieves a precisely opposite effect.

The composition of the residual liquid depends therefore, on the relative proportions of pyroxene and plagioclase removed, and the nature of the pyroxene and plagioclase crystallising at that time.

The three variation diagrams represent the extreme cases and indicate that nepheline-bearing rocks may be produced through the segregation of pyroxene from a normal alkali-basalt magma (Fig.2) and that other felspathoidal types could result from the segregation of plagioclase. (Fig.3). Where olivine is segregated early this desilicatory trend is prejudiced (Fig.1). It has been seen in the description of Elgon rocks that the segregation of olivine occurred only very rarely.

The mechanism producing this differentiation is envisaged as an initial sinking of the crystals in a tall magma column. When the upward movement of the magma in the conduit exceeded the speed of the sinking of the crystals, the accumulates would be carried to the mouth of the vent and from there blown out as crystal tuffs.

Where the sinking of the early formed crystals temporarily exceeded the upward movement of the magma column, the magma lower down the conduit was enriched in ferro-magnesian and this gave rise to the ankaratrite group of rocks. This mechanism has also been suggested by MacDonald (39) to explain these rocks in the Hawaiian province.

A further point which may be mentioned in connection with this type of differentiation is that the upper portion of the magma would probably be cooler than the lower reaches and crystallisation would be more advanced at the top of the column.

Although both early pyroxenes and early plagioclases are normally rich in lime, the percentage of this oxide in these minerals is not noticeably greater than that in basaltic magma. Consequently the loss of lime to the residual liquid is not very great in either case.

Very little soda or potash is removed during the crystallisation of pyroxene and there is a steady relative increase in alkalis in the residual liquid during the course of segregation. The plagioclases which are segregated to form crystal tuffs contain an appreciable amount of soda and practically no potash and, as a result, there is a significant relative increase of the latter oxide in the residual liquid. This is important, since in the desilicated milieu achieved by the removal of calcic plagioclase, leucite is able to form.

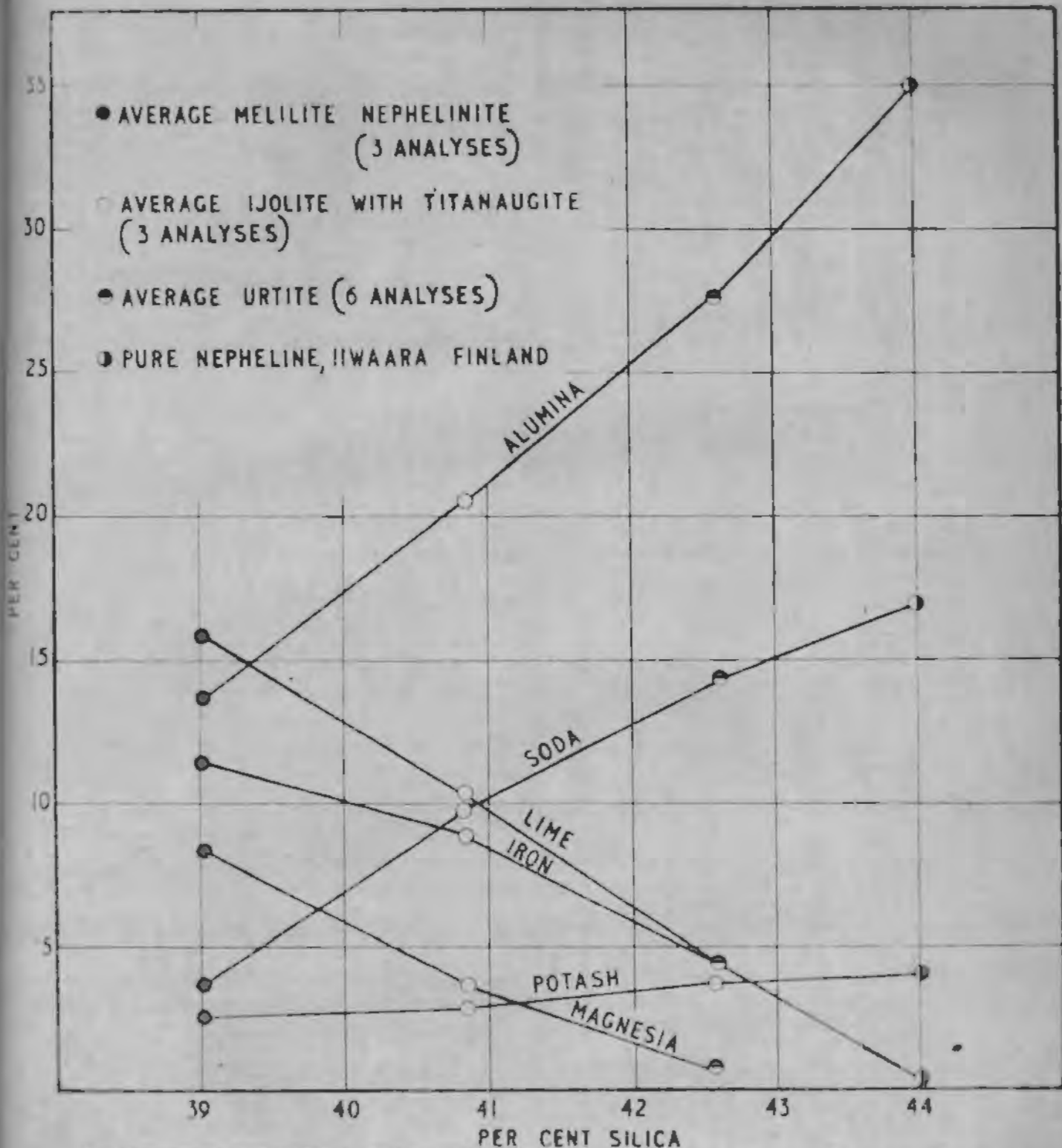


Figure 4. Variation diagram illustrating the desilication caused by the segregation of nepheline from an ijolite magma. Average analyses after Nockolds (1954). Nepheline from ijolite Iiwaara, Finland (Johannsen, 1938).

In addition, the marked relative increase in magnesia assists in the formation of olivines.

The Development of Melilite Rocks.

Although nephelinites predominate in the lava flows of Mount Elgon, rocks containing melilite are also found. During the crystallisation of nepheline in a nephelinitic (ijolitic) magma, silica, alumina, soda and some potash are subtracted from the liquid. In most complexes of this type, rocks suggesting the segregation of nepheline are present. The urtites are thought to be members of this group.

Figure 4 shows very clearly this trend of the residual liquid when nepheline is segregated from an ijolitic magma. Since the silica percentage of nepheline exceeds that of most ijolites, further desilication is caused. At the same time there is a marked relative increase in those oxides not involved in this crystallisation i.e. calcium, magnesium, titanium, iron and phosphorus. Minor constituents such as chromium and barium become progressively more significant.

The desilication resulting from the segregation of nepheline combined with the relative increase of lime in the residuum results in the formation of a series of lime silicates which require progressively less silica. This produces a series of minerals of decreasing SiO<sub>2</sub> : CaO ratio:-

Melilite	...	...	1.13 : 1
Melanite	...	...	1.10 : 1
Iiwaarite	...	...	0.80 : 1
Calcite	...	...	0.00 : 1

At the same time, titaniferous augite, perovskite, apatite and titaniferous iron ore are formed and the resulting rocks form the nephelinite-melilite nephelinite series, which is represented by the central group in Figure 5 (A-B).

The subtraction of nepheline from an ijolitic magma causes enrichment in lime, iron and magnesia in a silica-poor residuum, and leads to the formation of olivines, initially ferro-magnesian and later the lime-magnesian olivine, montecellite. Segregation of these olivines effects the establishment of two further series, i.e. those rocks containing excess olivine (and pyroxene), the nephelinite-melanephelinite-ankaratrite-uncompahgrite series (C-D, Figure 5), and the residual rocks, the alnoite-bergalite series (E-F, Figure 5). The more extreme members of these groups contain melilite, melanite, calcite and montecellite. The crystallisation of montecellite is thus the result of extreme desilication together with relative lime and magnesia enrichment. Closely related to

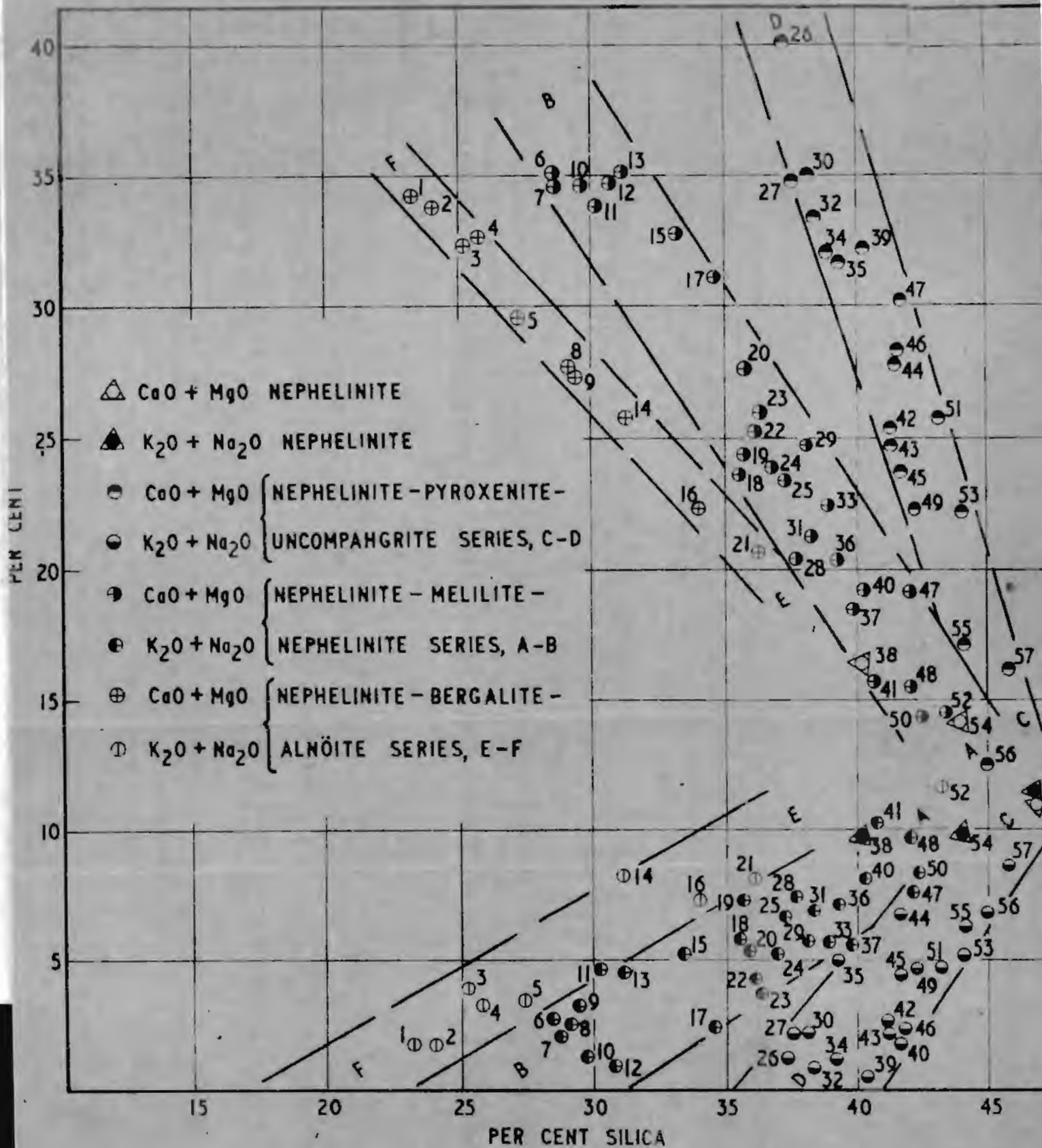


Figure 5. Diagram showing the trends of differentiation originating from nephelinitic magma. The rocks indicated by numbers on the diagram are listed in the appendix, p. 93.

these rocks and also the result of desilication and relative enrichment in iron, titanium, chrome and vanadium, are the jacupirangites. Chemically, the kimberlites belong to this series. The residual series is characterised by the presence of perovskite, chromite and barite.

It is possible that some of the alvikitic and beforstic alnöites, which appear to be the end members of this series, result from the squeezing out of the residual interstitial fluid. It is likely that these rocks grade in depth into normal alnöites.

#### The Origin of the Carbonatites.

The main trend of differentiation described so far has been towards a desilicated residuum. This, however, is not the only process operating in volcanoes of Elgon type, since phonolites and, more rarely trachytes, have at various times appeared amongst the lavas of Mt. Elgon. The deep-seated equivalents of these rocks frequently occupy the conduits of ancient volcanoes. It is therefore necessary to consider by what mechanism a volcano producing nephelinitic types could evolve a phonolitic differentiate.

The solution to the problem lies in the chemical nature of nephelinitic magma, which is capable of division into two portions. Depending upon the P-T-X conditions at the time of fractionation, these portions are either beforstite (magnesian carbonatite) and phonolite or alvikite (calcitic carbonatite) and trachyte. This statement is substantiated in the first instance by the chemical variation diagrams (Figs. 6 and 7) which depict the beforstite-nephelinite-phonolite (foyaite) series and the alvikite-nephelinite-trachyte series respectively. The members of these series bear a straight-line genetic relationship to each other. Holmes (1930, p. 446) states that "the fact that even with three analyses a straight-line diagram is achieved indicates that the rocks concerned are related in an unusually simple way". Fig. 6 is constructed from 38 and Fig. 7 from 26 analyses. These two variation diagrams strongly contest the suggestion that alkaline complexes originate through limestone syntexis.

Fig. 6 shows that there is a marked linear arrangement in the beforstite-nephelinite-phonolite (foyaite) series, and this diagram is considered to demonstrate the direct genetic relationship of the members of this series. Fig. 7 shows that the members of the alvikite-nephelinite-trachyte series are related in a similarly direct and genetic fashion. The precise reason for the difference in the two series lies in the nature of the respective carbonatite types. Of particular importance is the fact that for a given silica value the alvikites contain less Lime and magnesia and more iron than the beforstites.

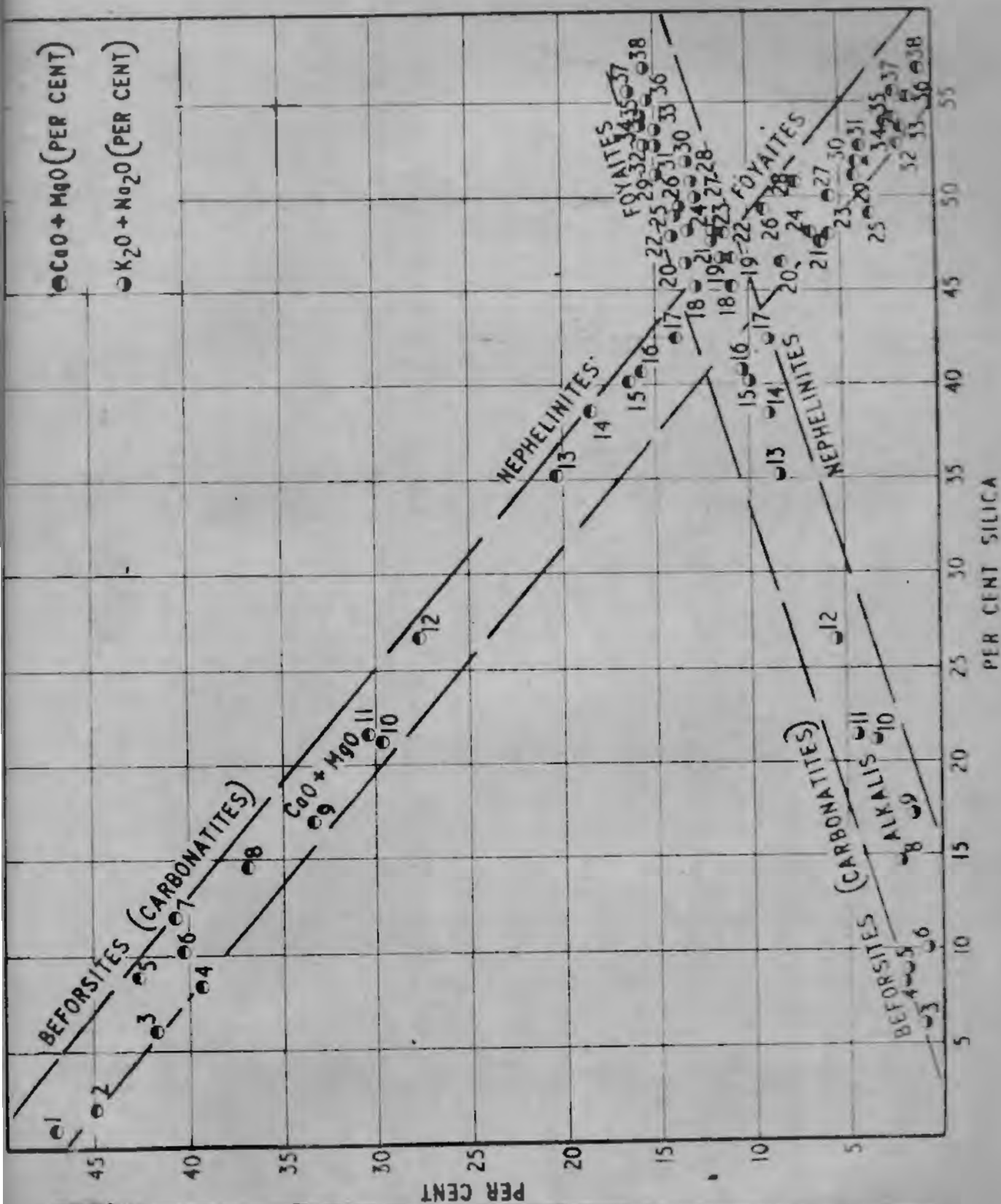


Figure 6. The beforosite-nephelinite-foyaite series. The rocks indicated by numbers on the diagram are listed in the appendix, p. 94.

Figure 7. The alvikite-nephelinite-trachyte series. The rocks indicated by numbers on the diagram are listed in the appendix, p. 95.

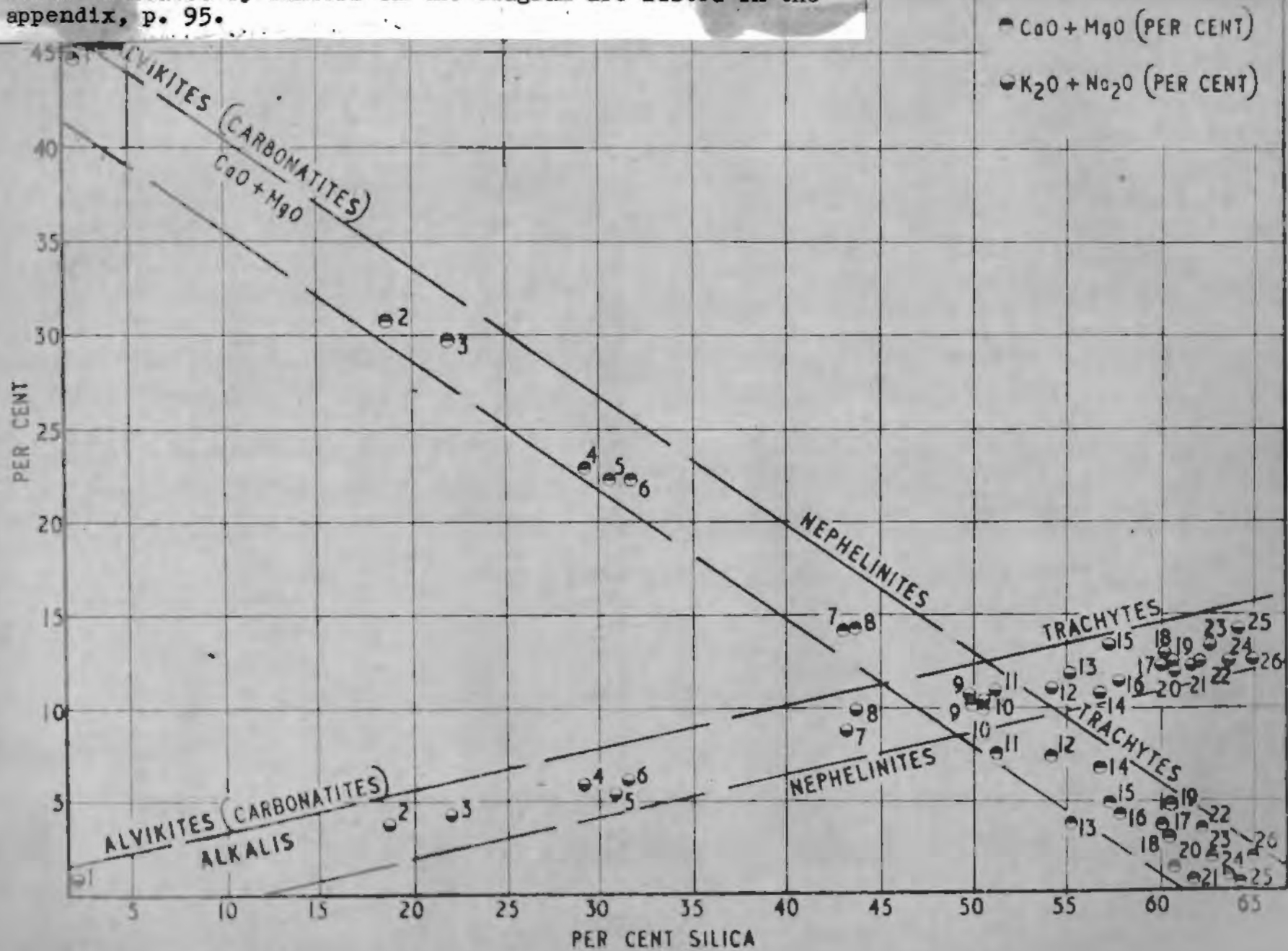


TABLE 1. - Chemical losses and gains involved in the development of Phonolites and Trachytes from Nephelinitic Magma.

	1	2	3	4	5
SiO <sub>2</sub>	43.59	48.04	+4.45	64.30	+20.71
Al <sub>2</sub> O <sub>3</sub>	15.07	19.56	+4.49	19.48	+4.41
Fe <sub>2</sub> O <sub>3</sub>	6.96	4.11	-2.85	0.19	-6.77
FeO	4.54	3.64	-0.90	0.21	-4.33
MgO	3.51	1.44	-2.07	0.13	-3.38
CaO	10.53	5.09	-5.44	0.32	- 10.21
Na <sub>2</sub> O	6.03	6.48	+0.45	6.40	+0.37
K <sub>2</sub> O	3.87	6.52	+2.65	7.72	+3.85
H <sub>2</sub> O+ } H <sub>2</sub> O- }	2.57	3.75	..	0.76	..
CO <sub>2</sub>	-	-	..	0.09	..
TiO <sub>2</sub>	2.71	1.41	-1.30	0.48	-2.23
P <sub>2</sub> O <sub>5</sub>	0.62	0.17	..	0.18	..
MnO	0.25	0.10	-0.15	0.02	-0.23
BaO	-	-	..	0.03	..
<b>Total</b>	<b>100.25</b>	<b>100.31</b>		<b>100.31</b>	

1. Elgon nephelinite. Analyst - N.Sahlbom
2. Elgon phonolite. Analyst - N Sahlbom.
3. Difference between 1 and 2.
4. Elgon trachyte. Analyst - B.C.King.
5. Difference between 1 and 4.

**TABLE 2.** Chemical composition of typical Uganda Nephelinites compared with that of a hypothetical mixture of phonolite and beforosite.

	1	2	3	4	5	6
SiO <sub>2</sub> ..	48.04	0.85	38.60	42.37	42.97	43.59
Al <sub>2</sub> O <sub>3</sub>	19.56	-	15.65	17.18	21.10	15.07
Fe <sub>2</sub> O <sub>3</sub>	4.11	8.44	7.89	8.66	6.45	6.96
FeO	3.64				4.14	4.54
MgO	1.44	15.82	4.32	4.74	2.65	3.51
CaO	5.09	31.30	10.33	11.34	8.45	10.53
Na <sub>2</sub> O	6.48	-	5.18	5.69	4.92	6.03
K <sub>2</sub> O	6.52	-	5.22	5.73	1.88	3.87
H <sub>2</sub> O+)	3.75		2.05	2.26	5.27	2.57
H <sub>2</sub> O-)					0.65	
CO <sub>2</sub>	-	43.51	8.70	-	0.07	-
TiO <sub>2</sub>	1.41	-	1.13	1.24	0.55	2.71
P <sub>2</sub> O <sub>5</sub>	0.17	0.43	0.65	0.71	1.11	0.62
MnO	0.10	0.02	0.08	0.09	0.22	0.25
BaO	-	-	-	-	0.05	-
SrO	-	-	-	-	0.05	-
Cl	-	-	-	-	0.01	-
Total...	100.31	100.37	98.80	100.01	100.54	100.25

1. Elgon phonolite. Analyst - N. Sahlbom.
2. Napak beforosite. Analyst - B.C. King.
3. 1 added to 2 in the ratio of 4 : 1.
4. 3 recalculated to 100% after deduction of CO<sub>2</sub>
5. Napak nephelinite. Analyst - B.C.King.
6. Elgon nephelinite. Analyst - N. Sahlbom.

Arithmetical proof can be adduced that nephelinite magma is capable of division into either beforseite and phonolite or iron-rich alvikite and trachyte magmas. In Table 1, typical Uganda rocks are considered. Columns 1 & 2 show that in the differentiation from nephelinite to phonolite magma, there is a marked decrease in iron, magnesia and lime and a relative increase in silica, alumina and alkalis. The material lost therefore, in the differentiation from nephelinite magma to either phonolite or trachyte is in fact the main substance of the carbonatites, viz. lime, iron and magnesia. The oxides showing a relative increase are precisely those in which the phonolites and trachytes are always enriched, i.e. silica, alumina and alkalis, mainly potash.

TABLE 1. Chemical losses and gains in the development of phonolites and trachytes from nephelinitic magma.

Considering the actual ratios of lime to iron to magnesia in columns 3 and 5, it is seen that in the first case lime predominates, while in the second, iron is of almost equal importance to lime. It should also be noted that the total loss or gain in column 5 greatly exceeds that in column 3. The differentiation producing the trachytes may therefore be considered to be more vigorous than that resulting in the production of phonolites. The following two empirical ratios have been arrived at:-

Nephelinite = 4 parts phonolite + 1 part beforseite  
Nephelinite = 3 parts trachyte + 2 parts ankeritic  
alvikite

An illustration of the nephelinite-beforseite-phonolite fractionation is given in table 2. A phonolite and a beforseite from the same petrographic province have been added in the ratio of 4 : 1, with the result shown in column 3. In column 4 the carbon dioxide has been removed and the remainder recalculated to 100%. The result is ijolitic in type and is similar in composition to the Uganda nephelinites which are given for comparison in columns 5 and 6.

### Addendum.

It is necessary to stress here the importance of the role played by sodic emanations in some volcanoes. In Table I, columns 3 and 5 show that there is a greater relative increase in potash than in soda. This may be directly attributed to the escape from the vent of the volatile soda compounds, such as sodium carbonate and chloride. These form conspicuous ashes and encrustations at the active volcano Oldonyo L'Engai in Tanganyika and as mentioned elsewhere, they constitute an economic source of these salts in the explosion craters of western Uganda. The relative increase in potash caused by the escape of soda results in the evolution of the potassic lavas, characteristic of provinces in which soda-lakes are common.

The Mechanism of Carbonatite Formation.

The structure of alkaline volcanoes in Uganda clearly demonstrates the intimate association of carbonatite with outbursts of Elgon type. Carbonatite fragments have been ejected from the throats of volcanoes such as Kerimasi, Oldonyo L'Engai (James, 1956) and Mount Elgon (Shackleton, 1944). If carbonatites are indeed magmatic derivatives, it is necessary to discover how such differentiates may be formed in the same magma chamber and from the same magma as that producing the rocks of the cone. Since the predominant flow type occurring on Mount Elgon, Napak and Kerimasi is nephelinitic, it is evident that some rapid and specialised form of differentiation has operated in the development of carbonatite from nephelinite. It is significant that the greater part of the cones of these volcanoes consists of pyroclastics, showing the large amount of gas associated with the eruptions.

Mount Elgon is a volcano of the central type and very large pyroclastic fragments have fallen many miles from the vent. This gives some idea of the tremendous gas pressure built up in the volcano during quiescent periods when the conduit was choked with congealed lavas. The great reduction of gas pressure during paroxysmal eruptions must have produced rapid chilling deep down in the system.

It is suggested that during periods of closure of the vent, tremendous pressures were built up within the volcano and much of the hyperfusible material was in solution in the magmatic fluid. At the moment of eruption which followed a quiescent period, the rapid reduction of pressure caused the spontaneous release of the dissolved volcanic gases in the magma chamber and magma column. Adiabatic expansion and cooling were most marked. This escape of gas caused agitation and frothing within the magma and water vapour, carbon dioxide and other volcanic gases migrated upwards, bubbling through the magmatic liquid. The passage of carbon dioxide through a liquid containing calcium and magnesium oxides in solution caused the formation of carbonates. Prof. L. Ahrens (personal communication) confirms that this is a likely reaction.

The formation of calcite from a magma rich in CaO and CO<sub>2</sub> is the natural outcome of rapid cooling which reduces the temperature of the magma chamber, however temporarily, below the crystallisation temperature of calcite (1389°C. at 779,000 mm. pressure). Similarly, the carbonates of magnesium, iron, manganese, strontium and barium were formed. The carbonate particles were all

formed in close contact with the rapidly migrating gas bubbles and it is likely that some type of flotation occurred, carrying the carbonates up the magma column.

The carbonates were thus concentrated at the top of the magma column, where, owing to continued adiabatic cooling, they congealed. Also occluded within the carbonate mass were particles of the other components of the magma, which then crystallised in their simplest form. The minerals in the following list are formed in the carbonatite during explosive episodes and occur at Sukulu, Alnö, Iron Hill and Napak:-

Calcite	.. ..	..CaCO <sub>3</sub>	.. ..	.. ..	..Sukulu	Iron Hill	Alnö
Dolomite	.. ..	..MgCO <sub>3</sub>	.. ..	.. ..	..Sukulu	Iron Hill	Alnö
Siderite	.. ..	..FeCO <sub>3</sub>	.. ..	.. ..	..Sukulu	Napak	Alnö
Ankerite	.. ..	..(2CaCO <sub>3</sub> ;MgCO <sub>3</sub> ;FeCO <sub>3</sub> )	-			Iron Hill	-
Strontianite	.. ..	..SrCO <sub>3</sub>	.. ..	.. ..			Alnö
Witherite	.. ..	..BaCO <sub>3</sub>	.. ..	.. ..			Alnö
Carbon dioxide	..	..(bubbles in calcite)	Sukulu				Alnö
Quartz	.. ..	..SiO <sub>2</sub>	.. ..	.. ..	..Sukulu	Iron Hill	Alnö
Corundum	.. ..	..Al <sub>2</sub> O <sub>3</sub>	.. ..	.. ..			Alnö
Anatase	.. ..	..TiO <sub>2</sub>	.. ..	.. ..	..Sukulu	Iron Hill	Alnö
Pyrolusite	.. ..	..MnO <sub>2</sub> (after brookite)	Sukulu				Alnö
Baädeleyite	.. ..	..ZrO <sub>2</sub>	.. ..	.. ..	..Sukulu		
Microlites	.. ..	..Unidentified	.. ..	.. ..	..Sukulu		Alnö
Fluorite	.. ..	..CaF <sub>2</sub>	.. ..	.. ..	..Sukulu		Alnö
Barytes	.. ..	..BaSO <sub>4</sub>	.. ..	.. ..	..Sukulu		Alnö
Pyrite	.. ..	..FeS	.. ..	.. ..	..Sukulu		Alnö
Galena	.. ..	..PbS	.. ..	.. ..			Alnö

The minerals listed represent the simplest possible combination of the components present. Probably the most significant mineral is quartz, which is seen as tiny crystals set in the carbonate. Had sufficient time been available for reaction, calc-silicates would undoubtedly have been formed. During the examination of the Sukulu soil deposit, the ubiquity of these quartz crystals provided a constant puzzle.

Minute bubbles of carbon dioxide have been detected within the calcite at Alnö and Sukulu. This demonstrates not only the abundance of this gas available in the magma, but also the rapidity with which the calcite was formed. The presence of excess carbon dioxide, which is most common in the fine-grained central portions of the complex, is thought to be the reason for the rapid weathering of the centres at Sukulu. In each of the three centres there, the later sheets form a ring of hills almost enclosing a soil-filled valley.

The presence of tiny microlites also testifies to the rapid formation of the carbonate. It is evident that the crystallisation of complex silicates was unable to keep pace with the growth of the carbonates. Von Eckermann (1948, page 73) describing the sövite from the "central cone" at Alnö writes:-

"It is very fine-grained, reminding almost of a chilled margin rock. The only other minerals present are apatite and tiny microlites which could not be determined. Judging from the analysis, the calcite contains some carbonate of magnesia, iron, barium and strontium."

In the industrial process of fluidisation as practised in modern chemical engineering, particles are agitated and transported by gas streams. Such agitated beds, as they are called, are capable of assuming the properties of a liquid. When the gases are hot, reaction is facilitated and catalysed.

Considering a vertical volcanic conduit in which a very fluid magma is agitated by high velocity gas streams, it is reasonable to suppose that the products formed by reaction of the gas with parts of the magma would arrange themselves in a definite order of specific gravity. Field evidence clearly indicates that such a specific gravity gradient is, in fact, achieved in carbonatite-producing volcanoes.

The minerals involved are the following:-

<u>Mineral</u>	<u>Specific Gravity</u>
Calcite	2.7102
Dolomite	2.850
Magnesite	3.000
Ankerite	3.020
MnCO <sub>3</sub>	3.700
Strontianite	3.76
Witherite	4.291

The specific gravity of crystallised nephelinites is 3.00. The magma itself containing water and other gases would have been slightly lower. It is thus to be expected that the heavier carbonates would be less well defined and form only local segregations. They would also tend to contaminate the residual nepheline syenitic types below the carbonatite plug. This is confirmed by geochemical data which indicates that the rocks most strongly enriched in strontium and barium are the nepheline syenites and the carbonatites. At Alnö the latest dykes emplaced in the sövite zone are rich in barium.

Continued pressure from below, after the establishment of the specific gravity gradient would cause the telescoping of the carbonate fraction, resulting in the invasion of the upper members by the lower members. Field evidence conforms to this concept and the order of emplacement observed is as follows:-

1. Calcitic types.
2. Dolomitic types.
3. Ankeritic types.
4. Mn, Sr, Ba types sometimes as discrete bodies.
5. Nepheline syenites.

This pattern of intrusion is recorded from Sukulu, Chilwa island, Ondurakorume and Alnö island. Elsewhere the order of intrusion has not been directly discussed but it is clear from the description of Spitskop (2,198) that the same scheme is present there.

Structural evidence indicates that the carbonatites were emplaced in the condition of a plastic mush and the collection and transport of the minerals of the carbonatite are thought to have been effected by some mechanism such as fluidisation. The formation of the carbonates in frothing gas streams would ensure their flotation and transportation to the top of the magma chamber and at least part of the way up the conduit. As seen earlier, the removal of these carbonates from an ijolitic magma would leave a phonolitic or trachytic residual magma to follow them up the conduit.

Although evidence from volcanoes where the cone is still preserved shows that carbonatite formation occurred several times during the life of the volcano, the terminal phase of the eruption was the emplacement of carbonatite within the vent and into the wall rocks.

It was at this stage that a marked metasomatic aureole was established around the pipe. Two major types of fenite can be distinguished, firstly those surrounding the nepheline syenite or syenite, and secondly those close

to the carbonate. The main effect near the syenites was the introduction into the wall rock of amphiboles as well as some soda metasomatism. It is evident that only large bodies of nepheline-syenite type trapped beneath the carbonatite can produce any significant metasomatic effect. Dykes and small plugs of phonolite, tinguaitite and juvinites seen to be cutting granitic wall rock, effect little or no metasomatic exchange. It should be noted here that many of the rocks called "fenite" by von Eckermann are, in fact, genetically related members of the magmatic series, and the term should, consequently, be restricted to include only those contact rocks which show marked aberration when plotted on the variation diagram. The fenites surrounding the carbonate body are considered to be the result of physical admixture of fragments of wall rock under such conditions of temperature and pressure that new minerals were able to form in equilibrium with the relatively reduced silica percentage, and members of the sövite-silicate series appear to have been derived in this manner. In the Tororo complex (eastern Uganda), this type of fenitisation is clearly seen and brecciation of the granitic wall rock and digestion of the fragments by the engulfing sövites took place around the carbonate body. Outside this zone, the granitic wall rocks have yielded some of their silica to the carbonatite and grade from quartz syenites to syenites.

Reaction between the sövite and the wall rocks was very much more marked in the lower parts of the carbonate plug, owing to the greater temperature, pressure and concentration of hyperfusibles at the top of the crystallising magmatic body. In this region very large amounts of diopsidic pyroxene, often coarsely crystalline, were formed in conjunction with apatite, magnetite and biotite. In the formation of diopside, the lime and magnesia were supplied by the sövites and the silica obtained by reaction with the wall rock.

The closing phase in volcanoes of Elgon type appears to have been the telescopic subsidence of the central portion of the complex. This involved the collapse of the caldera, conspicuous ring faulting in the hypabyssal portion and the sagging of the laccolithic rocks, together with their consequent acquisition of centripetal dip. The latest rocks emplaced were essentially basic in character and crystallised as gabbros.

In those episodes where no carbonatite was formed, the nephelinitic magma congealed in the upper part of the conduit and the remainder crystallised as ijolite.

During the growth of the volcanic cone it is clear that sufficient pressure remained in the system to eject the carbonate as bombs or fragments, leaving a phonolitic or trachytic lava to well up into the caldera.

The final stage of the extrusive phase in volcanoes of Elgon type was the emplacement, within the vent, of the carbonatite body and when the system lacked sufficient explosive force to remove the obstruction, the extrusive phase was effectively terminated. At this stage there was trapped within the system a phonolitic (or trachytic) magma which was capable of plutonic crystallisation, and fairly coarse-grained nepheline-syenites and syenites were formed beneath the carbonate capping. At the same time, continued pressure was exerted upon the base of the obstruction, but it was not sufficient to remove the carbonate body. This pressure, together with heat recuperation within the system after the closure of the vent, caused the partial melting of the lower part of the carbonate body, and its injection in the form of conesheets, collar sheets and dykes around the central plug and into the wall rocks.

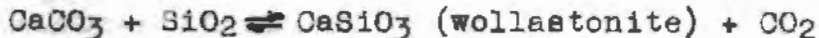
The congealing of the carbonatite led to the trapping of the residual liquid in a sealed system, so that plutonic conditions of cooling came into operation. An important consideration is the amount of water trapped in the system. In the system  $\text{CO}_2\text{-H}_2\text{O-K}_2\text{O-SiO}_2$ , investigated by Morey and Fleischer (1940) the percentage of  $\text{CO}_2$  in the vapour decreases as the partial pressure of  $\text{H}_2\text{O}$  increases, and the amount of water in the liquid phase increases linearly. In the closed system one would, therefore, expect to find an increasing development of the amphiboles and mica.

As the crystallisation of coarse-grained types continued, there was a progressive relative concentration of other hyperfusibles and the formation of considerable bodies of apatite and phlogopite in and around the base of the carbonates. Niobium, zirconium, yttrium and cerium entered the carbonatites, together with phosphorus and iron. The growth of pyrochlore was accompanied by that of asbestiform amphiboles. The hydrous conditions also encouraged the precipitation of large quantities of magnetite. (5, 1940).

In the field nearly all carbonatites are seen to contain dykes and bodies of sövite-breccias and these indicate that periodically the pressure beneath the plug was sufficient to break through locally. These fissures were, however, rapidly healed by the crystallisation of

further carbonate. It is interesting to note that the rocks containing the greatest amounts of pyrochlore are the sövite-breccias and late tangential dykes. In some cases, as at Chilwa, the temporary breaks in the carbonate cap caused the emplacement of felspathic breccias (chemically trachytes). At Sukulu, tingwaites are the only silicate rocks cutting the carbonatites.

Another effect of the trapping of the residual magma was the formation of wollastonite in the carbonate. V.M.Goldschmidt (1954) has worked out the stability curve of calcium carbonate and silica and has established that the reversible reaction:



moves to the right above 500°C. under moderate pressure. The presence of wollastonite in some of the carbonate rocks suggests that the sövites at the base of the plug were sufficiently reheated for the quartz and calcium carbonate to react.

#### The Source of Carbon Dioxide.

In considering the source of carbon dioxide in these complexes it is important to realise that the total amount of this gas required for the formation of carbonatite is not very large. In the differentiation described here, segregation of pyroxene and plagioclase leaves a desilicated residual magma relatively enriched in hyperfusibles. Table 2 shows that this nephelinitic magma may divide into four parts of phonolite and one part of carbonatite. Of this fifth portion of the residual magma considerably less than half is carbon dioxide. During their formation, the carbonatites drew not only upon the carbon dioxide in the magma in their immediate vicinity, but also upon carbon dioxide bubbles arising from great depth in the magma column.

Much has been written of the extraordinary amounts of carbon dioxide required to produce carbonatites. When considered in proper perspective against the vast volcanic piles produced by volcanoes of Elgon type, the amount of carbonate formed is insignificant. Estimates of the amount of lime present in Mount Elgon, assuming it to have a hypabyssal carbonatite equal in size to that of Sukulu (the largest so far described) have been made by K.A. Davies, T. Deans and the writer. These estimates agree very closely and it is believed that no more than

10% of calcium oxide is present in the total. Of this, by far the greatest proportion is combined in the silicate minerals of the nephelinite.

Two other factors are thought to contribute to the view that very large quantities of gas are associated with these volcanoes when observed during periods of activity. Firstly the narrowness of the conduit creates an impressive effect as high velocity gases are heard "roaring" through small cracks in the congealing lava in the crater. These emissions are, however, of brief duration and it is significant that during the growth of the Elgon cone thick vegetation was able to grow between major outbursts. Large tree trunks are found in the agglomerates throughout the succession and it is by no means certain that the vulcanicity of Elgon has been terminated. Secondly, the extreme fluidity of nephelinitic lava enables the prompt withdrawal of most of its included gases on release of pressure. Here it is of importance to note that nephelinite flows contain very few vesicles. This rapid release of gas, however, contributes a marked chilling effect at the point of maximum expansion and it is probably for this reason that very few nephelinite flows are found. They tend to congeal in the crater and to be ejected forcibly as tuffs and agglomerates.

It is clear that volcanoes of Elgon type depend for their activity upon the concentration of hyperfusibles in the upper parts of the system and as soon as the supply is exhausted the system seals itself and any further rocks entering the hypabyssal area crystallise as normal dolerites, gabbros or their derivatives.

A simple analogy is seen in the opening of a soda water bottle. Should the crown cork be removed rapidly, the gas is spontaneously released from solution and the bubbles carry with them a considerable portion of the contents of the bottle. When the cork is removed slowly and the pressure released gradually, most of the gas remains dissolved in the liquid. This appears to be the main difference between oceanic volcanoes and those on continental masses. The development of alkaline types is not controlled by the constitution of the surrounding crust, but by the structural environment in which they are evolved.

The total amount of carbon dioxide in volcanoes of Elgon type is thus probably no greater than that normally found in basaltic magmas, though the type of differentiation and the crustal structures causing it tend to concentrate the hyperfusibles.

Recent work by P. Baertschi on the relative abundance of oxygen and carbon isotopes suggests strongly that the carbon dioxide in these occurrences is not recycled but juvenile.

The Geochemistry of Carbonatites.

Main Constituents.

With the exception of Fe the cations present in the carbonatites as carbonates are found in the same ratio as in the nephelinites which preceded them in their occupancy of the vent. It appears that iron formed carbonates with less facility than did Ca, Mg, Sr and Ba. That the iron was in fact present in the correct ratio is indicated by the large amounts of magnetite.

The selective preference of carbon dioxide for the cations Ca, Mg, Fe, Mn, Sr and Ba is evident in the carbonatite complexes, and appears to be related to the ionic potential of members of this group.

The juvenile nature of the carbonates has been shown by P. Baertsche (3, 1951) who has determined the relative abundances of oxygen and carbon isotopes in a series of carbonate rocks from known carbonatite complexes and sedimentary limestones.

Carbonatite Sukulu  $\Delta$   $^{18}\text{O}/^{16}\text{O} = -20.2$

$\Delta$   $^{13}\text{C}/^{12}\text{C} = -6.9$

Carbonatite Spitskop  $\Delta$   $^{18}\text{O}/^{16}\text{O} = -20.6$

$\Delta$   $^{13}\text{C}/^{12}\text{C} = -7.8$

Magnesian Limestone  $\Delta$   $^{18}\text{O}/^{16}\text{O} = -4.0$   
Transvaal System

$\Delta$   $^{13}\text{C}/^{12}\text{C} = -2.2$

Another feature which may be diagnostic is the presence in the carbonatites of Sr, Ba, La and Y. (given here in descending order of abundance).

Strontium. Strontium occurs in the carbonatites to the order of 10,000 parts per million, though some zones may contain concentrations in excess of this. Faivre (1951)

has shown that limited solid solution of strontium and barium carbonates occurs with calcitic types.

It is significant that in the data compiled by Noll, nepheline syenites, trachytes and phonolites contain a considerable margin of Sr in excess of that in other rock types. The juxtaposition of strontium and barium-bearing carbonatites and nepheline syenites is observed in the field.

Strontium also enters the apatite in alkaline complexes.

Barium. This element is also found mainly in nepheline syenites, phonolites, trachytes and leucite-bearing rocks where it is captured by the potassic minerals. In the carbonatites it occurs as witherite or barytes. Owing to the close similarity of ionic radii, strontium, barium and calcium tend to replace each other.

Depending upon the portion of the carbonatite examined, barium may show a selective concentration over strontium.

Both strontium and barium tend to be relegated to the residual fractions of crystallising magmas.

Rare Earths. The relative enrichment in rare earths of the nepheline syenites was pointed out many years ago by Goldschmidt (c. 1934) and it is now known that an even higher concentration is found in many carbonatites. Once again it may be stated that the rare earths are concentrated in the residual fraction of a crystallising magma. They occur in many carbonates, fluor-carbonates and phosphates and owing to their similarity in ionic radius, tend to substitute for calcium, manganese and strontium.

Phosphorus. Phosphorus enters the carbonatite as apatite, though rare dahlite crystals are found. In some cases phosphorus joins with rare earths and thorium to form monazite.

Apatite is a common accessory in the nepheline syenites but is found in greatest concentration in the hydrothermal zone around the carbonatite where it occurs in coarsely crystalline form, in association with hydrobiotite and magnetite. In some cases, as at Palabora, it actively replaces the diopside formed by the reaction of the carbonatite and the wall rock.

Titanium. Titanium occurs in the carbonatite as anatase, perovskite and ilmene-rutile. In the hydrothermal zone, however, it occurs in magnetite and knopite, a cerium-iron titanite with thorium. A small amount of vanadium frequently accompanies the titanium.

Niobium. The main niobium mineral is pyrochlore, though koppite has also been found. Columbite occurs in some complexes and a niobian rutile has been reported. In the zone surrounding the carbonatite, niobium is rare and occurs mainly in knopite.

Zirconium. In the carbonatites, zircon is usually the most common zirconium mineral. Baddeleyite is also found and is probably as common in the hydrothermal zone. In the nepheline syenites below the carbonatite, catapleite, eudialyte and eucolite are found in addition to zircon and baddeleyite.

Copper. Most carbonatites contain small amounts of copper, mainly as chalcopyrite. In some complexes copper is present in sufficient quantities to warrant investigation as a commercial source.

Fluorine. Fluorine is usually present in the apatite of these complexes but may occur as fluorite, in some cases in sufficient quantity to warrant extraction.

Geochemical information is thus seen to support the concept of a carbonatite body trapping a crystallising nepheline syenite magma. Elements normally found in traces in magmas are relegated to the hydrous residual fluid at the top of the nepheline syenite body, that is to say at the base of the carbonatite plug. Ample opportunity is provided for these rarer constituents to seek the geochemical environment most suited to their nature. Calciphile elements enter the carbonatite while silica-loving elements migrate to the siliceous wall rock. Pneumatolytic and hydrothermal minerals are emplaced in the wall rock around the carbonatite, reacting there with the minerals already formed by reaction of carbonatite and wall rock. Reaction olivines are serpentinised and the diopsidea replaced by apatite, together with the deposition of hydrobiotites and titanium-rich magnetite.

Geochemically the carbonatites are distinguished from other carbonate rocks by the presence of significant amounts of strontium and barium, as well as juvenile carbon and oxygen.

CONCLUSIONS.

In eastern Uganda there is little evidence that alkaline types have been formed by the mechanism suggested by Daly and Shand. The high-tensioned, low-temperature, potassic-carbonate liquid suggested by von Eckermann (1948) as the original magmatic melt producing the rocks of the Alnö district, could not also produce the vast volume of soda-rich rocks of the volcanic cone.

The following sequence of events is suggested to explain both the structural and petrological relations observed in the field:-

1. The first stage was the injection on a regional scale of normal alkali basalt magma into sialic material. In cases where the magma was emplaced in relatively unstable, tensional areas, sills and dykes were the dominant forms. In their progress into the upper sialic layers, loss, by gravitational means, of olivine, led to the development of more acidic differentiates. Where this basaltic magma was emplaced in relatively stable inter-rift blocks, no such ready means of escape was available and great pressures were built up, enabling the penetration into the upper sialic zones.

2. As this high-tensioned magma approached the surface and the pressure within the magma more nearly equalled that of the superencumbent rocks, a tabular body was formed and an equivalent doming produced at the surface. This relatively rapid elevation of the land surface caused the radial erosion of the uplifted area, with resultant accumulation of coarse sediments at the periphery of the dome.

3. The up-doming of the country rock and the continued magmatic pressures resulted in the drilling of a central diatreme through which the magmatic products could pass. At this stage the gravitational segregation of pyroxene and to some extent plagioclase commenced in the magma chamber.

Pyroxenes and feldspars were explosively withdrawn from the liquid and deposited as crystal tuffs. This segregation caused desilication and nephelinitic types were produced. Where nepheline was also segregated melilite nephelinites were formed.

4. Adiabatic chilling of the lava passing through the conduit and chilling near the mouth of the vent caused by the escape and rapid expansion of magmatic gases, resulted in solidification at the top of the lava column, temporarily inhibiting surface activity.
5. Regeneration of pressure brecciated the solidified plug with the formation of tuffs and agglomerates. Small lava flows followed the brecciation in some cases, but generally the material in the mouth of the vent was rapidly cooled and solidified. The repetition of this cycle, often with relatively long pauses, resulted in the building of a large agglomerate cone with subsidiary intercalated lava flows.
6. In some cases, the rapid and prolonged escape of magmatic gases from the magma chamber during paroxysmal eruptions, rapidly reduced the temperature of the system. This release of pressure caused not only the drastic reduction of temperature due to gas expansion, but also the escape from solution of dissolved carbon dioxide. This resulted in the formation of carbonates and minerals of simple molecular structure as well as their transportation in frothing gas streams to the top of the magma chamber and up the conduit. This material which was of carbonatitic composition, was subjected during its ascent to continued adiabatic chilling and reached a final position near the mouth of the vent as a relatively solid body.
7. In cases where loss of temperature and pressure were of a temporary nature, the lower portion of the obstructing carbonate body was remelted and the upper portion brecciated and ejected as kalkbomben. In the agglomerates of Mount Elgon, some very large fragments of carbonatite have been found.
8. During waning activity, pressures within the system became too low to remove the carbonate body and it remained as an obstruction within the vent, effectively terminating the major extrusive phase. The residual liquid, of phonolitic or trachytic composition, was then trapped within a sealed system and "plutonic" conditions of crystallisation came into operation. At Sukulu, the only silicate rocks penetrating the carbonatite are tinguaites.
9. Continued pressure within the system, while unable to remove the carbonate body, nevertheless exerted considerable pressure upon its base. This pressure, together with the heat provided by the trapped magma, caused partial remelting of the lower carbonates and

and their emplacement around the side of the body and as cone- and collar-sheets penetrating the wall rocks. The effect of these movements on the crystallising magma beneath the plug was the introduction of characteristic fluidal textures in the foyaites and trachytes.

10. At this stage in the development of the hypabyssal complex, very considerable changes appeared in the wall rocks and in the lower portions of the carbonatite plug. The rapid sealing of the system by the withdrawal of carbonatites caused the trapping in the system of a considerable amount of the hyperfusible constituents. The course of crystallisation of the magma trapped below the plug assisted the late stage concentration of hyperfusible constituents and of those elements usually appearing in traces in the magma. Calcium-loving elements such as niobium, zirconium, phosphorus, fluorine, titanium and rare earths of the yttrium and cerium groups entered the carbonatites. Under these hydrous conditions, too, the increased oxidation ratio caused the precipitation of late iron ores, particularly magnetite. The development of hydrous minerals, mainly biotite, phlogopite and amphibole in and around the carbonate body was particularly marked at this stage, and gave rise to deposits of vermiculite. Reaction between the carbonatite and the wall rocks resulted in the production of large bodies of diopside rock and these, together with the vermiculites, apatites and iron ores, make up the characteristic mineral assembly almost invariably found surrounding sōvite plugs. It is stressed that metasomatic exchange and replacement at this time was very extensive and introduced amphiboles are frequently found several miles from the occurrence.

11. In most complexes so far investigated, late-stage ring-subsidence has caused the collapse of the caldera and the partial destruction of the volcanic cone.

12. Any further basaltic material passing into the complex after the collapse of the system, was emplaced into such parts of the complex as offered least resistance and crystallised as dolerites or gabbros in the closed system.

Strauss and Truter (1951) have pointed out the similarity between the anorthosite and magnetite-rich bands in the pyroxenite at Spitskop and those in the Bushveld Igneous Complex. The similarity between the chrome-rich zones in the Bushveld Complex and the generally chrome-rich paragenesis of Alnö Island is significant. It is suggested therefore, that complexes similar in type to the Bushveld Igneous Complex might be genetically related at the surface to multiple outbursts of Elgon type.

The sodic and potassic rocks of western Uganda followed a similar pattern of differentiation. The structural environment was, however, somewhat different and the outbursts manifested themselves not so much as vast volcanoes of the central type, but as smaller and more numerous centres scattered over a wide area. Of particular interest is the development, at the fumerolic stage, of swarms of explosion craters. It is thought probable that crystallisation of sodium chloride, sodium sulphate, sodium bicarbonate, potassium sulphate, calcium sulphate and some calcium carbonate has resulted from the explosive release and frothing of late-stage fumerolic gases through the residual magma. In western Uganda numerous small craters occupied by saline lakes constitute an important source of these salts.

In his review of the problems connected with the African carbonatites, W. Campbell Smith (1956) states that: "any theory to be adequate must answer, in addition to the two main problems, a number of subsidiary ones." (1956, p.212)

It will be seen that the thesis presented here is fully capable of explaining all the points mentioned and these are briefly discussed below.

1. "The very close association of the carbonatites with ijolites and pyroxenites and their perhaps less constant association with nepheline syenites."

This feature forms the basis of the arguments in the preceding pages. The dominant role of ijolite (nephelinite) magma in these volcanoes has been stressed. The ability of nephelinite magma during paroxysmal eruptions to fractionate into carbonatite and peralkaline fractions is the keystone of the present hypothesis. The reaction of calcitic and dolomitic carbonatite with the shattered siliceous wall rock to form pyroxene- and olivine-rich suites is an objective fact and these reactions are encouraged by the accession of hydrothermal emanations from the crystallising peralkaline rocks trapped below the carbonatite plug.

2. "The characteristic alteration, fenitisation, of the rocks surrounding the carbonatite complexes."

It has been pointed out earlier that many of the types considered by von Eckermann to be "fenites" or metasomatically altered country rocks are in fact genetically related members of the magmatic suite.

The main effect of fenitisation in these complexes is the development of pyroxene- and olivine-rich types by the reaction of carbonatite with the wall rock.

The mechanical fragmentation of the wall rock close to the carbonatite and the incorporation and digestion of the xenoliths by the sövite caused silica dilution and some homogeneous saturated or even under-saturated types were formed.

The introduction of hydrous minerals into the wall rock after the emplacement of the carbonate and the establishment of a distinct hydrothermal stage might also be described as fenitisation effects.

3. "Their content of characteristic "essential" minerals (apatite, magnetite, mica and vermiculite) and of rare "accessory" minerals, some carrying niobium and other rare earths."

The withdrawal of the carbonate fraction and its emplacement at the head of the magma column above the peralkaline residual liquid provides an ideal environment for the concentration of the rarer elements. The elements characterising the minerals introduced into the carbonatites after emplacement and into the wall rock, are those which tend to be relegated to the latest fluid fraction of a crystallising magma.

4. "The complex structure of some central carbonatite masses often in the form of successive rings differing in texture and sometimes also in composition, the carbonate then ranging from calcite to ankerite or dolomite and to siderite in that order."

The withdrawal of the carbonatite fraction and the establishment of a specific gravity gradient was followed by continued upward pressure which caused the telescoping of the various types of carbonate, the lower ones intruding the upper ones with the development of flow structures, ring dykes and cone sheets.

5. "Explosive activity, sometimes on a large scale, at some carbonate vents".

Paroxysmal eruption has been shown to be an essential prerequisite to the formation of a carbonate fraction in the hypothesis presented.

6. "Later dykes and veins of carbonatite cutting (the) central carbonate and associated alkaline rocks; and sometimes more than one period of carbonatite intrusion."

This has in part been dealt with in 4. The periodicity of vulcanism in Elgon type volcanoes is a fundamental precept in the hypothesis and is the reason why so many different rock types may be produced in a single volcano. The great variation in P-T-X conditions

in the magma as a result of this periodicity is a controlling factor in the petrogenesis. These conditions are different for each of four possibilities:

- (a) When the vent is open.
- (b) When the vent is closed.
- (c) When pressure is building up.
- (d) When pressure is rapidly reduced.

The course of crystallisation in the magma is different for each case.

7. "The great range in diameter of the vents from a few dozen feet to three or four miles."

While carbonatites may indeed occupy a large area, it is clear from the structural mapping of Sukulu that the actual vent was never very large. The great extent of the sövites results from the continued pressure from below the plug which caused the intrusion of the carbonatite into the wall rock surrounding the vent. This is evidenced by the presence of wall rock fragments within the carbonatite.

In some cases, as at Sukulu and Homa, subsidiary vents have been developed near the original conduit with consequent enlargement of the carbonatite area. Satellite vents such as Tororo(Sukulu), Theno(Toror) and Budeda(Elgon) have been produced some distance from the main vent.

It has been seen that complexes of apparently widely differing rock assemblages would be revealed by erosion to varying levels within the same complex and it is considered that the processes mentioned earlier are capable of producing the rock types found in most alkaline complexes in the East, Central and South African zone.

APPENDIX.DESCRIPTION OF ROCKS INDICATED BY NUMBERS ON FIGURES 5, 6 & 7.Figure 5.

1. Beforsitic alnöite, No. 63, Alnö, Sweden.
2. Alvikitic alnöite, No. 64, Alnö, Sweden.
3. Kimberlitic melanite-quachitite, No. 80, Alnö, Sweden.
4. Alvikitic alnöite, No. 65, Alnö, Sweden.
5. Alnöite, No. 68, Alnö, Sweden.
6. Porphyritic alnöite, No. 70, Alnö, Sweden.
7. Alnöite, No. 71, Alnö, Sweden.
8. Alvikitic alnöite, Alnö, Sweden.
9. Alvikitic alnöite, No. 72, Alnö, Sweden.
10. Alnöite-porphyrite, No. 74, Alnö, Sweden.
11. Vesicite, Vesec, Bohemia.
12. Jacupirangite, No. 38, Alnö, Sweden.
13. Turjaite, Turja, Kola peninsula, U.S.S.R.
14. Melilite-biotite rock, Isle Cadieux, Quebec, Canada.
15. Katungite, Chamakumba crater, Ankole, Uganda.
16. Bergalite, Elgon, Uganda.
17. Melanite-jacupirangite, No. 37, Alnö, Sweden.
18. Melilite basalt, Hohenstoffeln, Baden, Germany.
19. Melilite mafurite, Kabirenge, Ankole, Uganda.
20. Modlibovite, Modlibov, Bohemia.
21. Melilite basalt, Spiegel river, Cape Colony.
22. Quachitite, Hot Springs, Arkansas, U.S.A.
23. Medium-grained turjaite, Turja, Kola peninsula, U.S.S.R.
24. Melanite-melteigite, No. 30, Alnö, Sweden.
25. Melilite-nephelinite, Napak, Uganda.
26. Pyroxenite, No. 35, Alnö, Sweden.
27. Uncompahgrite, Gunnison county, Colorado, U.S.A.
28. Melilite-leucite-nephelinite, Ngoma crater, Tanganyika.
29. Jacupirangite melanite-melteigite, No. 34, Alnö, Sweden.
30. Melilite basalt, Howenegg, Baden, Germany.
31. Melilite-nephelinite, near Alekilek, Napak, Uganda.
32. Pyroxenite, Elgon, Uganda.
33. Melilite basalt, Boring, Bermuda.
34. Nepheline-hauynite-alnöite, Fergus county, Montana, U.S.A.
35. Pyroxenite, No. 33, Alnö, Sweden.
36. Nephelinite, Maluziguti ridge, Toro, Uganda.
37. Biotite-leucitite, Visoke, Belgian Congo.
38. Nephelinite, Etinde volcano, British Cameroons.
39. Melilite ankaratrite, Elgon, Uganda.
40. Leucitite, Katerusi, Belgian Congo.
41. Melanite micromelteigite, Melteig, Norway.
42. Nephelinitic augitite, Elgon, Uganda.
43. Melilite ankaratrite, D. 1681, Elgon, Uganda.
44. Melanephelinite, Napak, Uganda.
45. Melilite ankaratrite, Endebess, Elgon, Kenya.

46. Missouriite porphyry, British Columbia.
47. Arfvedsonite micromelteigite, Kola peninsula, U.S.S.R.
48. Olivine melanephelinite, Napak, Uganda.
49. Melilite-nephelinite, Elgon, Uganda.
50. Phonolitic etindite, Elgon Uganda.
51. Coppaelite, Rieti, Italy.
52. Melteigite-porphyry, Alnö, Sweden.
53. Nephelinite, Elgon, Uganda.
54. Melanephelinite, DGS 924, Elgon, Uganda.
55. Wesselite, Wesseln, Bohemia.
56. Tannbuschite, Tsao-shih-er, Manchuria.
57. Farrisite, Kjose, Oslo, Norway.
58. Nephelinite, Katzenbuckel, Odenwald.

Figure 6.

1. Carbonatite, Napak, Uganda.
2. Limestone, Sukulu, Uganda.
3. Beforsite, No. 99, Alnö, Sweden.
4. Alkorthosite-beforsite, No. 98, Alnö, Sweden.
5. Strontianite-bearing biotite-beforsite, No. 97, Alnö, Sweden.
6. Quartz-beforsite, No. 96, Alnö, Sweden.
7. Riebeckite-beforsite, No. 95, Alnö, Sweden.
8. Biotite-beforsite, No. 94, Alnö, Sweden.
9. Quartz-alkorthosite-beforsite, No. 91, Alnö, Sweden.
10. Picritic biotite-beforsite, No. 88, Alnö, Sweden.
11. Orthosite-beforsite, Snoskar, No. 87, Alnö, Sweden.
12. Biotite-melilite-beforsite, nr. Pottang, No. 85, Alnö, Sweden.
13. Orthosite-beforsite, Rasta, No. 84, Alnö, Sweden.
14. Melanite-nephelinite, No. 61, Alnö, Sweden.
15. Nephelinite, Etinde volcano, Kamerun.
16. Melanite-micromelteigite, Kerimasi, Tanganyika.
17. Calcitic analcite-tinguaite, No. 59, Alnö, Sweden.
18. Nephelinite, Omimi, Otago, New Zealand.
19. Biotite-aegirine-foyaite, Nkalonge, Nyasaland.
20. Melanite-juvite, No. 24, Alnö, Sweden.
21. Foyaite-porphyry, No. 58, Alnö, Sweden.
22. Foyaite-porphyry, No. 57, Alnö, Sweden.
23. Phonolite, Gortex, Elgon, Uganda.
24. Borolanite, Ross-shire, Scotland.
25. Tinguaitite, No. 56, Alnö, Sweden.
26. Alkorthosite-beforsite, nr. Bergesforden, No. 81, Alnö, Sweden.
27. Foyaite-porphyry, No. 55, Alnö, Sweden.
28. Foyaite-porphyry, No. 54, Alnö, Sweden.
29. Juvite, Fen district, Norway.
30. Average phonolite, Toro, Uganda (average 10 samples.)
31. Itsindrite, Madagascar

32. Biotite bearing aegirine-cancrinite microfoyaite, Mauze Hill, Nyasaland.
33. Phonolite, Siroko, Elgon, Uganda.
34. Nepheline syenite, Serra de Monchique, Portugal.
35. Biotite-bearing aegirine-augite foyaite, Mauze Hill, Chilwa Series, Nyasaland.
36. Biotite-aegirine microfoyaite, Mauze Hill, Nyasaland.
37. Aegirite-mica foyaite, Brathagen, Lougandal, Norway.
38. Phonolite, Mauze Hill, Nyasaland.

Figure 7.

1. Limestone plug, Sukulu, Uganda.
2. Alvikite, No. 114, Alnö, Sweden.
3. Crushed biotite alvikite, No. 112, Alnö, Sweden.
4. Corundum-bearing alkorthosite-biotite =alvikite, No. 106, Alnö, Sweden.
5. Corundum-bearing alkorthosite-picrite alvikite, No. 105, Alnö, Sweden.
6. Biotite alvikite, No. 103, Alnö, Sweden.
7. Alvikitic biotite orthosite, No. 101, Alnö, Sweden.
8. Nephelinite, caldera rim, Elgon, Uganda.
9. Covite, Magnet Cove, Arkansas, U.S.A.
10. Malignite, Kruger alkaline body, British Columbia.
11. Cancrinite syenite, Budeda complex, Elgon Uganda.
12. Gauteite (type) Muhlorzener forsthaus, Bohemia.
13. Felspathic intrusive, Dos village, Nyasaland.
14. Arsoite (cinimite) Ischia, Italy.
15. Orthoclase rock, Tundula Hill, Nyasaland.
16. Arsoite(trachyte), Ischia, Italy.
17. Pulaskite, Fourche Mountains, Pulaski Co., Arkansas, U.S.A.
18. Syenite, Leeufontein, South Africa.
19. Fenite, Melteig, Norway.
20. Solvsbergite, Salambidwe, Nyasaland.
21. Solvsbergite, Salambidwe, Nyasaland.
22. Fenite, Fen, Norway.
23. Hornblende solvsbergite, Oslo, Norway.
24. Solvsbergite, Axum, Abyssinia.
25. Trachyte, Bupoto, Elgon, Uganda.
26. Soda syenite, Iron Hill, Colorado, U.S.A.

ACKNOWLEDGEMENTS.

A large number of geologists have assisted the author during field visits over the past ten years and sincere thanks are extended to them for their invaluable advice and discussions.

Particular thanks are due to Dr. K.A. Davies, C.M.G., O.B.E., Professor F. Walker, Professor E.S.W.Simpson, Mr. H.G.C. Vincent and Dr. M. Mathias, who have supervised and encouraged the work since 1949.

Mr. A. Cawley, Director of the Geological Survey, Uganda, is thanked for permission to submit this paper as a thesis.

The author is also indebted to J.Genis and C. Key, research students at the University of Capetown, for their assistance during the final preparation of the paper.

REFERENCES.

1. Bowen, N.L., 1928. "The evolution of the Igneous Rocks." Princeton Univ. Press.
2. du Bois, C. "The Geology of Toror Hills, Karamoja, Uganda." Ph. D. Thesis, London University.
3. Davies, K.A., 1952, "The building of Mt. Elgon (East Africa)" Geol. Surv. Uganda, Mem. VII.
4. Dixey, F., Campbell Smith, W. & Bisset, C.B., 1935. "The Chilwa Series of Southern Nyasaland" Geol. Surv. Nyasaland, Bull. 5.
5. von Eckermann, H., 1918. "The Alkaline district of Alnø Island". Sverigea geol. unders., Ser. Ca No. 36.
6. Goldschmidt, V.M. 1954, "Geochemistry" Oxford Clarendon Press.
7. Holmes, A., 1930 "Petrographic methods & Calculations", London, T. Murby & Co.
8. James, T.C. 1956. "Carbonatites & rift valleys in East Africa" cyclostyled report, Geol. Surv. Tanganyika.
9. Johannsen, A., 1938, "A descriptive Petrography of the Igneous Rocks". Vol. IV, University of Chicago Press.
10. King, B.C., 1949 "The Napak area of Southern Karamoja, Uganda" Geol. Survey, Uganda, Mem. V.
11. Korn, H. & Martin, H., 1954 "The Messum Igneous Complex in South West Africa." Trans. Geol. Soc. S. Africa LVII, 83-124.
12. Key, C.A. Ph. D. Thesis in preparation, Univ. of Capetown.
13. Larsen, E.S., 1942, "Alkaline rocks of Iron Hill, Gunnison VCo. Colorado." U.S. Geol. Surv, Prof. paper, 197 A.
14. Mathias, M., 1956, "The Petrology of the Messum Igneous Complex South West Africa." Trans. Geol, Soc. S. Africa, LIX 1 - 35.
15. Morey, G.W. & Heischer, M. 1940, Bull. Geol. Soc. America, 51, 1035 - 1038.
16. Nockolds, S.R., 1954 "Average Chemical compositions of some Igneous Rocks." Bull. Geol. America, 65 1007-1032.

17. Odman, O.H. 1930. "Volcanic Rocks of Mt. Elgon in British East Africa." Geol. Foren. Forhandl., Bd 52 H4, pp 455-537.
18. Saggerson, E.P., 1953, "The Carbonatites of Homa Mountain" Proc. VI Interterr. Geol. Conf. Entebbe.
19. Shackleton, R.M. 1944, "Report on the geology of the area around Malakisi, North Kavirondo". Report Geol. Surv. Kenya.
20. Shackleton, R.M. 1951 "A contribution to the Geology of the Kavirondo Rift Valley" Quart. Journ. Geol. Soc. London, CVI, 345 - 392.
21. Simpson, E.S.W., 1954 "The Okonjeje igneous Complex, South West Africa". Trans. Geol. Soc. S. Africa, LVII, 125 - 172.
22. Strauss, C.A. & Truter, F.C. 1951, "The Alkali Complex at Spitskop, Sekukuniland, Eastern Transvaal". Trans. Geol. Soc. S. Africa, LIII 81 - 130.
23. Deans, T. and McConnell, J.D. 1955, "Isokite, a new mineral from Northern Rhodesia" Mineralogy Mag. V 30.
24. Shand, S.J. 1921 "The Nepheline rocks of Sekukuniland" Geol. Soc. S. Africa Trans. v 24.
25. Shand, S.J., 1931 "The Granite-syenite limestone complex of Palabora, E. Transvaal and Associated apatite deposits". Geol. Soc. S. Africa Trans. v. 34.
26. Gevers, T.W., 1949 Vermiculite at Loolekop, Palabora, North Eastern Transvaal: Geol. Soc. S. Africa Trans. Vol. 51.
27. Holmes, A. & Harwood, H.F., 1937, "The Volcanic area of Bufumbira" Geol. Surv. Uganda Mem. 3.
28. du Toit, A.L., 1931 "The Genesis of the pyroxenite-apatite rocks of Palabora, Eastern Transvaal" Geol. Soc. S. Africa Trans. v. 34.
29. Fockema, R.A.P. 1953 "Geology of the area around the confluence of the Elands & Crocodile Rivers." Geol. Soc. S. Afr. Trans. V. 55.
30. Fawley, A.P. & James T.C., 1955, "A Pyrochlore carbonatite Southern Tanganyika" Econ. Geology v. 50.
31. Baertschi, P. 1951, "Relative abundances of oxygen and carbon isotopes in carbonate rocks." Nature 168.

32. Campbell-Smith W., 1956 "Problems of African Carbonatites" Q.J.G.S. vol. 112.
33. Pecora, W.T. 1956. "Carbonatites". Bull. Geol. Soc. America vol. 67, part 2.
34. du Toit, A.L. 1937 "Our Wandering Continents" Oliver & Boyd.
35. Garson, M.S. & Campbell-Smith, W. "The Chilwa Series" Memoir I Geol. Surv. Nyasaland.
36. Dixey, F. 1956, "The East African Rift System". Col. Geol. & Min. Rec. Bull. supp. Vol. I.
37. Brouwer, H.A. 1957, Ph. D. Thesis Univ. of Cape Town.
38. Faivre. 1946. /Crystallographie Etude par diffraction des rayon X des carbonates mixte de calcium et de barium." Hebdom des Seances de l'acad. de Sci. C.R. v.222.
39. Macdonald, G.A. "The Hawaiian Petrographic Province". Bull. Geol. Soc. America. vol. 60.

## THE ORIGIN OF CARBONATITES AND RELATED ALKALINE ROCKS

By C. E. WILLIAMS

### ABSTRACT

A BRIEF REVIEW is given of the rock types and structures found in alkaline ring complexes and volcanoes of the Elgon type. The formation of undersaturated magma is attributed to the segregation of pyroxenes and plagioclase from a parent basaltic magma. Nephelinite is the type most commonly produced and constitutes the main lava flows of these volcanoes. The development of rocks containing melilite, melanite and primary calcite from nephelinitic magma is shown to be the result of the relative increase of lime, together with desilication in the residual liquid during the crystallisation and segregation of nepheline.

Chemical and arithmetical evidence is given to show that the removal of beforstic carbonatite from nephelinite magma leaves a phonolitic residual liquid, while the removal of iron-rich alvikitic carbonatite leaves a trachytic residuum. The mechanism of carbonatite formation is thought to be the exsolution and upward migration of bubbles of carbon dioxide during paroxysmal eruptions, the ascending gas chilling the magma and reacting with the dissolved oxides of calcium, magnesium, iron, manganese, barium and strontium to form carbonates. The rising gas streams serve to concentrate the carbonates by flotation.

### INTRODUCTION

THE ALKALINE CENTRES of eastern Africa constitute a distinct petrographic province and are clearly of similar origin, though they differ widely in age. The regional alignment of the various complexes, from the Sudan to the Transvaal, closely approximates to the pattern of rifting, and it is probable that volcanic activity has accompanied the rifting and dates from the earliest movements.

The petrographic unity of the various centres is maintained in spite of the diversity of the associated country rocks. The obvious consanguinity of the complexes renders it desirable that the members of the province should be considered as a whole rather than as separate entities, and any hypothesis put forward must be competent to explain all the observed phases.

Since the alkaline complexes differ considerably in age, they have been denuded to varying depths. This factor is of value in enabling the detailed examination, not only of the surface expression of the vulcanism, but also of deeper levels, extending to the roots of the associated hypabyssal complexes. Late stage subsidence and faulting provide much evidence regarding the nature of the plutonic complexes below.

In any consideration of the nature and origin of the carbonatites, it is important to realise that the rocks exposed in a particular alkaline complex represent only part of the problem to be elucidated. The problem is essentially three-dimensional and the types present at various levels within the same complex are different, although linked both structurally and genetically.

#### EXAMPLES OF ALKALINE COMPLEXES ERODED TO VARYING DEPTHS

The following alkaline occurrences exemplify the relation between structure and the petrographic types present at different erosion levels:—

*Mount Elgon, eastern Uganda* (Davies, 1952).—Mount Elgon is a volcanic cone, 50 miles in diameter at the base, and stands 10,000 feet above the surrounding plain. It is composed predominantly of agglomerates and tuffs, while the most common lavas are nephelinites. Also found on Elgon are melilite nephelinites, olivine nephelinites, melanephelinites, ankaratrites, tannbuschites, melilite nepheline basalts and melilite ankaratrites. Among the minor flows on Elgon there are phonolites, trachytes and trachy-andesites. Some plugs, sills and dykes of ijolite pegmatite, tinguaitite and members of the alnöite-bergalite series are present. The Tertiary pre-volcanic sediments as well as the nephelinite agglomerates contain numerous fragments of carbonatite (Shackleton, 1944).

*Napak, eastern Uganda* (King, 1949).—Napak represents the eroded remnants of a dominantly agglomeratic volcano similar to Mount Elgon. Nephelinite is again the most common lava. Also occurring in the cone are melanephelinites, olivine nephelinites, olivine melanephelinites, melilite nephelinites and olivine melilite nephelinites. Dykes of alkaline lamprophyre and ijolite are found. The original conduit of the volcano is now occupied by carbonatite, surrounded by a narrow zone of ijolite.

*Kerimasi, Tanganyika* (James, 1956).—Kerimasi is a volcanic pile in the Gregory Rift Valley consisting of stratified tuffs and agglomerates in which the fragments are mainly nephelinitic. Carbonatite is exposed on the crater rim. Thin beds of limestone are found on the slopes of the cone and in the eastern sector of the mountain the limestone is fine-grained and contains numerous angular fragments, up to 2 inches in diameter, of crystalline carbonatite. Close to Kerimasi is the active volcano Oldonyo Lengai which also produces nephelinitic material, mainly as bombs and tuff fragments. During a recent eruption, material consisting of calcite and sodium salts was ejected.

*Alnö Island, Sweden* (von Eckermann, 1948).—The alkaline complex of Alnö Island is considered by von Eckermann to be part of a volcanic diatreme and he classifies the rocks found there as follows:—

1. *Calcite-carbonatitic*—sövites (abyssal) and alvikites (hypabyssal).
2. *Dolomite-carbonatitic*—beforsites (hypabyssal).

3. *Alkali-syenitic*—juvites, ijolites, malignites, melteigites (abyssal) and foyaite porphyrites, tinguaites, nephelinites, melteigite porphyrites (hypabyssal).

4. *Ultrabasic*—melanite-biotitic: melanite ouachitites (hypabyssal); pyroxene-biotitic: ouachitites (hypabyssal); pyroxenitic: pyroxenites, jacupirangites (abyssal); peridotitic: kimberlites (hypabyssal); and melilitolitic: alnöites (hypabyssal).

5. The *quartz-syenitic* and *nepheline-syenitic* fenite paragenesis.

*The Chilwa Series, Nyasaland* (Dixey *et al.*, 1935).—The Chilwa Series comprises a group of vents filled mainly by limestone associated with syenites and nepheline syenites. In some cases, agglomerates, felspathic intrusives and breccias are present in the vents. The presence of nephelinite, olivine nephelinite, ijolite, phonolite, tinguaites, sölvbergite, foyaite, trachyte, orthoclase rock and dolerite has been recorded.

*Spitskop, Sekukuniland, South Africa* (Strauss and Truter, 1951).—The following rock types are recorded as surrounding the carbonatite at Spitskop: red and white umptekites; fayalite diorite and theralite; ijolite, urtite and melteigite; jacupirangite; nephelinised biotite pyroxenite; and foyaite. The conesheets of foyaite arise from a point directly below the central carbonatite, and erosion of the complex to a lower level would probably reveal an alkaline complex centred by foyaite. Of late formation are syenitic conesheets and two small plugs of aphanitic, amygdaloidal soda basalt.

*The Foyaite-gabbro association*.—The occurrence of gabbro, nepheline gabbro and diabase is frequently recorded in complexes centred by nepheline-syenite and syenite, and rather less frequently in complexes centred by carbonatite. In the former group may be mentioned the Messum (Korn and Martin, 1954, and Mathias, 1956) and Okonjeje (Simpson, 1954) complexes of South West Africa, the Mount Dromedary complex of New South Wales (Larsen, 1942) and the Chibina tundra area, Kola. In the second group are Iron Hill, Colorado, and Spitskop, Sekukuniland, South Africa.

An important consideration in any attempt to discover the origin of these rocks is the structural environment in which they occur. It is clear that they are associated with volcanic activity and can usually be related to specific centres. Regionally the centres have a linear distribution and occur along the more stable inter-rift blocks.

Mount Elgon, which is the youngest of the centres in Uganda, is a volcano of the central type, possessing the remnants of a caldera and some evidence of caldera collapse. Both Mount Elgon and Napak have pre-volcanic sediments below the agglomerate cone and Napak is situated on a conspicuous dome, 10 miles in diameter, which was formed prior to eruption. The elevation of this dome caused the rapid erosion of the central portion of the raised area, resulting in the peripheral accumulation of coarse sediments. The doming suggests the emplacement of a tabular body at no great depth, immediately prior to the drilling of the diatrema.

In this connection it is interesting to note that the alkaline complexes at Assynt and Mount Dromedary are thought to be in the form of laccoliths, while in the Ice River complex, Alberta, both stock and laccolith are present (Larsen, 1942). Ring and radial faulting associated with the late stage caldera collapse and carbonatite emplacement are found in most complexes.

An alkaline complex, therefore, in which carbonatite has played a genetic role may, depending upon the degree of erosion, be represented as an Elgon type volcano, a ring complex centred by carbonatite, a ring complex centred by nepheline syenite or trachytic rocks (with or without surrounding gabbroic rocks), or a layered laccolithic complex.

## PETROGENESIS

### THE DEVELOPMENT OF IJOLITIC TYPES

N. L. Bowen (1928) has shown that when a mineral crystallises from a magmatic liquid, it may be either segregated or at a later time react with the residual liquid to form another mineral in a reaction series. The permanent withdrawal of a mineral causes a relative increase or decrease in the percentage of any particular oxide in the residual magma depending on whether the mineral contains less or more of that oxide than the parent magma. If olivine, which possesses a lower percentage of silica than the parent magma, is segregated, there is an enrichment in silica in the residual liquid (fig. 1).

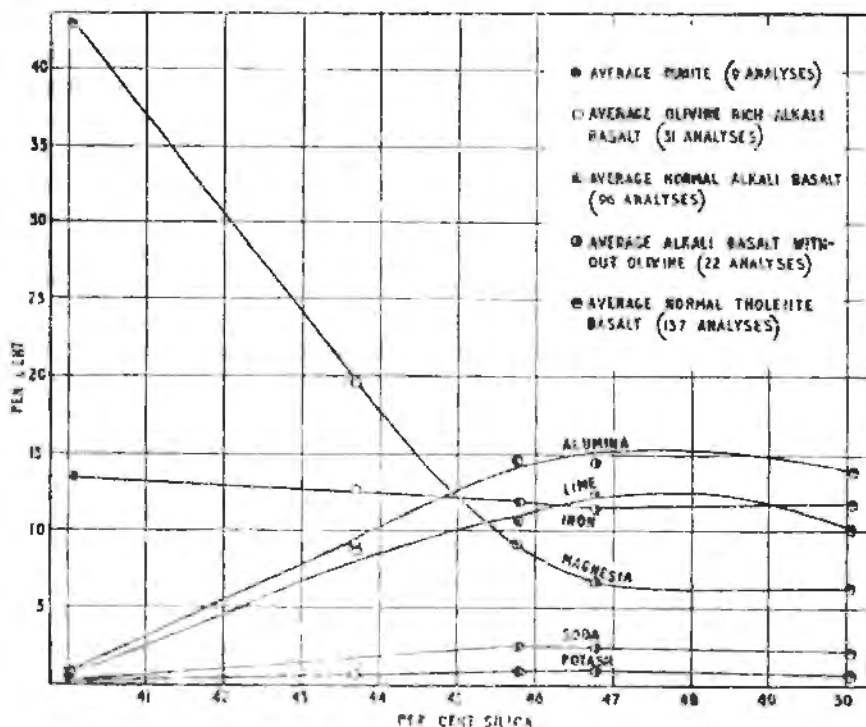


FIGURE 1. Variation diagram showing the effect of the segregation of olivine from normal alkali basalt magma. Average analyses after Nockolds (1954).

The nature of the residual magma during the crystallisation of olivine, pyroxene and plagioclase from basaltic liquid, depends primarily on the degree of permanent segregation or fractionation of the molecules involved in the crystallisation. These trends are illustrated in figures 1, 2 and 3. The three variation diagrams represent the extreme cases and indicate that nepheline-bearing rocks may be produced through the segregation of pyroxenes from a normal alkali basalt magma (fig. 2) and that other felspathoidal types could result from the segregation of calcic plagioclase (fig. 3). Where olivine is segregated early, this desilicatory trend is prejudiced (fig. 1).

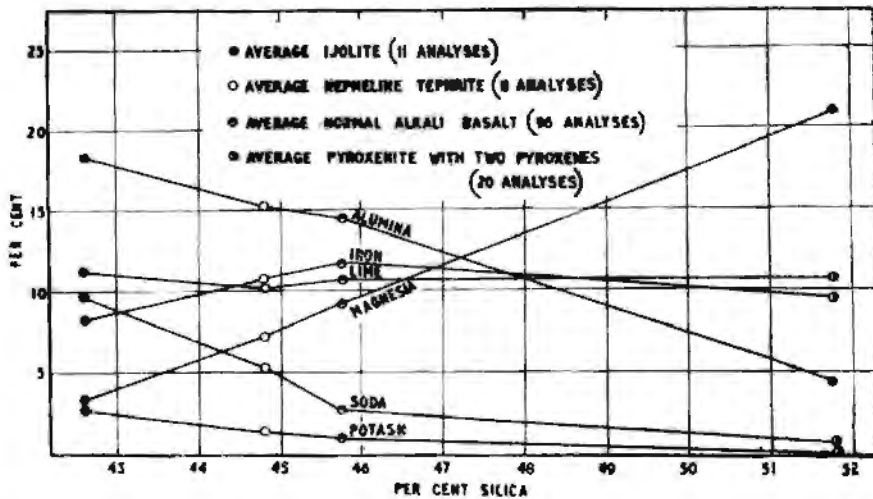


FIGURE 2. Variation diagram illustrating the desilication produced by the removal of pyroxenes from normal alkali basalt magma. Average analyses after Nockolds (1954).

Although both early pyroxenes and early plagioclases are normally rich in lime, the percentage of this oxide in these minerals is not notably greater than that in basaltic magma. Consequently the loss of lime to the residual liquid is not very great in either case.

Very little soda or potash is removed during the crystallisation of pyroxene and there is a steady relative increase in alkalis in the residual liquid during the course of segregation. The plagioclases which are segregated to form anorthosites, contain an appreciable amount of soda and practically no potash and, as a result, there is a significant relative increase of the latter oxide in the residual liquid. This is important since in the desilicated milieu achieved by the removal of calcic plagioclase, leucite is able to form. In addition, the marked relative increase in magnesia assists in the formation of olivines.

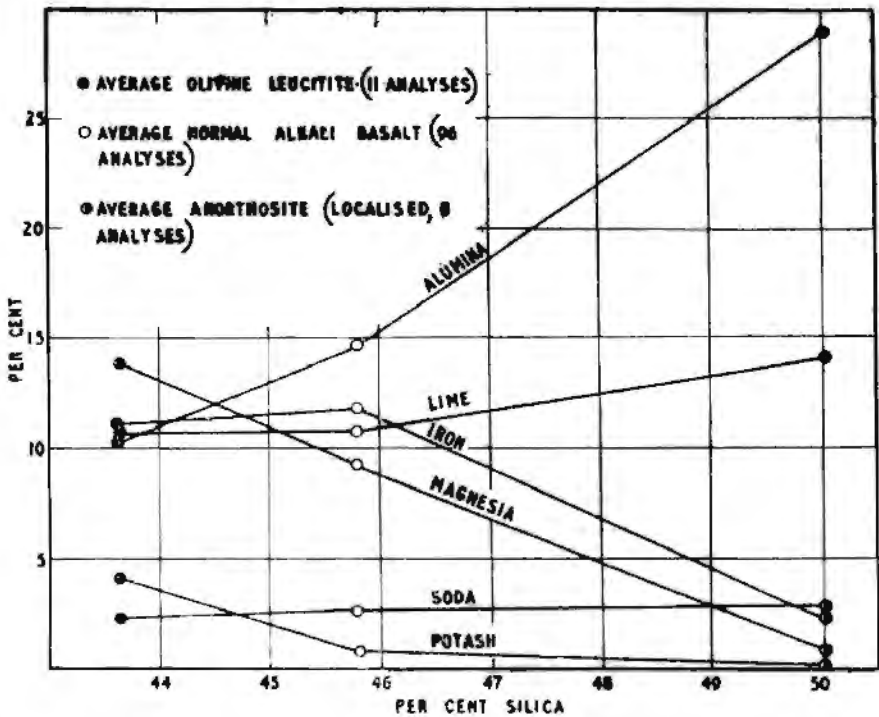


FIGURE 3. Variation diagram showing the trend of differentiation resulting from the removal of calcic plagioclase from a normal alkali basalt magma. Average analyses after Nockolds (1954).

#### THE DEVELOPMENT OF MELILITE ROCKS

Although nephelinites predominate in the lava flows of Mount Elgon, rocks containing melilite are also found. During the crystallisation of nepheline in a nephelinitic (ijolitic) magma, silica, alumina, soda and some potash are subtracted from the liquid. In most complexes of this type, rocks suggesting the segregation of nepheline are present. The urtites are thought to be members of this group.

Figure 4 shows very clearly the trend of the residual liquid when nepheline is segregated from an ijolitic magma. Since the silica percentage of nepheline exceeds that of most ijolites, further desilication is caused. At the same time there is a marked relative increase in those oxides not involved in this crystallisation, i.e. calcium, magnesium, titanium, iron and phosphorus. Minor constituents such as chromium and barium become progressively more significant.

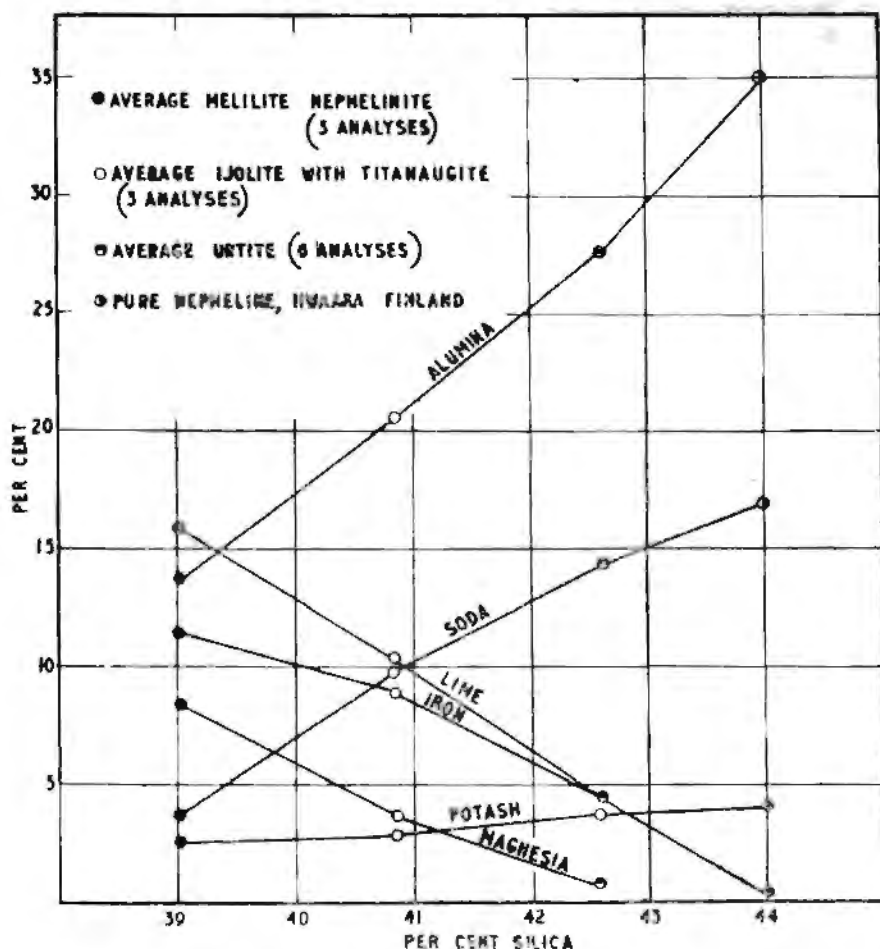


FIGURE 4. Variation diagram illustrating the desilication caused by the segregation of nepheline from an ijolite magma. Average analyses after Nockolds (1954). Nepheline from ijolite, Iiwaara, Finland. (Johannsen, 1938).

The desilication resulting from the segregation of nepheline combined with the relative increase of lime in the residuum results in the formation of a series of lime silicates which require progressively less silica. This produces a series of minerals of decreasing  $\text{SiO}_2:\text{CaO}$  ratio:—

Melilite	...	...	1.13 : 1
Melanite	...	...	1.10 : 1
Iiwaarite	...	...	0.80 : 1
Calcite	...	...	0.00 : 1

At the same time, titaniferous augite, perovskite, apatite and titaniferous iron ore are formed and the resulting rocks form the nephelinite-melilite nephelinite series, which is represented by the central group in figure 5 (A-B).

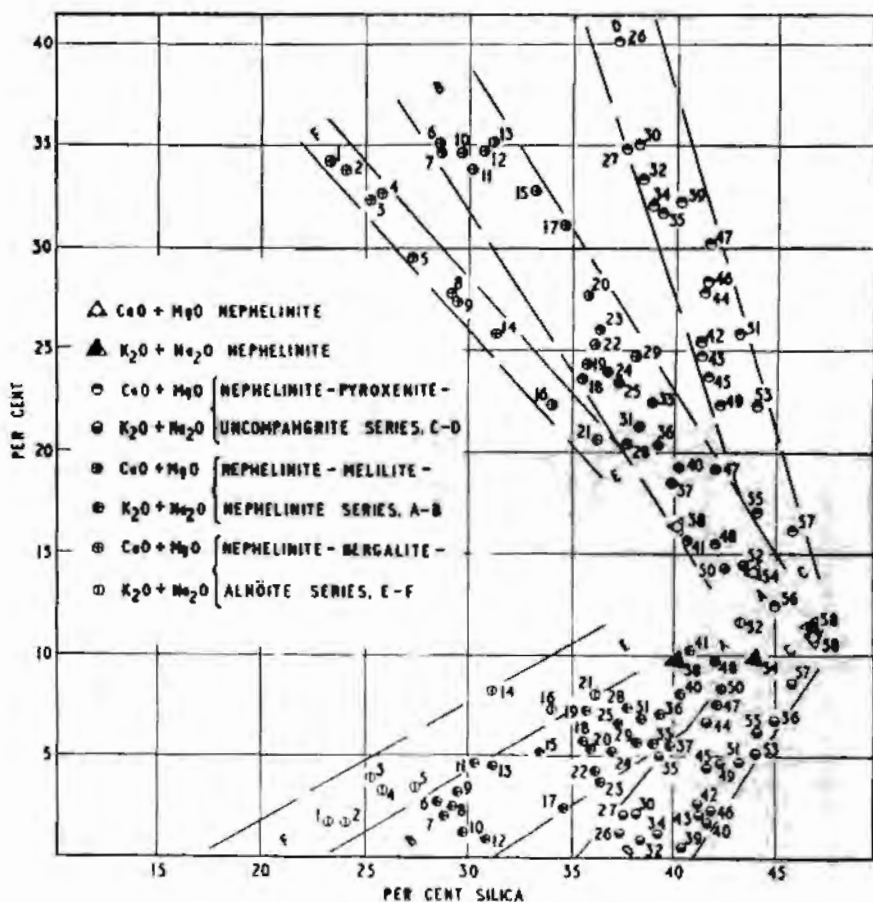


FIGURE 5. Diagram showing the trends of differentiation originating from nephelinitic magma. The rocks indicated by numbers on the diagram are listed in the appendix, p. 29.

The subtraction of nepheline from an ijolitic magma causes enrichment in lime, iron and magnesium in a silica-poor residuum, and leads to the formation of olivines, initially ferro-magnesian and later the lime-magnesian olivine, monticellite. Segregation of these olivines effects the establishment of two further series, i.e. those rocks containing excess olivine (and pyroxene), the nephelinite-melanephelinite-ankaratrite-uncompahgrite series (C-D, fig. 5), and the residual rocks, the alnöite-bergalite series (E-F, fig. 5). The more extreme members of these groups contain melilite, melanite, calcite and monticellite. The crystallisation of monticellite is thus the result of extreme desilication together with relative lime and magnesium enrichment. Closely related to these rocks and also the result of desilication and relative enrichment in iron, titanium, chrome and vanadium, are the jacupirangites. Chemically the kimberlites belong to this series. The residual series is characterised by the presence of perovskite, chromite and barite.

It is possible that some of the alvikitic and beforsitic alnöites, which appear to be the end members of this series, result from the squeezing out of the residual interstitial fluid. It is likely that these rocks grade in depth into normal alnöites.

#### THE ORIGIN OF THE CARBONATITES

The main trend of differentiation described so far has been towards a desilicated residuum. This, however, is not the only process operating in volcanoes of Elgon type, since phonolites and, more rarely, trachytes have at various times appeared amongst the lavas of Mount Elgon. The deep-seated equivalents of these rocks frequently occupy the conduits of ancient volcanoes. It is therefore necessary to consider by what mechanism a volcano producing nephelinitic types could evolve a phonolitic differentiate.

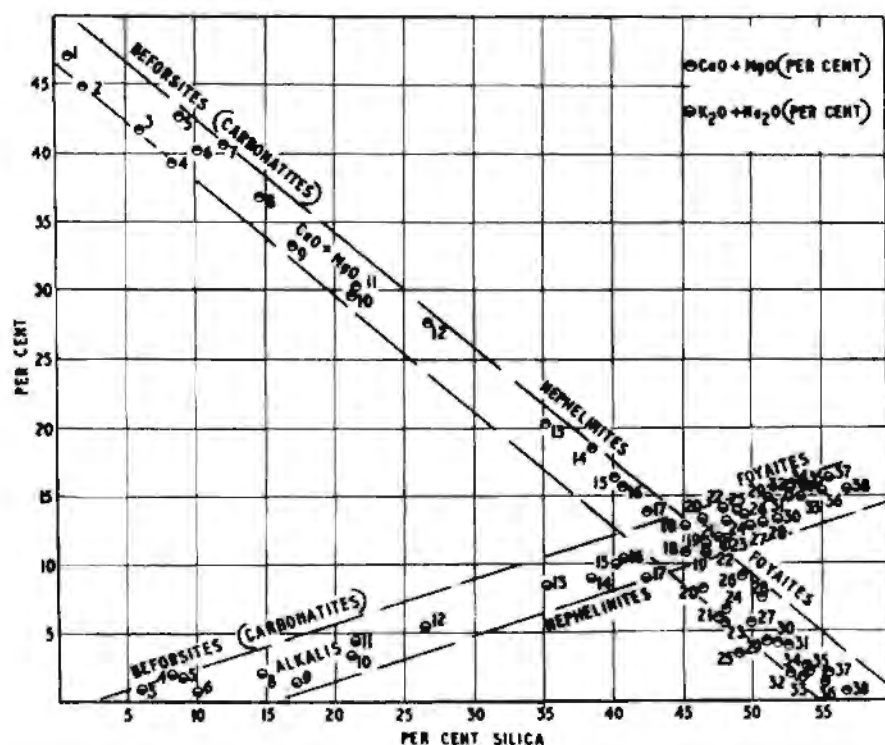


FIGURE 6. The beforsite-nephelinite-foyaite series. The rocks indicated by numbers on the diagram are listed in the appendix, p. 30.

The solution to the problem lies in the chemical nature of nephelinitic magma, which is capable of division into two portions. Depending upon the P-T-X conditions at the time of fractionation, these portions are either beforsite (magnesian carbonatite) and phonolite or alvikite (calcitic carbonatite) and trachyte. This statement is substantiated in the first instance by the chemical variation diagrams (figs. 6 and 7) which depict the

beforsite-nephelinite-phonolite (foyaite) series and the alvikite-nephelinite-trachyte series respectively. The members of these series bear a straight-line, genetic relationship to each other. Holmes (1930, page 446) states that "the fact that even with three analyses a straight-line diagram is achieved indicates that the rocks concerned are related in an unusually simple way". Figure 6 is constructed from 38 and figure 7 from 26 analyses. These two variation diagrams strongly contest the suggestion that alkaline complexes originate through limestone syntexis.

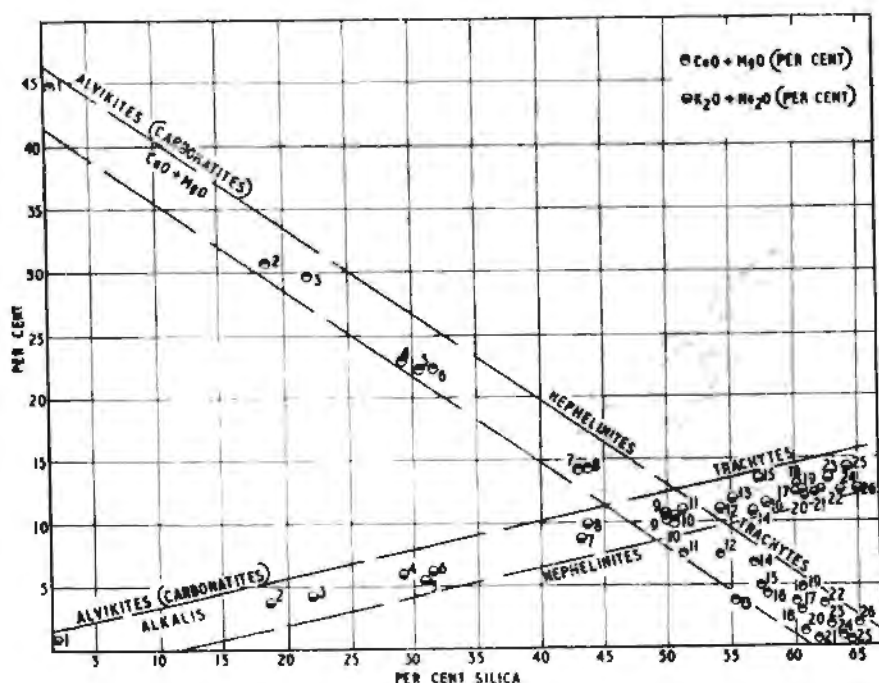


FIGURE 7. The alvikite-nephelinite-trachyte series. The rocks indicated by numbers on the diagram are listed in the appendix, p. 30.

Arithmetical proof can be adduced that nephelinite magma is capable of division into either beforsite and phonolite or iron-rich alvikite and trachyte magmas. In table 1, typical Uganda rocks are considered. Columns 1 and 2 show that, in the differentiation from nephelinite to phonolite magma, there is a marked decrease in iron, magnesia and lime and a relative increase in silica, alumina and alkalis. Similarly, in the differentiation from nephelinite to trachyte there is a significant loss of iron, magnesia and lime and a corresponding increase in silica, alumina and alkalis. The material lost, therefore, in the differentiation from nephelinite magma to either phonolite or trachyte is, in fact, the main substance of the carbonatites, namely, lime, iron and magnesia. The oxides showing a relative increase are precisely those in which the phonolites and trachytes are always enriched, that is silica, alumina and alkalis, mainly potash.

TABLE 1.—CHEMICAL LOSSES AND GAINS INVOLVED IN THE DEVELOPMENT OF PHONOLITES AND TRACHYTES FROM NEPHELINITIC MAGMA.

	1	2	3	4	5
SiO <sub>2</sub> .. ..	43.59	48.04	-4.45	64.30	20.71
Al <sub>2</sub> O <sub>3</sub> .. ..	15.07	19.56	-4.49	19.48	-4.41
Fe <sub>2</sub> O <sub>3</sub> .. ..	6.96	4.11	-2.85	0.19	-6.77
FeO .. ..	4.54	3.64	-0.90	0.21	-4.33
MgO .. ..	3.51	1.44	-2.07	0.13	-3.38
CaO .. ..	10.53	5.09	-5.44	0.32	-10.21
Na <sub>2</sub> O .. ..	6.03	6.48	+0.45	6.40	+0.37
K <sub>2</sub> O .. ..	3.87	6.52	+2.65	7.72	+3.85
H <sub>2</sub> O+ H <sub>2</sub> O- } ..	2.57	3.75	..	0.76	..
CO <sub>2</sub> .. ..	—	—	..	0.09	..
TiO <sub>2</sub> .. ..	2.71	1.41	-1.30	0.48	-2.23
P <sub>2</sub> O <sub>5</sub> .. ..	0.62	0.17	..	0.18	..
MnO .. ..	0.25	0.10	-0.15	0.02	-0.23
BaO .. ..	—	—	..	0.03	..
TOTAL .. ..	100.25	100.31		100.31	

1. Elgon nephelinite. Analyst—N. Sahlborn. (Davies, 1952).
2. Elgon phonolite. Analyst—N. Sahlborn. (Davies, 1952).
3. Difference between 1 and 2.
4. Elgon trachyte. Analyst—B. C. King. (Davies, 1952).
5. Difference between 1 and 4.

Considering the actual ratios of lime to iron to magnesia in columns 3 and 5, it is seen that in the first case lime predominates, while in the second, iron is of almost equal importance to lime. It should also be noted that the total loss or gain in column 5 greatly exceeds that in column 3. The differentiation producing the trachytes may therefore be considered to be more vigorous than that resulting in the production of phonolites. The following two empirical ratios have been arrived at:—

*Nephelinite = 4 parts phonolite + 1 part beforosite.*

*Nephelinite = 3 parts trachyte + 2 parts ankeritic alvikite.*

An illustration of the nephelinite-beforsite-phonolite fractionation is given in table 2. A phonolite and a beforosite from the same petrographic province have been added in the ratio of 4:1, with the result shown in column 3. In column 4 the carbon dioxide has been removed and the remainder recalculated to 100 per cent. The result is ijolitic in type and is similar in composition to the Uganda nephelinites, which are given for comparison in columns 5 and 6.

TABLE 2.—CHEMICAL COMPOSITION OF TYPICAL UGANDA NEPHELINITES COMPARED WITH THAT OF A HYPOTHETICAL MIXTURE OF PHONOLITE AND BEFORSITE.

	1	2	3	4	5	6
SiO <sub>2</sub> ..	48.04	0.85	38.60	42.37	42.97	43.59
Al <sub>2</sub> O <sub>3</sub> ..	19.56	—	15.65	17.18	21.10	15.07
Fe <sub>2</sub> O <sub>3</sub> ..	4.11	} 8.44	} 7.89	} 8.66	6.45	6.96
FeO ..	3.64				4.14	4.54
MgO ..	1.44	15.82	4.32	4.74	2.65	3.51
CaO ..	5.09	31.30	10.33	11.34	8.45	10.53
Na <sub>2</sub> O ..	6.48	—	5.18	5.69	4.92	6.03
K <sub>2</sub> O ..	6.52	—	5.22	5.73	1.88	3.87
H <sub>2</sub> O+ } H <sub>2</sub> O- }	3.75	} 2.05	} 2.26	} 16.08	5.27	} 2.57
CO <sub>2</sub> ..	—				43.51	
TiO <sub>2</sub> ..	1.41	—	1.13	1.24	0.55	2.71
P <sub>2</sub> O <sub>5</sub> ..	0.17	0.43	0.65	0.71	1.11	0.62
MnO ..	0.10	0.02	0.08	0.09	0.22	0.25
BaO ..	—	—	—	—	0.05	—
SrO ..	—	—	—	—	0.05	—
Cl ..	—	—	—	—	0.01	—
TOTAL ..	100.31	100.37	99.80	100.01	100.54	100.25

1. Elgon phonolite. Analyst—N. Sahlbom. (Davies, 1952).
2. Napak beforosite. Analyst—B. C. King. (King, 1949).
3. 1 added to 2 in the ratio of 4 : 1.
4. 3 recalculated to 100% after deduction of CO<sub>2</sub>.
5. Napak nephelinite. Analyst—B. C. King. (King, 1949).
6. Elgon nephelinite. Analyst—N. Sahlbom. (Davies, 1952).

The differentiation of nephelinite magma to alvikite and trachyte cannot be illustrated with local examples owing to the lack of analyses of sideritic alvikites from Uganda. Adequate evidence is, however, available from the Nyasaland occurrences where trachytes and felspathic breccias of trachytic composition are accompanied by carbonates of iron, manganese, lime and magnesia. Iron and manganese often occur in sufficient quantity to warrant investigation as a source of these metals (Dixey *et al.*, 1935).

Confirmatory evidence is also to be found in western Kenya in the Kavirondo Rift Valley where a sequence of nephelinites, phonolites and trachytes is found in association with tuffs and agglomerates. The pyroclastic sediments include coarse pyroxenic tuffs and agglomerates containing nephelinite and angular carbonatite fragments. Bedded limestones consisting of finely comminuted carbonatite are ubiquitous. It is of particular importance to note that the vents in this province produced augite-rich nephelinites, nepheline basalt, olivine basalt, tephrite and melilite-bearing types in addition to nephelinites, phonolites, trachytes and carbonatites (Shackleton, 1951).

Figure 6 shows that there is a marked linear arrangement in the beforosite-nephelinite-phonolite (foyaite) series, and this diagram is considered to demonstrate the direct genetic relationship of the members of this series. Figure 7 shows that the members of the alvikite-nephelinite-trachyte series are related in a similarly direct and genetic fashion. The precise reason

for the difference in the two series lies in the nature of the respective carbonatite types. Of particular importance is the fact that for a given silica value the alvikites contain less lime and magnesia and more iron than the beforsites.

### THE MECHANISM OF CARBONATITE FORMATION

The structure of alkaline volcanoes in Uganda clearly demonstrates the intimate association of carbonatite with outbursts of Elgon type. Carbonatite fragments have been ejected from the throats of volcanoes such as Kerimasi, Oldonyo Lengai (James, 1956) and Mount Elgon (Shackleton, 1944). If carbonatites are indeed magmatic derivatives, it is necessary to discover how such differentiates may be formed in the same magma chamber and from the same magma as that producing the rocks of the cone. Since the predominant flow type occurring on Mount Elgon, Napak and Kerimasi is nephelinitic, it is evident that some rapid and specialised form of differentiation has operated in the development of carbonatite from nephelinite. It is significant that the greater part of the cones of these volcanoes consists of pyroclastics, showing the large amount of gas associated with the eruptions.

Mount Elgon is a volcano of the central type and very large pyroclastic fragments have fallen many miles from the vent. This gives some idea of the tremendous gas pressure built up in the volcano during quiescent periods where the conduit was choked with congealed lavas. The great reduction of gas pressure during paroxysmal eruptions must have produced rapid chilling deep down in the system.

During periods of closure of the vent, tremendous pressures were built up within the volcano and much of the hyperfusible material was in solution in the magmatic fluid. At the moment of eruption which followed a quiescent period, the rapid reduction of pressure caused the spontaneous release of the dissolved volcanic gases in the magma chamber and magma column. Adiabatic expansion and cooling were most marked. This escape of gas caused agitation and frothing within the magma and water-vapour, carbon dioxide and other volcanic gases migrated upwards, bubbling through the magmatic liquid. The passage of carbon dioxide through a liquid containing calcium and magnesium oxides in solution caused the formation of carbonates.

The formation of calcite from a magma rich in CaO and CO<sub>2</sub> is the natural outcome of rapid cooling which reduces the temperature in the magma chamber, however temporarily, below the crystallisation temperature of calcite (1389°C. at 779,000 mm. pressure). Similarly, carbonates of magnesium, iron, strontium and barium were formed. The carbonate particles were all formed in close contact with the rapidly migrating gas bubbles and it is likely that some type of flotation occurred, carrying the carbonates up the magma column.

The carbonates were thus concentrated at the top of the magma column, where, owing to continued adiabatic cooling, they congealed. Also occluded within the carbonate mass were particles of the discrete oxides of the magma, which then crystallised in their simplest form. The minerals in the following list which are formed in the carbonatite during explosive episodes occur at Sukulu, Alnö, Iron Hill and Napak:—

Calcite .. ..	CaCO <sub>3</sub> .. ..	Sukulu ..	Iron Hill ..	Alnö
Dolomite .. ..	MgCO <sub>3</sub> .. ..	Sukulu ..	Iron Hill ..	Alnö
Siderite .. ..	FeCO <sub>3</sub> .. ..	Sukulu ..	Napak ..	Alnö
Ankerite .. ..	(2CaCO <sub>3</sub> ;MgCO <sub>3</sub> ;FeCO <sub>3</sub> )	—	Iron Hill ..	—
Strontianite .. ..	SrCO <sub>3</sub> .. ..	..	..	Alnö
Witherite .. ..	BaCO <sub>3</sub> .. ..	..	..	Alnö
Carbon dioxide .. ..	(bubbles in calcite)	Sukulu ..	..	Alnö
Quartz .. ..	SiO <sub>2</sub> .. ..	Sukulu ..	Iron Hill ..	Alnö
Corundum .. ..	Al <sub>2</sub> O <sub>3</sub> .. ..	..	..	Alnö
Anatase .. ..	TiO <sub>2</sub> .. ..	Sukulu ..	Iron Hill ..	Alnö
Pyrolusite .. ..	MnO <sub>2</sub> (after brookite)	Sukulu ..	..	Alnö
Baddeleyite .. ..	ZrO <sub>2</sub> .. ..	Sukulu	..	..
Microlites .. ..	Unidentified .. ..	Sukulu ..	..	Alnö
Fluorite .. ..	CaF <sub>2</sub> .. ..	Sukulu ..	..	Alnö
Barytes .. ..	BaSO <sub>4</sub> .. ..	Sukulu ..	..	Alnö
Pyrite .. ..	FeS .. ..	Sukulu ..	..	Alnö
Galena .. ..	PbS .. ..	..	..	Alnö

The minerals listed represent the simplest possible molecules of the particular substances. Probably the most significant mineral is quartz, which is seen as tiny crystals set in the carbonate. Had sufficient time been available for reaction, calc-silicates would undoubtedly have been formed. During the examination of the Sukulu soil deposit, the ubiquity of these quartz crystals provided a constant puzzle.

Minute bubbles of carbon dioxide have been detected within the calcite at Alnö and Sukulu. This demonstrates not only the abundance of this gas available in the magma, but also the rapidity with which the calcite was formed. The presence of excess carbon dioxide, which is most common in the fine-grained central portions of the complex, is thought to be the reason for the rapid weathering of the centres at Sukulu. In each of the three centres there, the later sheets form a ring of hills almost enclosing a soil-filled valley.

The presence of tiny microlites also testifies to the rapid formation of the carbonate. It is evident that the crystallisation of complex silicates was unable to keep pace with the growth of the carbonates. Von Eckermann (1948, page 73) describing the sövite from the "central cone" at Alnö writes: "It is very fine-grained, reminding almost of a chilled margin rock. The only other minerals present are apatite and tiny microlites which could not be determined. Judging from the analysis, the calcite contains some carbonate of magnesia, iron, barium and strontium."

Structural evidence indicates that the carbonatites were emplaced in the condition of a plastic mush and the collection and transport of the minerals of the carbonatite are thought to have been effected by some mechanism such as fluidisation. The formation of the carbonates in frothing gas

streams would ensure their flotation and transportation to the top of the magma chamber and at least part of the way up the conduit. As seen earlier, the removal of these carbonates from an ijolitic magma would leave a phonolitic or trachytic residual magma to follow them up the conduit. During the growth of the volcanic cone it is clear that sufficient pressure remained in the system to eject the carbonate as bombs or fragments, leaving a phonolitic or trachytic lava to well up into the caldera.

The final stage of the extrusive phase in volcanoes of Elgon type was the emplacement, within the vent, of the carbonatite body. When the system lacked sufficient explosive force to remove the obstruction, the extrusive phase was effectively terminated. At this stage there was trapped within the system a phonolitic (or trachytic) magma which was capable of plutonic crystallisation, and fairly coarse-grained nepheline syenites and syenites were formed beneath the carbonate capping. At the same time, continued pressure was exerted upon the base of the obstruction, but it was not sufficient to remove the carbonate body. This pressure, together with heat recuperation within the system after the closure of the vent, caused the partial melting of the lower portion of the carbonate body, and its injection in the form of conesheets, collar sheets and dykes around the central plug and into the wall rocks.

The congealing of the carbonatite led to the trapping of the residual liquid in a sealed system, so that plutonic conditions of cooling came into operation. An important consideration is the amount of water trapped in the system. In the system  $\text{CO}_2\text{—H}_2\text{O—K}_2\text{O—SiO}_2$ , investigated by Morey and Fleischer (1940) the percentage of  $\text{CO}_2$  in the vapour decreases as the partial pressure of  $\text{H}_2\text{O}$  increases, and the amount of water in the liquid phase increases linearly. In the closed system one would, therefore, expect to find an increasing development of the amphiboles and mica.

As the crystallisation of coarse-grained types continued, there was a progressive relative concentration of other hyperfusibles and the formation of considerable bodies of apatite and phlogopite in and around the base of the carbonates. Niobium, zirconium, yttrium and cerium entered the carbonatites, together with phosphorus and iron. The growth of pyrochlore was accompanied by that of asbestiform amphiboles. The hydrous conditions also encouraged the precipitation of large quantities of magnetite.

In the field nearly all carbonatites are seen to contain dykes and bodies of sövite breccias and these indicate that periodically the pressure beneath the plug was sufficient to break through locally. These fissures were, however, rapidly healed by the crystallisation of further carbonate. It is interesting to note that the rocks containing the greatest amounts of pyrochlore are the sövite breccias and late tangential dykes. In some cases, as at Chilwa, the temporary breaks in the carbonate cap caused the emplacement of felspathic breccias (chemically trachytes). At Sukulu, tinguaites are the only silicate rocks cutting the carbonatites.

Another effect of the trapping of the residual magma was the formation of wollastonite in the carbonate. V. M. Goldschmidt (1954) has worked out the stability curve of calcium carbonate and silica and has established that the reversible reaction:



moves to the right above 500°C. under moderate pressure. The presence of wollastonite in some of the carbonate rocks suggests that the sövites at the base of the plug were sufficiently reheated for the quartz and calcium carbonate to react.

It was at this stage that a marked metasomatic aureole was established around the pipe. Two major types of fenite can be distinguished, firstly those surrounding the nepheline syenite or syenite, and secondly, those close to the carbonate. The main effect near syenites was the introduction into the wall rock of amphiboles as well as some soda metasomatism. It should be noted here that many of the rocks called "fenite" by von Eckermann are, in fact, genetically related members of the magmatic series, and the term should, consequently, be restricted to include only those contact rocks which show marked aberration when plotted on the variation diagram. The fenites surrounding the carbonate body are considered to be the result of physical admixture of fragments of wall rock under such conditions of temperature and pressure that new minerals were able to form in equilibrium with the relatively reduced silica percentage, and members of the sövite-silicate series appear to have been derived in this manner. In the Tororo complex (eastern Uganda), this type of fenitisation is clearly seen and brecciation of the granitic wall rock and digestion of the fragments by the engulfing sövites took place around the carbonate body. Outside this zone, the granitic wall rocks have yielded some of their silica to the carbonatite and grade from quartz syenites to syenites.

Reaction between the sövite and the wall rocks was very much more marked in the lower parts of the carbonate plug, owing to the greater temperature, pressure and concentration of hyperfusibles at the top of the crystallising magmatic body. In this region very large amounts of diopsidic pyroxene, often coarsely crystalline, were formed in conjunction with apatite, magnetite and biotite. In the formation of the diopside, the lime and magnesia were supplied by the sövites and the silica obtained by reaction with the wall rock.

The closing phase in volcanoes of Elgon type appears to have been the telescopic subsidence of the central portion of the complex. This involved the collapse of the caldera, conspicuous ring faulting in the hypabyssal portion and the sagging of the laccolithic rocks, together with their consequent acquisition of centripetal dip. The latest rocks emplaced were essentially basic in character and crystallised as gabbros.

In those episodes where no carbonatite was formed, the nephelinitic magma congealed in the upper part of the conduit and the remainder crystallised as ijolite.

## THE SOURCE OF CARBON DIOXIDE

In considering the source of carbon dioxide in these complexes it is important to realise that the total amount of this gas required for the formation of carbonatite is not very large. In the differentiation described here, segregation of pyroxene and plagioclase leaves a desilicated residual magma relatively enriched in hyperfusibles. Table 2 shows that this nephelinitic magma may divide into four parts of phonolite and one part of carbonatite. Of this fifth portion of the residual magma considerably less than half is carbon dioxide. During their formation, the carbonatites drew not only upon the carbon dioxide in the magma in their immediate vicinity, but also upon carbon dioxide bubbles arising from great depth in the magma column.

It is clear that volcanoes of Elgon type depend for their activity upon the concentration of hyperfusibles in the upper parts of the system and as soon as the supply is exhausted the system seals itself and any further rocks entering the hypabyssal area crystallise as normal dolerites, gabbros or their derivatives.

A simple analogy is seen in the opening of a soda water bottle. Should the crown cork be removed rapidly, the gas is spontaneously released from solution and the bubbles carry with them a considerable portion of the contents of the bottle. When the cork is removed slowly and the pressure released gradually, most of the gas remains dissolved in the liquid. This appears to be the main difference between oceanic volcanoes and those on continental masses. The development of alkaline types is not controlled by the constitution of the surrounding crust, but by the structural environment in which they are evolved.

The total amount of carbon dioxide in volcanoes of Elgon type is thus probably no greater than that normally found in basaltic magmas, though the type of differentiation and the crustal structures causing it tend to concentrate the hyperfusibles.

## CONCLUSIONS

In eastern Uganda there is little evidence that alkaline types have been formed by the mechanism suggested by Daly and Shand. The high-tensioned, low-temperature, potassic-carbonate liquid suggested by von Eckermann (1948) as the original magmatic melt producing the rocks of Alnö District, could not also produce the vast volume of soda-rich rocks of the volcanic cone.

The following sequence of events is suggested to explain both the structural and petrological relations observed in the field:—

1. The first stage was the injection on a regional scale of normal alkali basalt magma into sialic material. In cases where the magma was emplaced in relatively unstable, tensional areas, sills and dykes were the dominant forms. In their progress into the upper sialic layers, loss, by

gravitational means, of olivine, led to the development of more acidic differentiates. Where this basaltic magma was emplaced in relatively stable inter-rift blocks, no such ready means of escape was available, and great pressures were built up, enabling the penetration into higher sialic zones.

2. As this high-tensioned magma approached the surface and the pressure within the magma more nearly equalled that of the super-encumbent rocks, a tabular body was formed and an equivalent doming produced at the surface. This relatively rapid elevation of the land surface caused the radial erosion of the uplifted area, with resultant accumulation of coarse sediments at the periphery of the dome.

3. The up-doming of the country rock and the continued magmatic pressures resulted in the drilling of a central diatreme through which the magmatic products could pass. At this stage, the gravitational segregation of pyroxene and to some extent plagioclase commenced in the magma chamber.

4. Adiabatic chilling of the lava passing through the conduit and chilling near the mouth of the vent caused by the escape and rapid expansion of magmatic gases, resulted in solidification of the top of the lava column, temporarily inhibiting surface activity.

5. Regeneration of pressure brecciated the solidified plug with the formation of tuffs and agglomerates. Small lava flows followed the brecciation in some cases, but generally the material in the mouth of the vent was rapidly cooled and solidified. The repetition of this cycle, often with relatively long pauses, resulted in the building of a large agglomerate cone with subsidiary intercalated lava flows. In the magma chamber, an increasing thickness of gravitationally segregated minerals was accumulated.

6. In some cases, the rapid and prolonged escape of magmatic gases from the magma chamber during paroxysmal eruptions rapidly reduced the temperature of the system. This release of pressure caused not only the drastic reduction of temperature due to gas expansion, but also the escape from solution of dissolved carbon dioxide. This resulted in the formation of carbonates and minerals of simple molecular structure as well as their transportation in frothing gas streams to the top of the magma chamber and up the conduit. This material, which was of carbonatitic composition, was subjected during its ascent to continued adiabatic chilling and reached a final position near the mouth of the vent as a relatively solid body.

7. In cases where loss of temperature and pressure were of a temporary nature, the lower portion of the obstructing carbonate body was remelted and the upper portion brecciated and ejected as kalkbomben. In the agglomerates of Mount Elgon, some very large fragments of carbonatite have been found.

8. During waning activity, pressures within the system became too low to remove the carbonate body and it remained as an obstruction within the vent, effectively terminating the major extrusive phase. The residual liquid, of phonolitic or trachytic composition, was then trapped within a sealed system and "plutonic" conditions of crystallisation came into operation. At Sukulu, the only silicate rocks penetrating the carbonatite are tinguaites.

9. Continued pressure within the system, while unable to remove the carbonate body, nevertheless exerted considerable pressure upon its base. This pressure, together with the heat provided by the trapped magma, caused partial remelting of the lower carbonates and their emplacement around the side of the body and as cone and collar sheets penetrating the wall rocks. The effect of these movements on the crystallising magma beneath the plug was the introduction of characteristic fluidal textures in the foyaites and trachytes.

10. At this stage in the development of the hypabyssal complex, very considerable changes appeared in the wall rocks and in the lower portions of the carbonatite plug. The rapid sealing of the system by the withdrawal of carbonatites caused the trapping in the system of a considerable amount of the hyperfusible constituents. The course of crystallisation of the magma trapped below the plug assisted the late stage concentration of hyperfusible constituents and of those elements usually appearing in traces in the magma. Calcium-loving elements such as niobium, zirconium, phosphorus, fluorine, titanium and rare earths of the yttrium and cerium groups entered the carbonatites. Under these hydrous conditions, too, the increased oxidation ratio caused the precipitation of late iron ores, particularly magnetite. The development of hydrous minerals, mainly biotite, phlogopite and amphibole, in and around the carbonate body was particularly marked at this stage, and gave rise to deposits of vermiculite. Reaction between the carbonatite and the wall rocks resulted in the production of large bodies of diopside rock and these, together with the vermiculites, apatites and iron ores, make up the characteristic mineral assembly almost invariably found surrounding sövite plugs. It is stressed that metasomatic exchange and replacement at this time was very extensive and introduced amphiboles are frequently found several miles from the occurrence.

11. In most complexes so far investigated, late stage ring-subsidence has caused the collapse of the caldera and the partial destruction of the volcanic cone.

12. Any further basaltic material passing into the complex after the collapse of the system, was emplaced into such parts of the complex as offered least resistance, and crystallised as dolerites or gabbros in the closed system.

Strauss and Truter (1951) have pointed out the similarity between the anorthosite and magnetite-rich bands in the pyroxenite at Spitskop and those in the Bushveld Igneous Complex. The similarity between the

chrome-rich zones in the Bushveld Complex and the generally chrome-rich paragenesis of Alnö Island is significant. The rocks of the Bushveld Igneous Complex are also notably rich in calcite. It is suggested, therefore, that complexes similar in type to the Bushveld Igneous Complex might be genetically related at the surface to multiple outbursts of Elgon type.

The sodic and potassic rocks of western Uganda followed a similar pattern of differentiation. The structural environment was, however, somewhat different and the outbursts manifested themselves not so much as vast volcanoes of the central type, but as smaller and more numerous centres scattered over a wide area. Of particular interest is the development, at the fumerolic stage, of swarms of explosion craters. It is thought probable that crystallisation of sodium chloride, sodium sulphate, sodium bicarbonate, potassium sulphate, calcium sulphate and some calcium carbonate has resulted from the explosive release and frothing of late-stage fumerolic gases through the residual magma. In western Uganda, numerous small craters occupied by saline lakes, constitute an important source of these salts.

It has been seen that complexes of apparently widely differing rock assemblages would be revealed by erosion to varying levels within the same complex and it is considered that the processes mentioned earlier are capable of producing the rock types found in most alkaline complexes in the East, Central and South African zone.

#### ACKNOWLEDGMENTS

Sincere thanks are extended to Dr. K. A. Davies, C.M.G., O.B.E., for his continued interest in the progress of this work and to Professor C. E. Tilley, F.R.S., for reading the draft script and making many helpful comments.

Thanks are also due to Dr. M. Mathias of the University of Cape Town for her useful advice and encouragement.

#### REFERENCES

- BOWEN, N. L., 1928. "The evolution of the igneous rocks." Princeton Univ. Press.
- DAVIES, K. A., 1952. "The building of Mount Elgon (East Africa)." *Geol. Surv. Uganda*, Mem. VII.
- DIXEY, F., CAMPBELL SMITH, W. and BISSETT, C. B., 1935. "The Chilwa Series of southern Nyasaland." *Geol. Surv. Nyasaland*, Bull. 5 (Revised, 1955).
- VON ECKERMANN, H., 1948. "The alkaline district of Alnö Island." *Sveriges geol. unders.*, Ser. Ca, No. 36.
- GOLDSCHMIDT, V. M., 1954. "Geochemistry." Oxford, Clarendon Press.
- HOLMES, A., 1930. "Petrographic methods and calculations." London, T. Murby & Co.
- JAMES, T. C., 1956. "Carbonatites and rift valleys in East Africa." Cyclostyled report, *Geol. Surv. Tanganyika*.
- JOHANNSEN, A., 1938. "A descriptive petrography of the igneous rocks." Vol. IV University of Chicago Press.
- KING, B. C., 1949. "The Napak area of southern Karamoja, Uganda." *Geol. Surv. Uganda*, Mem. V., 1948.
- KORN, H. and MARTIN, H., 1954. "The Messum igneous complex in South-West Africa." *Trans. Geol. Soc. S. Africa*, LVII, 83-124.

- LARSEN, E. S., 1942. "Alkalic rocks of Iron Hill, Gunnison County, Colorado." *U.S. Geol. Surv., Prof. Paper* 197A.
- MATHIAS, M., 1956. "The petrology of the Messum igneous complex, South-West Africa." *Trans. Geol. Soc. S. Africa*, LIX, 1-35.
- MOREY, G. W. and FLEISCHER, M., 1940. *Bull. Geol. Soc. America*, 51, 1035-1038.
- NOCKOLDS, S. R., 1954. "Average chemical compositions of some igneous rocks." *Bull. Geol. Soc. America*, 65, 1007-1032.
- SHACKLETON, R. M., 1944. "Report on the geology of the area around Malakisi, North Kavirondo." Cyclostyled report, *Geol. Surv. Kenya*.
- , 1951. "A contribution to the geology of the Kavirondo Rift Valley." *Quart. Journ. Geol. Soc. London*, CVI, 345-392.
- SIMPSON, E. S. W., 1954. "The Okonjeje igneous complex, South-West Africa." *Trans. Geol. Soc. S. Africa*, LVII, 125-172.
- STRAUSS, C. A., and TRUTER, F. C., 1951. "The alkali complex at Spitskop, Sekukuni-land, eastern Transvaal." *Trans. Geol. Soc. S. Africa*, LIII, 81-130.

## APPENDIX

### DESCRIPTION OF ROCKS INDICATED BY NUMBERS ON FIGURES 5, 6 AND 7

Figure 5 :

1. Beforsitic alnöite, No. 63, Alnö, Sweden.
2. Alvikitic alnöite, No. 64, Alnö, Sweden.
3. Kimberlitic melanite ouachitite, No. 80, Alnö, Sweden.
4. Alvikitic alnöite, No. 65, Alnö, Sweden.
5. Alnöite, No. 68, Alnö, Sweden.
6. Porphyritic alnöite, No. 70, Alnö, Sweden.
7. Alnöite, No. 71, Alnö, Sweden.
8. Alvikitic alnöite, Alnö, Sweden.
9. Alvikitic alnöite, No. 72, Alnö, Sweden.
10. Alnöite porphyrite, No. 74, Alnö, Sweden.
11. Vescite, Vesec, Bohemia.
12. Jacupirangite, No. 38, Alnö, Sweden.
13. Turjaite, Turja, Kola peninsula, U.S.S.R.
14. Melilite-biotite rock, Isle Cadieux, Quebec, Canada.
15. Katungite, Chamakumba crater, Ankole, Uganda.
16. Bergalite, Elgon, Uganda.
17. Melanite jacupirangite, No. 37, Alnö, Sweden.
18. Melilite basalt, Hohenstoffeln, Baden, Germany.
19. Melilite mafurite, Kabirenge, Ankole, Uganda.
20. Modlibovite, Modlibov, Bohemia.
21. Melilite basalt, Spiegel River, Cape Colony.
22. Ouachitite, Hot Springs, Arkansas, U.S.A.
23. Medium-grained turjaite, Turja, Kola peninsula, U.S.S.R.
24. Melanite melteigite, No. 30, Alnö, Sweden.
25. Melilite nephelinite, Napak, Uganda.
26. Pyroxenite, No. 35, Alnö, Sweden.
27. Uncompahgrite, Gunnison County, Colorado, U.S.A.
28. Melilite-leucite nephelinite, Ngoma crater, Tanganyika.
29. Jacupirangitic melanite melteigite, No. 34, Alnö, Sweden.
30. Melilite basalt, Howenegg, Baden, Germany.
31. Melilite nephelinite, near Alekilek, Napak, Uganda.
32. Pyroxenite, Elgon, Uganda.
33. Melilite basalt, Boring, Bermuda.
34. Nepheline-hauynite alnöite, Fergus County, Montana, U.S.A.
35. Pyroxenite, No. 33, Alnö, Sweden.
36. Nephelinite, Naluziguti ridge, Toro, Uganda.
37. Biotite leucitite, Visoke, Belgian Congo.
38. Nephelinite, Etinde volcano, British Cameroons.
39. Melilite ankaratrite, Elgon, Uganda.
40. Leucitite, Katerusi, Belgian Congo.
41. Melanite micromelteigite, Melteig, Norway.
42. Nephelinitic augitite, Elgon, Uganda.
43. Melilite ankaratrite, D.1681, Elgon, Uganda.

44. Melanepherinite, Napak, Uganda.
45. Melilite ankaratrite, Endeless, Elgon, Kenya.
46. Missourite porphyry, British Columbia.
47. Arfvedsonite micromelteigite, Kola peninsula, U.S.S.R.
48. Olivine melanepherinite, Napak, Uganda.
49. Melilite nephelinite, Elgon, Uganda.
50. Phonolitic etindite, Elgon, Uganda.
51. Coppaelite, Rieti, Italy.
52. Melteigite porphyry, Alnö, Sweden.
53. Nephelinite, Elgon, Uganda.
54. Melanepherinite, DGS.924, Elgon, Uganda.
55. Wesselite, Wessln, Bohemia.
56. Tannbuschite, Tsao-shih-er, Manchuria.
57. Farrisite, KJose, Oslo, Norway.
58. Nephelinite, Katzenbuckel, Odenwald, Germany.

Figure 6 :

1. Carbonatite, Napak, Uganda.
2. Limestone, Sukulu, Uganda.
3. Beforsite, No. 99, Alnö, Sweden.
4. Alkorthosite beforsite, No. 98, Alnö, Sweden.
5. Strontianite-bearing biotite beforsite, No. 97, Alnö, Sweden.
6. Quartz beforsite, No. 96, Alnö, Sweden.
7. Riebeckite beforsite, No. 95, Alnö, Sweden.
8. Biotite beforsite, No. 95, Alnö, Sweden.
9. Quartz-alkorthosite beforsite, No. 91, Alnö, Sweden.
10. Picritic biotite beforsite, No. 88, Alnö, Sweden.
11. Orthosite beforsite, Snoskär, No. 87, Alnö, Sweden.
12. Biotite-melilite beforsite, nr. Pottang, No. 85, Alnö, Sweden.
13. Orthosite beforsite, Rasta, No. 84, Alnö, Sweden.
14. Melanite nephelinite, No. 61, Alnö, Sweden.
15. Nephelinite, Etinde volcano, British Cameroons.
16. Melanite micromelteigite, Kerimasi, Tanganyika.
17. Calcitic analcite tinguaitite, No. 59, Alnö, Sweden.
18. Nephelinite, Omimi, Otago, New Zealand.
19. Biotite-aegirine foyaite, Nkalonge, Nyasaland.
20. Melanite juvite, No. 24, Alnö, Sweden.
21. Foyaite porphyry, No. 58, Alnö, Sweden.
22. Foyaite porphyry, No. 57, Alnö, Sweden.
23. Phonolite, Gortex, Elgon, Uganda.
24. Borolanite, Ross-shire, Scotland.
25. Tinguaitite, No. 56, Alnö, Sweden.
26. Alkorthosite beforsite, nr. Bergeforsen, No. 81, Alnö, Sweden.
27. Foyaite porphyry, No. 55, Alnö, Sweden.
28. Foyaite porphyry, No. 54, Alnö, Sweden.
29. Juvite, Fen district, Norway.
30. Average phonolite, Toro, Uganda (average 10 samples).
31. Itsindrite, Madagascar.
32. Biotite-bearing aegirine-cancrinite microfoyaite, Mauze Hill, Nyasaland.
33. Phonolite, Siroko, Elgon, Uganda.
34. Nepheline syenite, Serra de Monchique, Portugal.
35. Biotite-bearing aegirine-augite foyaite, Mauze Hill, Chilwa Series, Nyasaland.
36. Biotite-aegirine microfoyaite, Mauze Hill, Nyasaland.
37. Aegerite-mica foyaite, Brathagen, Lougandal, Norway.
38. Phonolite, Mauze Hill, Nyasaland.

Figure 7 :

1. Limestone plug, Sukulu, Uganda.
2. Alvikite, No. 114, Alnö, Sweden.
3. Crushed biotite alvikite, No. 112, Alnö, Sweden.
4. Corundum-bearing alkorthosite-biotite alvikite, No. 106, Alnö, Sweden.
5. Corundum-bearing alkorthosite-picrite alvikite, No. 105, Alnö, Sweden.
6. Biotite alvikite, No. 103, Alnö, Sweden.
7. Alvikitic biotite orthosite, No. 101, Alnö, Sweden.
8. Nephelinite, caldera rim, Elgon, Uganda.
9. Covite, Magnet Cove, Arkansas, U.S.A.
10. Malignite, Kruger alkaline body, British Columbia.
11. Cancrinite syenite, Budeda complex, Elgon, Uganda.

12. Gauteite (type) Muhlorzener forsthaus, Bohemia.
13. Felspathic intrusive, Dos village, Nyasaland.
14. Arsoite (cinimite) Ischia, Italy.
15. Orthoclase rock, Tundulu Hill, Nyasaland.
16. Arsoite (trachyte), Ischia, Italy.
17. Pulaskite, Fourche Mountains, Pulaski Co., Arkansas, U.S.A.
18. Syenite, Leeufontein, South Africa.
19. Fenite, Melteig, Norway.
20. Sölvbergite, Salambidwe, Nyasaland.
21. Sölvbergite, Salambidwe, Nyasaland.
22. Fenite, Fen, Norway.
23. Hornblende sölvbergite, Oslo, Norway.
24. Sölvbergite, Axum, Abyssinia.
25. Trachyte, Bupoto, Elgon, Uganda.
26. Soda syenite, Iron Hill, Colorado, U.S.A.

SUKULU COMPLEX, EASTERN UGANDA  
AND  
THE ORIGIN OF THE AFRICAN CARBONATITES.

C.E. WILLIAMS.

A brief summary indicating why the thesis is considered to constitute an original contribution to the Science.

Submitted in fulfilment of the requirements for the degree of Ph. D. at the University of Cape Town.

## SUMMARY.

The thesis presented is a compilation of both published and unpublished work carried out during the past ten years. The arguments and conclusions are based largely on field observations together with a study of the chemical composition of the rocks involved.

Part I of the paper deals with the structure, petrography and economic geology of the Sukulu Complex. Structural Geology. The mapping of the Sukulu-Tororo complex provided the first detailed examination of the structure of an African carbonatite.

The most important result of this survey was the demonstration that the carbonatites were emplaced in a plastic condition, in the form of "collars", dykes and ring-dykes, into and around an earlier calcitic plug which occupied the conduit. This concept is diametrically opposed to that previously accepted. (Strauss & Truter, Spitskop. von Eckermann, Alnö Island). Later work in other areas (Chilwa Island, Ondurakarume, Homa Mountain) has confirmed the author's interpretation.

The regional and surface structure connected with alkaline complexes is discussed and the definite genetic relationship of carbonatites with Elgon type volcanoes is stressed. Petrography. Owing to the deep weathering of the complex at Sukulu the associated alkaline rocks are poorly exposed but the

examination of borehole cores shows that the rock types found in many other African carbonatites are also present here.

Economic Geology. The economic soil deposit discovered by the author in 1949 is described. This deposit consists of an easily worked, deep eluvial soil containing the four economic minerals apatite, magnetite, pyrochlore and baddeleyite. The soil covers the perimeter of the carbonatite and fills the wide valley embayments running into the centre of the complex.

The description given constitutes the first detailed discussion of the economic geology of a new type of deposit.

A brief classification of economic mineral deposits associated with the carbonatite complexes is included.

## PART II. The Origin of the African Carbonatites.

A review is given of the rock types and structures found in alkaline ring complexes and volcanoes of Elgon type. The formation of undersaturated magma is attributed to the segregation of pyroxenes and to some extent plagioclase from a parent basaltic magma. Nephelinite is the type most commonly produced and constitutes the main lava flows of these volcanoes. The development of rocks containing melilite, melanite and primary calcite from nephelinitic magma is shown to be the result of the relative increase in lime, together with desilication of the residual liquid during the crystallisation and segregation of nepheline. Chemical variation diagrams are presented in support

of these contentions.

Chemical and arithmetical evidence is given to show that the removal of beforstic carbonatite from nephelinitic magma leaves a phonolitic residual liquid, while the removal of iron-rich, alvikitic carbonatite leaves a trachytic residuum.

The mechanism of carbonatite formation is thought to be the exsolution and upward migration of bubbles of carbon-dioxide during paroxysmal eruptions, the ascending gas chilling the magma and reacting with the dissolved oxides of calcium, magnesium, iron, manganese, barium and strontium to form carbonates. The rising gas streams serve to concentrate the carbonates by agitation and flotation with the establishment of a specific gravity gradient. Revival of pressure from below caused the typical intrusion pattern observed.

The hypothesis presented reconciles all the recorded field and chemical data on African carbonatites.

Should the hypothesis gain general acceptance, it would be possible to reduce greatly the unwieldy nomenclature in this branch of petrography.

It is of interest to note that confirmatory laboratory evidence has recently appeared (O. Tuttle, "Nature", March, 1959) which demonstrates the feasibility of the existence of magmatic carbonates as a separate phase .



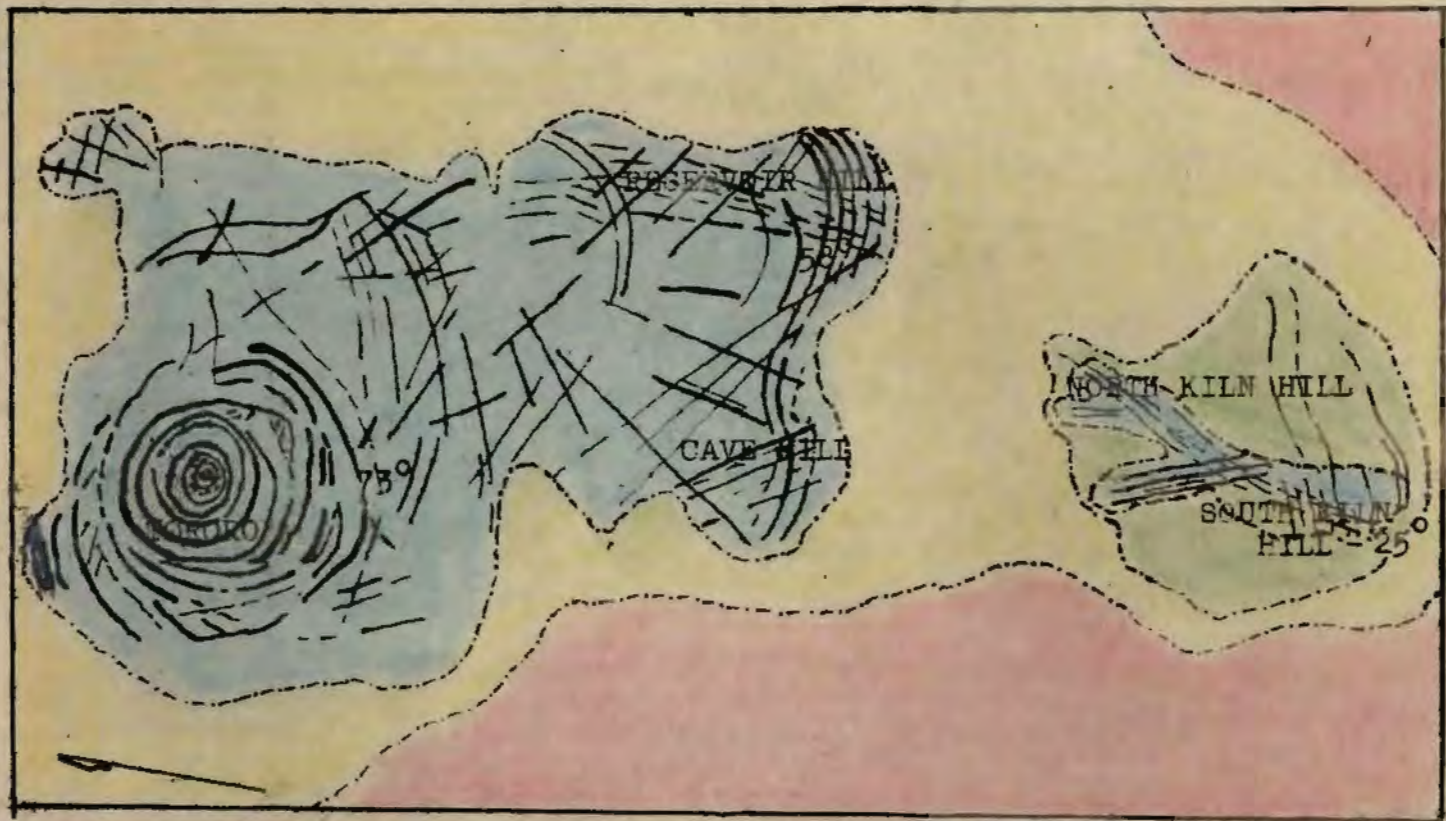
PROCES.

Critique Photography of ~~PERROD~~, SUKULU HILLS

Date Photographed 15th Jan. 1951. Showing Structures.

When ordering Please quote No...50 •

HARWARD MALLICKIAN & CO. LTD.  
P. O. Box 2159. NITROCOI.



Scale 1:10,000.

Simplified trend diagram of Tororo Hills. Trend lines represent lamellar flow in Sövite.

Syenite.  
Granite  
Mixed rocks.



NEPHELINE  
MAGMA

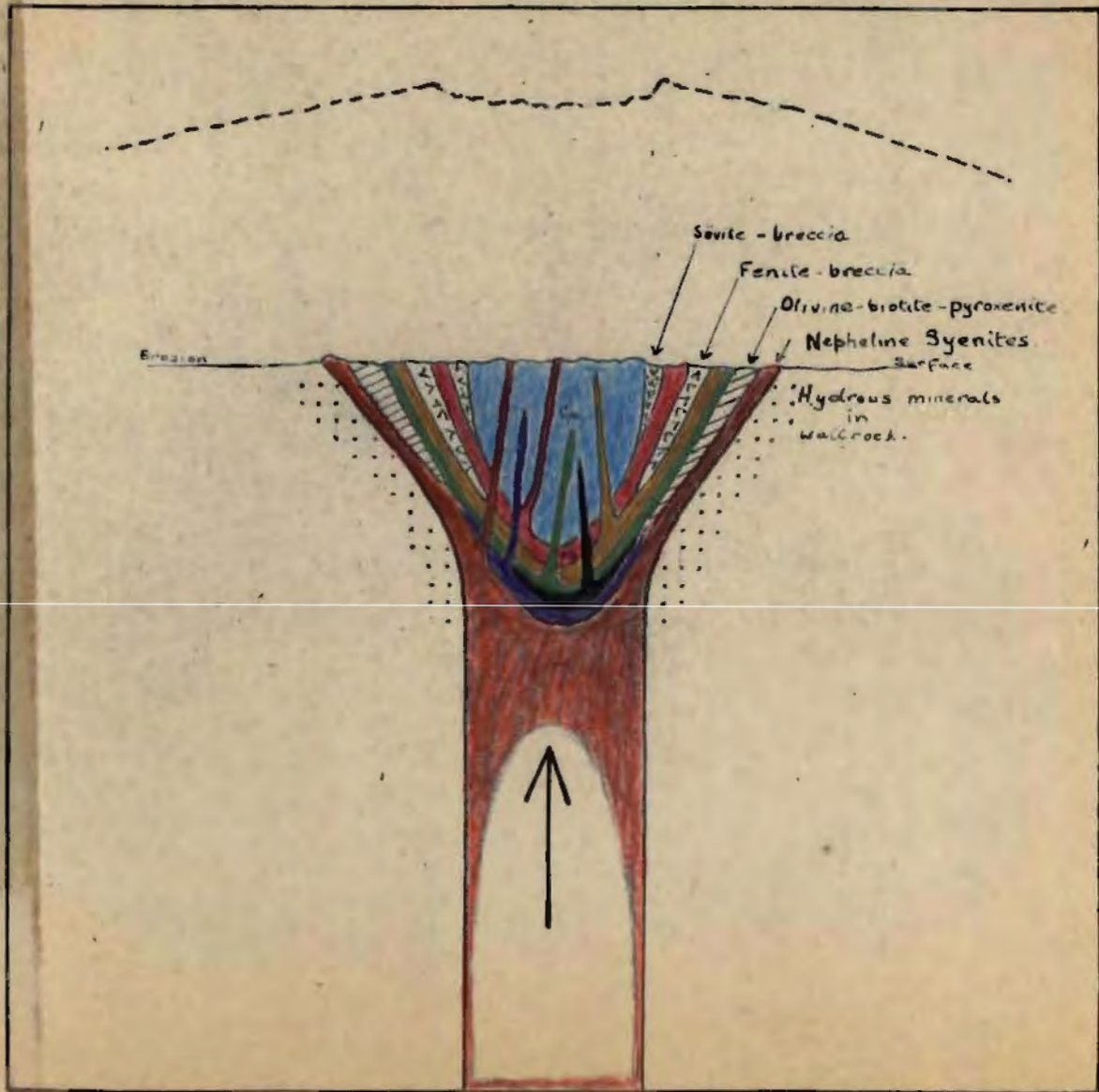
||



← CALCITIC  
← DOLOMITIC  
← ANKERITIC  
← MANGANESE  
← STRONTIUM  
← BARIUM

} CARBONATES.  
IN ORDER OF  
SPECIFIC GRAVITY.

← RELATIVE ENRICHMENT  
IN  
Silica, Alumina and Potash.



# GEOLOGICAL MAP OF SUKULU EASTERN UGANDA



KEY TO GEOLOGICAL MAP		KEY TO STRUCTURE OVERLAY	
Carbonatite.....		Massive structures.....	
Sukulu-type soil.....		Clear flow.....	
Laterite.....		Indistinct flow.....	
Sovite-breccia.....		Dyke-like.....	
Fenite-breccia.....		Faults.....	
Tinguaita.....			

Scale 1:10,000