THE GEOLOGY OF
THE ALKALINE COMPLEX OF RANGWA, WESTERN KENYA,
AND ITS RELATION TO THE SURROUNDING VOLCANICS.

A thesis presented for the degree of
Doctor of Philosophy in the University of London,

by

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ABSTRACT

The complex is composed of alkaline plutonic rocks, pyroclastics and carbonatites, whose outcrop pattern is concentric.

The alkaline plutonics consist of a central body of biotite uncompahgrite, turjaite and ijolite, only part of which survives, and small outlying intrusions of carbonatite and nepheline syenite and areas of brecciation, fenitisation and felspathisation of the basement. The biotite uncompahgrite is formed by the metasomatism of the inner part of a mass of pyroxenite and melteigite, the outer part of which is intruded by ijolitic conesheets and dykes.

The pyroclastics, which were emplaced later than the central alkaline plutonics, consist of banded agglomerate, which was formed by fluidisation, and tuffs, which were deposited subaerially and under water. Most of the pyroclastics dip inwards, and they have been downfaulted along their outer boundary.

The main carbonatites have been emplaced in several phases, all of which are related to central foci. They consist of small conesheets and dykes, a partial ring of coarse micaceous carbonatite, and a plug of banded, magnetite-rich carbonatite. They are associated with brecciation and felspathisation.

The complex is intruded by late alkaline silicate dykes.

Rangwa is at the centre of a large dissected nephelinite volcano, beneath which the basement has been domed. The central plutonic complex was emplaced before most of the nephelinite eruptions.

The pyroclastics on Rangwa are tentatively correlated with conglomerates and tuffs, which occur beneath the main nephelinites to the north and northwest of the volcano, and many of the nephelinite lavas and agglomerates of the volcano are thought to have been erupted from a centrally-placed vent on Rangwa.

ACKNOWLEDGEMENTS

I thank Professor B.C. King, who supervised my work on Rangwa, for his advice and critical reading of the manuscript.

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PART I.

INTRODUCTION.

I

THE SCOPE OF THE PRESENT STUDY

The aims of the thesis are to describe the geology of the Rangwa alkaline complex, to piece together the history of the Kisingiri Volcano of which Rangwa is the centre, and finally to examine the significance of the volcano in a broader setting and discuss its petrogenesis.

Part I of the thesis is a general introduction. It includes a description of the geographical background, a review of previous work in the area, and an account of my own methods of work.

Part II is concerned with the geology of Rangwa and the surrounding basement. On Rangwa, most of the stages in the growth of the volcano can be seen; therefore a full description of the rock types with their field relations, petrography and structure is given. From it the order and modes of emplacement of the rocks and the structural events at the centre can be deduced. Some groups of rocks are closely associated with stages in the structural development, so structural sections are integrated with the chapters on the relevant rocks. There is a wide variety of both rock types and structures, some of which are most unusual. The plutonic part of Rangwa includes an occurrence of biotite uncompahgrite, which is thought to be a unique rock. Also of special interest are the high level emplacement of carbonatite, and the considerable subsidence of the volcanic centre.

Part III contains a summary of the geology of the periphery of the volcano, a comparison between some of the strata there and their inferred counterparts on Rangwa and a history of the whole volcano. My own work supplements what had been done previously on the outlying volcanics and sediments (Kent 1944, McCall 1958, Shackleton 1951 and Whitworth 1953 and 1958), and the purpose was to find horizons that could be correlated with some of the vent rocks on Rangwa.

In Part IV the conclusions of the preceding chapters are summarised, and some aspects of the rocks at Rangwa and the Kisingiri Volcano are compared with those at other plutonic and volcanic alkaline centres, as well as at some nonalkaline centres. This is valuable, because erosion at Kisingiri has reached a critical level and both plutonic and volcanic rocks are exposed. Comparison can therefore be made with other centres over a wide time range; moreover many of the phenomena found at Kisingiri are not confined to alkaline complexes, but are features associated with intrusive complexes and volcanoes of a great variety of types.

II

GEOGRAPHICAL DESCRIPTION OF RANGWA AND THE KISINGIRI VOLCANO

1. PHYSICAL GEOGRAPHY.

At the north east of Lake Victoria, near the mouth of the Kavirondo Gulf (Figures 1 and 2), there is a group of mountains and islands which form the remains of a dissected Tertiary volcano. Following earlier usage, this will be called the Kisingiri Volcano.*

Most of it is in the district of South Nyanza, south of the Kavirondo Gulf. Some of the outlying volcanics occur north of the Gulf too on the Uyoma peninsula in Central Nyanza. The rocks extend from latitude S. 20' to S. 40', and from longitude E. 34° to E. 34°. 20'.

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*The earliest reference to the name I can find is in Winston Churchill's "My African Journey" (1908), in which Kisingiri is the name of one of the boats in the flotilla which took him down the Nile from Lake Albert. It is uncertain whether the derivation of this name is connected. Oswald (1914) refers to the mountains that compose the volcano as the Kisingere Plateau, and all geologists since have called the whole volcano the Kisingiri Volcano. The channel between Rusinga and Mfwangano is called the Kisingere Channel on the 1:50,000 ordnance survey map (1962).

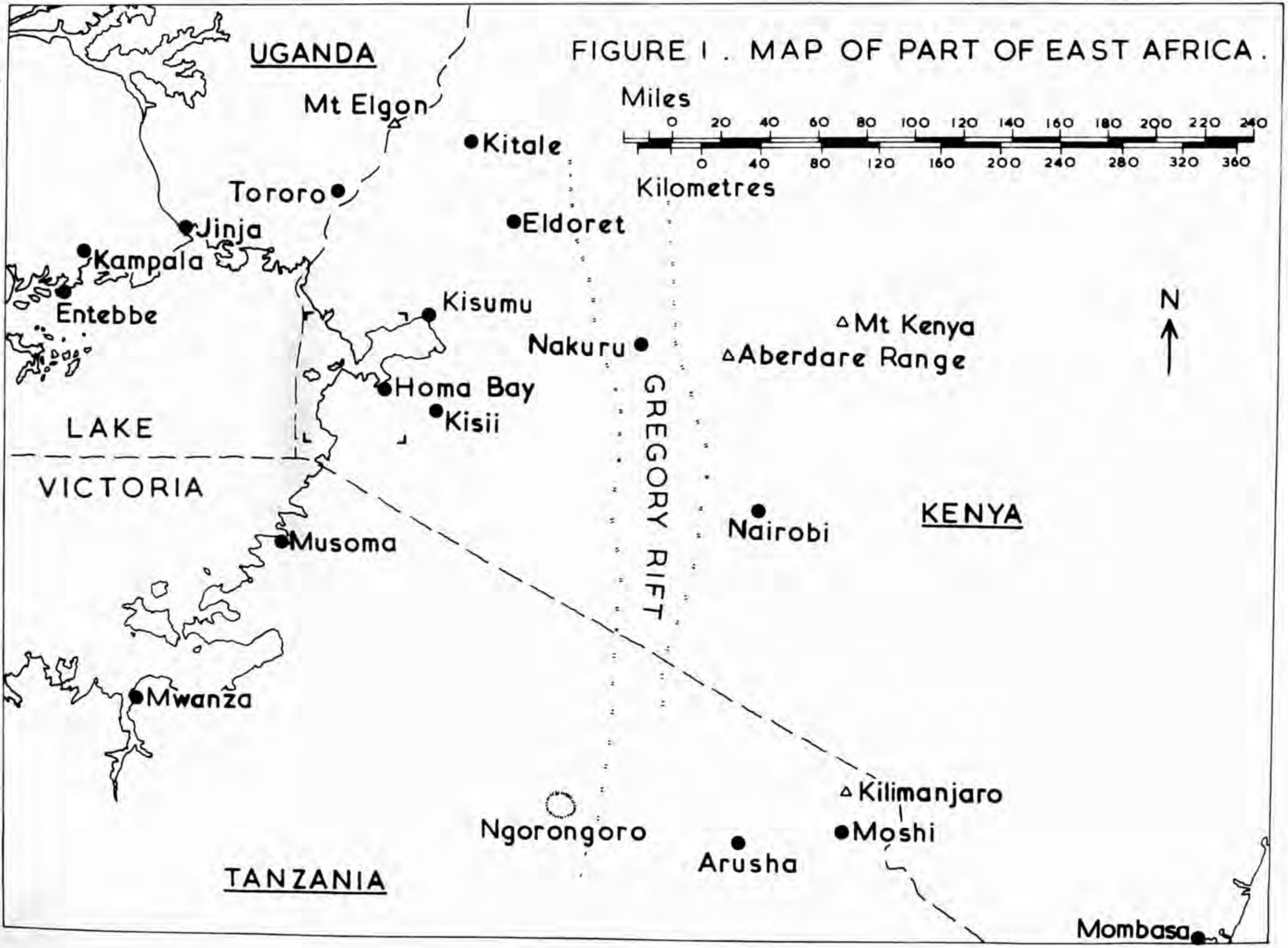

FIGURE I. MAP OF PART OF EAST AFRICA.

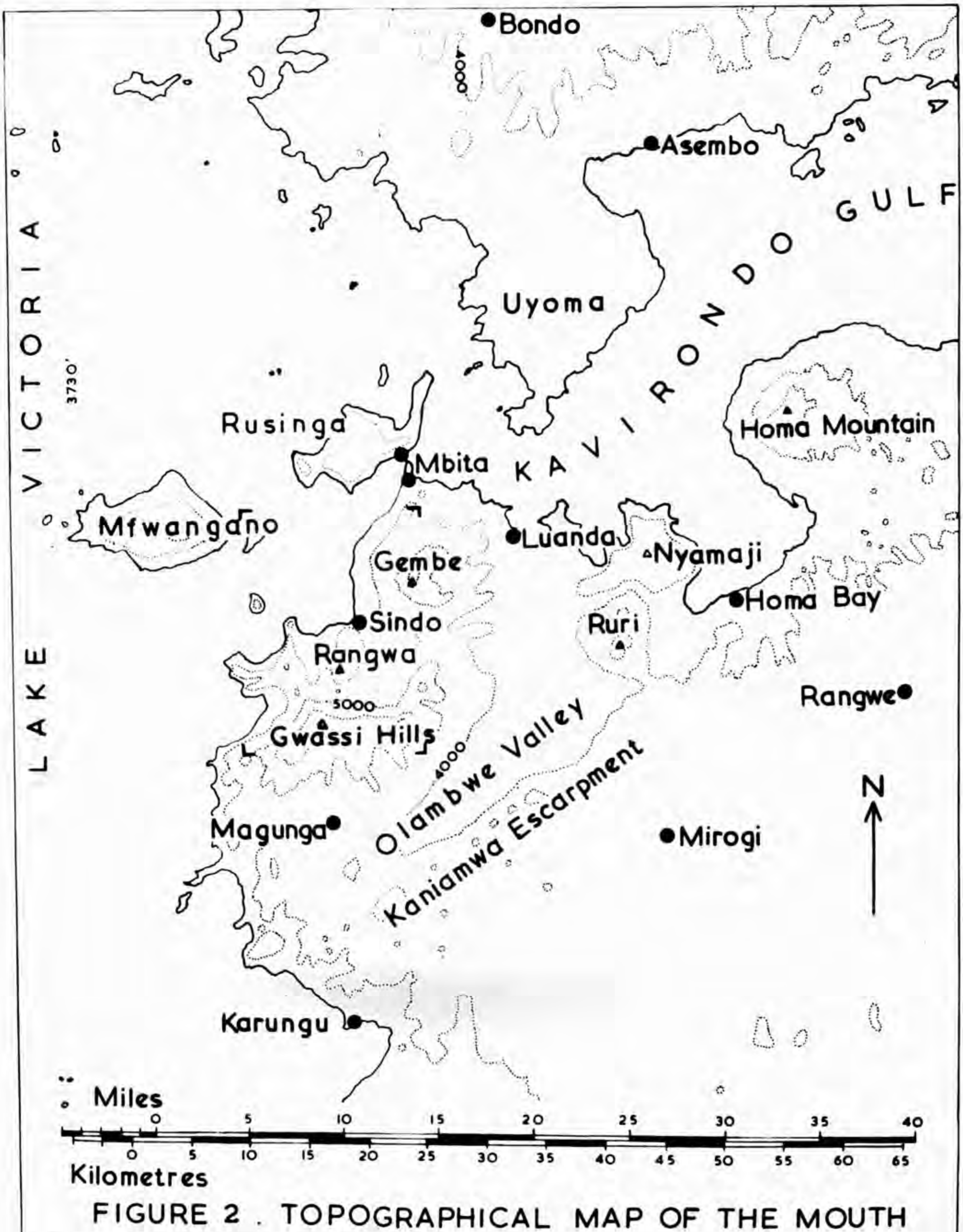

FIGURE 2 . TOPOGRAPHICAL MAP OF THE MOUTH OF THE KAVIRONDO GULF.

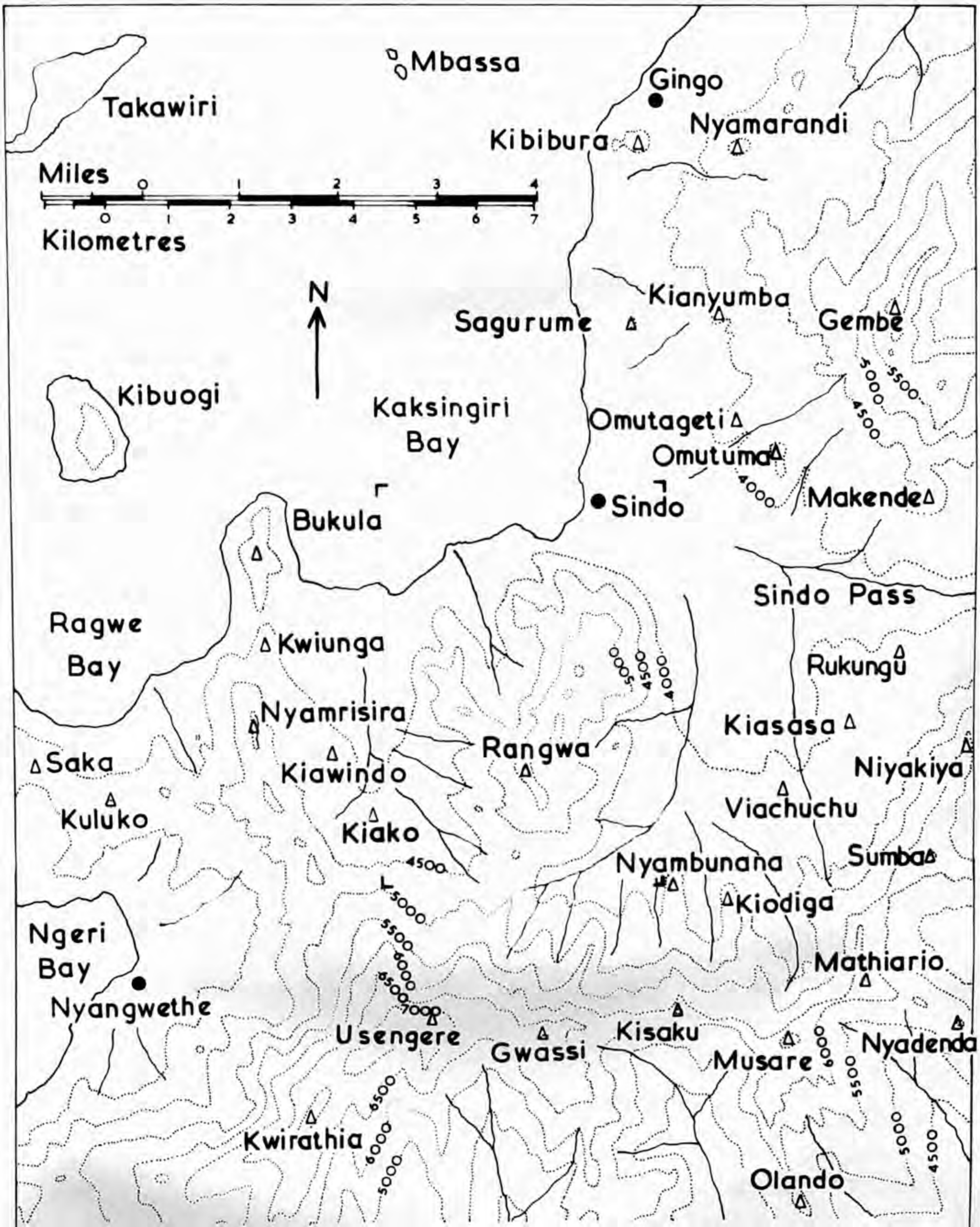

FIGURE 3. TOPOGRAPHICAL MAP OF RANGWA AND ITS SURROUNDINGS.

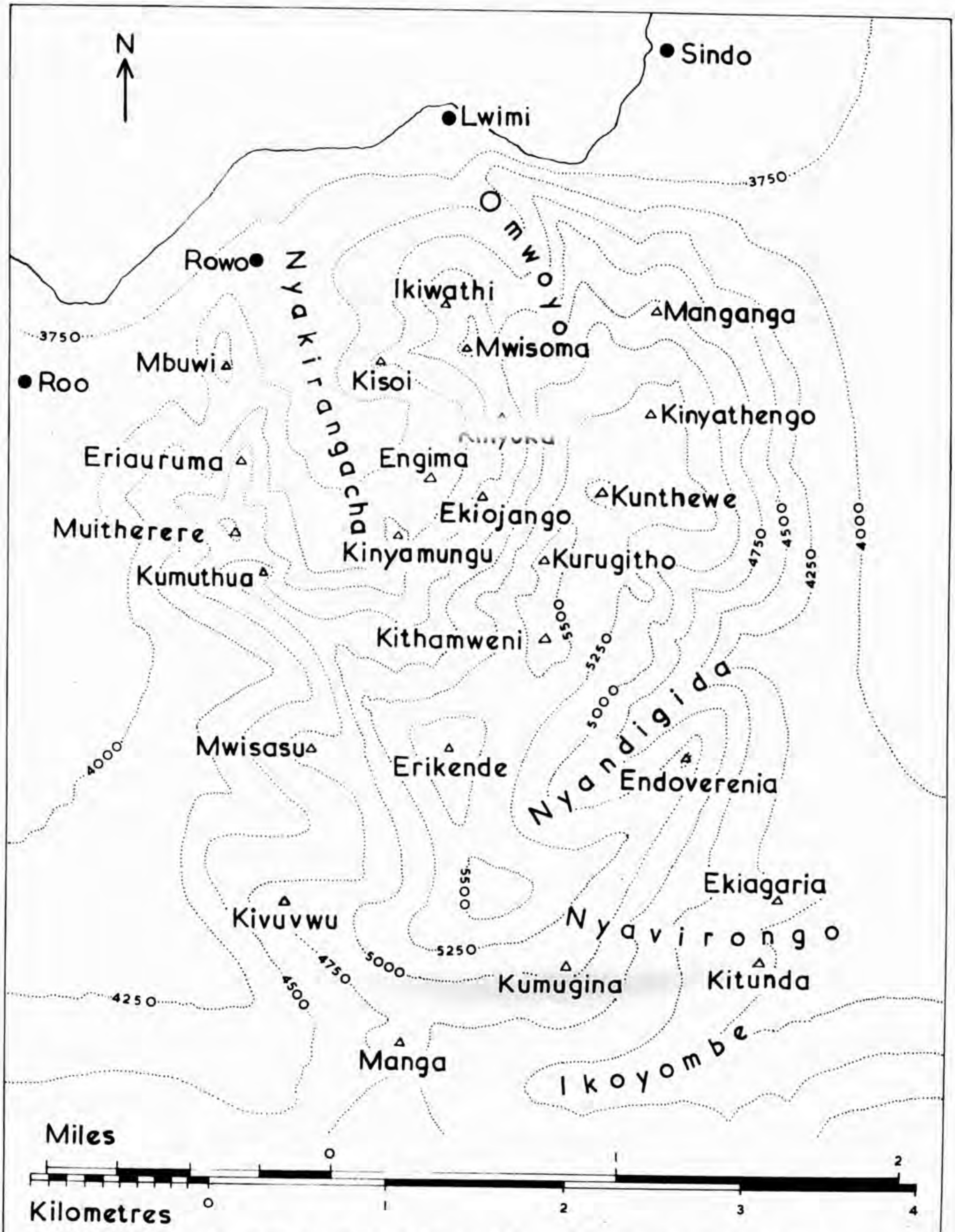

FIGURE 4 . TOPOGRAPHICAL MAP OF RANGWA.

The central arena of Nyakirangacha, most of which is thought to be floored by the Kinyamungu Carbonatite can be seen. It is partly ringed by a ridge consisting of Ekiojango Breccia; Kisoi is part of this ridge.

The outflow of Nyakirangacha is to the north west, and thick alluvium extends right into the valley.

Omwoyo is a long, curved valley.

Plate 2. Panoramic view of Rangwa from the north.

The large north - south valley marks a fault plane with a throw of several hundred feet to the west. To the east of it the boundary between the Lower Agglomerate and the Bedded Tuff occurs near the top of the large cliff on Manganga. To the west of it, the eastern part of the bounding cliff is composed of Bedded Tuff, and the western part of Upper Agglomerate.

Beneath the Upper Agglomerate cliffs, exposures of alkaline plutonics occur among the talus.

GWASSI HILLS.

The base line from which much of the map of Rangwa was constructed runs for two miles north-south across the alluvium-covered plain to the east of Rangwa.

The base of the Bedded Tuff is a clear line at the top of the main cliffs, marked by either small scarps or changes in the vegetation. The boundary can be seen to dip inwards in the wooded valley between Kinyathengo and Kunthewe.

The pronounced hump to the east of the top of Kunthewe marks the contact between the Bedded Tuff and the Upper Agglomerate.

The smooth curve of the outer limit of the pyroclastics and the uniform angle of slope of the talus can be seen.

The continuous nature of the outer limit of the pyroclastics can be seen. The boundary rises from 4000 feet above sea level near the lake to over 5000 feet in the south. Nyandigida is one of the long curved valleys which dissect Rangwa. Small deposits of recent alluvium occur below it.

Plate 4. Panoramic view of Rangwa from the east.

On Usengere, the large cliffs consist of nephelinite agglomerate without intercalations of lava. The base of the volcanics occurs at the small feature which runs through the white spot.

The outer limit of the pyroclastics is marked by a thickening of of the vegetation, and rises several hundred feet from north to south. In the valley of Nyavirongo, Banded Tuff and biotite uncompahgrite are exposed within ten yards of each other.

Kumugina consists entirely of alkaline plutonics. Their angle of slope is less steep and less regular than that of the talus elsewhere round Rangwa.

Plate 5. Panoramic view of Rangwa from the South east.

North of Ekiagaria, only sporadic exposures of alkaline plutonics protrude through talus slopes.

To the west of Rangwa, the bounding cliffs of the pyroclastics are not pronounced or continuous.

To the south of Rangwa, the outer limit.of the pyroclastics is clearly defined. Near Manga the belt of uncompahgrite and ijolite replaces the talus slopes beneath the pyroclastics. Manga is composed of ijolite and melteigite underlain by biotite uncompahgrite.

The connecting ridge between Manga and Usengere is composed of fenitized granite. The hill in the foreground is composed of nephelinite agglomerate at a far lower level than the granite or the dome on either side.

6. Panoramic view of Rangwa from the south west.

te 1. Panoramic view of Rangwa from the north west.

Gumba is composed of a succession of conglomerates and tuffs, separated from other exposures on Rusinga by a thick band of alluvium but correlated by Whitworth (1953) with the lower part of the succession on Kiahera Hill.

At Sienga Point, the melanite nephelinite is exposed at lake level, and the conglomerates and tuffs of the Kiahera series are missing. The thickness of the melanite nephelinite is far greater than on Kiahera Hill, and it is overlain by nephelinite agglomerate (Shackleton's Kiangata Agglomerate) and nephelinite lava (Shackleton's Lunene Lava) on Lugongo.

The succession on Kiahera Hill consists of conglomerate and tuffs (Shackleton's Kiahera Series 1951), overlain by melanite nephelinite (the Rusinga Agglomerate of Shackleton). Part of Shackleton's Hiwegi Series, mostly tuffs, some containing accretionary lapilli, is exposed at the top of Kiahera Hill.

The Mfwangano Fault runs through the Mbita Channel, where its throw is at least 500 feet. To the north of it, nephelinite lava rests on tuff at the top of Hiwegi Hill; to the south, nephelinite agglomerate is exposed at lake level.

The continuation of the fault can be seen as a small scarp on Uyoma.

7. The Kisingiri Volcano from Mbasa Island.

On Nyamarandi, nephelinite lava overlies melanite [illegible]; and Kibibura is composed entirely of melanite neph[illegible].
On Gembe itself, there is no-melanite nephelin[illegible] nephelinite lava occurs at the base of the succession. [illegible] feet of lava are succeeded by nephelinite agglomerate [illegible] with lava flows.

[illegible] of the erosion "caldera" round Rangwa (11 miles from [illegible]) can be seen, and the remnants of the basement dome are represented by Omutageti and the Bukula-Kwiunga ridge. If these parts of the dome are projected inwards, they would clear the top of Rangwa easily.

The contact between basement and volcanics occurs just above the steepening of the slope on the ridge between Gembe and Omutageti.

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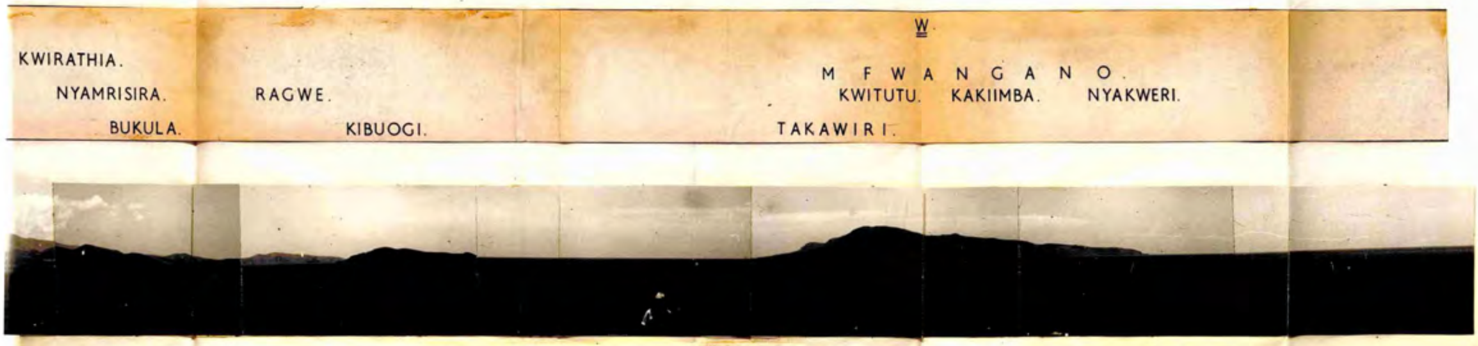
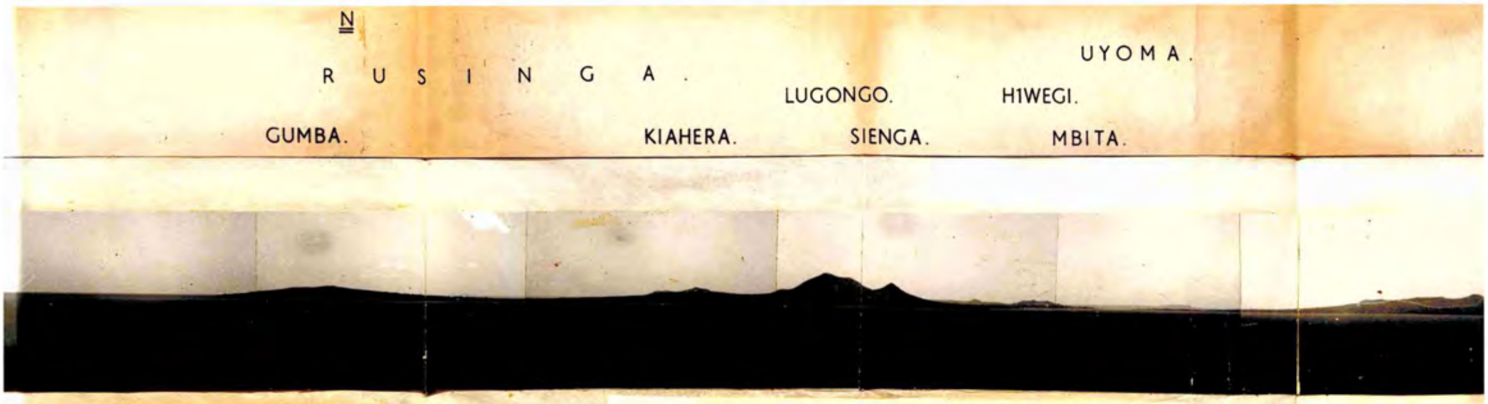


The Mfwangano Fault runs between Kibuogi and Takawiri and Mfwangano. Here it must have a throw of at least 1500 feet, since Kibuogi is composed entirely of nephelinite lavas and agglomerates, whereas at the south east of Mfwangano the base of the nephelinite agglomerate occurs 600 feet above lake level.

ot between basement and volcanics occurs in the dip between
the main mass of Usengere.
slopes of the volcanics can be seen both on Ragwe and Kibuogi.

Takawiri is composed entirely of granitic basement, and a small exposure of granite occurs at the south east corner of Mfwangano.

The succession on Mfwangano consists of conglomerates tuffs and melanite nephelinite, which have been correlated by Whitworth (1961) with the main sequence on Rusinga. They are succeeded by nephelinite agglomerate (Whitworth's Upper Agglomerate), which forms large east- and north-facing cliffs, and nephelinite lava (Whitworth's Cap Lava). The dip slope of the nephelinite agglomerate and lava can be seen.



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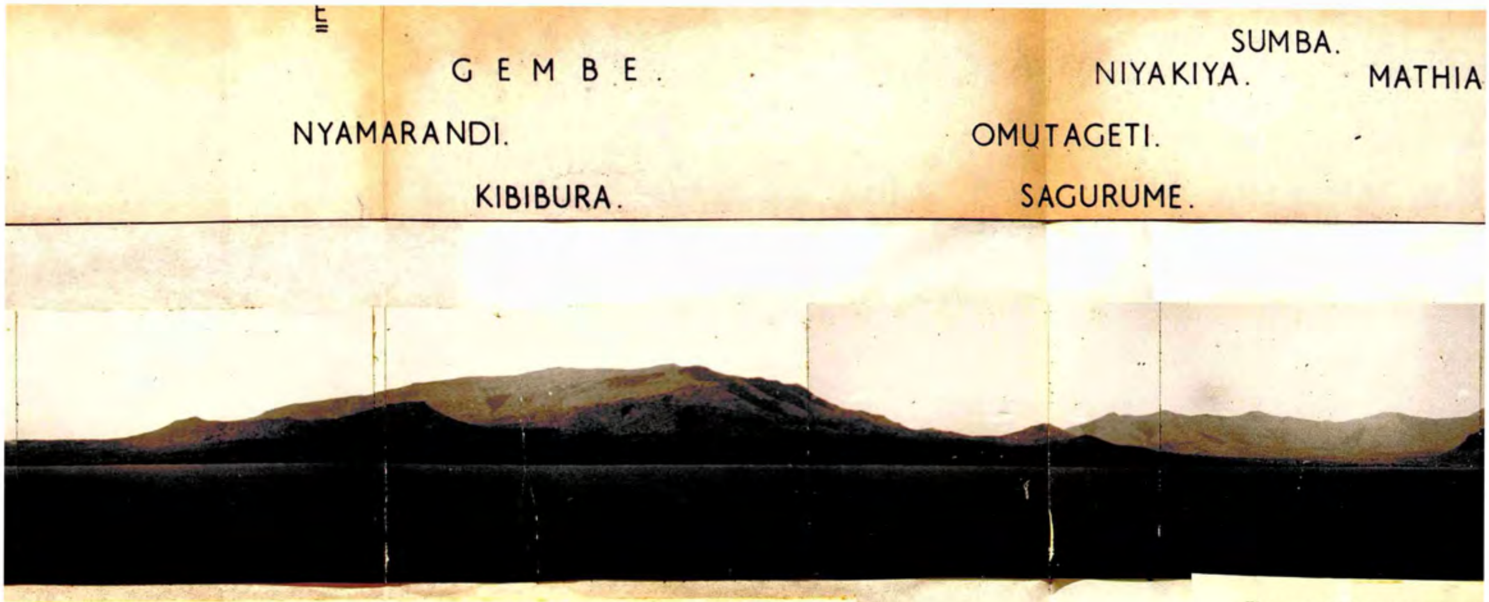
The continuation of the fault can be seen as a small scarp on Uyoma.

7. The Kisingiri Volcano from Mbassa Island.



On Nyamarandi, nephelinite lava overlies melanite nephelinite, and Kibibura is composed entirely of melanite nephelinite.

On Gembe itself, there is no melanite nephelinite, and nephelinite lava occurs at the base of the succession. Over 1000 feet of lava are succeeded by nephelinite agglomerate intercalated with lava flows.

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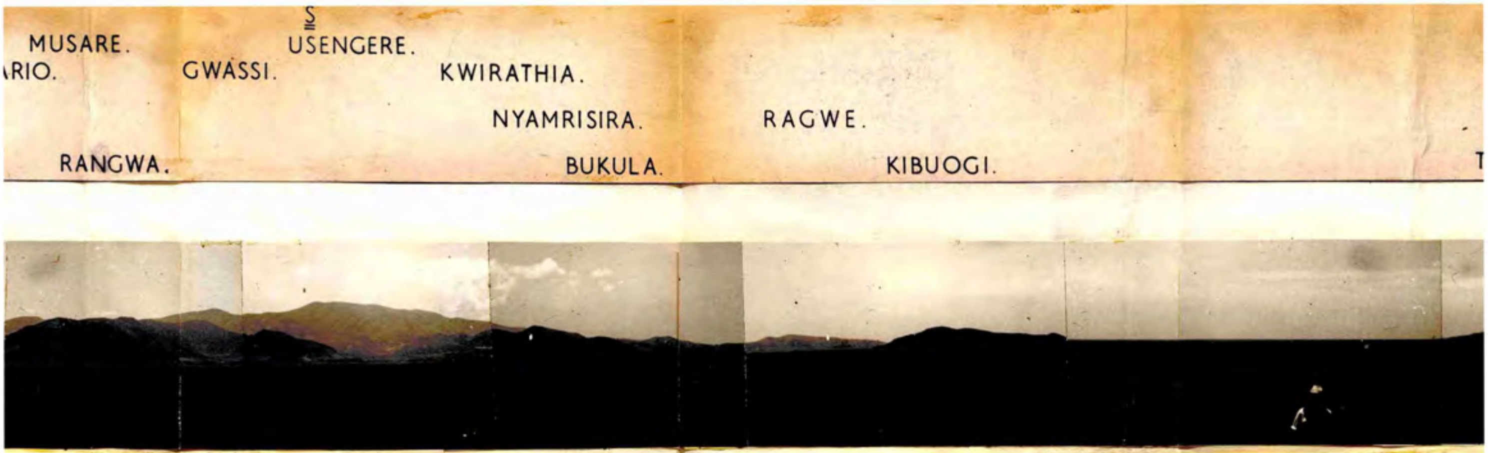

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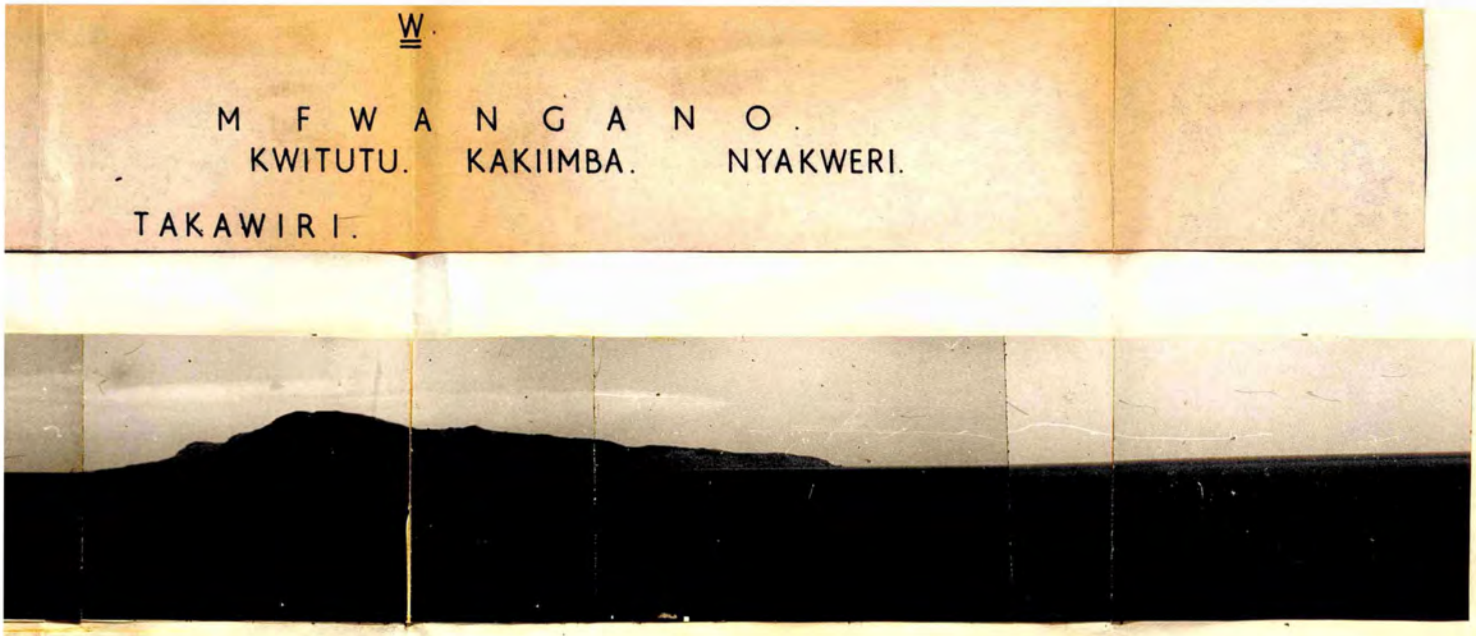

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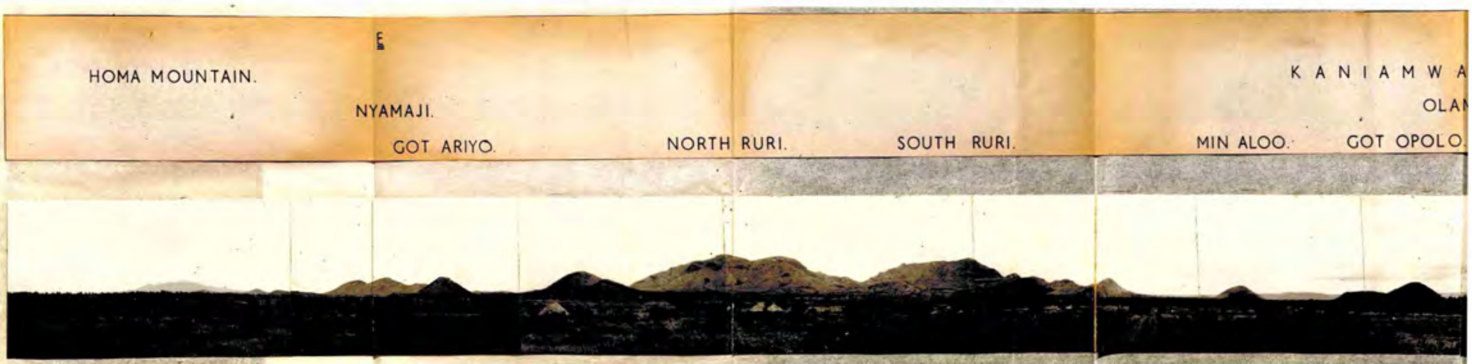


Plate 8. Ruri and the Kisingiri Volcano from between Mbita and Ruri.

Rangwa is framed by the outward-dipping volcanic masses of the Gwassi Hills and Gembe, on which the dips of lava flows can be seen clearly. If projected to the centre of the volcano, they would clear the top of Rangwa by at least 1000 feet.

Many of the hill tops on Rusinga rise to similar heights. These are capped by nephelinite lava. Beneath the lava there is a complicated succession of conglomerates, tuffs and melanite nephelinite lava.

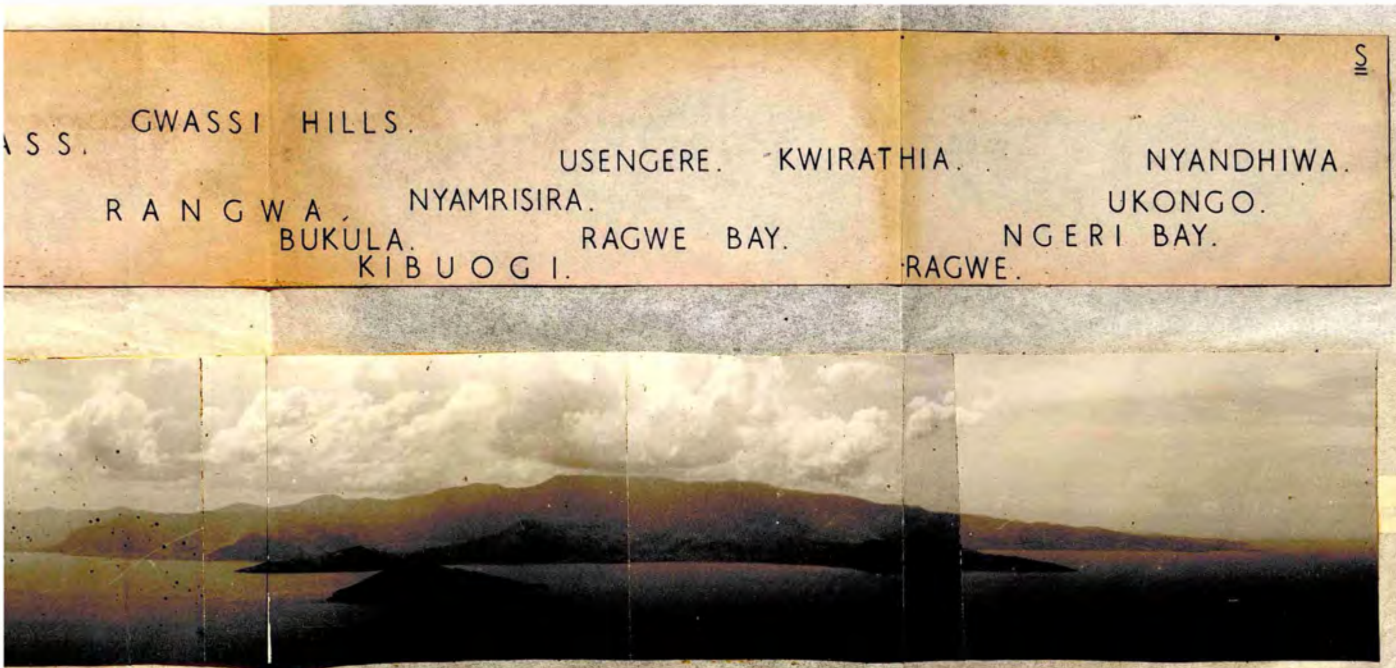
A dip slope of nephelinite lava can be seen running from the top of Gembe to the Mbita Channel. Gembe rises about 2500 feet above the level of Lake Victoria.

Usengere and Kwira
The west side of

The Mfwangano fault runs between Rusinga and the mainland, and north of Takawiri.

Takawiri is composed of unfenitised granite, and Mbassa of fenitised granite.

A ridge of basement concentric with the edge of Rangwa runs from Bukula to Nyamrisira.



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Usengere and Kwirathia are capped by a dip slope of nephelinite.
The west side of Ragwe Point is a dip slope also.

A ridge of basement concentric with the edge of Rangwa runs from
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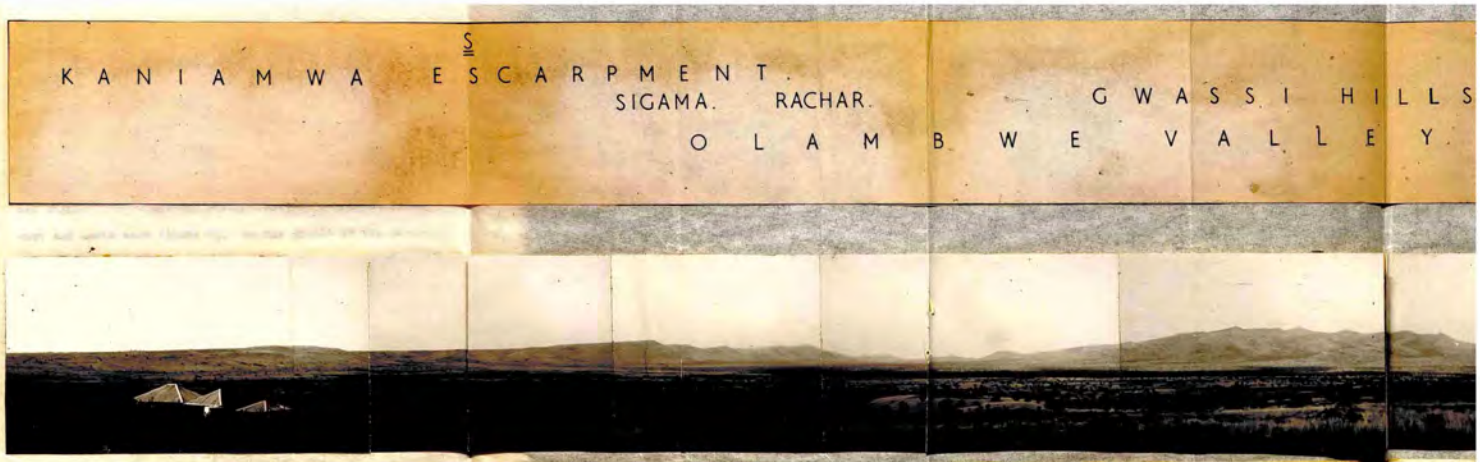

The Kaniamwa Escarpment runs north east - south west for nearly twenty miles. On Sigama it is 1500 feet high. Most of the scarp is composed of nephelinite lava and agglomerate. Bands of tuff occur near the base at the northern end.

Homa Mountain, North Ruri and South Ruri are carbonatite and alkaline plutonic centres. Most of the small conical hills are plugs of phonolite.

The nephelinite lava and agglomerate of the Gwassi Hills is highly dissected by radial valleys. The ridges between them are often dip slopes.

Plate 10. The Kaniamwa Escarpment from near Ruri.

Th

re

Continuous bands of lava can be seen on Gembe.

Got Jope and Min Aloo are both phonolite plugs.

The Olambwe Valley has a thick covering of black cotton soil.

The centre of the volcano is Rangwa, an oval hill, 3½ miles from north to south and 3 from east to west. It is 5,666 ft. high and just under 1,900 ft. above lake level, which currently stands at 3,730 ft. above sea level. Rangwa is surrounded by cliffs and big talus slopes; the cliffs form an almost continuous smooth curve in the east and south (Figure 4 and plates 2, 3, 4 and 5), but are broken by valleys in the west and north west (plate 6). In the middle of the mountain is a flat arena, Nyakirangacha, with a radius of about a mile and flanked by impressive cliffs that are broken only by a drainage outlet several hundred yards across to the north west (plate 1). Between the two circles of cliffs, the western part of Rangwa consists of a line of sharp peaks, Mbuwi, Eriauruma, Muitherere and Kumuthua, the highest, which rises to 1,300 ft. above the lake, and the eastern and southern parts are formed by

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However, it is not a locally used place name, but a word meaning "To Borrow" in Kisuba, the local language. Possibly it is a corruption of "Kaksingiri", the name of the location in which much of the volcano lies.

In this work, locally derived names are used wherever it is feasible. Place names will be discussed further in the section on mapping.

a higher humpbacked ridge, comprising Erikende (the summit of Rangwa), Endoverenia, Kithamweni, Kurugitho, Kunthewe and Kinyathengo, and dissected by concentrically arranged valleys of which Omwoyo (plate 1) and Nyandigida (plate 4) are the longest.

Rangwa forms a sharp feature in a broad flat basin floored by alluvium on all sides except the north, where the talus slopes drop into the lake. Beyond the alluvium, there is a partial ring of basement hills. They are rounded and some are as high as Rangwa (plate 7). They are mostly at distances of between 1 and 4 miles out, and in the south, one of them, Manga, connects Rangwa with Gwassi (plate 6). It is composed partly of alkaline plutonics, and two spurs of alkaline rocks and basement, Kitunda and Ekiagaria, project from Rangwa to the south east (plate 5).

The basement zone is overlooked by the remnants of an inward facing scarp, sometimes of cliffs, but usually just steep stony slopes. They are the inner edge of the sheets of volcanics that dip away from Rangwa, and are found between 2 and 5 miles out. The volcanics to the east, south and west form mountains. Gembe lies to the north east, and is a ridge with a gentle outward slope, rising to 6,230 ft. (Figures 2 and 3 and plates 7 - 10). To the south east, south and south west, a continuous scarp, the Gwassi Hills, is separated from Gembe by the Sindo Pass; it runs from Sumba to Kwirathia (plates 7 - 10), and Usengere, at 7,450 ft.

is the highest hill. From a distance, the mountains appear to be solid dip slope masses (plate 7), but in fact they are highly dissected by long straight radial valleys.

To the south east, the volcanics of Gwassi and Gembe disappear under the Olambwe Valley, a broad flat alluvium-covered plain, in which the Olambwe River, the only stream of any size in the area, meanders. Beyond the valley is the Kaniamwa fault line scarp, 1,800 ft. high opposite Gwassi, but petering out at either end (plate 10). At the south end, the valley is blocked by low parallel ridges of volcanics, and at the north there are the hills of the Ruri and associated alkaline complexes, as well as numerous small conical plugs of phonolite (plate 8).

A complementary fault line scarp, probably once as big as the Kaniamwa Escarpment but now much dissected, lies to the north west of the volcano. It is represented by the islands of Mfwangano, Takawiri and Rusinga, as well as by a small scarp on Uyoma. It is parallel to the Kaniamwa Escarpment, and, like it, is highest opposite the volcanic centre. South east of this fault, the basement hills are missing, and only small amounts of volcanics survive, forming Kibuogi Island and Ragwe Point (Figure 2 and plate 7). Mfwangano is a triangular island rising 1,700 ft. above lake level, and about 8 miles across, with rugged cliffs to the south and east, and a gentle dip slope running north west (plate 7).

Takawiri is a small low basement island. Rusinga is the same size as Mfwangano, but with more varied topography, a reflection of more complicated geology and the fact that erosion has proceeded further (plates 7 and 9). The rocks on Rusinga and Mfwangano differ from the rest of the volcanics in that they include a large proportion of sediments and tuffs with non-volcanic fragments.

Outward from the areas described, the volcanics cover large stretches of featureless plateau and plain, both south east of the Kaniamwa Escarpment and on Uyoma.

2. CLIMATE AND VEGETATION.

The area has a varied rainfall, probably averaging 40 inches near the lake, but much higher in the Gwassi Hills, which have several storms a week for most of the year. Some isolated pockets on the coast, such as Ngeri Bay, benefit from being near high ground, and have comparable rainfalls. Most of it falls during the long rains in March and April, and the short ones in October, and comes as violent afternoon or evening thunder storms that are blown down from the Kisii Highlands. The rains often fail, as they did in March 1965, or come at different times of year; this caused the floods of December 1961 which raised the level of the lake by 7 ft. Much of the rain that does fall is lost through evaporation and runoff, causing a large amount of gulley erosion.

Except for a few small streams on Mfwangano and the Olambwe River, the rainfall is not enough to support permanent streams.

The influence of the lake and the height above sea level prevent excessively high temperatures. However, it is nearly always sunny, and the temperatures sometimes rise to over 80°, especially in January, the hottest month. The effect of the temperature is modified by breezes from and to the lake.

Where they are not under cultivation, the plains and lower slopes of the hills have a seasonal covering of long grass sprinkled with Acacia and Euphorbia candelabra trees. The hills support several types of vegetation. The higher parts of Usengere are smothered by primary tropical rain forest with tall trees and creepers. Most of Rangwa, parts of the Gwassi Hills and Mfwangano have thick secondary thorn and Euphorbia bush. Apart from patches of forest, the rest of the volcanics are covered with tall grass. The basement hills normally have little soil cover, and only support short grass. With this one exception, the distribution of vegetation is related more to climatic conditions, past land usage and seasonal burning than to the underlying geology.

3. SETTLEMENT AND COMMUNICATIONS.

At the present day, the area has a scattered population, and communications are poor. The district and county administrative centre is at Homa Bay. Local administration is organised by the chiefs of the five locations of Kaksingiri, Gwassi, Gembe, Rusinga and Mfwangano, each of which supports a few thousand people.

The inhabitants are Basuba, from a small group of Bantu tribes; they speak a language similar to Luganda, and came from Uganda in several waves about 400 years ago, ousting or assimilating their Masai predecessors. They in turn are being assimilated by the much larger Lwo, a Nilotic tribe.

They live mainly by subsistence farming, and grow maize, millet cassava and sweet potatoes; some cash crops, such as sisal, cotton and groundnuts have been introduced. Each family village keeps large herds of cattle and goats. As they are used for paying bride price, they are bred for numbers rather than quality. Hence there is overgrazing, and this, with the annual grass burning and torrential rain, causes rapid soil erosion. Fishing provides a major source of food and income.

Settlement today is sparse enough to allow shifting cultivation, but, as most of the hillsides are covered with long-abandonned terracing, the population must have been far greater once. Outbreaks of Sleeping Sickness have caused the reduction, and the Olambwe Valley is still worse infested with the disease than any other part of East Africa.

There are few roads in the area; the main ones are dry weather roads to Sindo via Mbita, and to Karungu and Magunga, both from Homa Bay. As well, there are some tracks in the Olambwe Valley, a track from Sindo to Nyangwethe, and a road to the EAPT repeater station on the top of Gembe.

III

PREVIOUS WORK IN THE AREA

Parts of the Kisingiri Volcano have attracted considerable geological attention. The first geologist to publish work on the area was Oswald (1914), who concentrated mostly on the Tertiary sediments at Karungu. He travelled by boat down the Kavirondo Gulf, and round the Gwassi Hills. He realised that they are volcanic, and compared them with the Plateau Basalts of Scotland and Northern Ireland. However, he did not appreciate that the hills are the remnants of one large central volcano. He gives a good stratigraphic description of the beds at Karungu, and suggests that the change in sediment type is due to the downgrading of a large river.

Most of the rest of the work to date has been concerned with the stratigraphy and palaeontology of Rusinga and Mfwangano islands. The bedded sequence on Rusinga was discovered by Wayland (1931). Kent (1944) gives an account of the geological work accomplished on Rusinga and elsewhere in the Kavirondo Rift during the 1934 - 1935 East African Archaeological Expedition; he considered that the position and order of the beds is influenced by large scale thrusting, and that the Kavirondo Rift is formed by compression.

Shackleton (1951) describes the stratigraphy of Kiahera Hill on Rusinga and gives a very detailed map; this is useful, as the hill provides outcrops of most of the sedimentary units found on the island. He couples his account with broader observations on Rusinga and the Kavirondo Rift. He disagrees with many of Kent's conclusions, and maintains that the Rift is formed by tension. Also, he shows that the large granite and limestone boulders, which Wayland and Kent found on the east side of Gumba Hill, and supposed were in situ basement, are in fact exotic fragments in part of the volcanic and sedimentary sequence.

Whitworth (1953) mapped Gumba peninsula at the eastern end of Rusinga, and the sequence of lithologies he describes is correlated with the one on Kiahera, though, unfortunately, they are given a new set of names.

Whitworth (1958) gives a general geological description of Mfwangano, and relates the stratigraphy to that of Rusinga. He also attempts to show that the Mfwangano fault is an unimportant structure; this is based on the mistaken assumption that Kibuogi Island to the south of Mfwangano is composed of granite basement, when in fact, it is nephelinite and nephelinite agglomerate.

Leakey and MacInnes have worked extensively on the fossil fauna on Rusinga and Mfwangano (1953 etc.), but the palaeontology is not tied in with the stratigraphy, and their work is important in the present context only in so far as it shows the variety and excellent state of preservation of the fossils. These are good clues to the environment and type of sedimentation which buried the animals.

McCall (1958), in his account of the Gwasi area quarter degree sheet, describes the main rock types found on the Kisingiri Volcano, provides a well reasoned synthesis of the history of the volcano and discusses its origin fully.

Rangwa itself figures little in geological literature. Shackleton (1951) recognised it as the volcanic centre and saw that it is composed largely of agglomerate and carbonatite. McCall (1958) gives descriptions of some of the rocks and a map, but by correlating most of the agglomerate on Rangwa with the Kisingiri nephelinite agglomerate, he does not put Rangwa into a true relationship with the rest of the volcano.

Frequent reference will be made throughout this thesis to McCall's work, and that of Oswald, Kent, Shackleton and Whitworth will be discussed more fully in Part III.

IV

METHODS OF WORK AND ROCK NOMENCLATURE

1. FIELD WORK.

Two seasons were spent in the field, one from August 1964 to March 1965, and the other one from January to March 1966. The earlier season was used to map Rangwa, and the latter to make traverses on the periphery of the volcano.

The only survey map covering the area is the Kenya Ordnance Survey sheet 129/1, Gwassi, published in 1962. The scale is 1:50,000, and it is based on air photographs taken in 1947, 1948 and 1961, as well as some field survey data, including a triangulation point on top of Usengere. The contours are at intervals of 50 ft., but with such scant ground control, they are not accurate enough to be enlarged for geological mapping.

McCall (1958) gives a map of Rangwa at a scale of 4 inches to the mile (1:15,840), on which the contours are interpolated from air photographs at intervals of 100 ft. This is the only previous geological map, but the topography is less accurate than on the survey map.

Since the present work was to be done at scales of 1:10,000 and 1:5,000, neither of the above was adequate. So a new map was constructed incorporating both the geology and the topography at the same time. All the mapping was done on a plane table and heights were measured with an Indian clinometer.

The first field map covers most of Rangwa at a scale of 1:10,000. At the start the shoreline and chief's camp at Sindo were plotted in from the Survey map. However, that shoreline predates the 1961 floods, and the new coast was mapped in from the old one, which survives as a discontinuous line of reeds in the lake. The position of the Sindo school was then found, and a baseline was measured from it, running for about two miles north south across the flat land east of Rangwa. From the shore and baseline the main peaks on Rangwa were plotted on the map and their heights calculated. A network of spotheights was then constructed round the peaks, and the geology was mapped from these.

The geology and topography round Nyakirangacha proved to be too intricate for mapping at 1:10,000. So the United Nations team of geologists working in western Kenya kindly supplied an enlargement to 1:10,000 of the 1961 1:50,000 air photograph, which was used to construct a 1:5,000 map. The points plotted on the 1:10,000 map were put at their correct positions in relation to the air photograph on a trace over it, and the 1 kilometre grid from the map was put onto the trace in a distorted form to fit in with the points. All prominent features (cliffs, hilltops etc.) were traced to find their positions relative to the distorted grid, and transferred to a map with the original straight line grid at a scale of 1:5,000. By this method, the edges of the 1:5,000 map fit in well with the 1:10,000 one. Heights of about 250 prominent points were measured using the Indian clinometer at a central viewpoint in Nyakirangacha. Geological mapping in the thickly wooded parts was done on small sketch maps prepared from the 1:5,000 map.

Finally, the 1:10,000 map was enlarged to 1:5,000, and a map of the entire area was produced at that scale. Contours were interpolated at intervals of 50 ft., using the spot heights, and the positions of cliffs, hills and ridges. The map has a 1 km grid (20 cm on the map), and, for the purpose of giving grid references, this grid is numbered in the same way as on the Survey map.

Place names used are local ones; parts of Rangwa are generally called after old heroes, who took to the hills when their country was invaded. All the names included on the maps have been verified many times, and where they differ from those used on previous maps it is in the interests of accuracy.

During the second field season, some of the geology of Rangwa, particularly the plutonic centre to the south east and parts of the central carbonatite, were re-mapped. The inner contact between the domed basement and the volcanics was mapped, and extensive traverses were made across the hills and islands that make up the periphery of the volcano. To this end, a week each was spent on Rusinga and Mfwangano, and shorter visits were made to Kibuogi, Takawiri, Mbassa, Ngeri Bay, Karungu, Magunga and Kaniamwa; also traverses were made up the volcanic scarp on Gembe and the Gwassi Hills.

2. PETROGRAPHIC, CHEMICAL AND X-RAY WORK.

310 thin sections, covering all the rock types that were found on and around Rangwa, were examined, and in the rock descriptions reference is made to the relevant specimens. Polished surfaces of most of the specimens of tuffs, agglomerates and breccias were prepared, as these show the textures and relations between fragments far better than thin sections.

8 new chemical analyses (Analyst - Mr. H. Lloyd) of ijolites, turjaites and uncompahgrite are presented and discussed.

The specific gravity of all the specimens of carbonatite was determined using a Joly Balance, to give an indication of the types of carbonate present in them.

Some specimens of carbonatite were stained with sodium alizarin sulphonate (Mitchell 1956) to distinguish calcite from dolomite and ankerite. A few rocks containing very fine-grained felspar were stained with sodium cobaltinitrite (Chayes 1952 and Bailey and Stevens 1960) to show how much of it is potash felspar. 10 specimens of Lower Agglomerate and 10 from the Tuff Group were analysed for carbon dioxide with a view to finding their carbonate content.

The x-ray diffractometer at the Department of Geology, Leicester University, was used (with the help of Mr. J. Dixon, Mr. M.G. Clarke and Mr. A.M. Flegg) to determine the type of carbonate in some specimens, and to test whether much of the amorphous potash felspar in the pyroclastics is orthoclase or microcline.

3. ROCK NOMENCLATURE.

A. ROCKS OF THE MAIN PLUTONIC COMPLEX.

The names used for rocks of the plutonic complex to the southeast of Rangwa are biotite pyroxenite, biotite uncompahgrite, turjaite, melteigite, ijolite and urtite. The rocks which they define can all be plotted near the edges of a triangular diagram illustrating the proportions of the three main minerals in them, pyroxene, melilite and nepheline (Figure 7); and the names signify areas in the triangle. Since the compositions of the rocks form continuous gradations, any attempt to split them up is arbitrary, so as few names as possible have been used. Areas near the corners of the triangles are:-

1. Biotite pyroxenite which consists of predominantly diopsidic pyroxene, with minor amounts of biotite, perovskite and magnetite. This usage follows that of Holmes and Harwood (1932 and 1937) for fragments in the potash-rich volcanics of Southwest Uganda.

2. Biotite uncompahgrite, in which melilite is the main

mineral, and which contains variable amounts of biotite, perovskite and magnetite and, sometimes, pyroxene. This name was used by McCall (1958), and the rock differs from the uncompahgrite described by Larsen (1942) from Iron Hill, in that biotite is an essential and sometimes major constituent.

3. Urtite, which is mainly nepheline and contains small quantities of aegirine-rimmed aegirine augite. It is similar to the type urtite from the Kola Peninsula (Ramsay 1896 in Johannsen 1938, Volume 4, pp 316 - 317).

No name is given for a rock whose composition is intermediate between those of biotite pyroxenite and biotite uncompahgrite, and the boundaries between the two is put where significant quantities of melilite begin to appear. Following Ramsay (1921 in Johannsen 1938, Volume 4, pp 323 - 324), the name turjaite is given to any rock which contains both nepheline and melilite, except when one of them is present in very small quantities. For the rocks intermediate in composition between biotite pyroxenite and urtite, the usage of Brogger (1921) is followed; in melteigite, there is less than 50% nepheline, in ijolite 50% - 70%, and in urtite more than 70%. None of these rock names carries any connotation of grainsize or texture, both of which are variable.

B. THE PYROCLASTICS.

The extrusive fragmental rocks which make up the greater part of Rangwa itself are classed as agglomerates and tuffs according to the predominant size grade of the fragments. Williams and Wentworth (1932) classified pyroclastics by size grade into tuff (up to 4 mm fragment size), lapilli tuff (4 - 32 mm) and agglomerate (over 32 mm). On Rangwa, the term "lapilli tuff" is not used, because of the ambiguity it would cause, as many of the tuffs contain accretionary lapilli; also it is impossible to use any strictly defined classification since the fragment size within one bed or band is often variable, but where sub-division is meaningful, a rock whose average fragment size is over 4 mm is called an agglomerate, and less than 4 mm a tuff. In the agglomerates and tuffs, the fragments tend to be rounded or sub-angular.

The group names, Lower Agglomerate, Tuff Group and Upper Agglomerate refer to divisions within the pyroclastics in which the predominant size grade differs, although bands of tuff sensu stricto are frequent within the Lower Agglomerate.

The oblate spheroids that are characteristic of the Banded Tuff are called "accretionary lapilli", the term used by Moore and Peck (1962); the term "pisolites" used for similar spheroids from some of the tuffs on Rusinga and Mfwangano by Whitworth (1953 and 1958) is discarded because it is ambiguous, since pisolites, like oolites, are normally thought to be spheroids which have grown by chemical precipitation in a calcareous environment.

C. THE CARBONATITES.

The name "carbonatite" is only applied to rocks in which the carbonate is considered to be the original mineral and not to those that have been carbonated; the term "metacarbonatite" proposed for the latter by Verwoerd (1966) is considered to be unnecessary and misleading. Brogger's definitions "sovite" for carbonatite from large masses with calcite as its major constituent and "alvikite" for its hypabyssal counterpart (1921), are both used. Dolomite and ankerite do not occur often in the carbonatites on Rangwa, and hardly ever as the principal constituents; so, unless otherwise stated, the carbonatites referred to in this work consist mainly of calcite.

D. ALTERED COUNTRY ROCK AND FELSPATHIC BRECCIA.

Most of the rocks considered in this section fall within the scope of Sutherland's definitions (1965), and some of these are used. However, the end products of the processes of alteration are so varied that it is, in general, misleading to use a stereotyped terminology with which to describe them. Unaltered but shattered country rock is termed "breccia", as are the rocks which are shattered in association with the central carbonatites; most of the latter are carbonated and felspathised, and some contain fragments of carbonatite; the only feature all the breccias have in common is that they contain angular fragments. The altered country rocks are described in terms of the mineral introductions and changes involved; so there is no need to differentiate precisely between rock types. However, the term "fenite" is used for rocks into which aegirine and sodic amphibole have been introduced without any great change in the original felspars. "Felspathic fenite" refers to rocks which have been altered so that they contain appreciable quantities of newly formed potash felspar, in addition to the sodic ferromagnesian minerals (it is not clear from Sutherland's definitions whether her "felspathic fenite" contains the latter or not). The term "felspar rock" is used to refer to rocks that have been formed by alteration, in which potash felspar predominates, and which contain little or no aegirine or sodic amphibole.

E. THE LATE DYKES.

The phonolite that is found in a few dykes is a distinctive rock which conforms closely to Johannsen's description of that rock (1938 pp 122 - 127 Volume 4).

Most of the late dyke rocks have been defined as lamprophyres; they are mafic rocks of a highly porphyritic nature, in which the groundmass has been almost entirely altered. They contain a wide variety of minerals, but the same associations tend to occur throughout the group. The rocks of this group can legitimately be classified as lamprophyres on the basis of any definition available (for example Johannsen 1939, Volume 1, p 262, and Hatch, Wells and Wells 1952, pp 348 - 349), although some of them can equally correctly (McCall 1958) be defined as nephelinites.

PART II.

THE GEOLOGY OF RANGWA.

V

THE BASEMENT

A partial ring of basement between 1 and 4 miles wide occurs between the alkaline rocks and pyroclastics of Rangwa and the inward facing scarps of volcanics on Gembe, the Gwassi Hills and the islands. Much of this area is covered by thick alluvium, and the basement is intruded and altered by alkaline plutonics in many places. (Figure 5).

The basement rocks described here are at least 10 miles from any other exposure of basement.

1. THE DISTRIBUTION OF THE BASEMENT ROCKS.

Most of the rounded hills that surround Rangwa are composed of granite, and their appearance is reminiscent of granite hills elsewhere; they are steep but smooth, and, although there is little actual exposure, the soil cover is thin and the surface is littered with boulders to such an extent that the vegetation is normally sparse.

Only two areas of exposure of nongranitic basement were found. On the ridge of Kwiunga, 2 miles west of Rangwa, several narrow bands of schist, amphibolite and quartzite occur which strike west-north-west east-south-east, and are nearly vertical. A set of similar bands, including one of banded ironstone, outcrop

Plate 11. Exposure of unaltered granite on Takawiri.

Plate 12. Exposure of banded quartzite west of Rukungu.

on the ridge that encircles Rukungu, $2\frac{1}{2}$ miles east of Rangwa.

Much of the area of supposed basement is covered by alluvium and soil. At a distance from Rangwa of between 2 miles in the south and 8 miles in the north, outward-dipping nephelinite lavas and agglomerates overlie the basement; this contact, which is seldom well-exposed, occurs at heights varying from lake level (3,730 ft) to 5,500 ft. The main areas of outcrop of basement are on the Bukula-Nyamarisira ridge, Manga, the rounded hills below the scarps of the Gwassi Hills and Gembe, and the low-lying island of Takawiri. Inwards from these, the basement is submerged in alluvium or covered by the lake, and there are no outcrops on the plains to the east, north and west of Rangwa.

On Manga, the ridge connecting Usengere with Rangwa, basement rocks are exposed close to the central alkaline plutonics, and fenitised basement occurs on the western parts of Kitunda and Ekiagaria. Apart from these exposures and a few scattered blocks of highly altered basement in the talus slopes below the Rangwa pyroclastics, there is no indication of the position of the contact between the basement and the central plutonic complex.

The contacts between the basement and the numerous small outlying areas of alkaline rocks will be described in Chapter VI, and the pattern and significance of the position of the base of the lava will be discussed in Part 3.

2. DESCRIPTION OF THE ROCK TYPES.

No detailed description is attempted, since the importance of the basement in this work is that it provides the material on which the alteration processes associated with the intrusion of the alkaline plutonics operated. The main types of rock exposed around Rangwa are quartzite, mica schist, amphibolite, ironstone and granite.

A. QUARTZITE.

The quartzite is sometimes pure, but generally contains small quantities of microcline and muscovite. The size of the quartz grains varies between .05 and 1.5 mm, and the different size grades form bands with sharp boundaries between them (plate 12 and RFP 172, plate 13). Most of the plates of muscovite follow the boundaries. The quartz forms an irregular and interlocking mosaic (often in lenses parallel to the banding), especially when coarse grains are included in a finer groundmass. Microcline crystallizes interstitially to the quartz grains.

B. MICA SCHIST.

The schist is never well-exposed, and it was impossible to obtain unweathered specimens of the more micaceous rocks. The amount of mica varies between 15% (RFP 170) and 75% (RFP 173, plate 14); in the former case most of the mica is biotite, but muscovite

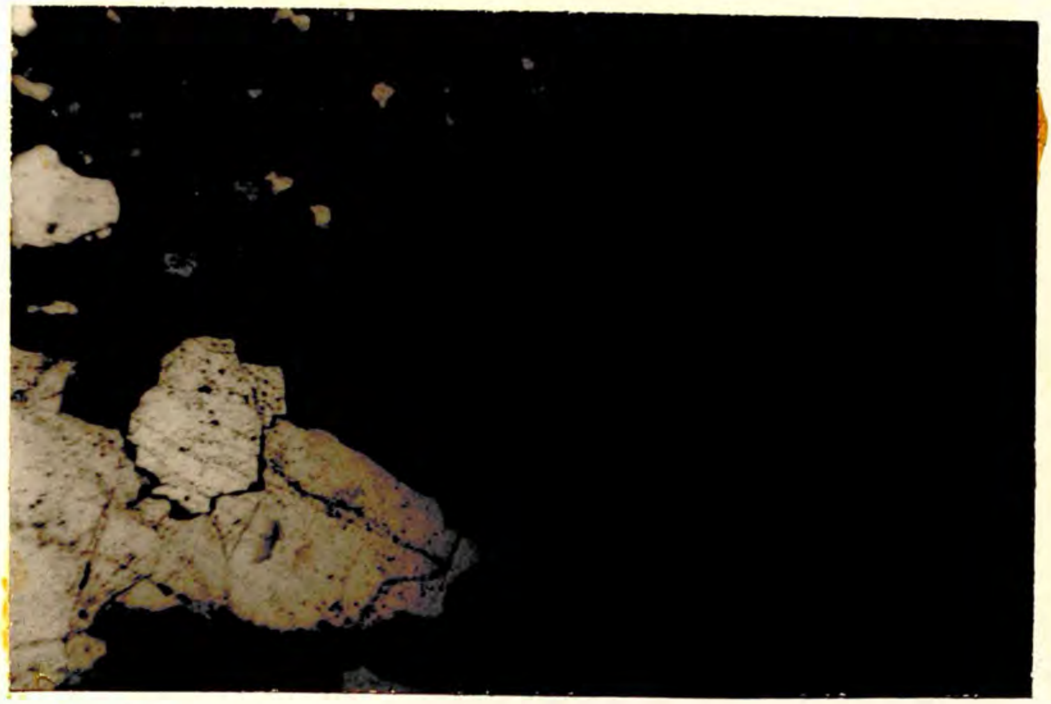


Plate 13. Boundary between coarse-grained and fine-grained bands in quartzite (under crossed polarisers). (RFP172). x25

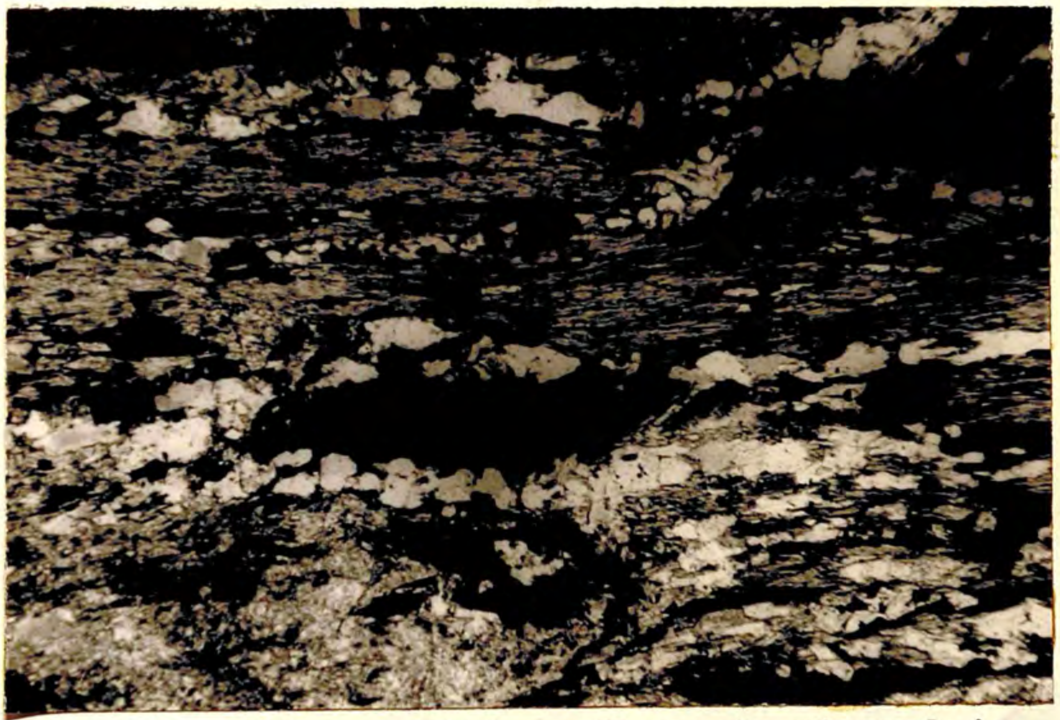


Plate 14. Mica schist. The main mineral is muscovite. Several large crystals of biotite occur with a different orientation from the muscovite. The white bands are quartz crystals. (RFP173). x55

in the latter. The mica is always orientated, and a feature of RFP 173 is that the direction of orientation of the biotite is different from that of the muscovite.

The other main mineral in the schist is quartz, and lesser amounts of microcline, plagioclase, hornblende are common. Patches of brown ore are present, but these are probably weathering products.

C. AMPHIBOLITE.

Amphibolites contain over 50% hornblende. The blue-green variety, similar to the hornblende of the granite, occurs in quartz-rich amphibolites (RF 335), but in purer sorts that contain over 85% hornblende (RF 334, plate 15), the pleochroism is:-
Z - dark green, Y - olive, X - pale yellow green. The hornblende forms subhedral orientated crystals, which give the rock a schistose appearance in hand specimen.

Quartz and untwinned zoned plagioclase occupy the spaces between the hornblende crystals.

Most of the amphibolite occurs unaltered on Bukula, west of Rangwa, but small amounts of the quartz-rich type were found at several localities east and north of Rangwa. Being predominantly green, these are easily confused in the field with alkaline intrusives and exposures south of Gingo and west of Rukungu were mapped as such; thin section evidence, however, shows that these are only

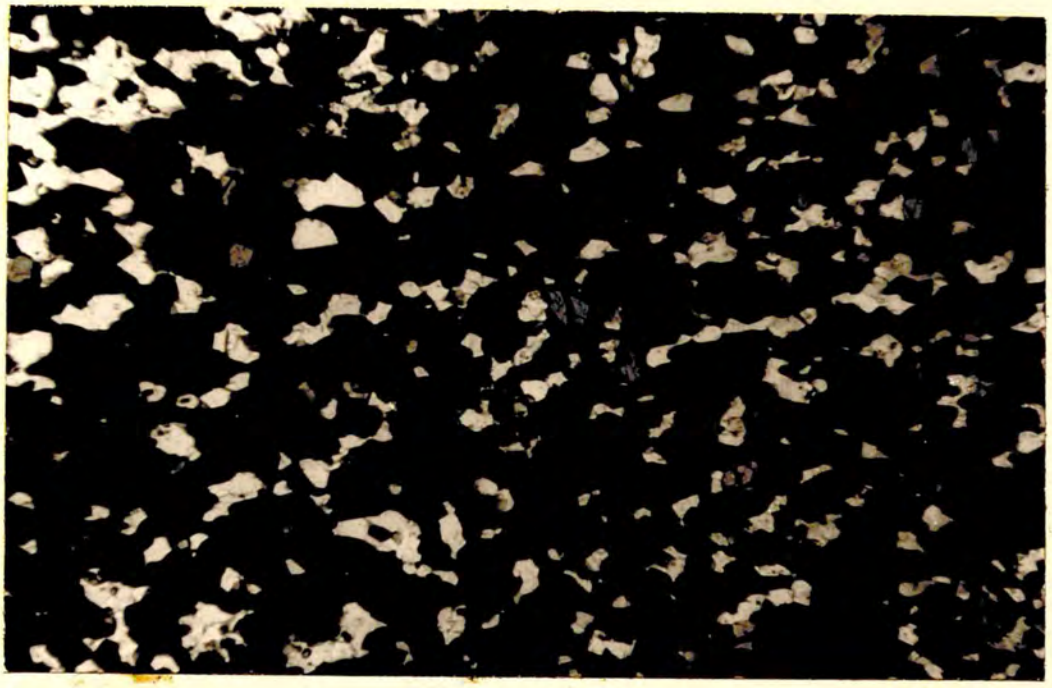


Plate 15. Amphibolite. The pale material is quartz. Most of the hornblende is showing maximum absorption. (RF334). x80.

Plate 16. Chalcedony vein in the Banded Ironstone (under crossed polarisers). (RF268). x155.

slightly altered amphibolite.

D. BANDED IRONSTONE.

The ironstone has well-defined regular bands, which are about 3 mm thick, and are highly folded (RFP 114). Much of the rock consists of rounded grains of opaque black ore, and these are graded within each band; their size varies from .05 to .5 mm, and the coarser parts of the bands are richer in ore. There is no sharp boundary between bands.

The ore is in a groundmass of larger irregular quartz crystals, and patches of yellow-brown non-crystalline material of high relief occur sporadically.

In one specimen from near the Rukungu vent (RF 268, plate 16), the ironstone is cut by small veins of chalcedony and euhedral quartz, which cause minor dislocation. The only other occurrence of euhedral quartz is within the Kinyamungu Carbonatite, and it is not known whether the veins of it in the ironstone are features from before the igneous activity or have a similar late stage origin to the quartz in the carbonatite.

E. GRANITE.

The granite may be banded or massive, and is medium or coarse grained. Porphyritic varieties were seldom found. It weathers pale red, but weathering is not deep except when close to alkaline intrusives. The normal minerals in it are quartz, microcline and oligoclase, with accessory muscovite, biotite or hornblende. Granite sometimes contaminates the schist and amphibolite.

Quartz forms irregular segregations and zones which may compose at least 40% of the granite (RF 338, plate 17), and the normal grain size is about 5 mm. The crystals are anhedral, and, especially in the banded granite, the segregations are streaked out, and the quartz is very strained and shattered. Groups of rounded inclusions of quartz with similar orientation may be included in the microcline (RFP 75, plates 18 and 19).

Microcline occurs as clear, unaltered crystals, which may be 2 cm across, and compose up to half the rock. It shows polysynthetic twinning on the albite and pericline laws, and single large crystals penetrate and enclose all the other minerals, though this relationship may be reversed with plagioclase (plates 20, 21 and 22 show relations between the felspars).

The most common plagioclase in the granite is oligoclase with a composition varying between An_{24} and An_{30}. Very fine polysynthetic twinning on the albite law is common (RF 342, plate 23); however, the oligoclase is generally sericitised (plate 24), especially in the middle of the crystals, so that the twinning is often obscured. The margins are clear and more albitic. Usually, oligoclase forms small plates, though it may occur as anhedral crystals of similar habit to the microcline, in which case it encloses irregular streaks of microcline and may be antiperthitic.

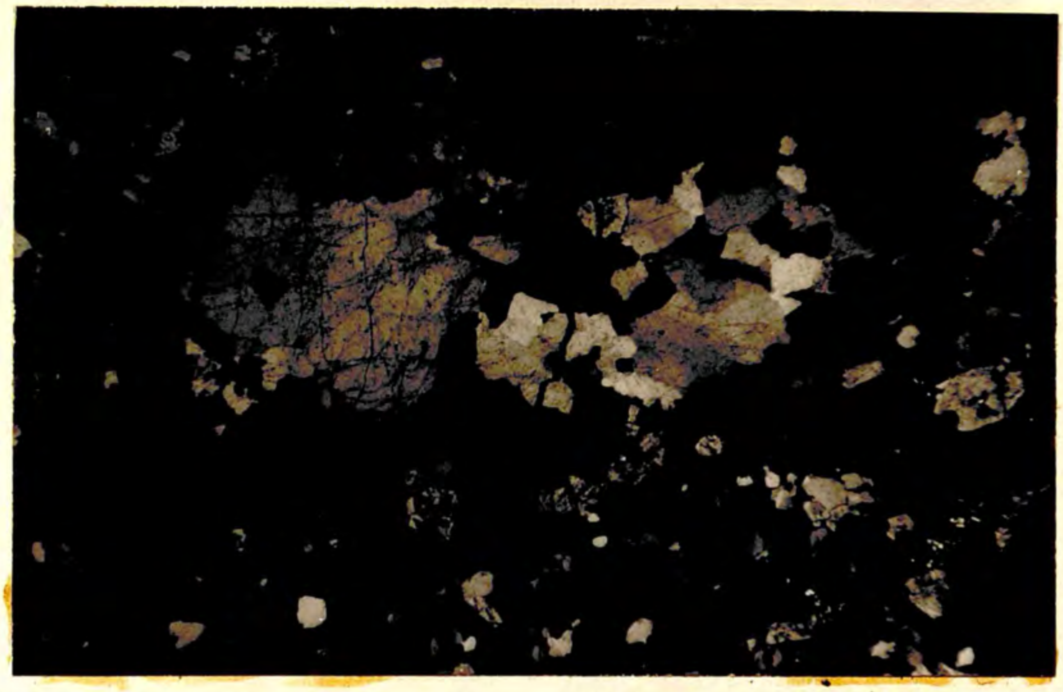


Plate 17. Quartz segregation in granite (under crossed polarisers). (RF338). x25.

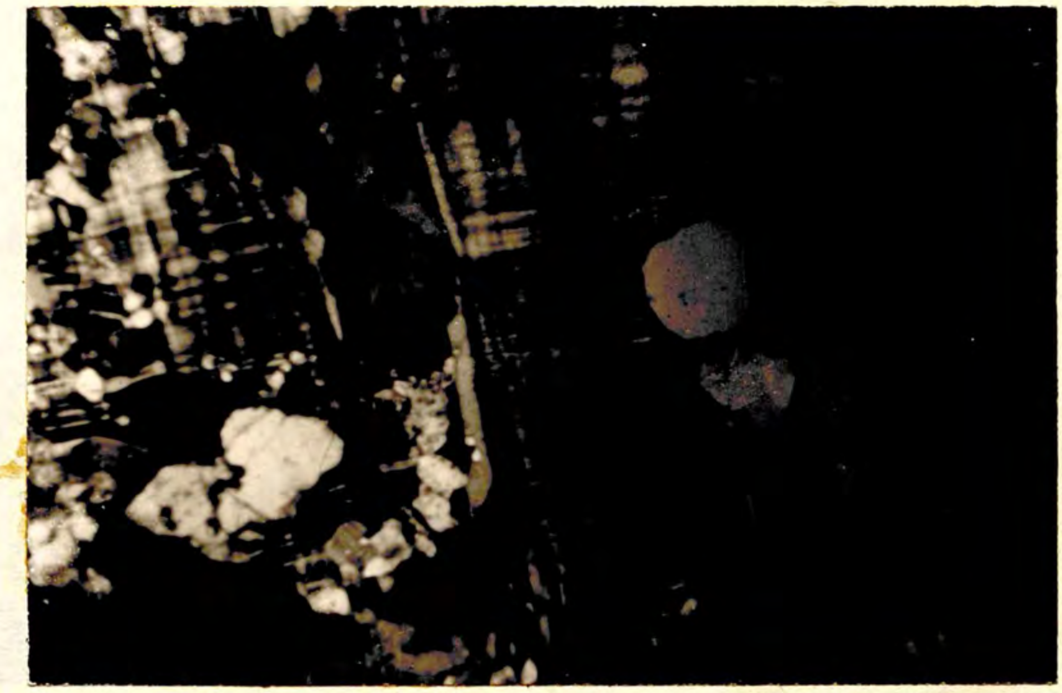


Plate 18. Quartz included in microcline in the granite (under crossed polarisers). (RFP75) x55.

Plate 19. Quartz included in microcline in the granite (under crossed polarisers). (RFP75). x155.

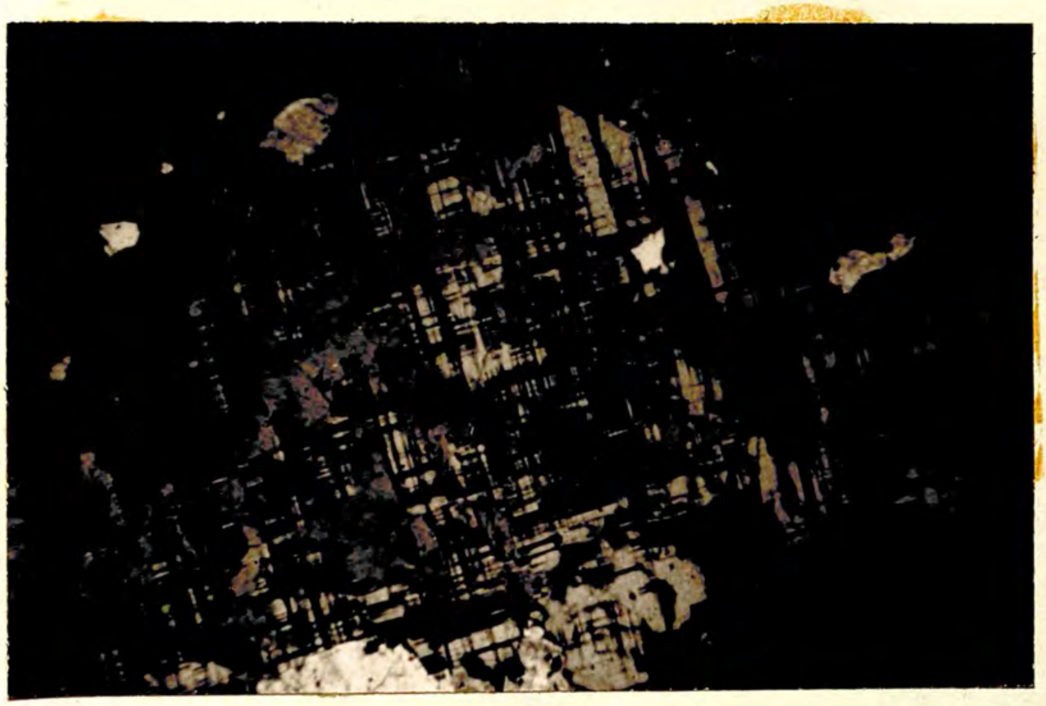


Plate 20. Perthite in the granite. The grey, untwinned felspar is oligoclase (under crossed polarisers) (RF335). x25.

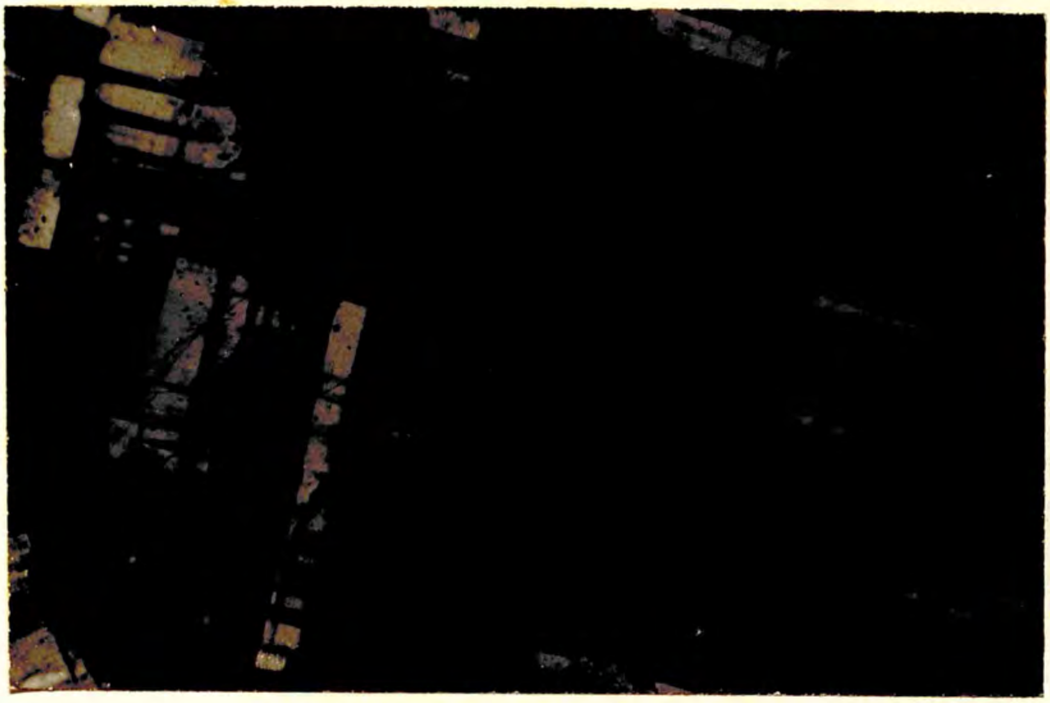


Plate 21. Perthitic intergrowth between microcline and oligoclase in unaltered granite (under crossed polarisers). (RFP10). x155.

Plate 22. Perthitic intergrowth between microcline and oligoclase in unaltered granite (under crossed polarisers). (RFP10). x155.

Plate 23. Twinned oligoclase in granite (under crossed polarisers). (RF342) x80.

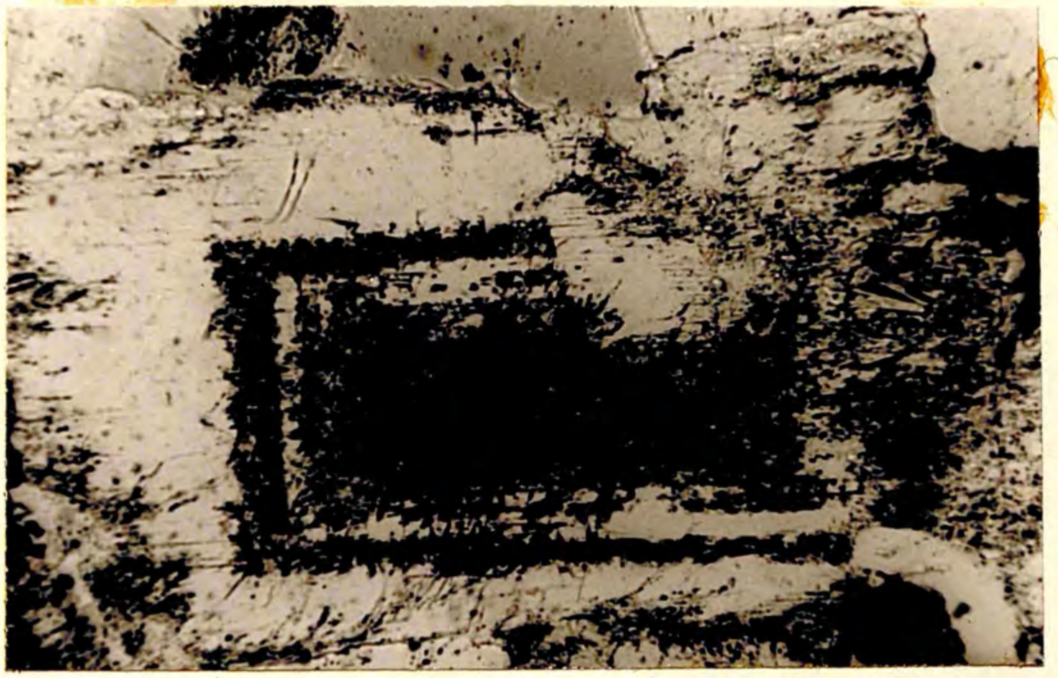


Plate 24. Sericitised oligoclase with unsericitised, albitic border in granite (under crossed polarisers). (RFP37). x155.

The microcline is occasionally perthitic.

These features and relationships between quartz and the felspars may persist into the fenitised and felspathised counterparts of the granite, and it is important to realise that all of them, in particular sericitisation and the inclusion of rounded patches of quartz in felspar, are original features.

Hornblende, which is not an essential mineral, but may account for 5% of the rock is pleochroic:- Z - blue green, Y - green and X - pale yellow green, and forms small subhedral crystals which have parallel orientations in the banded granite. Biotite and muscovite are more prominent in the banded granite, where they tend to occur together; biotite may overgrow quartz (RF 338). Much of the granite does not contain any mafic minerals (RF 337, RFP 75 etc).

3. GENERAL REMARKS.

McCall (1958, p 20 - 23) considers that the metamorphic rocks exposed round Rangwa are "interfolded members of the Nyanzian and Kavirondian Systems", and that the granite was emplaced during the post-Kavirondian orogeny, along with the Nyagongo, Muhoro and Angugo granites to the south and south east, with which it is petrographically similar. Apart from stating that this must be a considerable simplification of a complicated metamorphic history, it would be presumptuous to fault or enlarge upon McCall's interpretation of the basement rocks.

Frequent reference will be made to them throughout this work. Their compositions and textures are relevant when those of the fenites and felspar rocks are considered and many recognizable fragments of basement occur in the agglomerates on Rangwa and Rukungu, and in the sedimentary volcanic sequences on Rusinga and Mfwangano.

Vl

THE EARLY PLUTONIC ROCKS

Since the approach to the geology of Rangwa in the present work is largely historical, and age relations can generally be established, the rocks are normally listed and described in their order of emplacement. The relative ages of the alkaline plutonic rocks are not always clear; they are therefore placed in two groups depending on their relations, proved or inferred, with the central pyroclastics and carbonatites on Rangwa.

The first group includes the central biotite uncompahgrite and ijolite complex to the south east of Rangwa, as well as many smaller outlying intrusions, the largest of which are the Sagurume ijolite, the carbonatite on Kiako (Figure 5), and the Rukungu agglomerate vent (though partly extrusive, the vent is part of the ring formed by the outlying intrusives). Areas of brecciated, fenitised and felspathised country rock are commonly, though not invariably, associated with the plutonics.

The second group, described in Chapter IX, consists entirely of small alkaline dykes, which cut the pyroclastics and carbonatites on Rangwa and the peripheral volcanics as well as the alkaline plutonics and basement.

1. DISTRIBUTION.

On the basis of their outcrop pattern the early alkaline plutonics form:-

1. A large central complex.
2. Small concentrically arranged outlying intrusions.

A. THE CENTRAL COMPLEX.

The central complex is composed mainly of melilite-and-nepheline-bearing rocks, which occupy a crescentic area to the south east of Rangwa (Figure 5 and plate 5); its greatest width is three quarters of a mile, and its length is two miles. The inner boundary is marked by the break in slope at the edge of the pyroclastics, and the outer one, which tends to be obscured by alluvium, forms a large arc to the north west of the dry gulley of Ikoyombe. On the outer slopes of Manga, Kitunda and Ekiagaria, there is an exposed contact between alkaline plutonics and fenitised basement. The whole area slopes away from Rangwa at a lower angle than the talus slopes elsewhere round the pyroclastics, and at both ends outcrops are obscured beneath talus and soil.

The topographic features at the outer edges of the complex mark changes in the predominant rock type. The main outward-sloping mass consists predominantly of uncompahgrite and turjaite, whereas the three marginal hills, Manga, Kitunda and Ekiagaria, have steep inward-facing slopes of ijolite. The gradational boundary dips outwards, and, on Manga, ijolite can be seen to overlie melilite-bearing rocks. At the north of the area, a narrow sloping band of

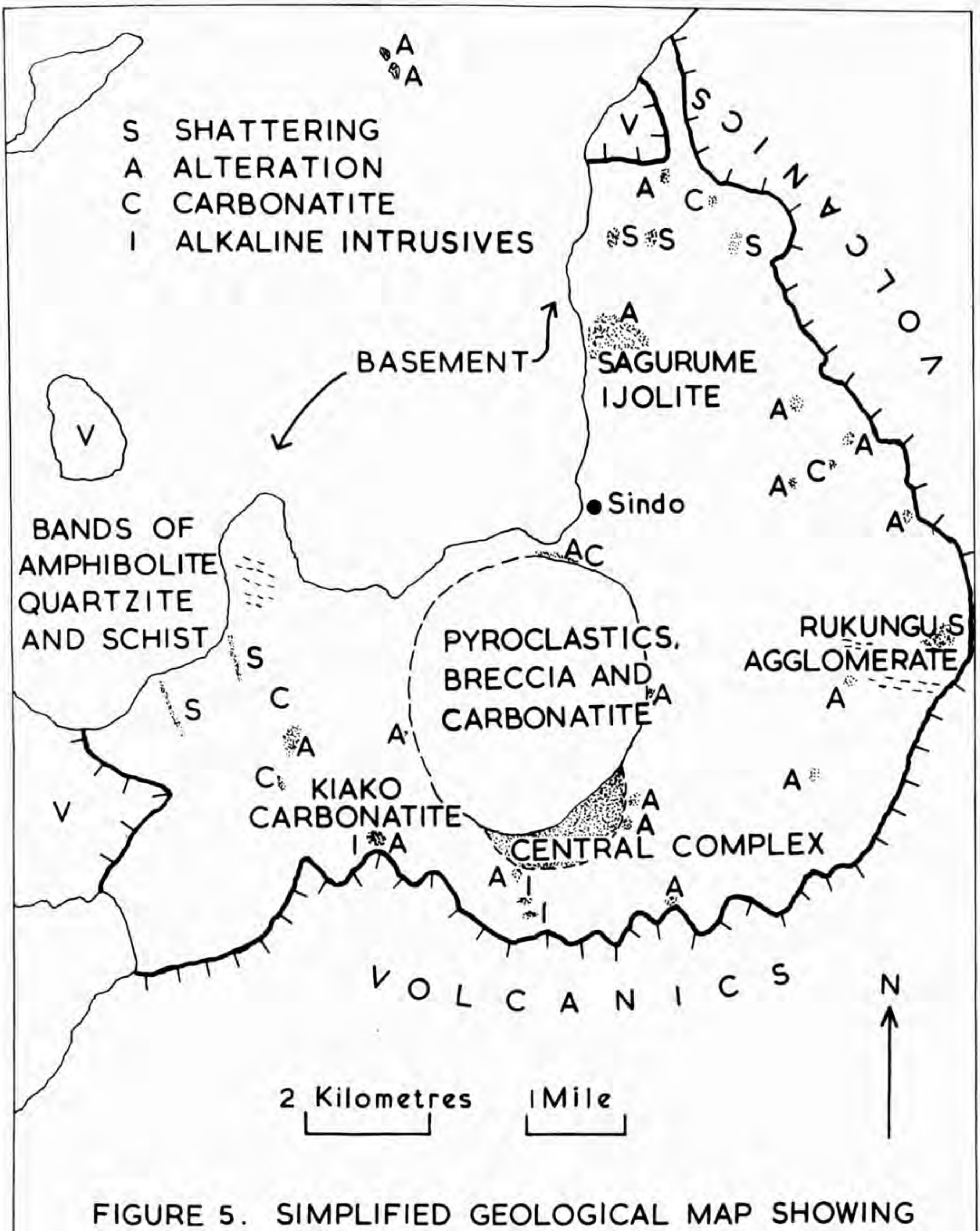


FIGURE 5. SIMPLIFIED GEOLOGICAL MAP SHOWING THE AREAS OF OUTCROP OF BASEMENT, ALKALINE PLUTONICS, RANGWA VENT ROCKS AND VOLCANICS.

ijolite outcrops against the uncompahgrite. The ijolite appears to cover the uncompahgrite like a partial skin, which is being pealed off by erosion.

Fenite outcrops for at least a hundred yards outside the ijolite, and loose blocks of fenite were found at several places among the talus slopes round Rangwa, notably near Nyandigida, to the north east of Rangwa, and in the west. In the north, near the track from Sindo to Roo, there is a very weathered exposure of fenite, carbonatite and an altered rock which contains magnetite and perovskite and may have been either pyroxenite or uncompahgrite.

B. THE OUTER RING OF PLUTONICS.

Nearly all the other alkaline plutonics are part of a discontinuous ring, which occurs between 1½ and five miles out from Rangwa, and may well be partly hidden by the volcanics. Usually the rocks outcrop on the basement hills.

Starting in the north (Figure 5), and moving round Rangwa in a clockwise direction, the following occurrences of alkaline plutonic rocks and shattered or altered basement were found.

The two small islands of Mbassa, five miles north of Rangwa are composed of shattered and altered basement without any plutonics. A band of slightly fenitised amphibolite outcrops in the gulley to the east of Gingo (plate 57), and several small blocks of carbonatite were collected nearby. Much of the country rock is brecciated south of the gulley. Sagurume, two miles north of Rangwa, consists of ijolite in the south and fenite in the north; the outer boundary is roughly concentric with the edge of Rangwa, and the position of the inner boundary is not known. The fenite outcropping along the talus slopes north of Rangwa indicates that this ijolite is not connected with the central plutonic complex at the surface. Several carbonatite dykes, as well as zones of altered basement occur on the hills below Gembe.

Three miles west of Rangwa, the small and poorly exposed pyroclastic vent of Rukungu occupies a wooded hollow 200 yards across, where agglomerate and bedded tuff are exposed surrounded by basement which is unaltered except for shattering and veining very close to the vent, and a narrow zone of alteration to the west of it. The basement is brecciated and altered at several localities south east of Rangwa.

On Kiako, two miles south west of Rangwa and close to the contact between the basement and volcanics, an irregular patch of carbonatite is surrounded by an extensive area of fenite and felspar rock. Another large area of altered basement outcrops between Kiawindo and the main Bukula-Nyamarisira ridge, unaccompanied by carbonatite. Carbonatite occurs in several places on Kwiunga, and the basement is shattered along the lines of two large gulleys between Bukula and Ragwe.

Many of these outcrops, especially the ones at Kiako, are close to the nephelinite lava and agglomerate cover.

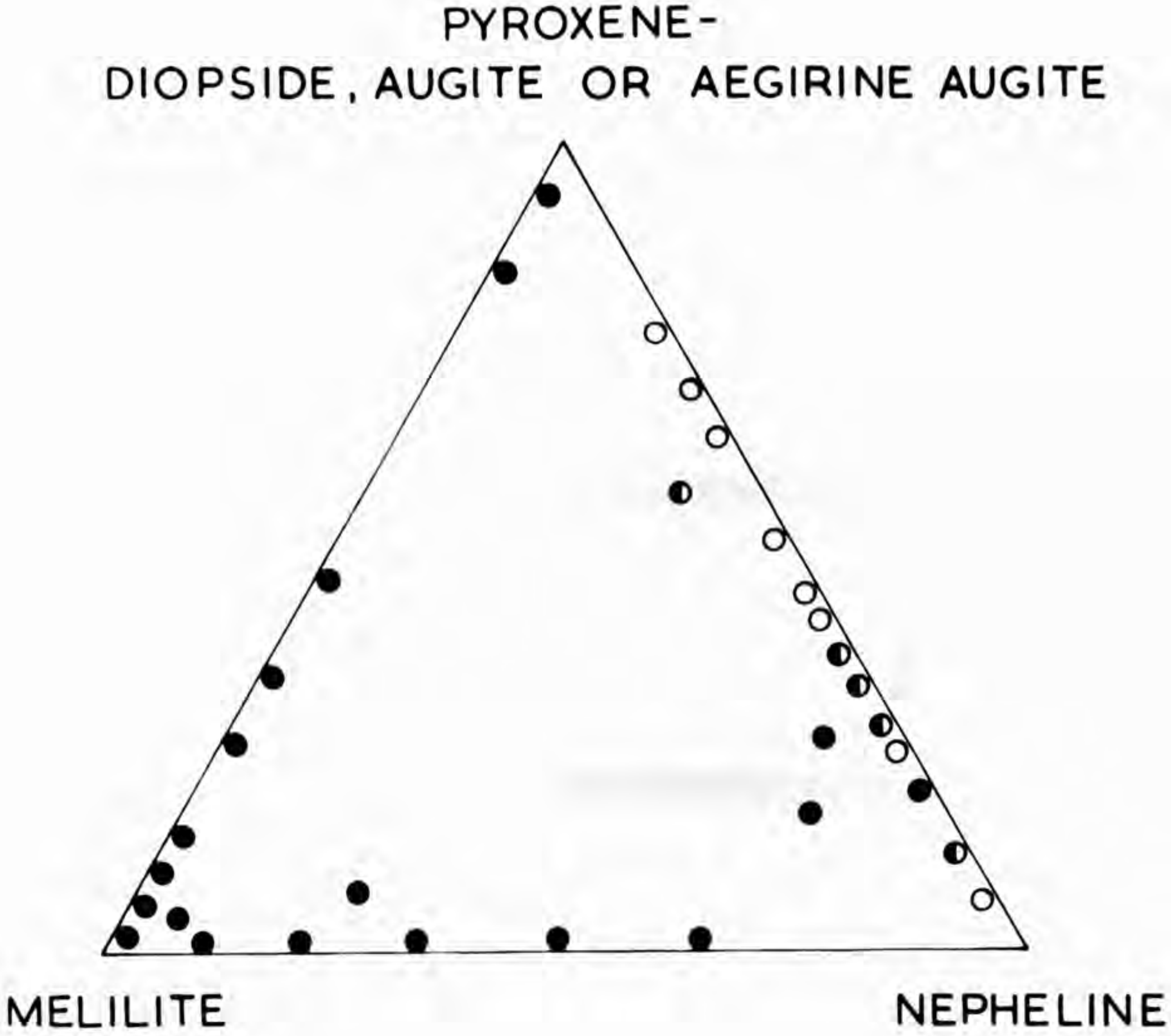
2. DESCRIPTION OF THE ROCK TYPES.

The main groups of rocks are described under these headings:-

1. The biotite pyroxenite - biotite uncompahgrite - ijolite group.
2. Carbonatite.
3. Nepheline syenite.
4. Rukungu agglomerate.
5. The brecciated and altered country rock associated with the intrusives.

A. THE BIOTITE PYROXENITE - BIOTITE UNCOMPAHGRITE - IJOLITE GROUP.

The rocks in this series are intimately related in their field relations, mineralogy and chemistry. Only urtite, ijolite and melteigite occur on Sagurume, but at the central complex both uncompahgrite containing varying amounts of pyroxene and members of the ijolite series are present as well as turjaite (Figure 6). The only occurrences of true biotite pyroxenite without either melilite or nepheline are as fragments in the agglomerate on Rangwa. Except for some varieties of uncompahgrite, which are very rich in magnetite, perovskite and biotite, all the rocks contain over 80% of pyroxene, melilite or nepheline or mixtures of two of these constituents. Thus on a triangular diagram, the corners of which represent the



● CONTAINS MAGNETITE, PEROVSKITE AND BIOTITE.

◐ CONTAINS MAGNETITE AND/OR PEROVSKITE BIOTITE AND MELANITE.

○ CONTAINS MELANITE AND SOMETIMES BIOTITE.

FIGURE 6. THE MODAL PROPORTIONS OF THE MAJOR CONSTITUENTS OF THE BIOTITE PYROXENITE, BIOTITE UNCOMPAHGRITE AND IJOLITE.

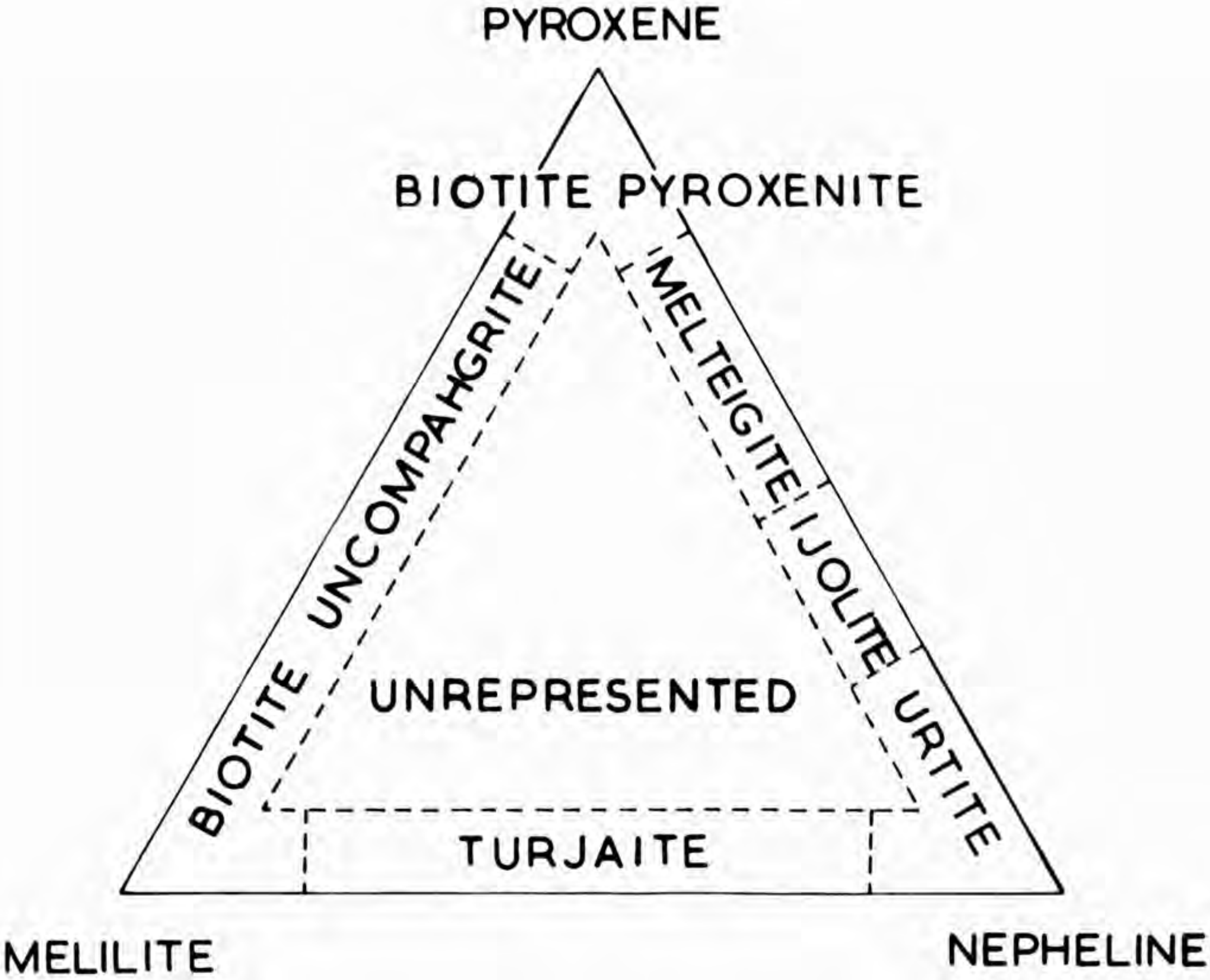


FIGURE 7. DIAGRAM ILLUSTRATING THE NOMENCLATURE USED FOR THE ROCKS OF THE CENTRAL PLUTONIC COMPLEX.

three main minerals, the modal compositions of the rocks plot close to the sides (Figures 6 and 7). Since there is continuous variation in composition and considerable inhomogeneity of grain size and composition both over short distances in the field and within individual thin sections, detailed petrographic descriptions alone do not give a true picture of the series. Only brief descriptions of representative samples of biotite pyroxenite, biotite uncompahgrite and ijolite are therefore given, and more attention is paid to the relations among the rock types and among individual minerals, both of which conform to consistent patterns.

(1) REPRESENTATIVE DESCRIPTIONS.

(a) BIOTITE PYROXENITE.

Two examples of comparatively unaltered biotite pyroxenite (in RF 22) were found as fragments in the Lower Agglomerate, and rocks that are similar except that they contain melilite occur within the uncompahgrite on Kumugina. In hand specimen, the pyroxenite is dark green with irregular black streaks. The groundmass of the rock consists of medium-grained anhedral diopside; it is unzoned, but cloudy, probably because of incipient alteration. Small plates of biotite are scattered through the rock, but are concentrated mainly in the black streaks, where they occur with anhedral crystals of magnetite rimmed by perovskite and a few well-formed crystals of perovskite. Biotite envelopes the magnetite and perovskite, and pale brown melanite is sometimes associated. Small rounded and irregular crystals of apatite occur throughout.

(b) BIOTITE UNCOMPAHGRITE.

The biotite uncompahgrite is banded both by grain-size and composition; it is normally coarse or very coarse, and is composed of up to 85% melilite, which is cream-coloured on weathered surfaces, and cut by minute cleavage cracks. Bands containing biotite, perovskite and magnetite are always present, and large books of biotite up to 4 cm across are especially prominent in the field (plate 25). Pyroxene sometimes occurs within the melilite as green, elongated crystals. If there are large quantities of nepheline with the melilite, the weathered surface of the rock becomes pink rather than cream-coloured, although small amounts of nepheline are hard to recognize in hand specimen.

In thin section, it can be seen that the biotite, perovskite and magnetite bear much the same relation to one another as in the biotite pyroxenite. Melilite forms very large dissected plates, and is sprinkled with small rounded apatite crystals.

In fine-grained uncompahgrite, the mineral relations are similar but the rock is predominantly black in hand specimen.

(c) IJOLITE.

Like the biotite uncompahgrite, the ijolite is banded, although with less regularity. Apart from the marginal facies of the central

Plate 25. Exposure of coarse-grained biotite uncompahgrite on Kumugina. The black spots are flakes of biotite.

Plate 26. Typical texture of the fine-grained banded ijolite and melteigite. White is nepheline, grey is pyroxene and black melanite. (RFA223). x55.

complex it is generally coarse-grained, and nepheline, the main constituent, is pink on weathered surfaces. The bands of dark material consist mainly of large crystals of pyroxene and melanite; the latter is black and shows a glittering surface when fractured.

The nepheline crystals are large and subhedral, but the pyroxenes are very variable in size. Melanite forms irregular patches, generally close to the pyroxenes, and sometimes enclosing corroded grains of perovskite. Sphene and wollastonite may occur within the nepheline, and apatite in euhedral grains is an ubiquitous constituent of the ijolites.

(2) RELATIONS BETWEEN THE ROCK TYPES.

Field work has shown that the central plutonic complex can be subdivided into a number of concentric zones (Figure 10), the boundaries of which are gradational and depend on variations in predominant rock type, structure and the presence of minor intrusions:-

1. Immediately within the fenite, fine-grained ijolite and melteigite, with steep outward-dipping compositional banding, occur; this zone is only represented by a few exposures on top of Manga, Kitunda and Ekiagaria.

2. Inwards, the ijolite becomes coarser, and in the hollows between the outlying hills and the main complex, turjaite occurs, together with uncompahgrite which contains many needle-like pyroxene crystals, as well as a little biotite. The ijolite and turjaite have

irregular schlieren of dark minerals with variable orientation and are intruded by melteigite and melanite ijolite conesheets that are up to 2 ft. thick and have inward dips of between 20° and 45° and are cut by radial dykes of coarse pegmatitic ijolite and urtite (plates 27 and 28, 31 and 32).

3. Towards Kumugina, the amount of nepheline in the turjaite decreases, and the main rock type is pyroxene-rich uncompahgrite, with inward-dipping compositional banding between types rich and poor in magnetite, perovskite, biotite and pyroxene. It is cut by radial dykes of very coarse turjaite and ijolite which sometimes contains large subhedral pyroxenes aligned perpendicular to the walls of the dyke (plate 30); large books of black biotite are always present. Occasionally, the very coarse turjaite occurs as irregular masses, but it generally shows an intrusive relationship with the normal uncompahgrite. All these rock types are cut by small conesheets of fine-grained ijolite and melteigite.

4. Normal uncompahgrite with regular inward-dipping bands (plate 29) often merges with irregular masses of the very coarse uncompahgrite with prominent black biotite. A few fine-grained ijolite and turjaite conesheets are present, but these die out towards the centre.

5. Within a hundred yards of the edge of the pyroclastics on Rangwa, the melilite becomes altered along small vertical veins to a very fine-grained mineral of high relief, which is thought to be

Plate 27. Fine-grained melteigite conesheet intruding biotite uncompahgrite.

Plate 28. Small dykes of melanite ijolite intruding banded biotite uncompahgrite, and cutting a conesheet of melanite ijolite.

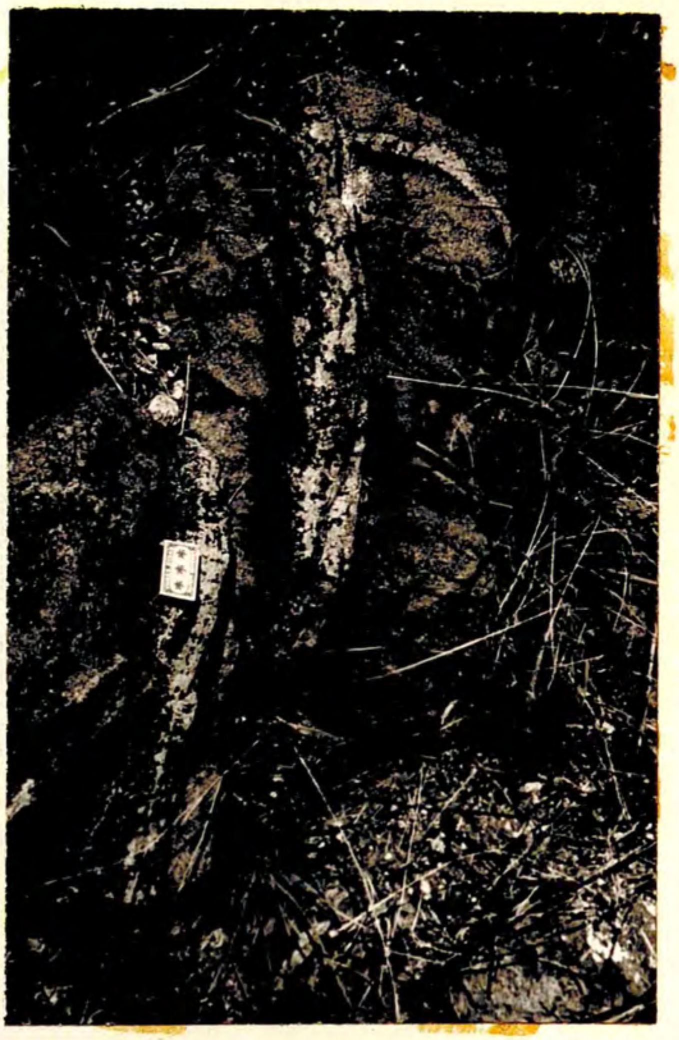


Plate 29. Exposure of banded biotite uncompahgrite on Kumugina.

Plate 30. Part of a co~~a~~arse ijolite dyke which cuts the uncompahgrite. Pyroxenes are orientated perpendicular to the edges of the dyke.

Plate 31. Chilled margin of melanite ijolite conesheet intruding ijolite. (RFP141). x25.

Plate 32. Chilled margin of ijolite dyke intruding biotite uncompahgrite. Many of the larger grey crystals in the dyke are biotite. (RFA1). x25.

diopside. Nearer the pyroclastics, the melilite has been converted almost entirely to a felt of minute crystals of this mineral, and pale brown melanite has formed round most of the magnetite and perovskite.

On Sagurume, the ijolite is poorly banded, and no zoning was recognized.

The textural and structural relations of the ijolites are matched by those of the uncompahgrites. Indeed, it seems that the various phases of the one pass into the other by the appearance of essential melilite. For example, conesheets and dykes of coarse pegmatitic ijolite intrude the ijolite and uncompahgrite near the margins: on a traverse inwards, these become more melilite-rich, and magnetite, perovskite and biotite crystals begin to appear, until the dykes are of turjaite; finally the intrusive relationship is lost, and the coarse-grained material occurs as streaks and patches of coarse-grained uncompahgrite in banded uncompahgrite. The finer-grained melteigite and ijolite conesheets exhibit a similar phenomenon; nepheline survives closer to the centre of the complex, and an intrusive relationship is always shown where nepheline is present. Near the edge the poorly banded ijolite has an equivalent in the uncompahgrite that has schlieren of dark minerals, and the multiple conesheets of melanite ijolite which cut it may be analogous to the regular banding shown by the normal uncompahgrite (Figure 10 illustrates the relations between the rock types of the central complex).

(3) MINERALOGY.

The rock-forming minerals are described and special emphasis is placed on their associations and environments.

(a) DIOPSIDE AND AEGIRINE-AUGITE.

The pyroxene of the pyroxenites and melilite-bearing rocks is a pale green diopside; in the nepheline-bearing rocks, its composition varies with the amount of nepheline. When little nepheline is present, it is the same pale green diopside; as the amount of nepheline increases, the pyroxene becomes a darker and yellower green, and the X:c angle decreases to about 35°, indicating a trend towards aegirine. Pyroxene seldom occurs in rocks containing both melilite and nepheline (Figure 6).

In the pyroxenite, the pyroxene crystals are up to 1 mm long, anhedral and unzoned. In the melilite-bearing rocks, the pyroxenes occur either as large irregular crystals, which interlock with the melilite (RFA 2, plate 34), or as bladed crystals up to 2 cm long (RFA 7, plate 33), which often crystallize in the form of a cross (RFA 15, plate 35). The latter are sometimes subhedral, but normally they are embayed by the surrounding melilite, and there may be rounded inclusions of pyroxene showing parallel orientation in the melilite (RFA 16, plate 36). The crystals are seldom zoned, and the melilite does not cause any alteration products to develop round

Plate 33. Euhedral crystal of pyroxene within a large crystal of melilite in biotite uncompahgrite. (RFA7). x25.

Plate 34. Pyroxene crystal partly replaced by melilite in biotite uncompahgrite. (RFA2). x25.

Plate 35. Part of a cross-shaped pyroxene crystal surrounded by melilite in biotite uncompahgrite (RFA15). x25.

Plate 36. Pyroxene crystal with very irregular edges surrounded by melilite in biotite uncompahgrite. (RFA16). x155.

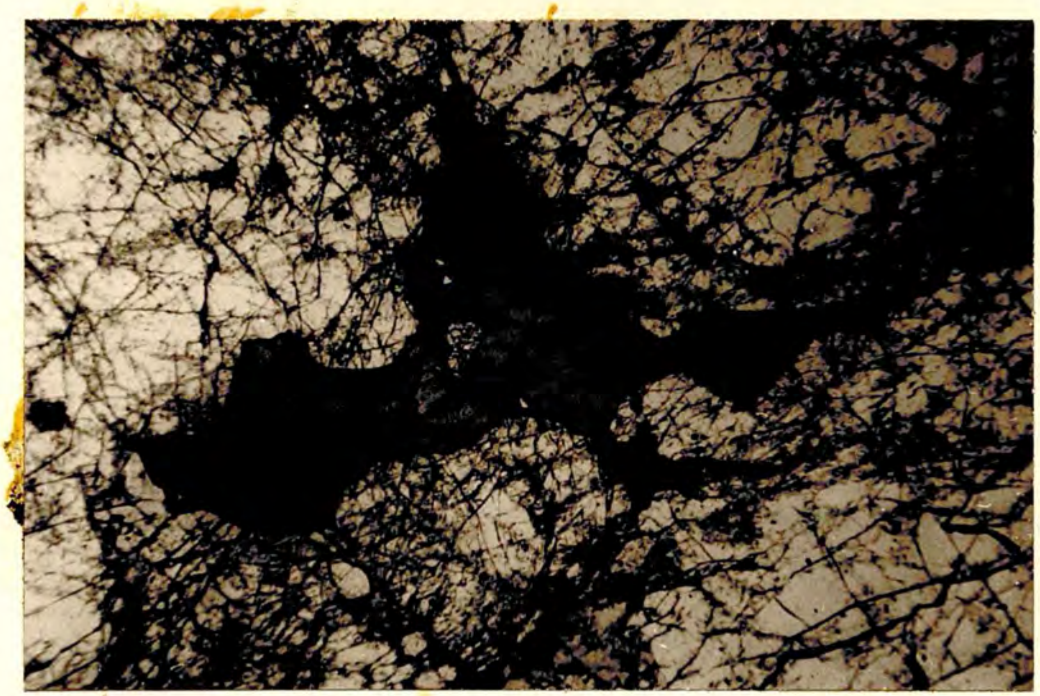


Plate 37. Anhedral pyroxene crystal surrounded by nepheline in urtite. Small amounts of melanite occur at the edges. (RFA39). x25

Plate 38. A felt of tiny crystals replacing melilite in altered biotite uncompahgrite. Possibly they are pyroxenes. (RFA33). x310.

their edges.

Occasionally the pyroxenes in the nepheline-bearing rocks are pale green unzoned diopside, especially in the melteigites. Most of the pyroxenes in the ijolite and urtite are zoned and more soda-rich. The zoning is complicated, and in each crystal there are a large number of oscillatory zones, in which the X:c angles decrease gradually and increase sharply outwards. Frequently there are minor disconformities between sets of zones (RFA 6). The overall effect is that the X:c angles decrease towards the crystal edges. These pyroxenes become darker green towards their margins. When they touch each other the crystals have straight edges, but they tend to be embayed and partly absorbed by nepheline, and relics of pyroxene crystals survive separated, but retaining the same orientation within nepheline (RFA 39). Their edges are usually converted to fibrous aegirine and sodic amphibole.

Near the boundary with the pyroclastics, most of the melilite in the uncompahgrite is altered to a felt of tiny colourless crystals which are thought to be diopside, none of which are more than .005 mm long (RFA 33, plate 38).

In general, pyroxene seems to have crystallized earlier than melilite or nepheline.

(b) MELILITE.

Melilite occurs in varying quantities in the uncompahgrite and

Plate 39. Characteristic appearance of melilite in biotite uncompahgrite. (RFA2). x25.

Plate 40. Melilite rimmed by fibrous cebollite and enclosed by nepheline in turjaite. The picture includes several small prisms of apatite. (RFA17). x25.

turjaite. It is uniaxial and negative; the birefringence colours are variable throughout the first order but are normally very low. The refractive indices of one sample of melilite with very low birefringence (from RFA 2) are W = 1.633 and E = 1.627, but the melilite with greater birefringence has higher refractive indices. The low refractive indices indicate that a high component of sodium melilite is present, and, because the melilite is negative, the amount of the gehlenite molecule probably exceeds that of the akermanite molecule (Ferguson and Buddington 1919 and Nurse and Midgley 1953 in Deer, Howie and Zussman 1963, Volume 1 pp 249 - 251).

Crystals of melilite in the uncompahgrite are large, often up to several centimetres across, and enclose clusters of magnetite, perovskite and biotite, and remnants of pyroxenes. They are shattered, cracked and strained (RFA 2, plate 39). In rocks that contain minor nepheline, the texture and mineral associations of the uncompahgrite survive, but the melilite is partly replaced by nepheline (RF 216). When more nepheline is present, the melilite survives as irregular inclusions within the nepheline, and it is normally rimmed and penetrated by cebollite fibres, (RFA 17, plate 40).

Melilite has generally crystallized after pyroxene and before nepheline.

(c) NEPHELINE.

Nepheline is found in the ijolites and turjaites. Regardless of the sizes of crystals of other minerals, it forms large subhedral plates. It is normally fresh, but may be altered to cancrinite.

In the melteigite, small crystals of unzoned diopside occur with nepheline, but normally pyroxene and melilite are zoned, altered or replaced when nepheline is present: also magnetite and perovskite tend to be replaced by melanite (Figure 8 shows these changes diagrammatically).

(d) AEGIRINE AND SODIC AMPHIBOLE.

Aegirine forms round pyroxene crystals along their borders with nepheline; its X:c angle is very low and it is green with slight pleochroism between light and dark. It forms minute fibres that are orientated parallel to the lengths of the crystals and are best developed at crystal ends (RFA 6, plate 41).

Tiny fibres of a blue-green amphibole occur with the aegirine. Because of the anomalous brown, yellow and blue birefringence colours, the extinction angles of the fibres cannot be measured accurately, but are probably very low. Pleochroism is slight, between pale green and pale blue-green. It was impossible to determine the optic orientation or 2 V of the fibres. The mineral is tentatively identified as arfvedsonite (Deer, Howie and Zussman, 1963, Volume 2 pp 369 - 372).

Aegirine and sodic amphibole were not found except where coating larger pyroxenes when they border on nepheline.

(e) CEBOLLITE.

Between the nepheline and melilite, there is a layer of fine orientated fibres, which is between .1 and .6 mm thick, and similar fibres penetrate cracks and cleavage planes in the melilite when it is in contact with nepheline. The fibres are pale green, and show no pleochroism; their birefringence is low, and extinction is more or less straight. They are length slow, and their refractive index is higher than that of Canada Balsam. Most of the fibres are subparallel, but sometimes radiate from small centres scattered along the edge of the nepheline (RFA 17, plates 42, 43 and 44).

Larsen (1942) recorded alteration of melilite in the uncompahgrite at Cebolla Creek, Iron Hill to a similar material, which he called cebollite, a new mineral, and his analysis shows that it is a hydrated calcium aluminium silicate. The material from Rangwa has not been X-rayed yet; it is tentatively identified as cebollite.

The formation of cebollite near nepheline, and as patches within nepheline, which probably represent altered melilite (RFA 3) show that its occurrence is analogous to that of the pyroxene alteration products where nepheline is present. Further evidence that the nepheline crystallized after the melilite in any one rock is that cebollite may enclose magnetite and perovskite, minerals which crystallized early, with the melilite.

Other alteration products of melilite form streaks and patches of brown noncrystalline material within the crystals.

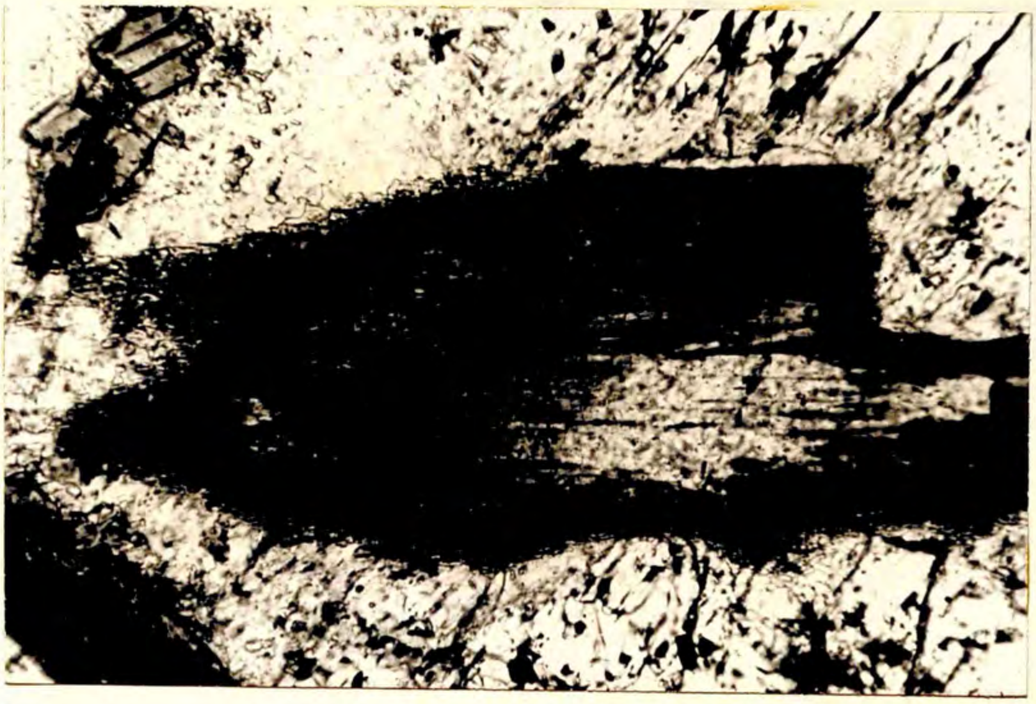


Plate 41. Aegirine-augite rimmed by fibres of aegirine and sodic amphibole and enclosed by nepheline in ijolite (RFA6). x80.

Plate 42. Fibres of cebollite in turjaite. (RFA40). x310.

Plate 43. Small cebollite fibres between melilite (at the top) and nepheline in turjaite. (RFA17) x155.

Plate 44. Small cebollite fibres between melilite and nepheline in turjaite. The fibres radiate from points close to the nepheline. (under crossed polarisers). (RFA17). x155.

(f) MAGNETITE AND PEROVSKITE.

Magnetite, perovskite and biotite occur predominantly in the pyroxenite and uncompahgrite, and they are seldom present in nepheline-bearing rocks.

Magnetite seldom occurs on its own, and when it does it is subhedral. Generally, it is ringed and irregularly replaced by perovskite (RFA 16, plate 46). Perovskite, however, frequently occurs alone as euhedral grains which are often 2 mm across (RF 216, plate 47), and have high relief, low birefringence and typically complex twinning in several directions (RF 216, plate 48). When associated with magnetite, perovskite is poorly twinned and anhedral. An analysis of perovskite from Rangwa carried out by the Mineral Resources Department of the Directorate of Colonial Geological Surveys (McCall 1958) shows that it is a columbian variety and contains 0.56% Nb_2O_5 and 0.73% rare earths.

Most of the magnetite and perovskite are among the earliest formed minerals in the rocks of the complex. They occur within and among both pyroxene and melilite crystals, and may cross the boundaries between them (RFA 16).

Both minerals occur in segregations, which give the uncompahgrite its banded appearance (plate 29), and in clusters; RFA 14 contains a cluster of small perovskite crystals 3 cm across, which are rimmed by melanite.

Plate 45. Magnetite crystal in melilite in biotite uncompahgrite. The rims of perovskite and biotite are not shown clearly. (RFA16). x55.

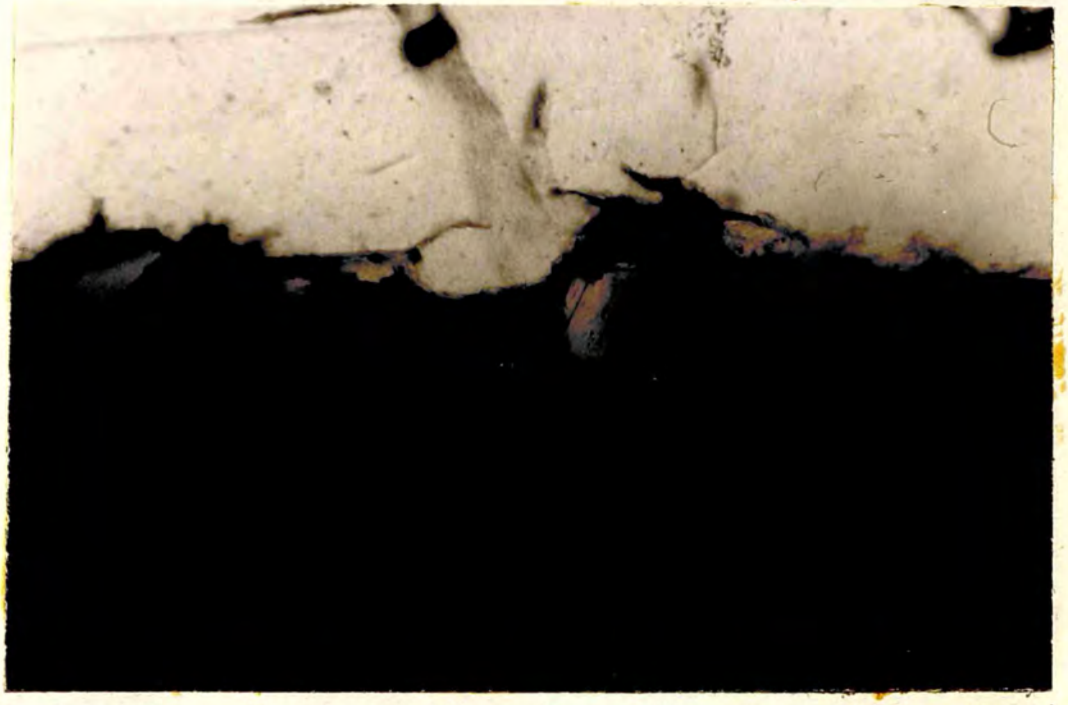


Plate 46. Part of the edge of a magnetite crystal in biotite uncompahgrite. Narrow rims of perovskite and biotite are visible. (RFA16). x620.

Plate 47. Euhedral perovskite crystal enclosed by pyroxene in biotite uncompahgrite. (RF216). x55.

Plate 48. Twinning in perovskite in biotite uncompahgrite (under crossed polarisers). (RFA16). x155.

(g) BIOTITE.

Biotite, which is an essential constituent of the biotite uncompahgrite, but occurs sporadically in all the rocks of the complex, is pleochroic between pale yellow-brown and golden brown, and has a 2 V of less than 10°. In RFA 7 a mineral was found which has reverse pleochroism to biotite, but otherwise similar properties. In RFA 5 a biotite crystal contains cleavage flakes that show reverse pleochroism; both these occurrences are in nepheline-bearing rocks and they rim pyroxenes. The biotite of the ijolite is paler, redder and less pleochroic than that of the uncompahgrite and pyroxenite.

Biotite occurs largely in the pyroxenite, uncompahgrite and turjaite. It is found mainly with magnetite and perovskite, which it frequently rims. Large irregular plates of biotite may enclose these two minerals completely (RFA 16, plate 49), and biotite sometimes engulfs and penetrates grains of perovskite (RFA 12). Biotite also occurs separately, and over 40% of RFA 12 consists of irregular intergrowths of it, and the large books that are typical of the very coarse-grained uncompahgrite frequently occur on their own.

Both in the melilite-and-nepheline-bearing rocks, biotite may rim pyroxene, and enclose fragments of pyroxene of parallel orientation poikilitically (RFA 5 and RFA 7, plates 50 and 51). Biotite also occurs occasionally along the crystal edges and cleavage planes of melilite and nepheline.

The biotite is normally unaltered and unstrained, but many of

Plate 49. Biotite enclosing a magnetite crystal in biotite uncompahgrite.

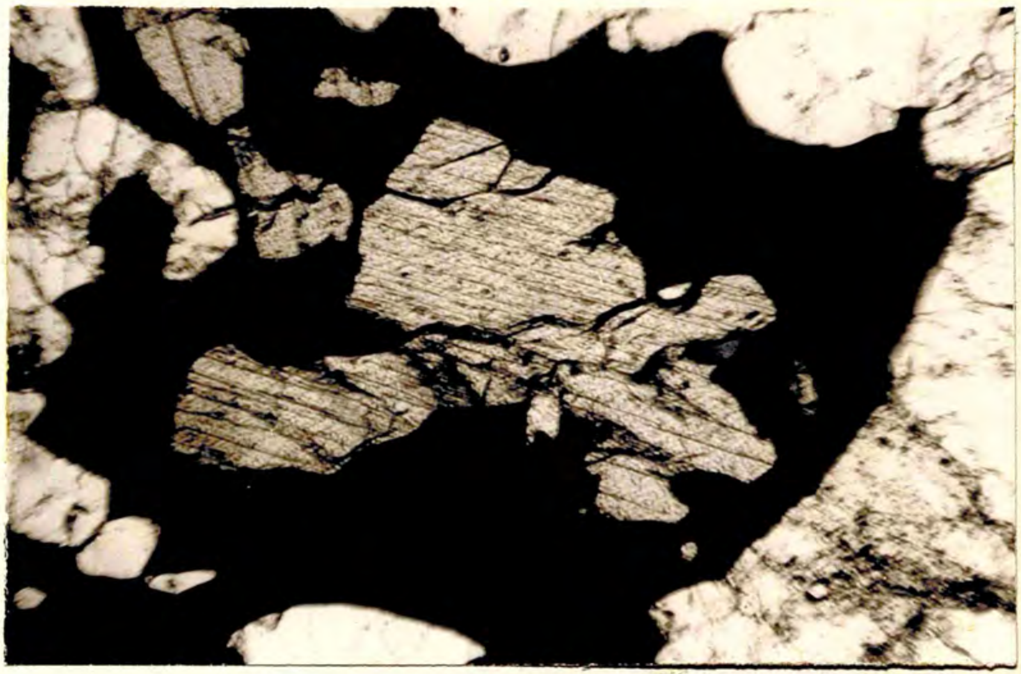


Plate 50. Biotite enclosing pyroxene poikilitically in ijolite. (RFA5). x55.

the fine-grained ijolite dykes that cut the uncompahgrite and ijolite (plates 31 and 32) contain small plates of strained biotite that is bleached round the edges. It is possible that these were picked up from the uncompahgrite into which the ijolite was intruded.

From these textural relationships, biotite generally appears to have crystallized later than magnetite and perovskite, and sometimes later than pyroxene, melilite and nepheline.

(h) SPHENE AND MELANITE.

Sphene is a very minor constituent of some of the ijolites. It forms small euhedral diamond-shaped crystals, both singly and in groups along the edges of nepheline crystals, and occurs as irregular inclusions within melanite. It is normally colourless. Sphene is never found in the pyroxenites or uncompahgrites.

Melanite is confined largely to rocks that contain nepheline. Its colour varies from pale brown to black, and it tends to enclose most other minerals poikilitically (plates 52 and 53). In some turjaites and melteigites, melanite encloses partly altered magnetite, perovskite and biotite (RF 215), and perovskite crystals can be seen in all stages of alteration to melanite. When large amounts of perovskite are surrounded by melanite (as in RFA 14) the melanite is normally pale brown.

In the typical melanite ijolite, the melanite includes pyroxene, nepheline and apatite crystals; it rings pyroxene and penetrates

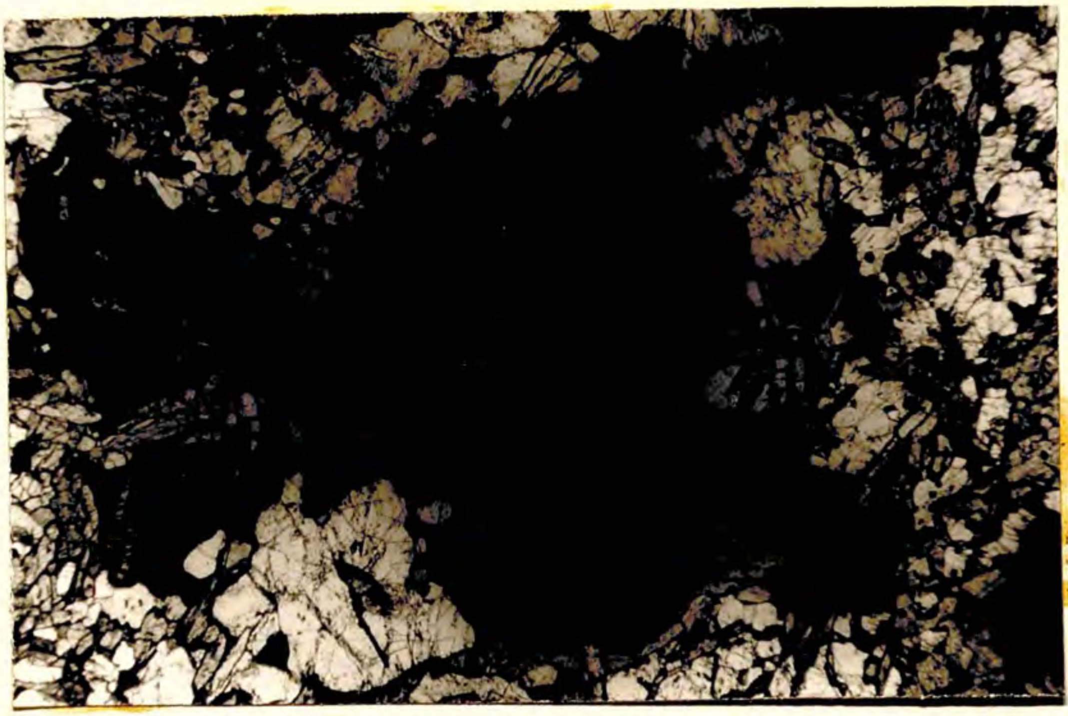


Plate 53. Melanite enclosing pyroxene crystals poikilitically. (RFP147) x25.

Plate 54. Irregular bodies of melanite in altered biotite uncompahgrite. (RFA29). x80.

along cleavage planes, whereas it replaces nepheline more completely (RF 347). It is either a homogeneous dark brown-black or it is zoned from dark to light brown, often several times. In the former case it forms irregular anhedral masses, but in the latter it has straight crystal edges (RFA 6). It is normally zoned in nepheline-rich ijolites and urtites.

Melanite is seldom found in the uncompahgrite, but the small ijolite dykes which cut the uncompahgrite cause extensive melanitisation. Rims of melanite several mm thick occur along the dykes, and extend into the uncompahgrite, altering the neighbouring magnetite, perovskite and biotite. Also in the uncompahgrite from near the boundary with the pyroclastics, much of the magnetite, perovskite, and biotite has been changed to pale unzoned melanite (RFA 29, plate 54). Even when it occurs in the uncompahgrite, melanite is a late-forming mineral, and only occasionally as in RFP 147 biotite is seen to ring melanite.

Both sphene and melanite are normal members of the mineral association that occurs with nepheline. They are both titaniferous minerals, and tend to replace the magnetite, perovskite and, to a lesser extent, the biotite of the pyroxene-and melilite-bearing rocks (Figure 8 illustrates the mineral relations diagrammatically).

(i) WOLLASTONITE, PECTOLITE AND CANCRINITE.

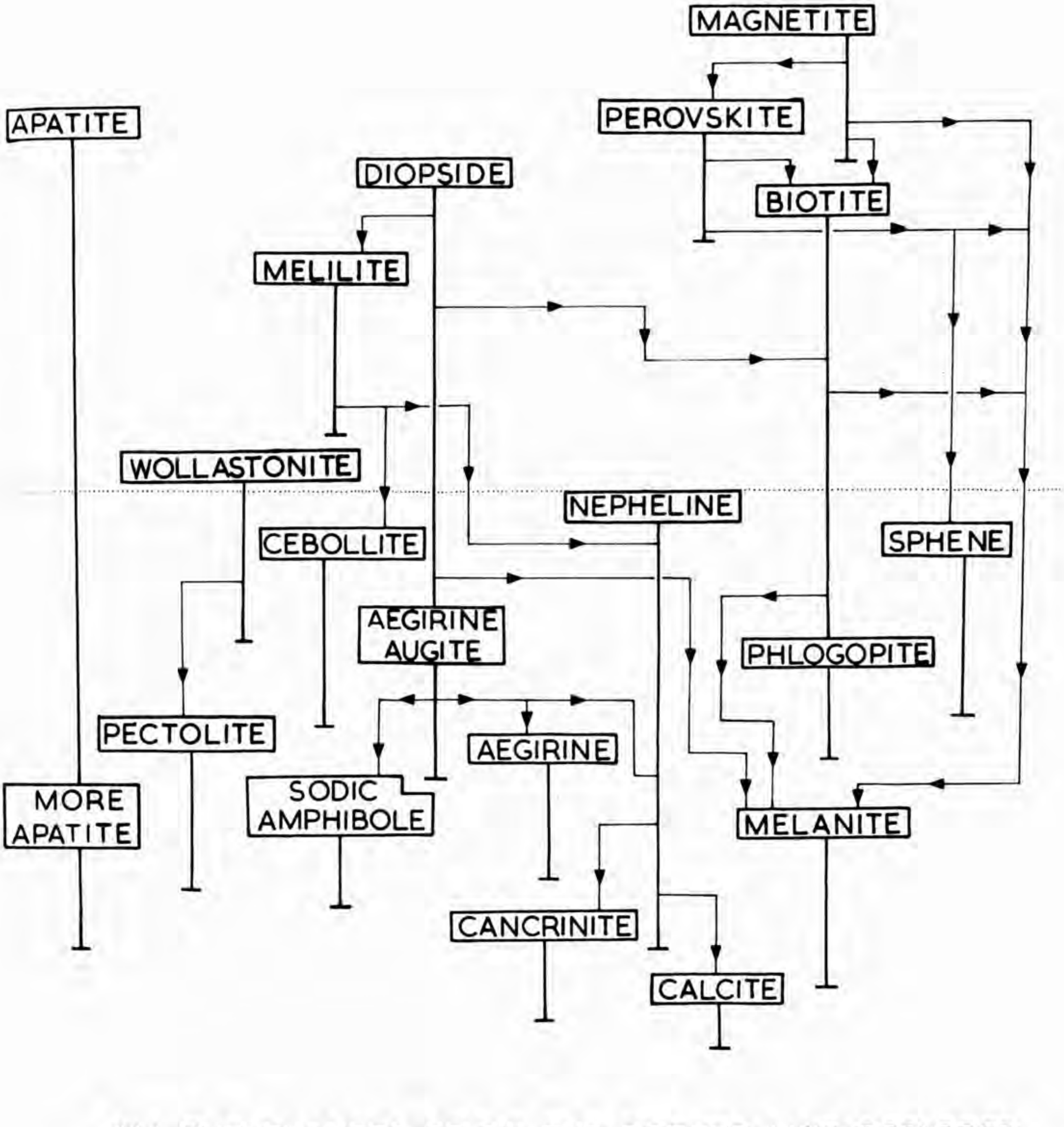
Wollastonite forms small colourless crystals of much the same habit as the pyroxenes of ijolites. It is found both within nepheline crystals and alongside pyroxenes. Wollastonite, especially when surrounded by nepheline, is ringed by very fine fibres of pectolite (RF 346).

Cancrinite is a sporadic alteration product of nepheline, and is found mainly in the ijolites on Sagurume. Generally, as in RFA 36, cancrinite forms plates up to 2 mm across of micaceous appearance within the nepheline crystals, and they are probably the result of late stage alteration. But occasionally, as in RF 222, extreme alteration of nepheline to cancrinite and minor amounts of natrolite happens near veins of very fine-grained green pyroxene and noncrystalline material. The veins occur along minor zones of dislocation across which large pyroxenes have been displaced by about a millimetre.

Wollastonite, pectolite and cancrinite are all accessories in the rocks richest in nepheline, and none were found in pyroxenite, uncompahgrite, turjaite or melteigite.

(j) APATITE.

Apatite occurs in all the alkaline rocks at and around Rangwa. It usually constitutes one or two per cent of any rock, but sometimes there is at least 10 per cent of it. It occurs as small crystals either singly or in groups showing parallel orientation within crystals of practically every mineral and the crystals may be rounded or euhedral.



ALL THE CHANGES BELOW THE DOTTED LINE OCCURRED DURING OR AFTER THE INTRODUCTION OF SUBSTANTIAL AMOUNTS OF NEPHELINE.

FIGURE 8. DIAGRAM SHOWING RELATIONS BETWEEN THE MINERALS IN THE ROCKS OF THE CENTRAL PLUTONIC COMPLEX.

Small amounts of it are present in all the minerals in the pyroxenite and uncompahgrite, especially the melilite (RFA 16), and it forms rounded crystals, which may cross the boundaries between pyroxene and melilite. However, far more apatite is enclosed by nepheline, and apatite crystals were never found to cross the boundaries between nepheline and either melilite or pyroxene. The apatite associated with nepheline is normally euhedral-subhedral; it is therefore likely that a separate generation of apatite crystallized with the nepheline.

From these observations, it seems that apatite has crystallized throughout the entire crystallization history of the alkaline plutonics.

B. CARBONATITE.

The early carbonatites belong to two types. One type only outcrops in situ on Kiako, and possibly nearly in situ in the loose blocks found south east of Gingo. However, this rock is similar to many of the fragments of carbonatite found in the conglomerates to the north, and it is thought that an early carbonatite of this type formed at the centre of the central plutonic complex, but was partly broken up when the pyroclastics were erupted. The other small occurrences of carbonatite that intrude the basement constitute the second type.

(1) KIAKO CARBONATITE.

The outcrop pattern of carbonatite on Kiako is irregular and poorly defined; from the distribution of the few exposures found, it is probably about 50 yards across. The rock is white and coarse, and large subhedral magnetites and pyroxenes protrude on the weathered surface in bands which are almost vertical, although no significant trends were found in the strikes of the banding. The rock is composed mainly of clear carbonate, both untwinned and unstrained, in anhedral crystals up to 1 cm across. These occasionally have thin brown rims, as if iron-or-magnesium-rich material has been exsolved from them.

Aegirine is the chief minor constituent, and it is distinctive of the Kiako Carbonatite, as it seldom occurs in carbonatites elsewhere on Rangwa. Crystals of aegirine may be as much as 1.5 cm long, and though occurring in bands and clusters they are not orientated. They were probably originally subhedral, but have been broken up and altered by the carbonate. They are normally dark green, cloudy and unzoned. The cores of the crystals are frequently replaced by coarse cloudy carbonate, and sometimes crystals are broken into pieces which have slightly different orientation (RFP 65). Apatite occurs in two generations; it is either rounded and partly altered to carbonate, or euhedral with rows of minute inclusions. These two modes of occurrence of apatite are found in both the early plutonics and the central carbonatites. Magnetite is an occasional constituent.

(2) OTHER EARLY CARBONATITE.

Although widespread, most of the other early carbonatite occurs in such small bodies that it is subordinate to the brecciated and altered country rock with which it is associated. The carbonate itself is generally a mosaic of fine-or-medium-grained cloudy crystals, sprinkled with brown opaque material. None of the usual carbonatite accessory minerals are found, except for minor quantities of apatite. Varying amounts of felspar occur, and there is a gradation between felspar-free carbonatite and felspar rock. This relationship will be described when alteration of basement minerals to potash felspar and carbonate is considered (pp 61 - 65).

The carbonatite from a small outcrop on the talus slopes north of Rangwa (RFP 190) is somewhat unusual; it consists mainly of large elongated crystals of carbonate, surrounded and replaced by far smaller ones. No other minerals occur except for small patches of fine-grained felspar with cloudy edges. The field relations of this carbonatite are unknown, although it does outcrop near an exposure of fenite.

C. NEPHELINE SYENITE.

Small bodies of fine-grained nepheline syenite are generally associated with the larger alkaline intrusions. One dyke with a north-east south-west strike on Kiako is cut by the carbonatite there, but the nepheline syenite is seldom well enough exposed to show its form or field relations. Blocks of nepheline syenite were found near the margin of the ijolite on Manga, and within the fenite on Sagurume.

The nepheline syenites are dark green, fine-grained and homogeneous in hand specimen, and look not unlike the ijolite and melteigite which occur near the edge of the central alkaline complex. The nepheline (RFP 62) forms a groundmass of subhedral plates that are up to 3 mm across; these are partly altered to cancrinite, and have very prominent cleavage planes. Lesser amounts of untwinned anhedral orthoclase, which is cloudier than the nepheline, occur in the groundmass too. Up to 40% of the rock is aegirine augite, which forms small elongated crystals less than 1 mm long. They are rimmed by darker green aegirine, the outer limit of which is fibrous and ragged; the complex zoning found in the pyroxenes in the ijolite does not occur, and the centres of the crystals are more aegirine-rich than those of the ijolite. Often the pyroxenes are completely enclosed by nepheline. Wollastonite and sphene form sporadically, and carbonate is common both as an alteration product and in small veins.

The mineral paragenesis of the nepheline syenite is similar to that of the ijolite, except in the appearance of orthoclase and carbonate and the nonappearance of melanite.

D. RUKUNGU AGGLOMERATE.

At the Rukungu vent, intrusive and possibly extrusive agglomerate and extrusive bedded tuff are exposed, and, although detailed field relations cannot be established, some of the phenomena which will be described from Rangwa itself occur here. Whereas on Rangwa the contact between the pyroclastics and basement is not exposed, at Rukungu there is a gradation at the edge of the vent from unshattered basement to intrusive agglomerate. Here will be described the rocks that are found within the vent.

The agglomerate is unbanded, and does not show any flow texture, and provides evidence of whether it is intrusive or extrusive. The matrix, which is generally brown, consists of intergrowths of carbonate and fine-grained cloudy felspar. The fragments are closely packed and unsorted, but seldom larger than 2 cm across. They are rounded or subangular, and consist both of individual minerals and rocks, of which the following were found:- Granite, quartzite and mica schist (all unaltered), felspar rock, often with inclusions of phlogopite, highly carbonated material with possible pyroxene pseudomorphs (generally the most rounded fragments), and a rock consisting entirely of small phlogopite crystals. Fragmental quartz and all the original felspars in the granite survive, although the plagioclase is usually sericitised (RF 341). This implies that the fragments of felspar rock were already felspathised before the emplacement of the agglomerate.

Towards the centre of the vent, recognizable fragments of basement become fewer, the proportion of matrix to fragments increases, and there is considerable alteration to fine-grained cloudy potash felspar. Many of the fragments of fine-grained felspar and carbonate have irregular swirling edges and skins of opaque material (RFP 177). Frequently fragments are themselves fragmental, and have a similar texture and composition to the matrix.

The only exposure of possibly extrusive tuff found is composed of fine-grained carbonate and felspar, which replace fragmental material as well as some possible pseudomorphs after melilite in carbonate. The beds are .5-2 cm apart, and are roughly graded.

E. BRECCIATION AND ALTERATION.

Fenitisation and felspathisation are forms of alteration of the country rock associated with the intrusion of alkaline plutonics. The first step in both has been considered to be shattering of the country rock, as (von Eckermann 1948) a "thermal shock zone" develops. Around Rangwa, although shattering frequently accompanies alteration of the basement, brecciation may also occur which is apparently unrelated to alkaline intrusions; so the brecciation is described separately.

The processes of fenitisation and felspathisation as described at other localities (von Eckermann 1948 and Garson and Campbell Smith

1958) are found superimposed and with gradations between the two at Rangwa; it is therefore convenient to discuss them together.

(1) BRECCIATION.

Brecciation is chiefly seen in granite and quartzite and occurs in zones concentric with the edge of Rangwa (the two localities south of Ragwe Bay (plate 55), in irregular patches (especially south of Gingo) and round an agglomerate vent (at Rukungu).

The country rock is split into angular pieces whose size varies between that of rock fragments 10 cm across and parts of individual crystals (plate 56). Occasionally the matrix is iron-stained (RFP 75), but where this is not accompanied by any mineral alterations it is thought to be an effect of weathering. The brecciated quartzite from west of the Rukungu vent (RF 340) shows minor development of felspar interstitially in narrow veins that are about .1 mm across, but the fragments are of fresh quartzite, even at their edges. It has been seen that at the Rukungu vent, the country rock is completely broken up and its fragments rounded before any alteration is induced in it.

(2) ALTERATION.

The main minerals which have been introduced into the country rock during alteration are aegirine, sodic amphibole, newly formed felspar and carbonate. Sphene and apatite crystallize occasionally. The modes of occurrence of the main groups of minerals are presented

Plate 55. Exposure of brecciated granite near Ragwe Bay.

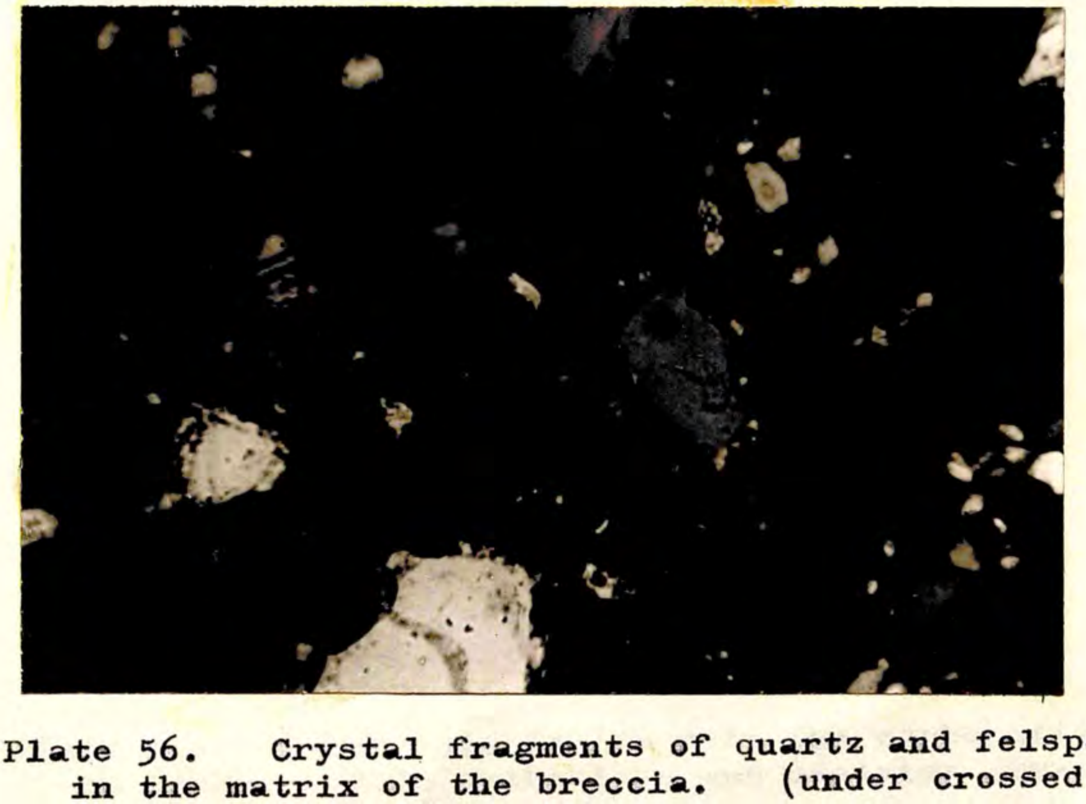


Plate 56. Crystal fragments of quartz and felspar in the matrix of the breccia. (under crossed polarisers). RF75 x155.

Plate 57. A band of slightly fenitised amphibolite in the gulley south of Gingo.

Plate 58. Felspathic fenite near the carbonatite on Kiako. Both orthoclase and aegirine crystals can be seen on the surface.

separately and then the relations between them are considered.

(a) AEGIRINE AND SODIC AMPHIBOLE.

The aegirine is dark green and slightly pleochroic. It is fibrous or crystalline, and the crystals tend to be cloudy. They are never zoned, and, from their low X:c angle, they must contain a very high proportion of the aegirine molecule.

The sodic amphibole is generally fibrous. When it is crystalline (as in RFP 103), the crystals are elongated and length fast. Birefringence is low, and the mineral has an almost uniaxial negative interference figure. The extinction position is unclear, because of anomalous blue, yellow, green and brown interference colours, but the maximum X:c angle is in the order of 26°. Maximum absorption is in the X direction, and the pleochroism is:-
X = bluish green, Y = pale bluish green, Z = yellowish green. The amphibole is identified as magnesioarfvedsonite or arfvedsonite. It is distinguished from most other amphiboles by its $X > Y > Z$ absorption, and shows the anomalous birefringence colours of the eckermannite-arfvedsonite series (Deer, Howie and Zussman 1963 Volume 3, pp 364 - 373). The low 2 V and the low X:c angle show that it belongs to the arfvedsonite end of the series.

Aegirine and sodic amphibole normally occur together; in comparatively unaltered rocks (RF 85), they both form fibres, which grow outwards from veins. The veins may be straight and as much as 1 cm across, and they sometimes show cross-cutting relations (RFR 21), but normally they follow the crystal boundaries of the host rock. Generally, the proportion of blue amphibole to aegirine is less in more altered rocks. Where the rock is highly veined, but most of the original minerals nevertheless survive, as in the specimens from Mbassa (RFP 101 and RFP 103), bundles of fibres of aegirine have cores of blue amphibole, and the fibres of the latter sometimes grade outwards into aegirine (plate 59). In more altered specimens, only a few fibres of blue amphibole are mixed with the aegirine, and blue amphibole may occur at the tips of radiating fibres of aegirine (RF 80). It is possible that much of the early-formed blue amphibole is changed to aegirine as alteration proceeds. Sometimes the fibres recrystallize into larger prisms as in RFP 191, over 80% of which is prismatic aegirine, but the aegirine may remain fibrous in rocks that contain large amounts of it, and, as in RF 79 and RF 80, (plate 60), aegirine fibres radiate from coalescing centres.

Quartz is the mineral most susceptible to attack by aegirine and blue amphibole, and it is penetrated and gradually engulfed by tiny fibres (RFP 103, plate 59). While some free quartz still remains, the centres of the hornblendes are converted to far smaller crystals of blue amphibole, which are sometimes associated with plates of biotite (RFP 112, plate 61). Diopside is also patchily replaced by blue amphibole (RFP 113), and biotite is altered to aegirine and blue amphibole along its cleavages.

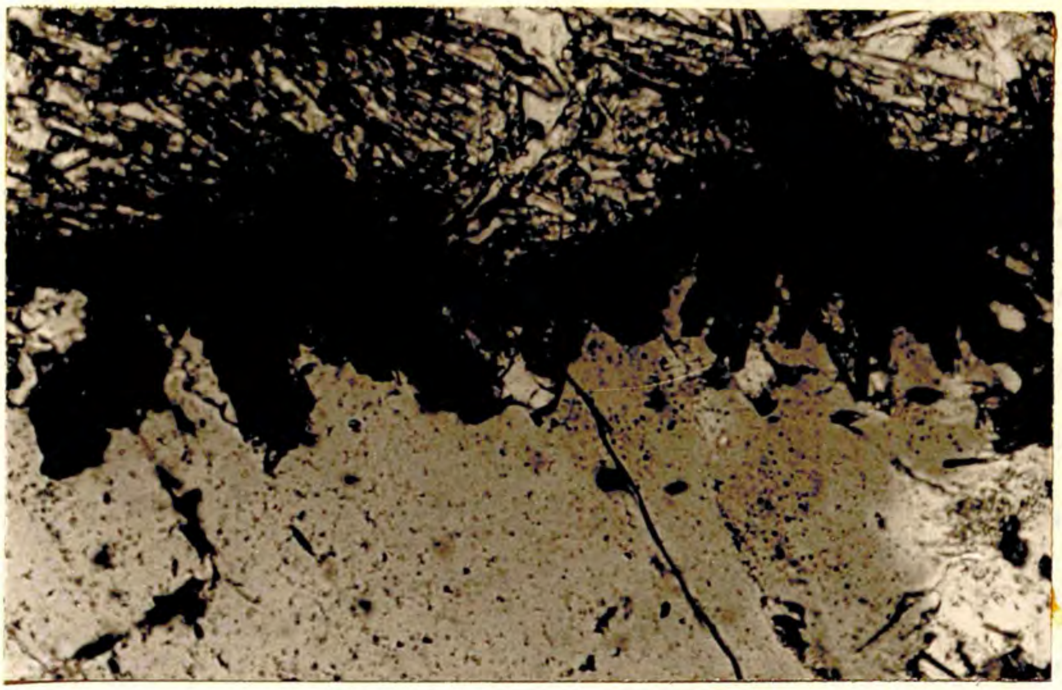


Plate 59. Sodic amphibole (pale fibres) and aegirine (dark fibres) at the edge of a quartz crystal in fenite. (RFP101). x310.

Plate 60. Bundles of radiating fibres of aegirine penetrating orthoclase in fenite. (RF80). x80.

(b) FELSPAR.

The original felspar in the basement only undergoes replacement by blue amphibole and aegirine to a limited extent, although, as in RFP 81, felspar may contain minute inclusions of sodic amphibole which have parallel orientation. However, the composition, texture and crystal size of the felspars are altered in a complex series of changes, some of which are contemporaneous with the introduction of aegirine and blue amphibole, but other changes may occur either before or after they have been introduced, and, latterly, felspars tend to invade and alter all previously formed constituents of the rock. The same sequence of changes is not followed in every instance.

The predominant felspars in the unaltered basement are microcline and partly sericitised oligoclase; these are sometimes intergrown, and occasionally perthitic. Whether aegirine and blue amphibole are present or not, the largest crystals of microcline break up, become cloudy and lose their characteristic twinning at an early stage. This happens patchily, and crystals may consist partly of true microcline and partly of untwinned, cloudy potash felspar (RFA 39). At the same time, albite is exsolved out of the microcline, so that the felspar may become crudely perthitic (RFA 40), and broken up fragments of potash felspar are often surrounded by clear felspar of higher relief, probably albite, especially when they bound on aegirine (RFP 101, plate 62). The rims are untwinned, except where they are well developed, as in RFA 39, when they show polysynthetic twinning. At the same time, oligoclase crystals become strained or shattered (RFP 185), and all twinning finally disappears as minute carbonate crystals grow in the middle of the already sericitised felspar. The albitic rims round the oligoclase remain, and, especially when aegirine is present, clear albite penetrates the oligoclase in irregular blotches (RFP 103, plate 63). Through these changes, patches of quartz may still survive within the felspar (RFP 184), although it seems that felspar must absorb some quartz at this stage. The above processes entail a nett gain in albite in the felspars, and are normally closely connected with the introduction of aegirine and blue amphibole.

The second category of felspar alteration is essentially a granulation of large felspar crystals, either original ones or alteration products, and their recrystallization as a mosaic of tiny felspars. This process is not unlike the breakdown of microclines in the unaltered breccia into a jumble of tiny closely-packed fragments (RFP 6), and takes place mainly along the edges and cleavage planes of large felspars in rocks that have suffered alteration. The recrystallization is generally patchy, as in RF 85, in which large crystals of microcline are partly changed to fine-grained cloudy potash felspar with shadowy extinction, but in extreme cases (RFP 181) all the original felspar may be broken down into dirty little crystals containing streaks of ore; no aegirine or sodic amphibole is present, and much of the original quartz survives, although it is cut and shattered by veins of felspar.

The third type of alteration involves a reorganization of the felspar into large homogeneous crystals and replacement of other minerals in the rock by felspar. It is nearly always one of the later alteration processes in a rock, so that the material upon which the process has acted was already highly altered. Large subhedral laths of cloudy potash felspar, which may be a centimetre long, and show well developed simple twinning, crystallize (RFP 161, plate 64). Sometimes, stringers of aegirine showing similar orientation indicate that large crystals of it had been introduced previously have been partly altered to felspar. The aegirine is generally very cloudy and altered to ore along its cleavage planes (RFP 64 and RFP 161, plate 65), and sodic amphibole is seldom present. Large recrystallized felspars normally form after the introduction of aegirine, but the reverse occasionally occurs. In RF 79 and RF 80, radiating fibres of aegirine and blue amphibole, which compose over 60% of these rocks, grow into plates of potash felspar from coalescing centres rather than from veins, which may well mean that they are alteration products of a mineral already present in the basement, such as hornblende. Sometimes, the felspars recrystallize and alter the other minerals in a rock which contains no aegirine or blue amphibole. In RFP 12, large crystals of orthoclase with clear albitic margins are superimposed on the original quartz and

Plate 61. Small crystals of sodic amphibole within a hornblende crystal in fenite. (RFP112). x155.

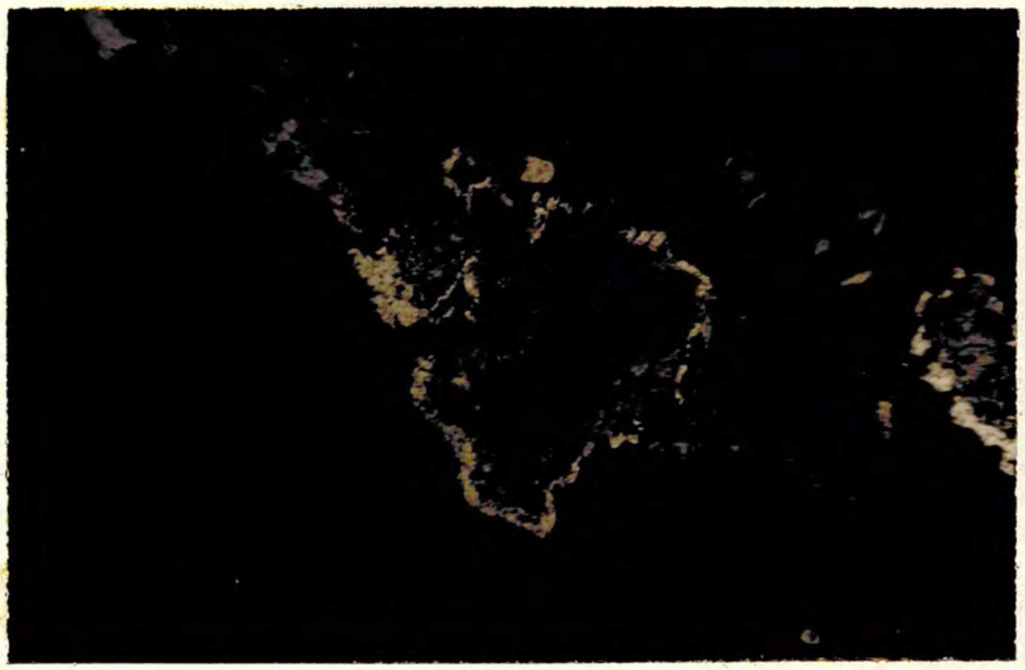


Plate 62. Albite which has grown within microcline in fenite (under crossed polarisers). (RFP101). x155.

Plate 63. Streaks of albite (grey) in oligoclase (black) in fenite (under crossed polarisers). (RFP103). x155.

Plate 64. Twinned potash felspar in felspathic fenite. (RFP161). x25.

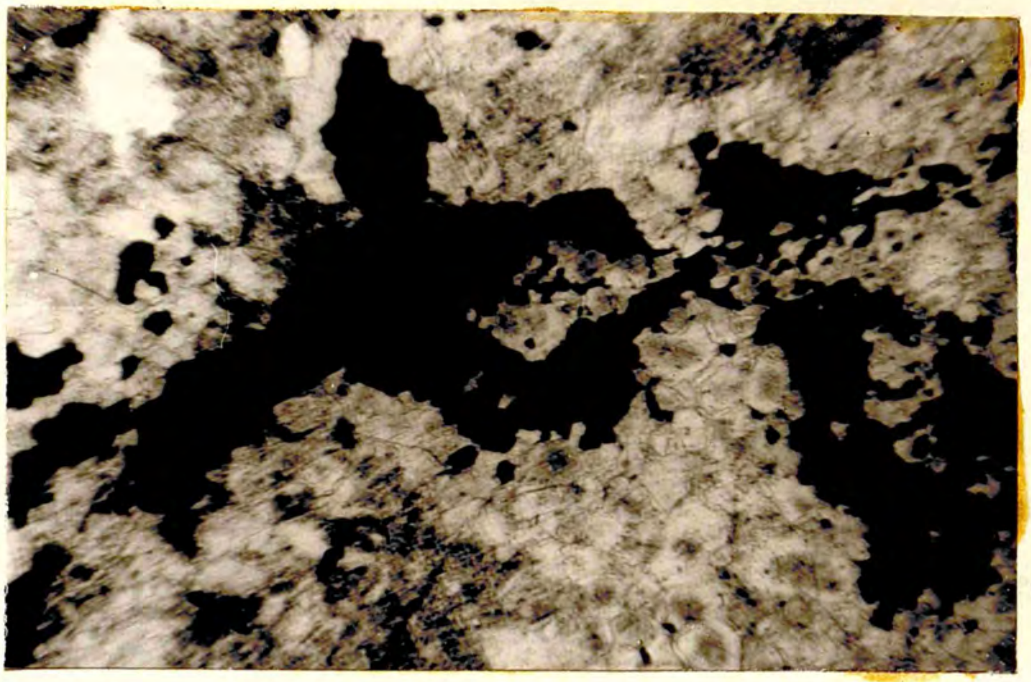


Plate 65. Cloudy aegirine, partly altered to ore and replaced by potash felspar in felspathic fenite. (RFP64). x25.

Plate 66. A phlogopite crystal in a carbonated fenite. (RFP12). x80.

microcline, and small amounts of brown ore are present with them, although it is uncertain if the ore is a weathering product.

Two dyke rocks (RFP 141 and RFP 150, both from the ridge between Manga and Usengere) consist mainly of felspars. RFP 150 contains large crystals of cloudy orthoclase, sometimes rimmed by clear albite; often the orthoclase is broken down into a mosaic of tiny anhedral crystals of felspar with some interstitial carbonate, and the positions of the original crystal boundaries are preserved by streaks of small albites and cloudy aegirines. Any large felspars which may have existed originally in RFP 141 have disappeared entirely, and only very small orthoclase crystals, sometimes showing simple twinning, and partly absorbed aegirines survive. These could be interpreted as the mobilised products of felspathisation.

(c) CARBONATE.

The formation of small crystals of carbonate within plagioclase during alteration has been mentioned already; more widespread carbonation occurs in the vicinity of carbonatite intrusions, and this carbonate is often associated with phlogopite. In RFP 12, veins of small cloudy carbonate crystals, which include plates of phlogopite lying parallel to the edges of the veins (plate 66), run between felspar crystals and penetrate their cleavage planes. Much of the original microcline, oligoclase and quartz survive (plate 68 shows), and there is no indiscriminate development of orthoclase along the

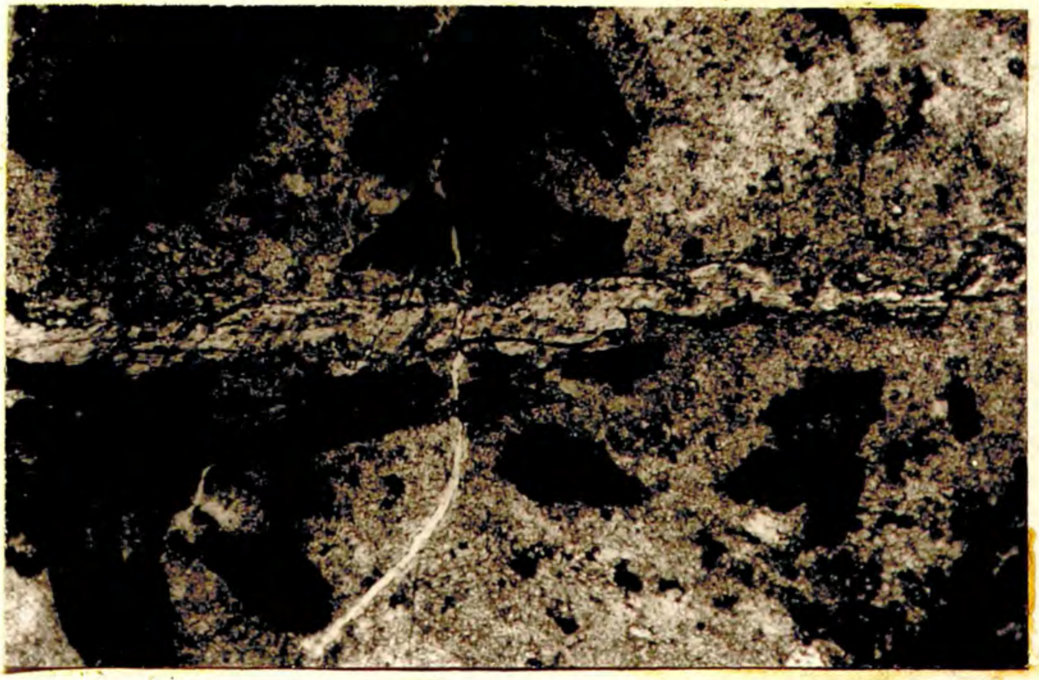


Plate 67. Carbonate veins in a rock consisting of orthoclase and aegirine. Much of the aegirine is altered to ore. (RFP64). x80.

Plate 68. Carbonate penetrating and breaking up quartz. The carbonate is associated with ore. (RFP12). x80.

veins, so that the introduction of carbonate need not be connected with recrystallization of the felspars. However, carbonate is normally found in rocks in which potash felspar predominates; in RFP 64 and RFP 161, both of which were collected from near the Kiako Carbonatite, turbid fine-grained carbonate occurs interstitially to large crystals of orthoclase. It replaces the orthoclase, and patches of felspar with the same orientation survive surrounded by carbonate. Also the rock is invaded by sets of late carbonate veins, which cut both the felspar and the earlier carbonate (plate 67).

When large quantities of carbonate cut the altered basement, they are normally later than a network of veins of noncrystalline red material (RFP 84). Along the contact, the carbonate tends to replace felspar irregularly, and it includes patches of cloudy orthoclase, generally rimmed by clearer albite. Since many of these inclusions are subhedral crystals, it is doubtful whether they represent what has survived after wholesale replacement by carbonate.

(3) RELATIONS BETWEEN BRECCIATION, ALTERATION AND THE PLUTONICS.

Brecciation and alteration of the country rock need not be associated with any alkaline plutonics at the present day erosion level. However, when alkaline plutonics are present, the basement is both brecciated and altered; so brecciation possibly caused lines of weakness which plutonics and their accompanying alteration followed preferentially.

The introduction of aegirine and blue amphibole is always found near the ijolite (RFA 39 from Sagurume and RF 85 from Ekiagaria), and with it the felspar is generally enriched in albite, and sometimes broken down into small crystals (RFP 181) to form fenite as defined by Sutherland (1965). Near intrusions of carbonatite, large plates of twinned orthoclase form, any mafic minerals tend to be reduced to noncrystalline ore and small amounts of carbonate are introduced (RFP 141) causing a felspathic fenite (Sutherland 1965) to develop. Large felspars normally form in a rock that already contains aegirine, and on Kiako, where carbonatite cuts nepheline syenite, it is reasonable to suppose that aegirine was introduced when the nepheline syenite was intruded, and that the carbonatite was responsible for the formation of large crystals of orthoclase. The smaller carbonatite dykes, mainly at least two miles out from the edge of Rangwa, do not cause such marked alteration in the felspars.

From these observations, it is possible to deduce what types of alkaline plutonics may occur beneath some areas of altered rocks where no plutonics are exposed. For example, the basement veined with aegirine and blue amphibole on Mbassa is probably underlain by ijolite, and carbonatite probably exists under the basement that contains large orthoclase crystals on Kiawindo. The alteration in the rocks at the northern margin of Rangwa may have been caused by both ijolite and carbonatite.

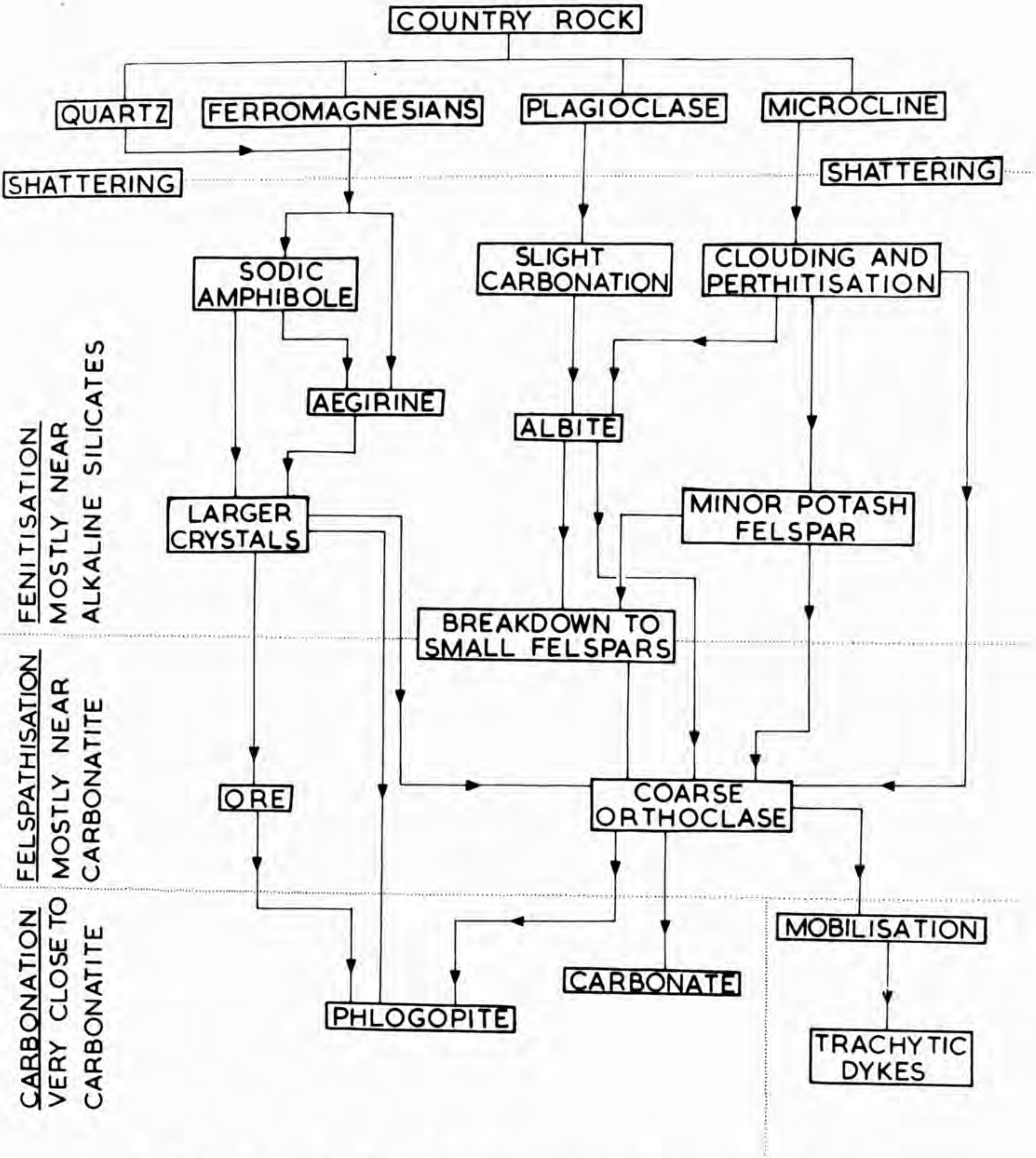


FIGURE 9 . DIAGRAM SHOWING THE MAJOR MINERAL CHANGES THAT OCCURRED DURING ALTERATION.

3. STRUCTURE.

A. THE RELATION BETWEEN THE PLUTONICS AND DOMING.

The large centrally placed intrusive complex clearly shows both concentric and radial structures. The form and disposition of the other alkaline bodies which occur between Rangwa and the encircling volcanic mountains are much more difficult to assess, owing to widespread blanketing by alluvium. Where seen, however, the boundaries of these smaller intrusions do not show a regular pattern, although the ijolite of Sagurume and the zones of brecciation near Ragwe Bay hint at a more regular arrangement.

Evidence for the existence and extent of a basement dome will be presented more fully later (pp 242 - 243). Here it is only necessary to observe that its existence can be inferred from the fact that the junction between volcanics and basement is everywhere up to 1,800 ft. higher on the inward-facing erosion scarps than it is around the periphery of the volcano. Moreover, the dome is disposed fairly symmetrically around the Rangwa centre, suggesting that the association is not fortuitous, but that doming was related to central igneous activity.

There is evidence that doming occurred before the main volcanic activity (cf. Napak, King 1949, pp 15 - 16). The proximity of the Kiako Carbonatite to the junction between the volcanics and basement suggests that considerable erosion occurred before the eruptions of nephelinite. Moreover, the dips of the conglomerates near the base of the succession on Rusinga and Mfwangano, and of the successive outpourings of nephelinite lava on the mainland are so low that unless a pre-existing dome is postulated there would have been no gradient to maintain outward flow.

B. THE STRUCTURE OF THE CENTRAL COMPLEX.

The outer boundary of the central complex dips outwards, probably at a high angle, and it forms a smooth curve. Three main types of structure occur within the central complex, all of which can be related to a centre about a quarter of a mile within the boundary with the pyroclastics:-

1. Structures with steep outward dips.
2. Structures that dip inwards, mostly between 40° and 25°.
3. Vertical radial structures.

The first type is found only in the marginal fine-grained ijolite, and is represented by diffuse banding. The others occur throughout the rest of the complex. Towards the margins of the complex, the inward-dipping structures are conesheets of ijolite, which cut ijolite turjaite or uncompahgrite; farther in they are represented by compositional and textural banding in the uncompahgrite (Figure 10). Both conesheets and the banding have similar dips. The vertical planes are generally dykes of coarse ijolite or turjaite, and sometimes diffuse masses of coarse uncompahgrite.

The outward form and internal structures of the complex

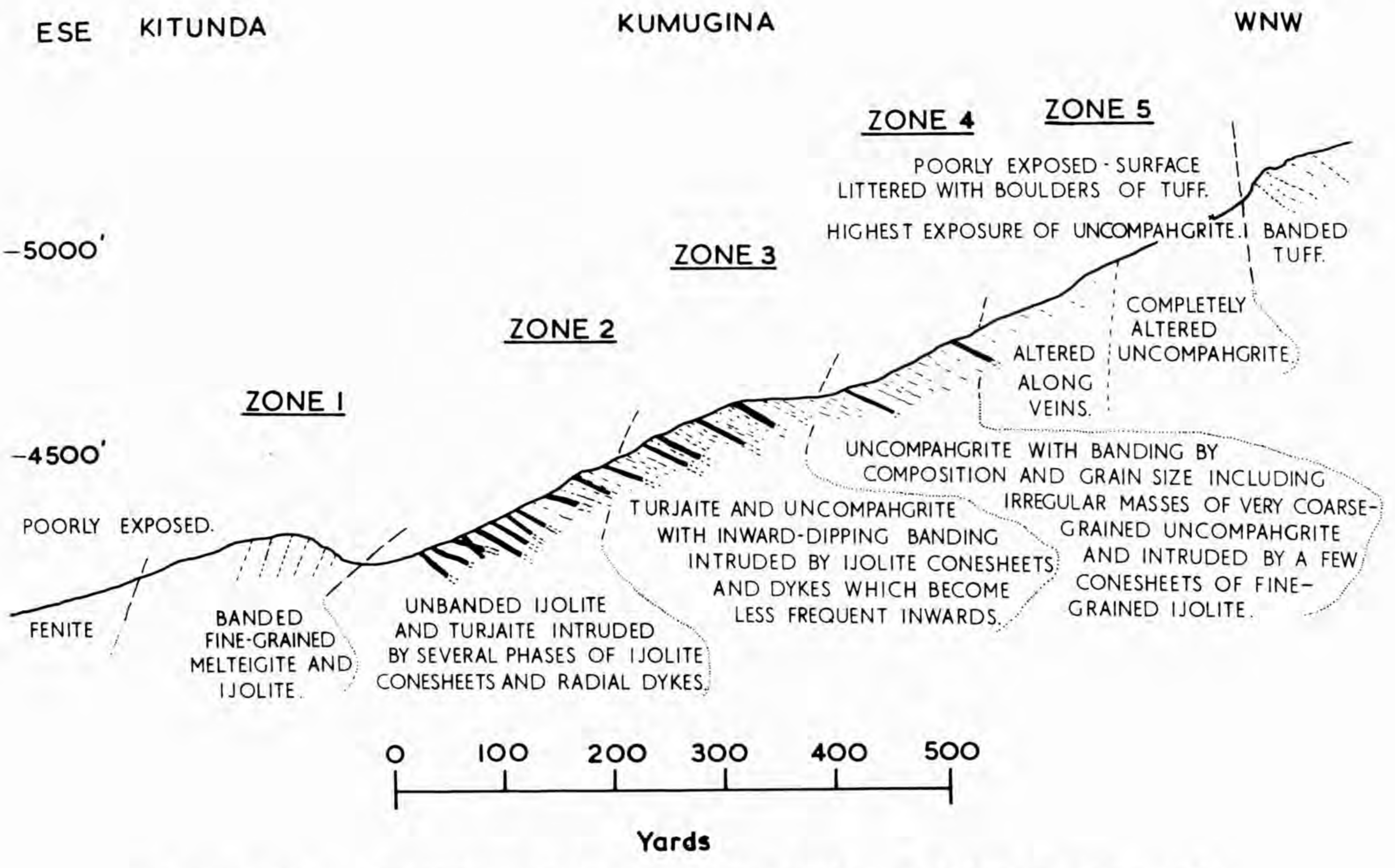


FIGURE 10. SECTION ACROSS THE CENTRAL PLUTONIC COMPLEX SHOWING THE ROCK TYPES AND STRUCTURES.

suggest that only a small part of a very much larger, dome-shaped mass of plutonics survives. The outward-dipping structures have the appearance of flow-banding. The inward-dipping structures can be projected to a focus 2,000 - 3,000 ft. below their present level of outcrop, or 1,500 - 2,500 ft. above sea level. The rocks with inward-dipping and radial vertical structures are only separated from those with outward-dipping banding by a narrow and irregular zone of ijolite and turjaite which has swirling flow textures. It can therefore be assumed that the ijolite conesheets and the compositional banding in the uncompahgrite were both superimposed on the earlier flow-banding.

4. THE GENESIS OF THE ALKALINE PLUTONICS.

A. THE CENTRAL COMPLEX.

Deductions are made concerning the origins of the rocks of the central complex from these lines of evidence:-

1. Field relations and mineral parageneses.
2. Chemical evidence.
3. Phase relations.

(1) FIELD RELATIONS AND MINERAL PARAGENESES.

The biotite pyroxenite and biotite uncompahgrite both contain the same assemblage of minor constituents, predominantly magnetite, perovskite, biotite and apatite. Where pyroxene and melilite occur together, the pyroxene is normally enclosed by the melilite and is frequently embayed by it. Occasionally, melilite replaces pyroxene almost entirely, but causes no alteration products to form around the pyroxene.

When nepheline is present, the pyroxene and melilite, and, except for apatite, all the minerals that are associated with them are either altered or replaced. Pyroxene is partly replaced by nepheline, and, except in some of the fine-grained melteigites, the pyroxene is zoned and more aegirine-rich, especially at its margins, than that of the pyroxenite and uncompahgrite; frequently it is ringed by fibres of aegirine and sodic amphibolte. Melilite undergoes partial replacement by nepheline and become rimmed by fibres of cebollite, which penetrates along the crystal boundaries and cleavage cracks of the melilite. The ijolites normally contain melanite, and a few carry small amounts of magnetite, perovskite and biotite, which are enclosed and partly replaced by melanite. Melanite sometimes forms within and along the margins of pyroxenes. When biotite occurs in the ijolites, it is generally paler and more phlogopitic than the biotite of the uncompahgrites. Sphene and wollastonite both occur in the ijolites, especially the ones richest in nepheline, and neither were found in the pyroxenite or uncompahgrite (Figure 8).

Except for the formation of pale brown melanite in some of the altered uncompahgrite, these mineral changes only occur when nepheline is present, and they are never reversed. This implies that at any one place nepheline crystallized from new material which was introduced during or after the crystallization of pyroxene and melilite and their typical accessories.

All the dykes and conesheets of the central complex, which have intrusive contacts and chilled margins, are of nepheline-bearing rocks, which frequently carry biotite of fragmental appearance. Several stages of dykes and conesheets were found, which often show crosscutting relations, and they intrude ijolite, turjaite and uncompahgrite. Along their edges, there is extensive melanitisation, and the pyroxenes in the rocks they intrude become more aegirine-rich along the contact.

Any explanation for the nonoccurrence of ijolite dykes and conesheets towards the centre of the complex must be tentative, as the present outcrop pattern is such that none of the intrusions of ijolite can be followed inwards, since exposures, although numerous, are isolated. But from the evidence of field relations and mineralogy, it appears that both the ijolite conesheets and dykes and the banded uncompahgrite are imposed on an earlier intrusion, part of which survives in the marginal melteigites.

Because of the replacement relationship between pyroxene and melilite, it is thought that the central part of this earlier intrusion was originally composed mainly of pyroxenite, and that uncompahgrite was formed metasomatically from it. On the grounds of the relations between the minerals of pyroxenite and uncompahgrite, Temple and Grogan (1965) suggest that the uncompahgrite of Iron Hill, Colorado, originated by a similar form of metasomatic replacement from pyroxenite.

The structural unity of the ijolite intrusions and the banded uncompahgrite implies that they are related phenomena, and it is possible that both resulted from the intrusion of the same material, which caused metasomatism centrally, but gave rise to dykes and conesheets marginally.

(2) CHEMICAL EVIDENCE.

Eight analyses of uncompahgrite, turjaite and rocks of the ijolite series from the central complex are presented:-

ANALYSES

	RFA 14	RFA 15	RFA 16	RFA 26	RFA 34	RFA 36	RFA 39	RF2 17
SiO_2	34.47	32.84	35.76	34.05	38.89	37.01	37.70	32.63
TiO_2	8.28	6.61	5.06	4.74	3.11	4.50	0.57	4.05
Al_2O_3	16.40	4.78	6.28	4.29	17.35	16.84	28.36	11.42
Fe_2O_3	6.02	8.54	7.90	7.98	4.93	8.08	1.69	7.97
FeO	3.59	7.24	6.34	5.71	3.56	2.40	0.87	6.22
MnO	0.05	0.13	0.15	0.06	0.12	0.12	0.06	0.17
MgO	3.75	8.93	9.05	9.59	5.70	1.40	0.92	6.83
CaO	15.30	26.48	23.49	29.31	12.11	16.12	8.55	20.79
Na_2O	7.08	2.06	2.60	1.70	7.91	7.94	12.20	4.70
K_2O	2.88	0.64	1.46	0.24	4.42	3.08	5.18	2.85
H_2O+	0.56	0.45	0.41	1.15	0.40	0.98	1.47	0.62

	RFA 14	RFA 15	RFA 16	RFA 26	RFA 34	RFA 36	RFA 39	RF2 17
H_2O-	0.08	0.08	0.07	0.08	0.07	0.12	0.12	0.09
P_2O_5	0.83	0.50	1.41	0.04	1.36	0.66	1.80	1.09
CO_2	0.23	0.28	0.26	0.27	0.24	0.91	0.76	0.36
	99.52	99.56	100.24	99.21	100.19	100.16	100.25	99.79

NORMATIVE COMPOSITIONS

	RFA14	RFA15	RFA16	RFA26	RFA34	RFA36	RFA39	RF217
Anorthite	7.87	1.89	1.14	3.34	-	1.20	7.20	1.83
Leucite	10.59	2.96	6.76	1.13	20.53	14.30	5.93	13.21
Kaliophilite	-	-	-	-	-	-	13.10	-
Nepheline	32.44	9.43	11.90	7.78	34.91	36.35	55.59	21.58
Acmite	-	-	-	-	2.12	-	-	-
Diopside	13.41	22.77	30.37	22.92	7.45	7.54	-	1.51
Wollastonite	-	-	-	-	-	12.96	-	-
Olivine	2.21	8.25	5.99	9.35	7.55	-	1.60	11.40
2 CaO SiO_2	9.08	29.44	20.33	34.24	12.44	6.81	5.79	27.65
Magnetite	-	4.57	6.33	4.83	2.85	-	1.58	8.86
Haematite	6.02	5.42	3.60	4.66	2.23	8.08	0.66	1.84
Ilmenite	7.69	12.56	9.61	9.01	5.82	5.32	1.08	1.69
Apatite	1.94	1.11	3.33	0.10	3.22	1.58	4.27	2.59
Calcite	0.52	0.64	0.59	0.61	0.55	2.07	1.73	0.82
Perovskite	7.20	-	-	-	-	2.88	-	-
	98.97	99.04	99.85	98.97	99.67	99.09	98.54	98.51

Analyst - Mr. H. Lloyd.

RFA 14. Turjaite from the central plutonic complex.

RFA 15. Biotite uncompahgrite from the central plutonic complex.

RFA 16. Pyroxene-rich uncompahgrite from the central plutonic complex.

RFA 26. Biotite uncompahgrite from the central plutonic complex.

RFA 34. Ijolite from a conesheet in the central plutonic complex.
RFA 36. Ijolite from Sagurume.
RFA 39. Urtite from Sagurume.
RF217. Biotite uncompahgrite from the central plutonic complex. This specimen possibly contains some nepheline, though it was not observed in thin section.

The norms of these have been calculated, and the chemical constituents have been plotted on the triangular diagram; - SiO_2- Al_2O_3, Na_2O and K_2O - CaO, MgO, and FeO (Figure 11).

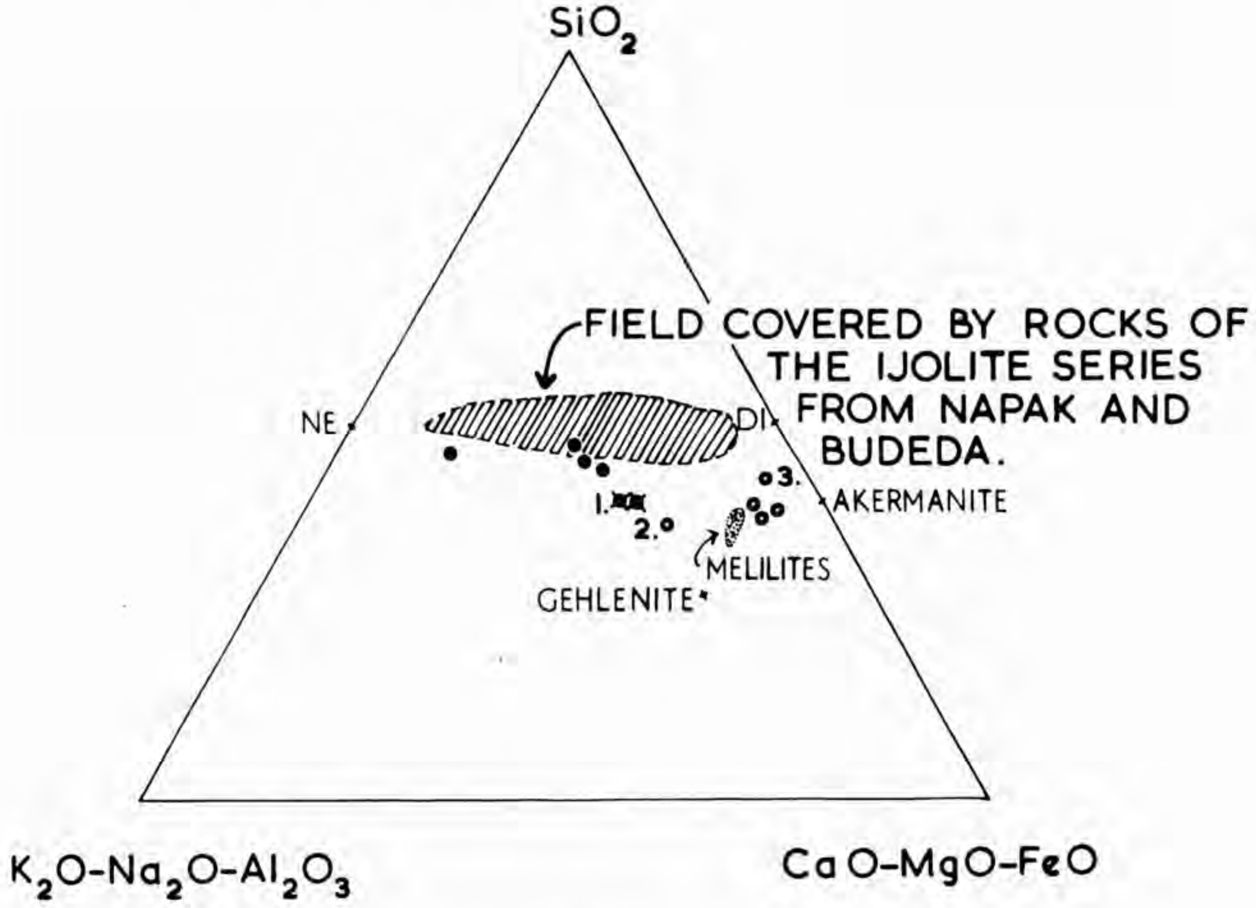
Much of what the analyses show is to be expected from the petrography. The calcium content is far higher in the uncompahgrites than in the ijolites, and that in the turjaite is intermediate. The magnesia content varies with the proportion of pyroxene present, so that the turjaite contains less magnesia than the uncompahgrites and some of the ijolites. The ijolites and turjaite contain far more alumina, soda and potash than the uncompahgrite. The uncompahgrites tend to contain less silica than the ijolites, but a Harker diagram shows that amounts of none of the other minerals in the rocks analysed show any recognizable trends when plotted against silica content.

The presence of melilite is reflected in the norms of the uncompahgrites by the presence of calcium orthosilicate and lesser amounts of olivine. The ijolites contain high normative nepheline, and the normative nepheline in the uncompahgrites probably results from the soda melilite component of the melilite. Normative leucite

1. TURJAITE FROM NAPAK (KING 1965)

2. A THIN SECTION OF THIS SPECIMEN CONTAINS NO NEPHELINE, BUT THE ANALYSIS SUGGESTS THAT NEPHELINE MAY HAVE BEEN PRESENT IN ANOTHER PART OF THE SPECIMEN.

3. PYROXENE-RICH UNCOMPAHGRITE.



- ○ UNCOMPAHGRITE INCLUDING 2 ANALYSES PRESENTED BY McCALL (1958).
- ✱ TURJAITE.
- ● MELTEIGITE, IJOLITE AND URTITE.

FIGURE 11. DIAGRAM SHOWING THE RELATIVE AMOUNTS OF SiO_2, K_2O-Na_2O-Al_2O_3 AND CaO-MgO-FeO IN ROCKS ANALYSED FROM THE CENTRAL PLUTONIC COMPLEX.

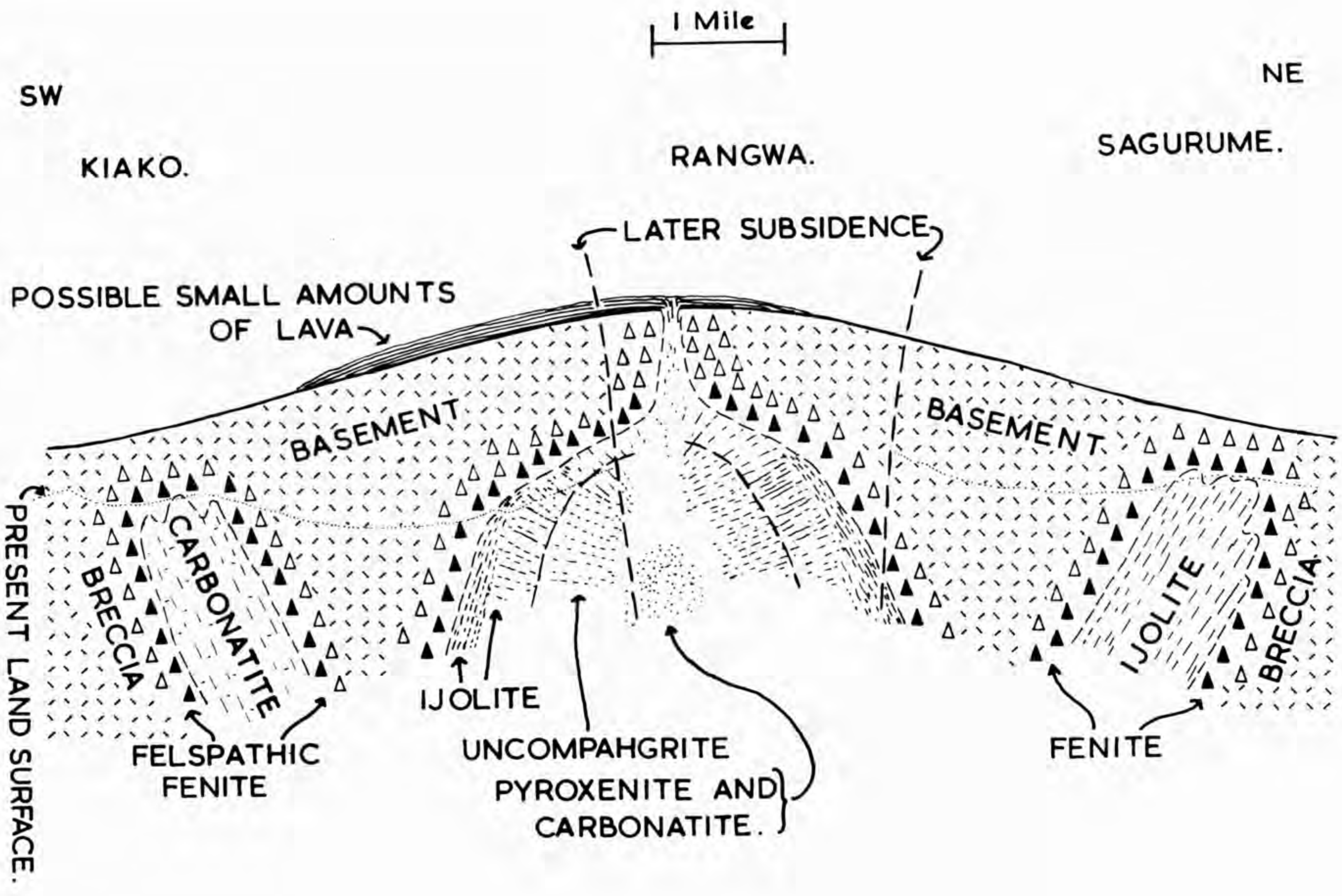


FIGURE 12 . INFERRED SECTION ACROSS THE PREVOLCANIC DOME AFTER THE INTRUSION OF THE EARLY ALKALINE PLUTONICS.

and kaliophilite result from the biotite in the uncompahgrite and potash in the nepheline of the ijolites. The normative diopside of the uncompahgrites is far higher than that of the ijolites, possibly because it includes some of the lime and magnesia from the melilite. High normative ilmenite or perovskite in most of the rocks is a reflection of high titania content. Anorthite appears in the norms, but never in the modes.

On the SiO_2 - Al_2O_3, Na_2O, K_2O - CaO, MgO, FeO diagram, the analyses plot along a curved path diverging from that of the pyroxenites and ijolites from Napak and Budeda (King 1965, Figure 9, and Figure 11 of this work). The pyroxene-rich uncompahgrite from Rangwa plots close to the pyroxenites from Eastern Uganda, but below the nepheline-diopside join, the normal uncompahgrites plot close to the melilite field on the diagram, and turjaite plots nearer to the Na_2O, K_2O, Al_2O_3 corner than the uncompahgrites. The trend of the plots suggests that the parent member of the series had a composition approximating to that of a pyroxenite.

Ijolites of a very wide range of mineral compositions occur (Figure 6). If more analyses of them were available, it seems that they would plot along the diopside-nepheline join. Thus two series are present. King (1965, p 83) has suggested that the linear form of the trend of the ijolite series "suggests the predominance of a single process" and the close relation of the trend to the fields of mineral phases indicate that the evolution of the ijolite series has "been dependent on sequences of crystallization of minerals". It is likely that the curved trend of the uncompahgrite and turjaite was caused by metasomatic replacement from pyroxenite.

(3) PHASE RELATIONS.

Most of the chemical components of the rocks of the ijolite series can be represented as mixtures of nepheline and diopside (Figure 11), and it seems that simple fractional crystallization of nepheline and pyroxene could account for the relations between the two minerals in the ijolites.

The uncompahgrites and turjaites can also be related to mixtures of nepheline and diopside. Bowen (1928, 1956 edition, pp 260 - 263) describes the pseudobinary system, diopside-nepheline. At all compositions liquid survives to low temperatures, and the crystals which have formed at higher temperatures react with the liquid; at temperatures below 1200° melilite is formed throughout most of the composition range, together with either diopside, olivine or olivine and nepheline. The result is that crystal phases form which are much poorer in silica than the original melt together with a liquid which is richer in silica. The melilite formed by these reactions is a sodium melilite with a refractive index of about 1.630, either positive, or negative, always with low birefringence or isotropic, not unlike the melilite of the uncompahgrite and turjaite.

These results have several applications when the origin of the uncompahgrite is considered; they show that melilite will crystallize under certain conditions from a wide range of mixtures of end-members of the compositions of nepheline and diopside, that diopside, melilite and nepheline do not crystallize simultaneously in any part of the system, and that a mineral can crystallize which is less siliceous than either of the end-members of the system. It is suggested that the uncompahgrite and turjaite were formed by a mixing of pyroxenite and melteigite which had already formed with a liquid from which nepheline would crystallize. If the melilite was formed in this way, the more siliceous residual liquid must have been removed.

B. THE FENITES AND FELSPAR ROCKS.

There are two distinctive types of altered country rock, the fenites and felspar rocks. Sometimes there are gradational varieties, and sometimes the latter is superimposed on the former. Generally it can be established that the country rock before alteration was granitic.

In the fenites, aegirine and sodic amphibole have crystallized, and much of the felspar has recrystallized. The aegirine and sodic amphibole occupy distinct veins, which may be at least a centimetre across, as well as occurring along the edges of the minerals of the granite, and penetrating them, especially the quartz, in small fibres. In more altered rocks, the proportion of sodic amphibole becomes less, and the crystals of aegirine grow larger. Albite tends to form in both the microcline and oligoclase of the basement when they are close to the sodic ferromagnesians. The veins are presumably the paths along which the material which caused the mineral introductions and recrystallizations moved. Since the rock that has been altered was normally leucocratic, both iron and magnesia must have been introduced to form the ferromagnesian minerals. As sodic pyroxene and amphibole and albite have formed, soda must have been introduced also. This process is similar to the fenitisation described by von Eckermann (1948, pp 27 - 43) at Alno, and by Garson and Campbell Smith at Chilwa (1958 pp 14 - 23).

When felspar rocks develop, large euhedral or subhedral crystals of homogeneous potash felspar are formed from any felspars which were in the rock previously (cf. Garson and Campbell Smith 1958, p 28). Where felspathisation affects rocks which already contained aegirine, it is partly replaced by felspar and partly converted to ore. Variable quantities of carbonate are introduced, both interstitially and replacing the felspar and aegirine. Normally, there is no evidence of mobilisation, except possibly in two dykes composed predominantly of potash felspar. Potash must have been introduced into the felspar rocks.

Field relations suggest that the fenites tend to be related to alkaline silicate rocks, and felspathic fenites to carbonatite. Rocks which show both types of alteration outcrop close to both silicate rocks and carbonatite; on Kiako, carbonatite cuts nepheline syenite, and in the altered country rock nearby fenitisation can be shown to precede felspathisation and carbonation of the basement (cf. Budeda, King and Sutherland 1967). Evidence of the nature of the contacts is inconclusive; the contact between ijolite and fenite is never exposed, but it is thought to be fairly sharp. Fenitisation round Rangwa never proceeds to the formation of nepheline, and quartz is nearly always present even at exposures 10 - 20 yards from ijolite. Because of the association of fenite with ijolite, it is suggested that fenitisation was caused by the intrusion of ijolite.

Some of the early carbonatite is intimately mixed with the country rock, which has been converted to potash felspar and ore close to the boundary. As with the contacts between carbonatite and pyroclastics and breccia on Rangwa itself, the development of felspar and the destruction of the original texture of the basement increases towards the carbonatite. Fenitisation appears to be related to veins, whereas felspathisation causes a more homogeneous form of alteration.

It is to be expected that rocks as different as ijolite and carbonatite should give rise to different types of alteration. Because the ijolite shows a trend towards soda enrichment, it is logical to suppose that the liquid from which it crystallized caused soda metasomatism. The development of potash felspar near carbonatites is harder to explain, as the carbonatite itself is not rich in alkalis. However, it is likely that the liquid from which the carbonatite may have crystallized was rich in alkalis, as their presence lowers the melting point of a mixture of carbonates considerably (pp 180 - 181). It is suggested that potash was the predominant alkali present in the liquids from which the carbonatites on and around Rangwa were formed, and that some of it gave rise to the minor amounts of potash felspar within the carbonatite, but most of it migrated into the host rock, where it caused alteration to potash felspar.

LOWER AGGLOMERATE.

FRAGMENTS. ROUNDED-SUBANGULAR.

UNALTERED.	ALTERED.
GRANITE. FENITE. BIOTITE PYROXENITE. BIOTITE UNCOMPAHGRITE. IJOLITE. CARBONATITE. NEPHELINITE.	LAVA. AGGLOMERATE TUFF.
<20 CM.	<20 CM.

MATRIX.

FINE-GRAINED CARBONATE, FELSPAR AND ORE WITH BLOBS CONTAINING ALTERED LAVA AND PSEUDOMORPHED SINGLE CRYSTALS. A LARGE PROPORTION OF THE ROCK.

EXTRUSIVE.

UPPER AGGLOMERATE.

FRAGMENTS. ROUNDED-ANGULAR.

UNALTERED.	ALTERED.
FENITE. BIOTITE PYROXENITE. BIOTITE UNCOMPAHGRITE. MELTEIGITE. IJOLITE. NEPHELINITE.	AGGLOMERATE. BEDDED TUFF. BANDED TUFF.
<20 CM.	<500 CM.

MATRIX.

AS FOR THE LOWER AGGLOMERATE BUT FAR LESS OF IT.

PROBABLY EXTRUSIVE AND INTRUSIVE.

EKIOJANGO BRECCIA.

FRAGMENTS. ANGULAR.

MOSTLY FELSPATHISED AND CARBONATED.

AGGLOMERATE AND TUFF.

CARBONATITE:-

- FROM SMALL CONESHEETS AND DYKES.
- OF THE EKIOJANGO TYPE.
- OF TYPES NOT FOUND IN SITU.

NEW IGNEOUS MATERIAL, UNALTERED AND ALTERED.

UNIDENTIFIED ALTERED FRAGMENTS.

<20 CM.

MATRIX.

HARDLY ANY. THE FRAGMENTS ARE SEPARATED AND CUT BY VEINS OF CARBONATE FELSPAR AND OCCASIONALLY QUARTZ.

INTRUSIVE.

KINYAMUNGU BRECCIA.

FRAGMENTS. ANGULAR.

MOSTLY CARBONATED.

CARBONATITE:-

- OF THE EKIOJANGO TYPE.
- OF THE KINYAMUNGU TYPE.

VERY ALTERED FRAGMENTS POSSIBLY OF NEW IGNEOUS MATERIAL.

<20 CM.

MATRIX.

CARBONATITE OF THE KINYAMUNGU TYPE.

INTRUSIVE.

FIGURE 13. SUMMARY OF THE FRAGMENT TYPES AND MATRICES OF THE LOWER AGGLOMERATE, UPPER AGGLOMERATE, EKIOJANGO BRECCIA AND KINYAMUNGU BRECCIA.

VII

THE PYROCLASTIC ROCKS

The pyroclastics, which cover about 80% of the area of Rangwa, can be split into three groups:-

3. Upper Agglomerate.
2. Tuff Group.
1. Lower Agglomerate.

The rock types and structures of the groups are closely related, since they are the products of a well-defined stage in the evolution of the volcano.

1. DISTRIBUTION.

The rocks have an oval outcrop pattern (Figure 14), which surrounds Rangwa. The oval is 3½ miles from north to south and 3 from east to west, and the width of outcrop varies between half a mile in the north and a mile in the south. The outer limit is the cliffs and break in slope that bound the main part of Rangwa. Even where there are few cliffs, a clear line of exposure is seen, and, except in the west where erosion has been greater, it is a smooth curve (plates 2 - 6). Though it changes altitude markedly, from 4,200 ft. near the lake to over 5,000 ft. in the south, as well as dipping into numerous valleys, the biggest of which is Nyandigida, the curve is not deflected; so the edge of the pyroclastics cannot

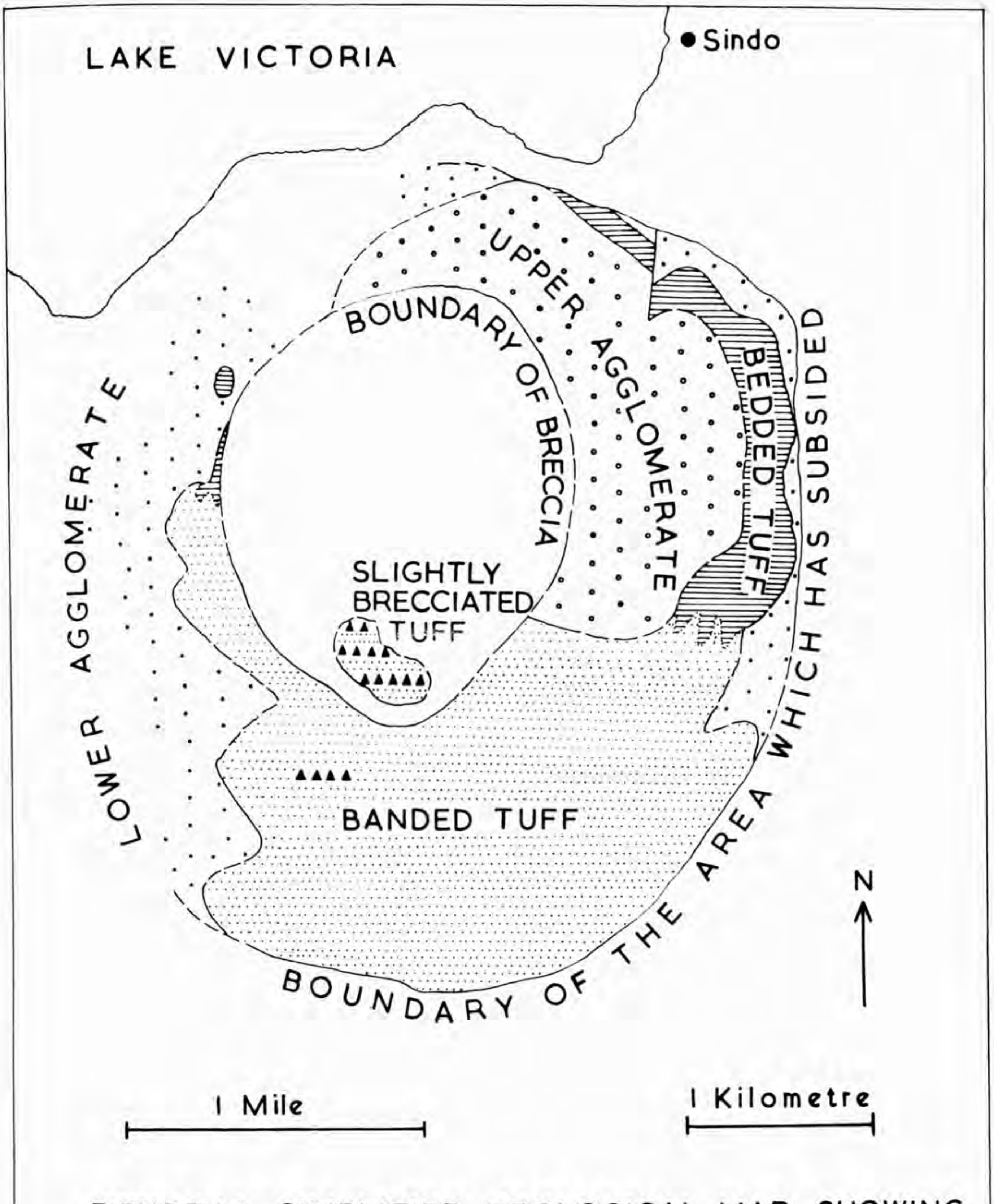


FIGURE 14. SIMPLIFIED GEOLOGICAL MAP SHOWING THE OUTCROP PATTERN OF THE PYROCLASTIC GROUPS ON RANGWA.

be far from the vertical.

For most of the way round, the bases of the cliffs disappear into secondary breccia, talus and alluvium, but, in the south and south west, the biotite uncompahgrite is exposed within ten yards of the pyroclastics, and in the north near the lake there is a weathered outcrop of fenite and carbonatite only 30 yards out from the cliffs of Upper Agglomerate. Also fenite boulders were found at several places in the talus slopes. On these grounds it is assumed that the outer cliffs are normally quite close to the actual boundary between the pyroclastics and the rocks of the plutonic centre described in the chapter VI.

The inner boundary has an oval form too, but it is gradational and is not marked by clearcut features. The increasing influence of the central carbonatites, which were intruded into the pyroclastics, cause a zone of shattering and incipient brecciation up to 100 yards wide. It occurs on the upper slopes round Nyakirangacha, and sometimes takes the form of a series of small inward facing scarps.

A. THE LOWER AGGLOMERATE.

The Lower Agglomerate is exposed round the edges of Rangwa, and forms most of the cliffs mentioned above, which are 400 ft. high to the north east (plate 2). Outcrops occur all the way round Rangwa except in the south and for a short distance in the north. The base is not seen, but the upper boundary with the Tuff Group is found at

4,200 ft. in the north, and 4,600 ft. in the south west and south east, where the agglomerate disappears beneath the tuff. The total width of outcrop is variable, but is seldom more than 400 yards, and the vertical extent exposed is up to 500 ft.

The upper boundary is gradational, as inward dipping bands of tuff become more frequent. Though it is nowhere well exposed, there are indications that it dips inwards. Besides the inward dip of the basal tuffs, the outcrops on Endoverenia and along the sides of Nyandigida show that the tuffs occur at a lower level towards the centre of Rangwa. Nyandigida is the largest of the concentrically arranged valleys, and along it the upper slopes are tuff and the lower ones agglomerate. Tuff occurs 150 ft. lower on the western side, which is the one closer to the centre of the complex.

B. THE TUFF GROUP.

The Tuff Group follows a very roughly concentric pattern, and is found most of the way round the mountain in a band of varying thickness. Apart from a small patch in the north and the whole of the southern margin, where tuff extends to the outer limit of the pyroclastics, the group occurs inside the Lower Agglomerate. The inner boundary is with the Upper Agglomerate in the north, and the brecciation associated with the central carbonatite intrusions in the south.

The tuff attains its greatest width of outcrop in the south, on Erikende, where it is up to a mile across, covering all the high ground between the slopes above Nyakirangacha and the outer limit of Rangwa. Tuff outcrops on the main ridge as far north as the saddle between Kithamweni and Kurugitho, where it is cut out by the Upper Agglomerate. From here to the north the width of outcrop becomes progressively narrower owing to truncation by the Upper Agglomerate, which was emplaced later. North of Kinyathengo the tuff is cut out altogether. West of Nyakirangacha the outcrops are less regular, and there are exposures of tuff on top of Kivuvwu, Kumuthua and Muitherere, as well as a small patch on Mbuwi.

C. THE UPPER AGGLOMERATE.

Because of bad exposure, the Upper Agglomerate is the least well defined of the pyroclastic groups; it occupies most of the high ground at the north of Rangwa, and the shape of outcrop is a rough semi-circle, including large parts of Ikiwathi, Kinyathengo, Kunthewe and Kurugitho. The outer boundary is with the tuff for most of the way round. However, in the north, the tuff is cut out, and the boundary is with the Lower Agglomerate, and for 200 yards the outer cliffs are composed of unweathered Upper Agglomerate. The only good continuous exposure of this rock occurs here. The north of Rangwa, close to the lake, shows the field relations between the three types of pyroclastic well (plate 2). Topographically, the outer limit of the Upper Agglomerate is normally marked by a slight steepening of the slope.

As with the other pyroclastic rocks, the inner boundary is reached when the rock becomes brecciated on the upper slopes to the east of Nyakirangacha.

2. DESCRIPTION OF THE ROCK TYPES.

The rocks that comprise both the fragments and the matrix in all the pyroclastic groups have many points of similarity.

A. LOWER AGGLOMERATE.

The Lower Agglomerate is massive, and there is little field evidence for bedding. Planes with inward dips of $25^\circ - 45^\circ$ are found, but it is uncertain how many of these are bedding or banding planes. In many cases, flow banding is parallel to these planes, but it is not always possible to prove this, as flow banding is seldom visible except on polished surfaces and thin sections. Some of them are followed by small carbonatite conesheets, and a few, especially the ones with steeper dips, may have been formed by the stress system caused by the carbonatite intrusion. At the top of the agglomerate succession, lenses of distinctly bedded rock occur among the lower tuffs.

The rock is dark grey and brown when it occurs comparatively unweathered on the cliffs. In this state, the matrix is often harder than the fragments, giving the rock a pockmarked appearance. More commonly, the majority of the fragments and the matrix have the same hardness, so that in the field the surface of the rock is smooth (plates 69 and 70), and when this is polished by baboons it is hard to recognize that it is an agglomerate. Away from the cliffs, the rock is more weathered, and becomes crumbly and red. The fragments are rounded-subrounded, and up to 10 cm across. They are unevenly distributed through the rock, and the percentage of matrix varies widely, but is usually more than 75%. There is a great variety of fragment types, but on the grounds of origin, mode of occurrence and amount and type of alteration they can be split into groups:-

1. Basement and plutonic fragments.
2. Volcanic fragments.

As will be evident from the descriptions, the matrix is formed from the same material as most of the volcanic fragments. For this reason the volcanics and the matrix are described together.

(1) BANDING IN THE LOWER AGGLOMERATE.

The presence of banding is by no means universal, and the form it takes depends on the proportion of volcanics and matrix in the rock. It is most pronounced where there are no basement or plutonic fragments, and where the volcanics and matrix are intimately mixed, or there is little distinction between the two. The contorted and irregular outlines of some of the volcanic fragments shows that they were often liquid or plastic when the rock was emplaced, and it is

Plate 69. Block of Lower Agglomerate. Most of the fragments are of altered lava.

Plate 70. Lower Agglomerate. Some fragments have been weathered out. One fragment is rimmed by a zone of alteration.

Plate 71. Banding of altered lava in the Lower Agglomerate. The elongated globules are thought to indicate the direction of flow. (RF34). True to scale.

Plate 72. Banded fine-grained material between angular fragments in the Lower Agglomerate. (RF70). x½

Plate 73. Banding displayed by small elongated fragments in the Lower Agglomerate. (RF71) x½.

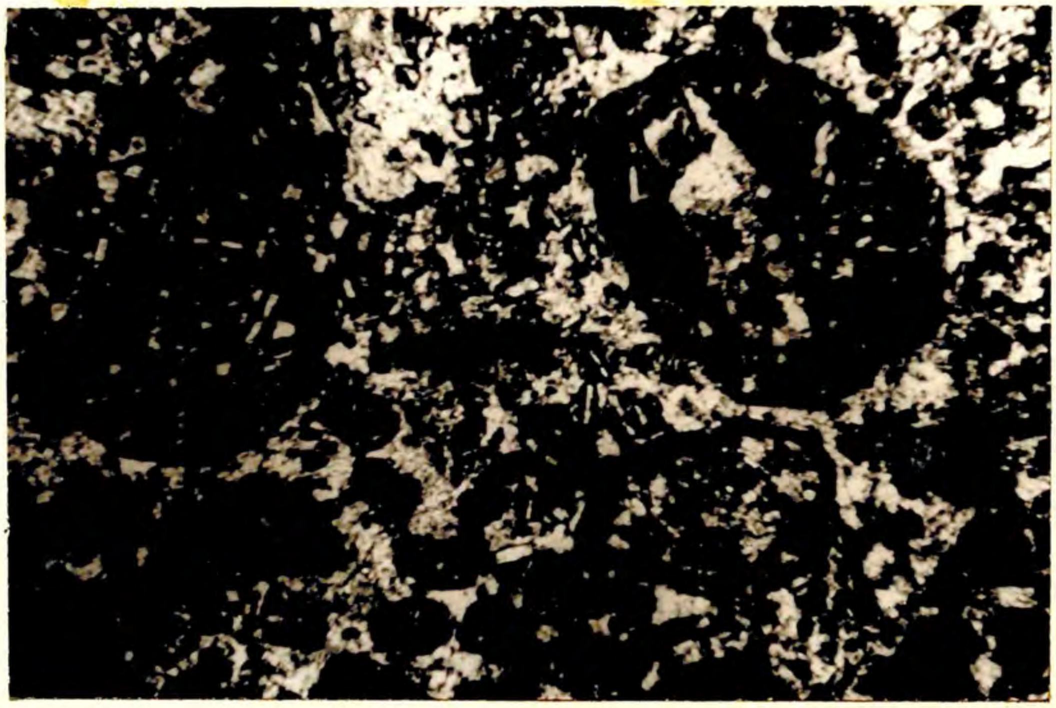


Plate 74. Typical texture of the Lower Agglomerate. The blobs contain pseudomorphs in carbonate. The pale interstitial material is fine-grained felspar and carbonate. (RF14). x25.

natural that an agglomerate of this sort should show the greatest amount of banding.

The banding takes several forms. In RF 34 (plate 71), it is very pronounced, and appears as strips of pale and dark material; instead of proper fragments, there are wispy patches of volcanic material with irregular edges. The patches are generally globular or bubble-shaped at one end, and have swirling flow lines concentric with them. RF 70 (plate 72) has well-formed and distinct fragments, which are unorientated, and the banding appears in the matrix only; several fine-grained pale bands run right across the rock, unaffected by the fragments. The commonest manifestation of banding (as in RF 71, plate 73) consists of an orientation of small elongated fragments, often with their edges flattened against each other.

Banding is seldom pronounced enough to be noticed on an uncut surface, but where it was found in the field its dip is parallel to the inward-dipping planes in the agglomerate.

(2) THE MATRIX AND VOLCANIC FRAGMENTS.

The distinction between the matrix and the volcanic fragments appears to be obvious in hand specimen, because of slight differences in colour and resistance to weathering, but in thin section it often ceases to exist. The reason is that so many features in each are similar.

The matrix consists of oval blobs between .1 and 2 mm across.

They have a skin of fine-grained material, enclosing either single crystals, crystal pseudomorphs or fine-grained altered lava. The volcanic fragments are altered lava, finer grained tuff or agglomerate and groups of blobs similar to the matrix. The fragments are surrounded by a skin, too. Both matrix and volcanics are equally felspathised and carbonated.

The fine-grained skin is a universal feature, and also surrounds the basement and plutonic fragments. It always has the same texture, but its thickness varies between .02 and .5 mm, depending on the size of the fragment it encloses. Normally there is a single continuous layer, which tends to round off the corners in the fragment or crystal underneath (as in RF 14, plate 74). It is composed of fine-grained dirty calcite and specks of dark noncrystalline material, and it is without obvious orientation or pseudomorphs. Since the skins occur round nonvolcanic as well as volcanic fragments, are of uneven thickness and do not have the texture of the lavas, they are not chilled edges, and the distinction can be seen well in lava fragments which have chilled edges surrounded by skins. Their lack of internal structure suggests that they are formed from material picked up after attrition between fragments.

The skins modify the shape of the components in the matrix to form oval blobs. The blobs seldom have any orientation, except in a distinctly banded rock (as in RF 71, plate 73), when they become distorted and stretched. Occasionally, the amount of skin is very much magnified as in RF 35 (plate 76), where one of the blobs is a perfect sphere, with a diameter of 2 mm and a double skin; the particle in the middle, an altered lava, only has a diameter of .5 mm.

Unaltered crystals of minerals within the blobs are apatite, biotite, felspar, magnetite and melanite. Apatite is the most frequent, and occurs as clear subhedral prisms up to .5 mm long; as the presence of apatite is widespread in both the plutonics and volcanics on and around Rangwa, these crystals could have originated from either, or be a product of the magma associated with the agglomerate. Biotite (sometimes ringed with melanite), felspar, magnetite and melanite all occur occasionally, and are probably of plutonic origin. All the minerals are seen in RF 35.

The identification of the pseudomorphs, which are far more common than original minerals, is speculative. Their outlines and cleavage patterns, as well as a knowledge of the minerals that occur unaltered in the plutonics and lavas, make it possible to suggest the original minerals from which some of them were formed:- nepheline, pyroxene, melilite, perovskite and melanite. Nepheline is represented by square patches of very fine-grained felspar up to .5 mm across (RF 63, plate 77). Pyroxene is pseudomorphed by a mosaic of small brown-stained calcite crystals, and retains the form and remnant cleavage of either length or cross sections

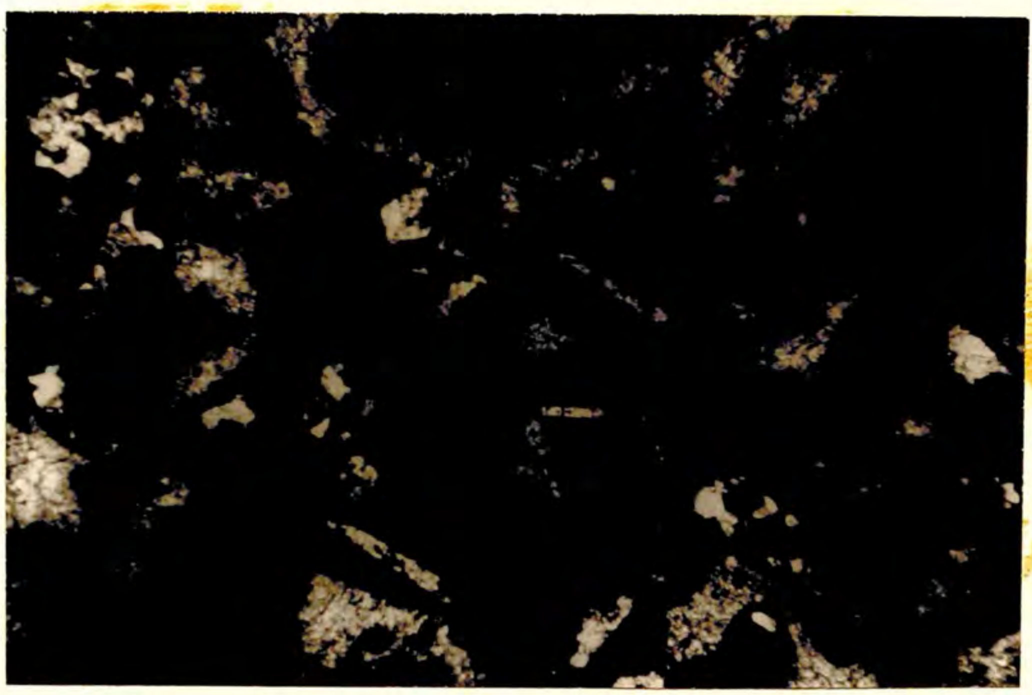


Plate 75. Blobs in the Lower Agglomerate. The centres of some of the blobs are pseudomorphs in fine-grained carbonate. The interstitial material is carbonate and felspar. (RF35). x25.

Plate 76. A big blob in the Lower Agglomerate. (RF35). x25.

(RF 15, plate 78). Tabular melilite changes to fine-grained clear calcite; in RF 35 (plate 79), a melilite pseudomorph 1 mm long has a median crack, a characteristic of the melilite in the lava. Perovskite always retains its crystal form, but is either replaced along its twin planes by ilmenite (plate 80) as in RF 2, or changed entirely to leucoxene. Melanite is still recognizably six-sided, though broken up and veined by calcite and felspar; it is opaque and unzoned, and irregular patches have been altered to ore minerals.

It appears that most of the minerals that survive in their original form, except possibly apatite, come from the basement or plutonics, but the ones that are pseudomorphed are lava minerals. The changes which occur follow a definite pattern. Nepheline is normally replaced by a felspar, whose occurrence is widespread in most of the rocks on Rangwa; the felspar forms tiny crystals with shadowy, shifting extinction (plate 77). The X-ray diffraction pattern shows orthoclase, and material in which it predominates contains 8% of potash. It has a slightly higher refractive index than orthoclase from the basement, and is presumed to be soda-rich orthoclase. Most other silicates are altered to calcite, and titanium-bearing minerals go to ilmenite or leucoxene.

Lava blobs and fragments are both composed of much the same material, but there is a difference in size and form. The blobs are never larger than 2 mm, and are generally less than .5 mm, whereas the lava fragments are nearly always larger than 5 mm, and have less

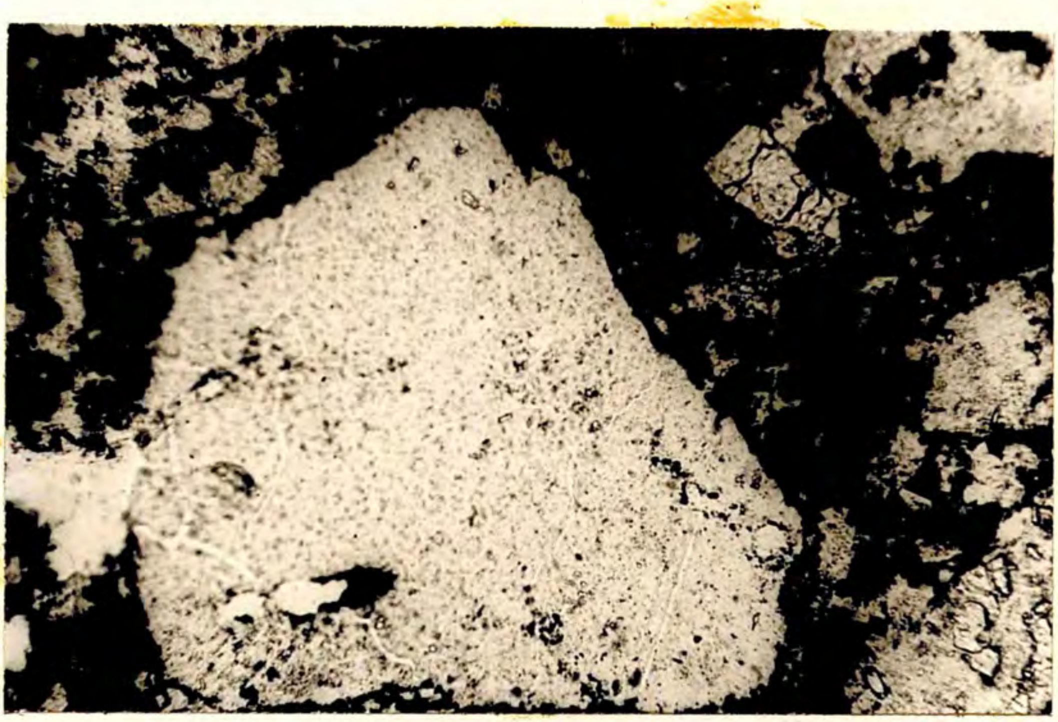


Plate 77. A possible pseudomorph after nepheline in fine-grained felspar in the Lower Agglomerate. (RF63). x155.

Plate 78. Possible pseudomorph after pyroxene in fine-grained carbonate in the Lower Agglomerate. The darkening towards the edges may correspond to the original zoning. (RF15). x80.

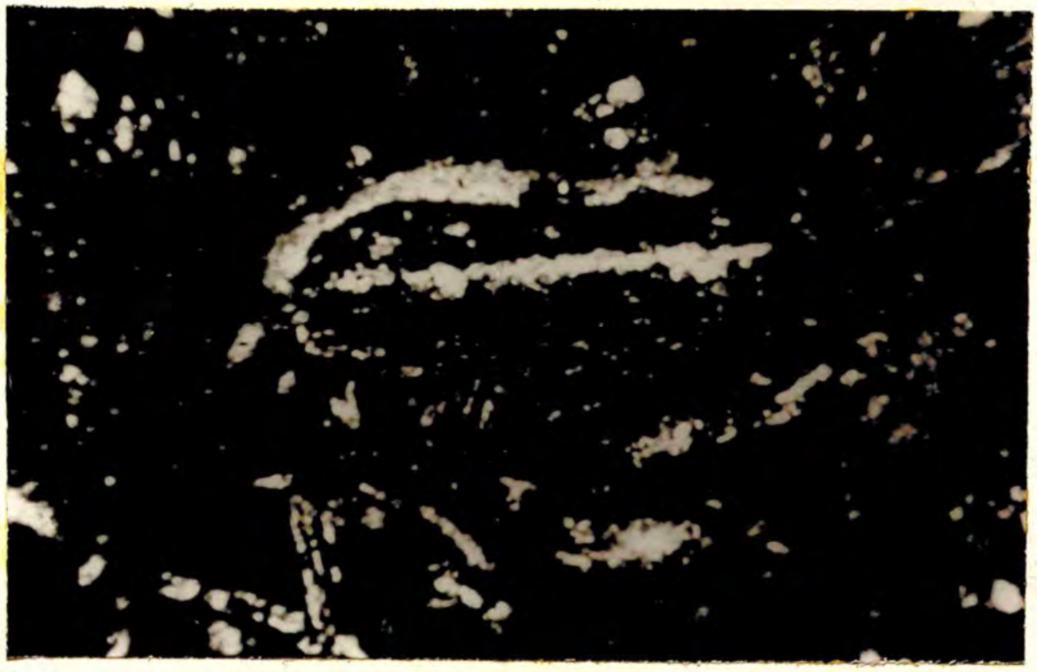


Plate 79. Possible pseudomorph after melilite in fine-grained carbonate in the Lower Agglomerate. (RF35). x55.

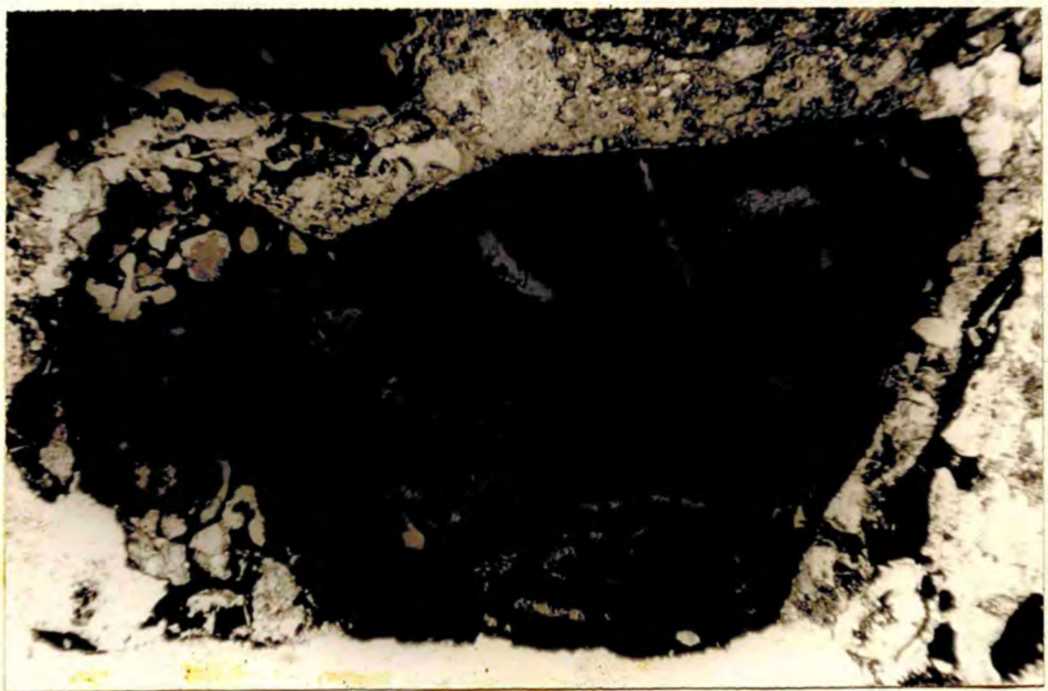


Plate 80. Possible pseudomorph after perovskite in ilmenite and carbonate. (RF2). x80.

Plate 81. Altered lava in the Lower Agglomerate. All the elongated crystals are pseudomorphed by cloudy carbonate (RF38). x55.

Plate 82. Small pseudomorphs at the margin of an altered lava fragment in the Lower Agglomerate. (RF17). x25.

regular outlines. Their texture is that of a porphyritic lava (especially in RF 35, RF 38, RF 50, RF 14 and RF 17 - plate 81). Often both the fragments and the blobs have chilled edges, which are evident from a finer grain size and the orientation of pseudomorphs parallel to the edge (RF 17, plate 82). But sometimes bits of lava had obviously cooled previously, and have sharp unchilled edges (RF 38).

Pseudomorphs in lava fragments show the same pattern of alteration as the pseudomorphs of single crystals. Apatite and ore minerals survive, nepheline goes to felspar and most other minerals to calcite. Typically, as in RF 17 and RF 38, the lava has a few large pseudomorphs up to 1 mm long in a groundmass of unorientated tiny needles and patches of ore. This texture is similar to that of the nephelinite and melanephelinite lavas of Kisingiri, in which the large crystals are pyroxene and nepheline, and the needles are pyroxene and sometimes melilite. In the altered lavas, there are few possible nepheline pseudomorphs, but frequent pyroxenes, which retain the crystal form of the unaltered ones. RF 36 has a pseudomorph in brown-stained calcite of a subhedral zoned pyroxene crystal, 2 mm long, in which the staining becomes more pronounced towards the edge. In RF 17 and RF 38, pseudomorphs show the remnant cleavages of both the prismatic and cross sections of pyroxene. The matrix of the volcanic fragments has small needles of calcite crystals after pyroxene and melilite, and small well-formed magnetite cubes and octahedra.

Besides the lava, the other types of volcanic fragment are bedded tuff, lapilli tuff, agglomerate and matrix material. Only one fragment each was found of either bedded or lapilli tuff. RF 134 contains a fragment of bedded tuff similar to that in the Tuff group, with evenly spaced beds 5 mm apart. In RF 100, a small fragment of red tuff has several orientated accretionary lapilli, with major axes of up to 3 mm.

Far more frequent are the fragments of every size, from 30 cm down to microscopic proportions, of agglomerate containing pieces of other finer pyroclastics. Sometimes, there may be as many as four generations of fragments within one fragment of agglomerate, as in RF 147 (plate 83).

In thin section, small fragments are often seen to be collections of blobs identical to those in the matrix. They have either consolidated prior to the formation of the agglomerate, in which case many of the blobs in the fragments are broken at the edges (RF 34, plate 84), or they solidified at the same time as the matrix, and the fragments have very contorted edges; when this happens, the blobs are never broken, but sometimes the ones inside the fragment are flattened against those outside it (RF 35, plate 85). The ultimate stage in mixing between fragments and matrix, which was referred to in the section on banding, is found in RF 38 (plate 86). Two types of matrix, alike except that one is darker than the other,

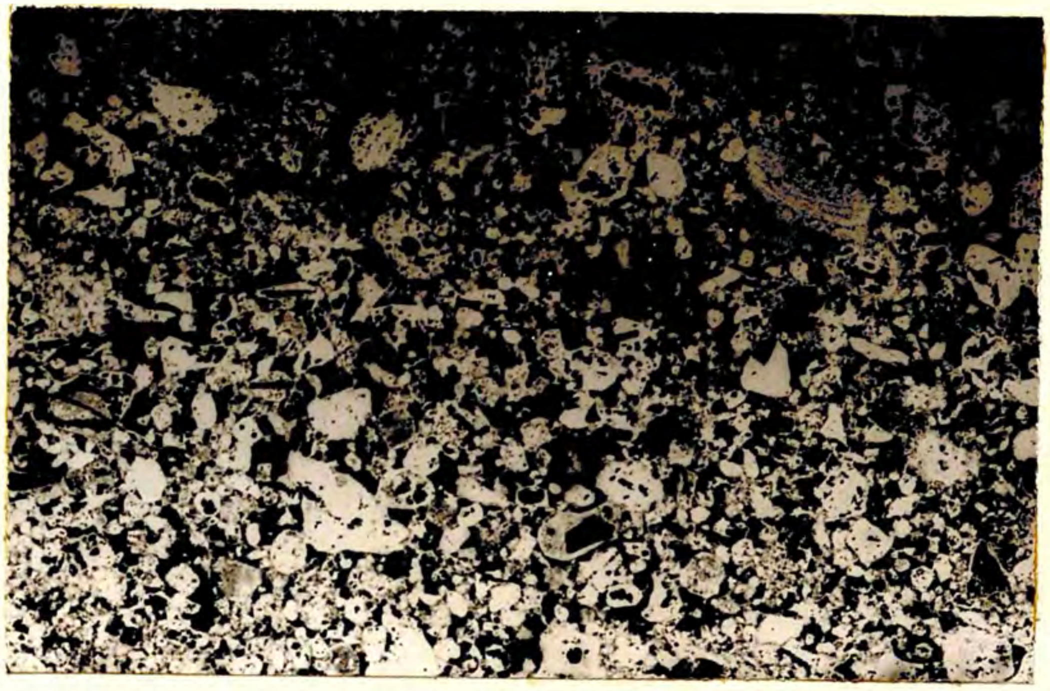


Plate 83. Typical texture of the Lower Agglomerate. Many of the fragments are themselves fragmental (negative). (RF147). x5.

Plate 84. A broken blob at the edge of a fragment in the Lower Agglomerate. The pale interstitial material is fine-grained carbonate. (RF34). x55.

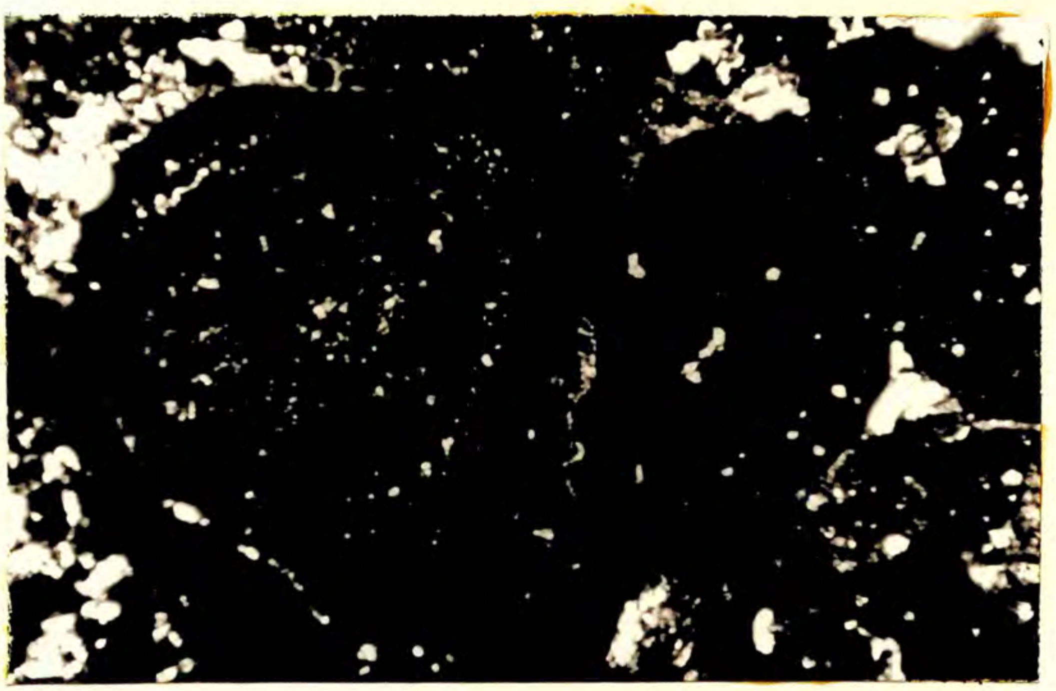


Plate 85. A blob in a fragment flattened against one outside it in the Lower Agglomerate. (RF35). x55.

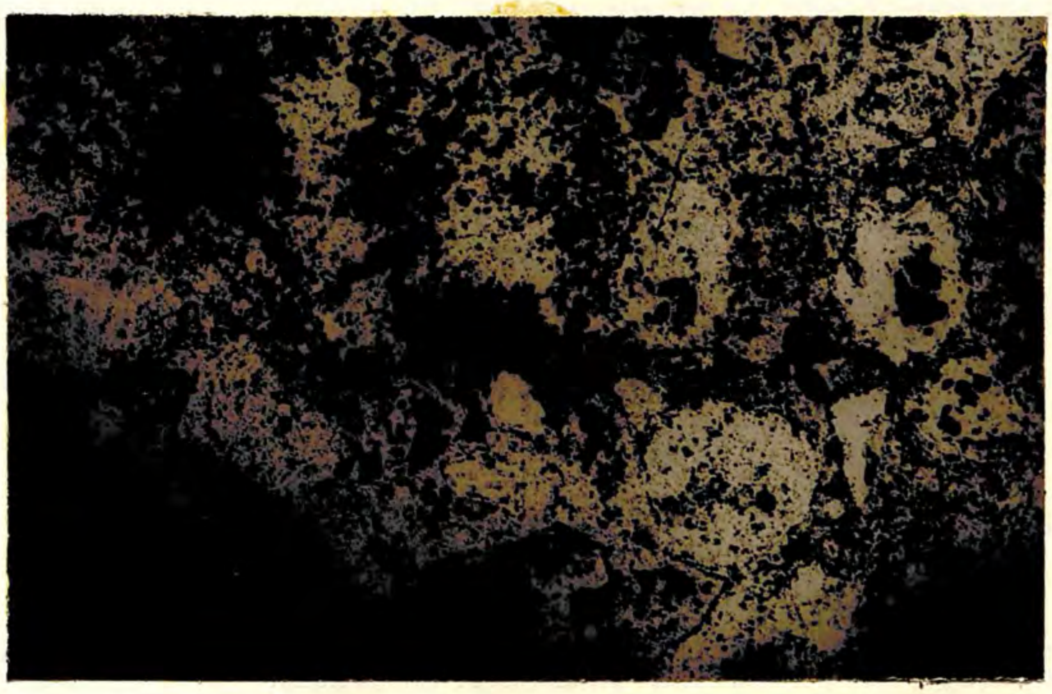


Plate 86. Mixing of two matrix types, one darker than the other, in the Lower Agglomerate. (negative). (RF38). x5.

occur in a rock in which no clearly defined fragments occur. The darker type protrudes into the paler type in tongues, and engulfs bits of it. A variation on this pattern is seen in RF 99 (plate 87), in which a tongue of agglomerate with fragments of up to 1 cm across penetrates a far finer-grained agglomerate.

Between the fragments and blobs, there is an interstitial packing, largely opaque, but with some carbonates and felspar. It never accounts for more than 10% of the rock.

(3) BASEMENT AND PLUTONIC FRAGMENTS.

The basement and plutonic fragments comprise only a small proportion of the Lower Agglomerate that is exposed (less than 5%). But they are important as they show that not all the material that occupied the position of Rangwa prior to the formation of the agglomerate has been removed from the vent. A study of the range of types of fragments tends to confirm the structure deduced for the alkaline plutonic rocks, and gives useful evidence for correlation with some of the extrusive fragmental rocks on Rusinga and Mfwangano.

Types represented in the fragments are granite, fenite (several grades), ijolite, biotite uncompahgrite, biotite pyroxenite, carbonatite and nephelinite (probable dyke rock). All these rocks, including the biotite pyroxenite, the only one which is never found in situ, are described elsewhere (chapter VI). So in this section, it is not necessary to cover more than how they occur and how they have been altered.

The fragments have features which mark them off sharply from the volcanic component of the rock. Being more resistant, they protrude on weathered surfaces, and it is easy to see them wherever they occur in the field. Though occurrences are widely scattered, there is a discontinuous zone of higher frequency along the base of the cliffs to the north and north east. Except for the fact that fenite fragments are found most often, the proportions of different types are random, and bear no relation to the nearest in situ exposures of plutonics.

The fragments, which are up to 20 cm across, normally occur in groups of one type, and it is evident that the groups are the shattered residue of larger fragments (plate 88). Whether fragments are angular or rounded depends on the amount of attrition after breakup. In some specimens, most of them are angular, and there is only a small quantity of matrix between them (RF 61 and RF 102 - plate 89), but they are often rounded in the same way as the volcanic ones, and the amount of chemical alteration at the edges of fragments is related to the degree of rounding (plate 90). The main rock type in RF 61 and RF 102 is low grade fenite, consisting of 80% cloudy orthoclase, with clear quartz and microcline, and there is only minor recrystallization to finer grained felspars at the edges. However, in the rounded fragments,

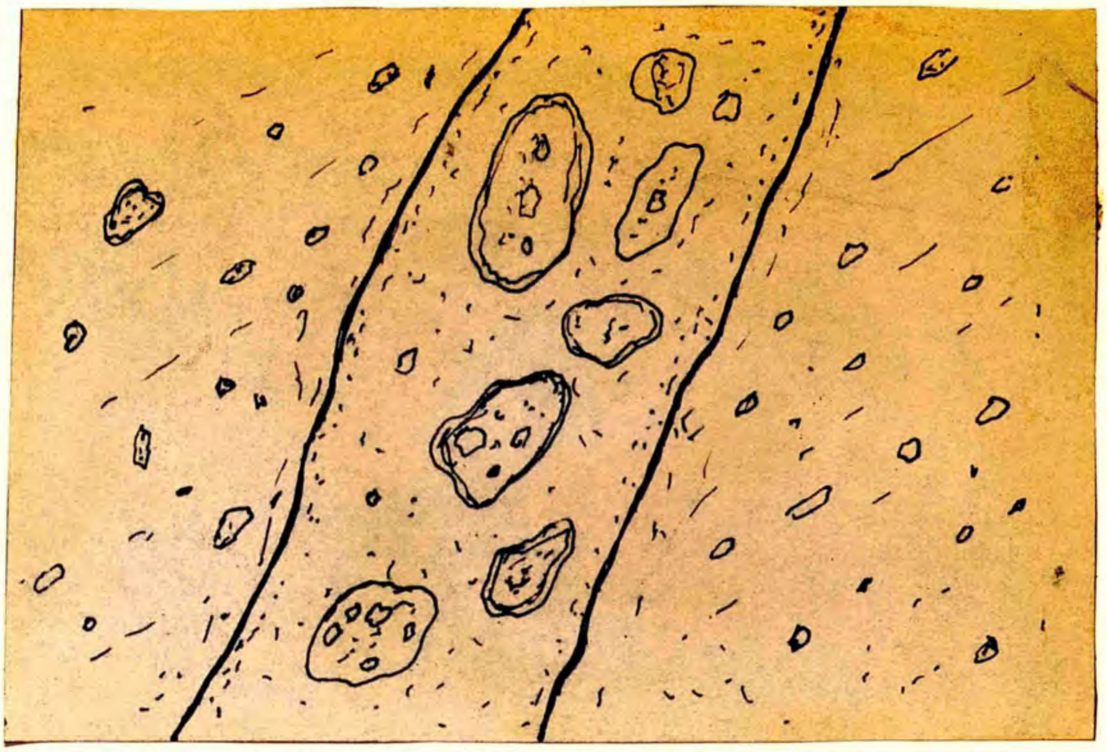


Plate 87. Part of a tongue of agglomerate which cuts more fine-grained, banded agglomerate in the Lower Agglomerate. (RF99). x2. Drawing of hand specimen.

Plate 88. Exposure showing angular fragments of fenite in the Lower Agglomerate. They are parts of a shattered rounded fragment.

Plate 89. Chips of felspathised granite in the Lower Agglomerate. (RF61). x½.

Plate 90. Rounded ijolite fragment in the Lower Agglomerate on Manganga. The reaction rims round it have been weathered out.

alteration is more extensive. RF 54 (plate 91) is a specimen of uncompahgrite, ringed by a series of zones 5 - 10 mm thick. Inside the fine-grained skin several layers of clear calcite are succeeded by a layer of dark brown noncrystalline material. Inside this, all the constituents of the rock are highly calcified. Sometimes, the rounded fenite and ijolite fragments are coated by recent deposits of potassium chloride (plate 90).

Most of the minerals in these fragments can survive in an unaltered state. Orthoclase in the fenite is always very cloudy, in contrast to the clearer orthoclase in the in situ fenite (RF 85). All the minerals found in ijolite are preserved intact (as in RF 45). In biotite uncompahgrite, the perovskite, magnetite and biotite are normally unchanged, whereas the melilite is altered along its cleavage planes to a pale noncrystalline material (RF 51, plate 92), or cut by bands of calcite (RF51, plate 93). The biotite pyroxenite (RF 22, described in the chapter VI) is unaltered but for a slight cloudiness in the pyroxene. Carbonatite is hard to recognize in a rock which contains so much carbonate anyway; but in RF 46 and RFP 187 there are fragments consisting of clear calcite and magnetite crystals. It is thought that these are recrystallized carbonatite.

Some partly altered coarse nephelinite is associated with fenite in two specimens (RF 61 and RF 102 - plate 94). It survives as a rock with diopside phenocrysts up to 6 mm long in a groundmass

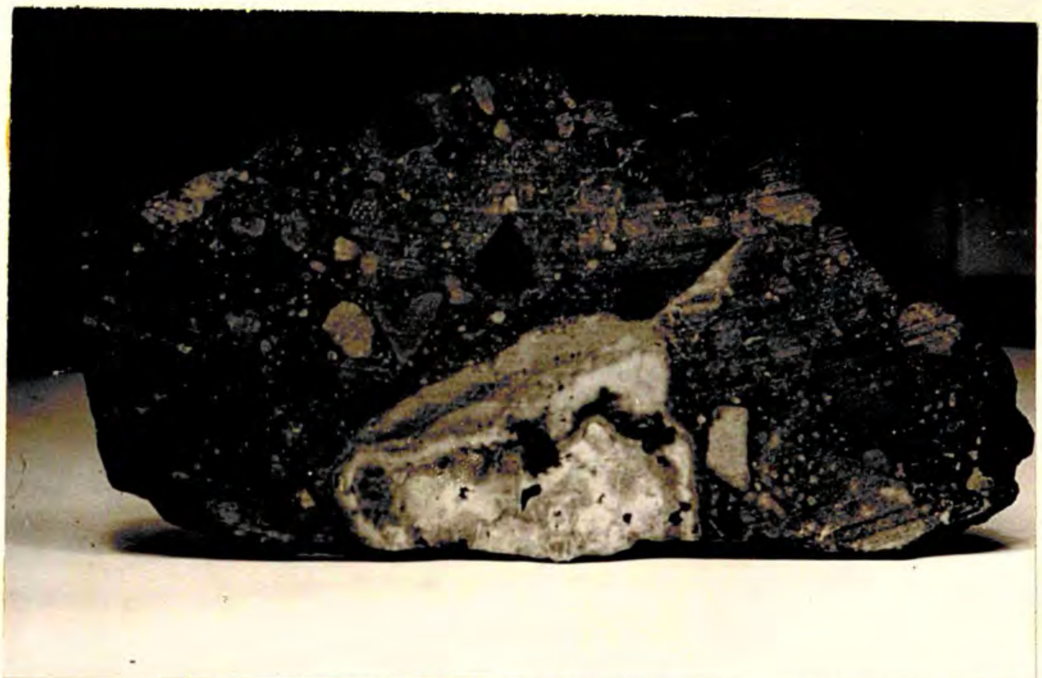


Plate 91. Reaction rims, composed of carbonate and ore round a biotite uncompahgrite fragment in the Lower Agglomerate. (RF54). x$\frac{3}{4}$.

Plate 92. Melilite altered to carbonate along its cleavage planes and in small veins in a fragment of biotite uncompahgrite in the Lower Agglomerate. (RF51). x80.

Plate 93. Slight alteration of melilite along its cleavage planes in a fragment of biotite uncompahgrite in the Lower Agglomerate (under crossed polarisers). (RF51). x55.

Plate 94. Comparatively unaltered nepheline fragments associated with chips of felspathised granite in the Lower Agglomerate. (RF61). x$\frac{1}{2}$.

of carbonate, felspar and magnetite. In both cases it is intimately connected with the fenite, and is only separated from it by a band of very fine felspar. Since the nephelinite is less altered than what is found in the volcanic component of the agglomerate, and its texture is different, it probably represents earlier dykes in the granite, which had solidified prior to the formation of the agglomerate.

(4) CARBONATION AND FELSPATHISATION.

The alteration of much of the Lower Agglomerate to carbonates and zeolites is due to a process of autometasomatism and not to the introduction of carbonate when the later carbonatites were emplaced. This is clear from several features seen in the pattern of alteration, and is confirmed by chemical work.

In the volcanic component, nepheline normally changes to felspar (the X-ray diffraction pattern of the felspar shows that it is generally orthoclase, except close to the basement fragments where some microcline survives) and most other silicates to carbonates. This happens in the middle just as much as at the edges of fragments. Apart from felspathisation of some of the interstitial material, only actual crystals are altered, and the boundaries of both pseudomorphs and fragments are still firm, with very little growth of secondary material across them. This process is universal, but the indiscriminate development of large calcite and felspar crystals, which tends to destroy the texture of the rock, only occurs near carbonatite intrusions; it will be described in the following chapter.

The basement and plutonic fragments, though they contain many of the same minerals that are altered in the volcanic fragments, notably nepheline, pyroxene and melilite, are largely unchanged, except for the reaction rims round the edges. The rims often contain layers of pure calcite, and are formed by the inward migration of carbonate. So clearly the carbonate originated from the volcanic part of the rock rather than from external sources.

A selection of specimens in which there are negligible amounts of basement and plutonic fragments was tested for the percentage by weight of CO_2; the weight percentage of $CaCO_3$ was calculated, since the X-ray diffraction pattern of a representative sample of specimens of the pyroclastics shows calcite to be the predominant carbonate, although there are occasionally small amounts of dolomite and ankerite, and the following results were obtained:-

RF 37	24.64%
RF 143	29.27%
RF 142	29.98%
RF 39	30.33%
RF 38	33.10%
RF 49	35.21%
RF 2	35.46%

RF 23	36.23%
RF 72	37.24%
RF 35	40.95%

The results show that, despite the large quantities of carbonate, the spread of values is not great. The Lower Agglomerate is never found in contact with the central carbonatites, but the effect of proximity can be seen in the carbonate values of the Tuff Group (see below), which are raised to over twice the normal under the influence of the Mwisasu Carbonatite. So if the widespread carbonation was caused by underlying carbonatite or by the small scale carbonatite dykes and conesheets, the values would be far higher and more erratic.

The possibility that the carbonation and felspathisation were caused by the late action of groundwater is unlikely, as the alteration is far greater than and very different from what occurs in most of the nephelinite agglomerates of the Kisingiri Volcano, although both must have been subjected to similar groundwater conditions.

The water and other volatiles responsible for the carbonation and felspathisation are regarded as having been integral constituents of the agglomerate at the time of its emplacement. The process may be analogous to the alteration of some of the felspars and the groundmass of teschenite to analcite and zeolites, as in the Lugar Sill (Tyrrell 1917), or the late stage alteration of nepheline to cancrinite and pectolite in the ijolites at Napak (King 1949).

B. TUFF GROUP.

The tuff, although continuity of outcrop pattern and structure shows that it forms one unit, can be split into two facies:-

1. Bedded Tuff.
2. Banded Tuff.

The Bedded Tuff occurs predominantly in the north, and the Banded Lapilli Tuff in the south. The boundary between the two lithologies runs west from the lower part of Nyandigida, and must be somewhere between the tuff outcrops on Mbuwi and Muitherere. Because of poor exposure, the boundary on the map is tentative, and the positions from which the specimens were collected show that there must be interfingering.

(1) BEDDED TUFF.

The Bedded Tuff consists of a series of evenly spaced layers that appear prominent in the field, because of differential weathering (plate 95). They have an average inward dip of 14°; in the north east, they are often level, and elsewhere they may dip as much as 25°. The greatest exposed thickness of the Bedded Tuff is about 750 ft. north west of Nyandigida, but it is not known how thick the succession was originally.

The sequence shows little variation, except that the lower part includes bands of agglomerate. Beds are between 2 mm and 3 cm thick, and the same ones are continuous over long distances, but the thickness of each bed is never constant (plates 96 and 97). Most exposures show small disconformities in the bedding (plates 96, 97 and 98 and figure 18). These are not the result of straightforward crossbedding, but of a succession of minor erosion surfaces, which sometimes occur every few centimetres. So the direction of overlap is random. The configuration of the surfaces is a series of gentle troughs and humps, and the beds above them are continuous, though they thicken in the troughs and thin out over the humps.

Slump structures are an occasional feature (plate 99). The bedding is disturbed, but unbroken, for several feet, after which the normal bedding is resumed.

A number of sedimentary features can be seen within each bed. There is rough grading (RF 10 and RF 11, plate 100), although sorting is never efficient. Coarser fragments sometimes sink into the top of the bed below (RF 10, plate 101). The surface between beds may be wavy (RF 11, plate 102); the normal length of the waves is 10.5 mm and the amplitude is 1.5 mm; however they are far less regular than conventional ripple marks. A revealing situation exists when the lower parts of beds include bits from the beds below. In RF 129, several very fine beds, each about 1 mm thick, are succeeded by a coarser one, which breaks into the beds

Plate 95. Bedded Tuff with minor erosion surfaces, succeeded by a coarser bed, from a loose block from the north-east of Rangwa.

Plate 96. Minor erosion surfaces and thickening and thinning of beds in the Bedded Tuff, from an overturned block.

Plate 97. Bedded Tuff with fine beds and few erosion surfaces.

Plate 98. An erosion surface in the Bedded Tuff.

Plate 99. Slumping in the Bedded Tuff.

Plate 100. The top of a graded bed in the Bedded Tuff. The pale fragments are of carbonate. (RF11). x25.

Plate 101. A fragment in the Bedded Tuff which has sunk into the top of the bed below. Most of the pale material is carbonate. (RF10). x80.

Plate 102. Ripple-like features between beds in the Bedded Tuff. (RF11). x25.

below, and contains slivers from them (plate 103). In RF 11, the surface between beds has the waves mentioned above, but they are always assymetrical in the same direction, and irregular patches of loose material are broken off from the lower bed and included in the upper one.

The tuff, which is dark grey or brown in hand specimen, is hard and well-consolidated, but highly altered. It is composed almost entirely of fragmental material, which is normally subangular, and whose grain size varies between .002 mm and 4 mm; hence there is no distinction of matrix from fragments. Data from petrological work is disappointing, and many specimens examined in thin section are an amorphous mass of brown and red material. Fragments consist largely of intergrowths of calcite and felspar. Apart from the occasional piece of altered lava, it is impossible to spot any pseudomorphs. For this reason, it is thought that many of them represent partly crystallized, carbonate-rich volcanic glass. Usually the calcite and felspar are cloudy, and the fragments are enclosed in dark rims (RF 10, plate 104). The gaps between fragments may be occupied by elongated patches of clear calcite.

Few unaltered mineral fragments are found. Most specimens have some fragmental apatite, and occasionally perovskite.

RF 47, while retaining most of the other features of the Bedded Tuff, has numerous broken accretionary lapilli. They will be discussed in a later section.

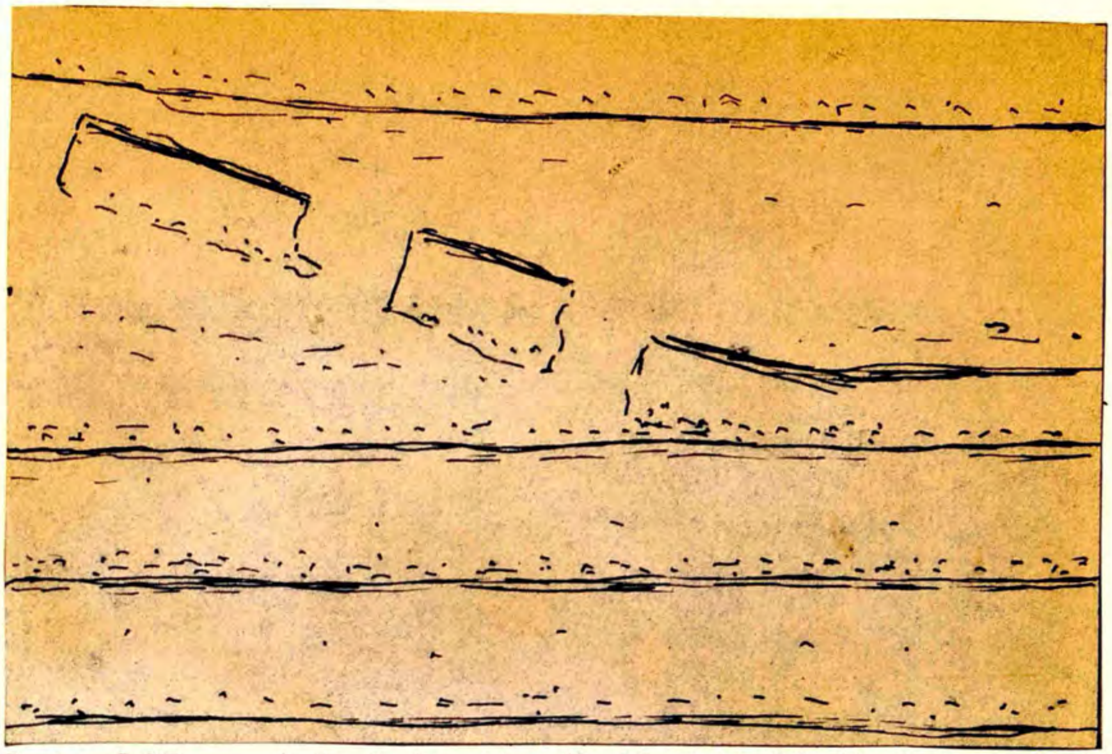


Plate 103. A bed in the Bedded Tuff that has been broken up by and included in the bed above. (RF129). x3. Drawing of hand specimen.

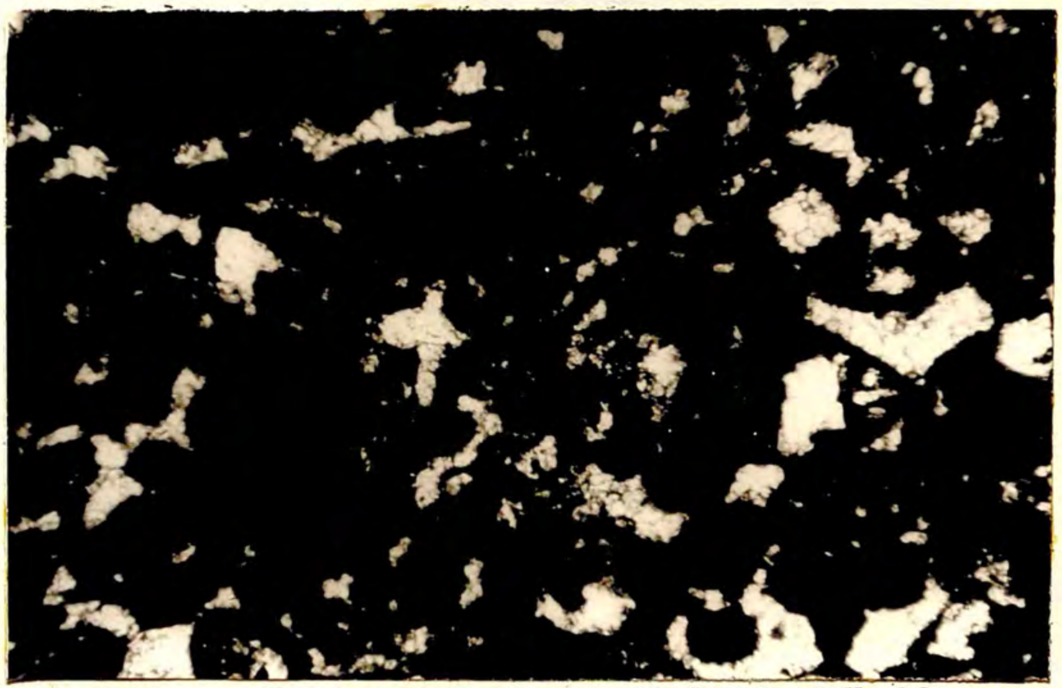


Plate 104. Typical texture of Bedded Tuff. Fine-grained carbonate and felspar occur between mainly non-crystalline fragments. (RF10). x80.

(2) BANDED TUFF.

The Banded Lapilli Tuff is a hard well-consolidated rock, whose colour varies from light to dark grey. Although the rock generally contains accretionary lapilli, the texture and appearance are not constant, because of changes in the composition and proportion of the other components. The tuff is stratified, and has poorly defined bands (plate 105) along which the oval lapilli are aligned; the banding is partly due to variations in the proportion of fragments to matrix. However, grading of the fragments is infrequent, and, unlike the beds in the Bedded Tuff, the bands are not clearly seen in the field, and sedimentary structures are never found. The average dip of the bands towards the centre of Rangwa is 28°, and it varies between 20° and 50°.

The matrix, which is always a large part of the rock and sometimes the whole of it, is generally grey, but occasionally white (RF 162, plate 106), or red (RF 20). The smaller the number of fragments, the darker coloured and finer grained the matrix becomes. It consists of minute specks of opaque noncrystalline material in a background of shadowy calcite crystals. It is clearly fragmental, but the edges of the fragments are blurred and indeterminate (RF162, plate 107). When the matrix is white, it is formed from unclouded calcite in crystals up to 5 mm across. In RF 20 there is a far larger amount of felspar than carbonate; otherwise felspar seldom found.

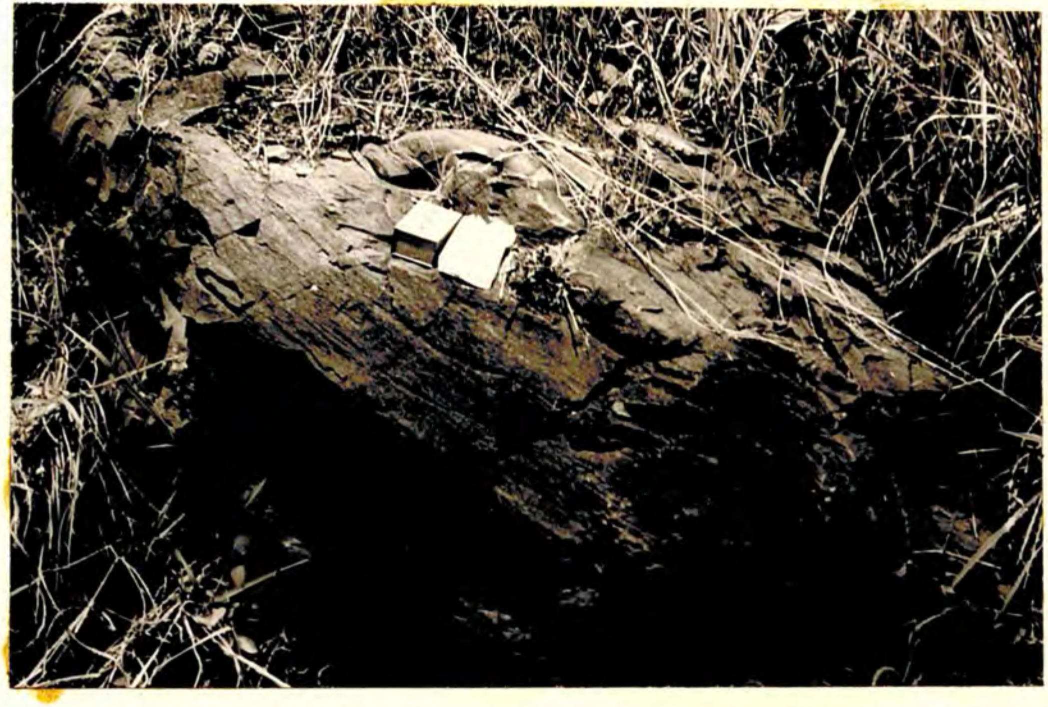


Plate 105. Exposure of Banded Tuff on Endoverenia.

Plate 106. Banded Tuff with a matrix of crystalline, white carbonate. (RF162). x½.

The matrix always includes a few crystals and pseudomorphs of other minerals, and these have been identified:- apatite, pyroxene, biotite, nepheline, melilite, melanite and magnetite. As in the other pyroclastics, apatite is present universally as small, subhedral crystals. Pyroxene is normally unaltered, but sometimes partly calcified. The common type is diopside with several rims of aegirine-augite, and is similar to the pyroxene found in the nephelinite lavas (RF162, plate 108); sometimes the pyroxenes consist of irregular patches with slightly different extinction angles. Biotite occurs in most specimens, and is either unaltered or partly carbonated. The carbonation affects the pyroxene and biotite more in the middle of the crystals than at the edges, and an extreme case is found in RF 58 , which includes a group of calcite crystals enclosed in a rim of biotite. Nepheline is present unaltered in a few specimens (RF 92), and there are zeolitised pseudomorphs in many more (RF 139). Melilite is never found unaltered, but cloudy calcite crystals occur in small needles, some of which have a median crack; these are thought to be pseudomorphs after melilite (RF 160, plate 110). The rock nearly always contains euhedral melanite crystals (RF 112, RF 160, plate 111), which are prominent in the field. Unlike that in the ijolite, the melanite is not a replacement mineral; it is not zoned but is black or dark brown throughout. Anhedral black specks, which occur everywhere in the rock, are probably composed of magnetite

Plate 107. The texture of the Banded Tuff. Most of the pale patches are carbonate. A crystal of biotite is in the middle. (RF162) x80.

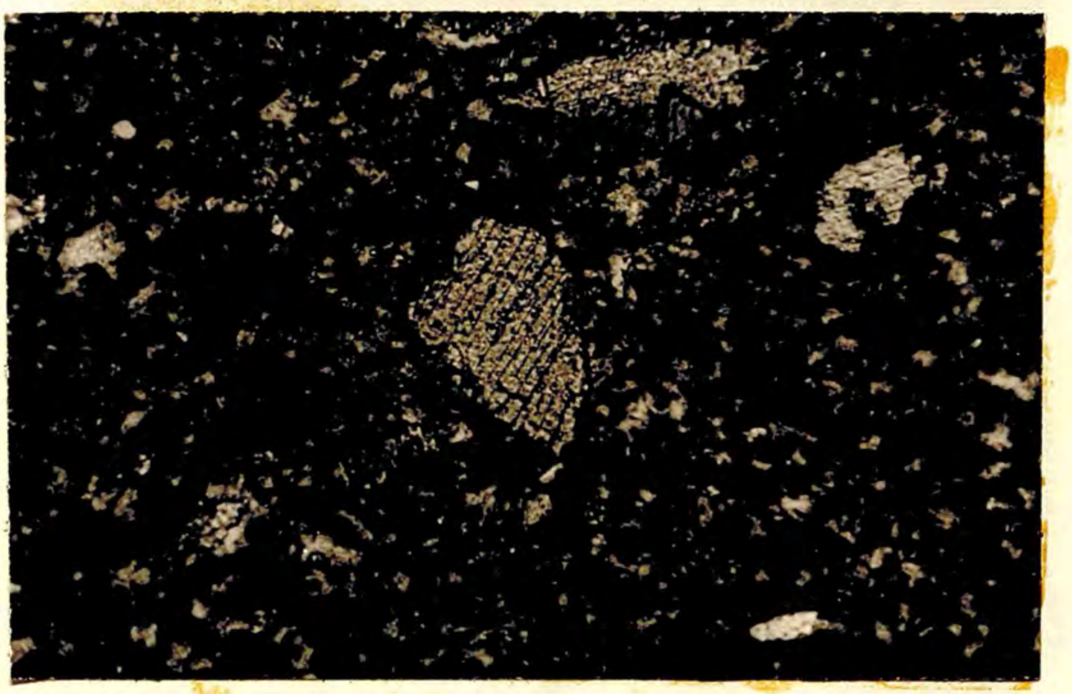


Plate 108. A pyroxene crystal in the Banded Tuff. (RF162). x155.

Plate 109. A partly calcified pyroxene crystal in the Banded Tuff. (RF96). x80.

Plate 110. A possible pseudomorph after melilite in carbonate in the Banded Tuff. (RF161). x80.

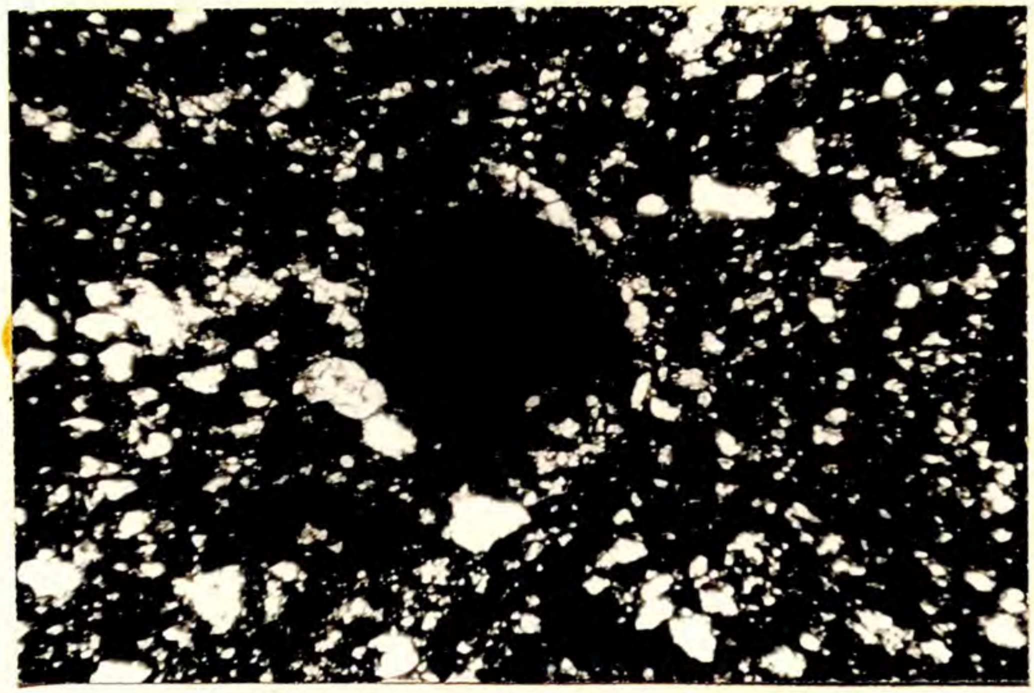


Plate 111. Euhedral melanite crystal in the Banded Tuff. (RF112). x80.

Plate 112. Fragment of altered lava coated with fine-grained material in the Banded Tuff. (RF92). x25.

or one of its alteration products.

The size of the crystals and crystal fragments varies with the grain size of the rest of the matrix, which falls between an average of .05 mm in RF 96 and 2 mm in RF 58. There is seldom any orientation among the minerals, and even the biotite does not lie parallel to the banding planes in the tuff. Crystal edges, especially of the pyroxene and biotite, are ragged but without reaction rims, and they are occasionally coated with fine noncrystalline material as is a euhedral nepheline crystal in RF 92 .

The larger fragments in the Banded Tuff are lava, plutonic fragments, carbonated glass and ash and lapilli and broken lapilli. Lava fragments are infrequent; they are up to 1 cm across, and generally include unaltered pyroxene and magnetite, but the other minerals have been changed to carbonate and felspar (RF 158, plate 113); their texture is similar to that of the lava fragments from the Lower Agglomerate. They have irregular outlines and are aligned parallel to the banding. In RF 158 and RF 163 (plate 114), the edges of the fragments are so tortuous that they must have been liquid or plastic at the time of formation of the rock.

No basement fragments were found, and only one specimen contains a recognizable plutonic fragment; in RF 304, there is a rounded fragment of highly felspathised ijolite. Sometimes fragments of clear carbonate occur, but it is uncertain whether

Plate 113. The groundmass of an altered lava fragment in the Banded Tuff. Magnetite and pyroxene crystals are set in noncrystalline material. (RF158). x310.

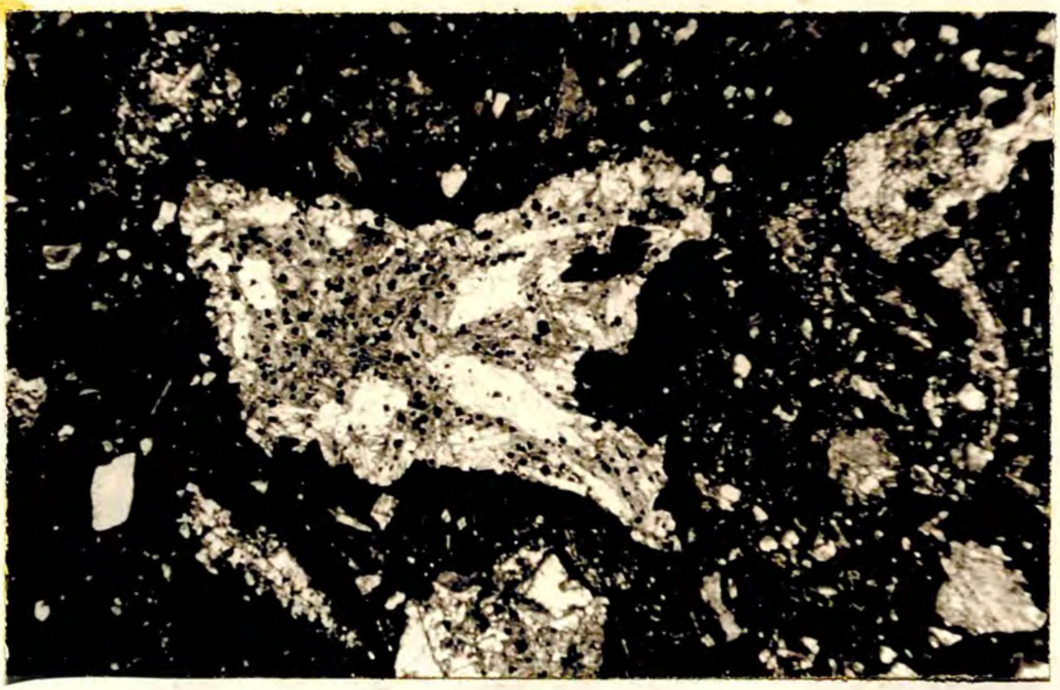


Plate 114. An altered lava fragment with irregular edges in the Banded Tuff. The large pale areas are pseudomorphs in fine-grained carbonate. (RF158). x55.

these are carbonatite.

Far more frequent are laths of dark material up to 2 cm long and with sharp ends. Their occurrence is widespread, and they accentuate the stratified appearance of the tuff. They are noncrystalline, and are formed from dark brown, speckled material (RF 134, plate 115). Usually clear calcite crystals are formed in them, and these will be referred to in the section on carbonation. The laths are considered to be decomposed carbonate-rich glass.

Accretionary lapilli are the most distinctive feature of the tuff, and are found in varying quantities throughout; in some exposures to the north of Rangwa, they comprise over 20% of the rock, (plate 116). They occur both alone and with fragments of the types described above, and tend to be concentrated in bands. They are regular oblate spheroids, (with the major axis which is the diameter of the circular section) lying in the plane of banding (plates of specimens of lapilli tuff - plates 117 and 118). The normal length of the major axis is about 7.5 mm; the longest one measured is 15.2 mm (in RF 20), and some specimens contain lapilli whose major axes measure only 2 mm (in RF 170 and RF 297), but the length appears to be fairly constant in any one specimen. The length of the minor axis is on average 62% of the major axis, but the percentage varies in different specimens. The spread of percentages is shown below, and they are the averages from specimens which contain enough lapilli for the calculation to be significant.

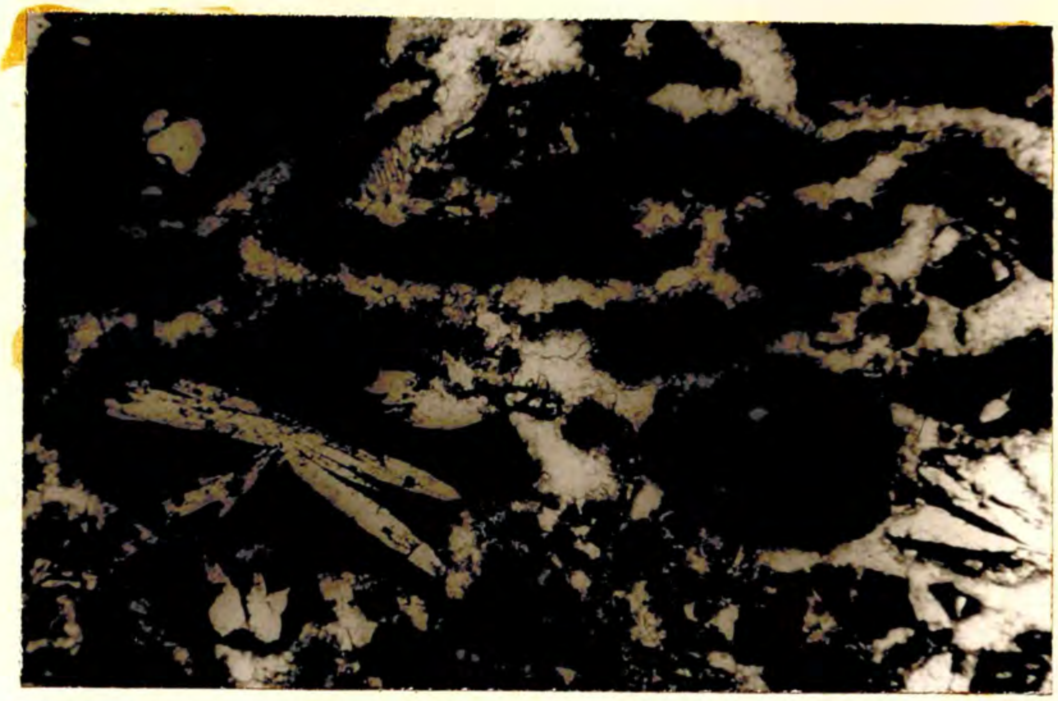


Plate 115. Dark laths in a matrix of pale carbonate in Banded Tuff. Large radiating carbonate crystals occur in the larger laths. (RF134). x25.

Plate 116. Exposure of Banded Tuff with lapilli protruding on the weathered surface from Manganga.

Plate 117. Accretionary lapilli in the Banded Tuff (negative). (RF96). x4.

Plate 118. Accretionary lapillus in Banded Tuff. (RF96). x25.

Plate 119. Grading at the margin of an accretionary lapillus in the Banded Tuff. (RF160). x80.

Plate 120. Broken accretionary lapilli in the Banded Tuff (negative) (RF160). x3.

Plate 121. Broken accretionary lapilli in the Banded Tuff (negative). (RF160). x10.

Plate 122. Broken accretionary lapillus with a thick skin in the Banded Tuff (negative). (RF160). x10.

The average size of the lapilli in each specimen is not given, because of the difficulty of deciding when a lapillus is cut exactly in half; however, opposite each example, the normal size of the other fragments in the rock is shown:-

RF 170	47%	None.
RF 135	49%	.5 mm.
RF 112	57%	.5 mm.
RF 160	57%	1.2 mm.
RF 297	59%	None.
RF 172	59%	2.5 mm.
RF 192	61%	2 mm.
RF 188	64%	4 mm.
RF 166	67%	None.
RF 20	70%	3 mm.
RF 92	70%	3 mm.
RF 181	71%	15 mm.
RF 169	76%	12 mm.

So, up to a point, the comparative length of the vertical axes of the lapilli increases with the size of the other fragments in the rock. Their shape is almost perfect, and there is the same amount of flattening at the top as at the bottom.

The lapilli are composed of the same cloudy fragmental material as the matrix of the tuff. Their centres are comparatively coarse, and the outsides fine; hence the colour changes from pale to dark grey, and the outsides are more compact, so that the lapilli tend to stick out on weathered surfaces (plate 116). A lapillus may be surrounded by several rings, and each one shows a gradation from coarse to fine material (RF160 and RF 112, plate 119). Most of the lapilli in one specimen have the same number of rings. These are continuous and slightly thickened along the banding planes; they are only broken occasionally (RF160, plate 120).

In most cases the lapilli are not formed round any nucleus, but sometimes (RF 92) there is a crystal or lava fragment at the centre. The material composing both the centre and the rings is unorientated, and apart from some apatite crystals no crystalline minerals are present. It tallies in every way with the description given above of the matrix.

Some broken lapilli are generally present, but the amount is random, and does not vary with the quantity of whole lapilli or with the size or quantity of other fragments in the tuff; however, bands with large amounts of broken lapilli do occur (RF162, plate 121). They are elongated slivers and include both coarse and fine material, with the fine-grained edge facing either upwards or downwards. The break in the fine material is sharp and angular, but the coarser part is indistinguishable from the matrix, and it is often impossible to see where the boundary is (RF162, plate 122). The broken bits of one lapillus are not found close to one another, and, unlike the shattered fragments in the agglomerate, reconstructing lapilli from their constituent parts is out of the question.

(3) MIXED AND TRANSITIONAL TUFF.

Occasionally, a specimen shows the characteristics of both types of tuff or a transition from one to the other. The mixing takes several different forms. Most of the phenomena found in these rocks have been described above; so only the combinations that occur are listed here. They will be referred to when the origin of the two types of tuff is considered.

In RF 167 (plate 123) Banded Tuff is succeeded by Bedded Tuff, and between them there is a surface of irregular ripples about 20 mm long and 4 - 6 mm high. The Banded Tuff has lava and finer-grained tuff fragments in a dark grey matrix with phenocrysts of melanite and pseudomorphs after nepheline. The base of the Bedded Tuff is dark and very fine-grained, and contains swirling flow lines which are roughly concordant with the surface at the base, and which merge into tongues and die out in one direction. Above this, there are several fine pale beds between 1 and 3 mm thick, disrupted by minute faults that do not extend into the beds below. RF 47 has alternating bands of tuff with whole lapilli and sets of beds packed with broken ones; the broken ones are unusual in that they are in a well-bedded rock, and their centres are conventional whereas the matrix is felspathic and composed of well-defined angular particles, as in the Bedded Tuff. Most of the

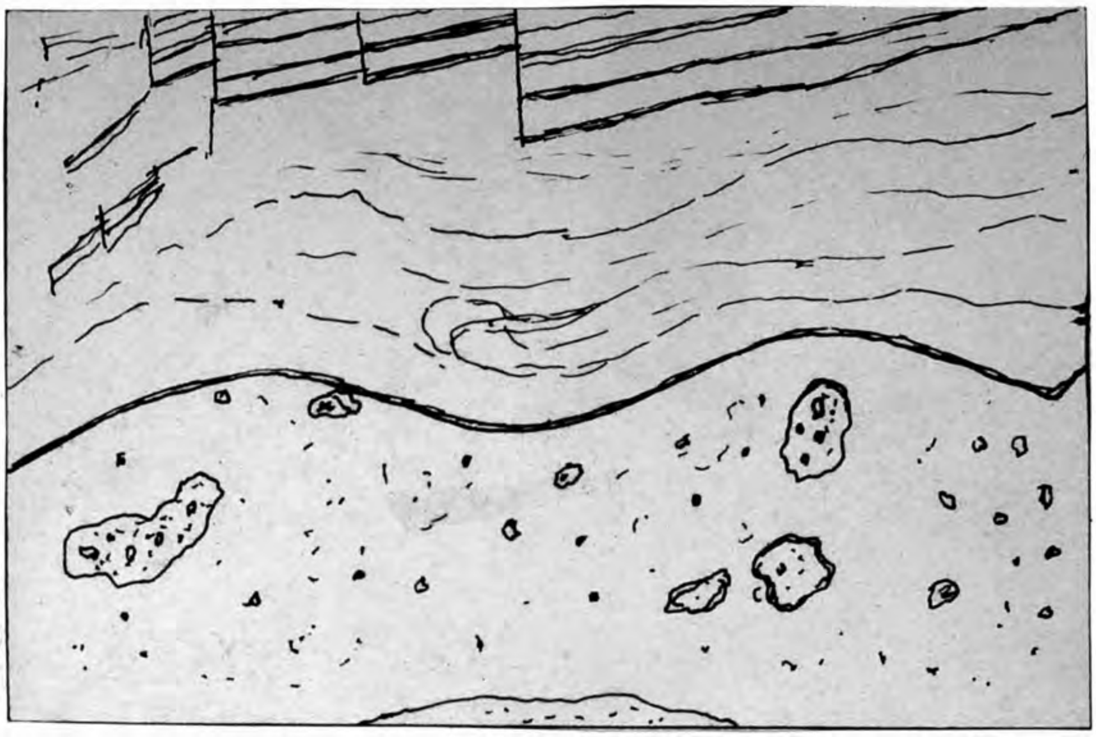


Plate 123. Banded Tuff succeeded by Bedded Tuff, with a surface of ripples between them. In the Bedded Tuff, material with possible flow textures is succeeded by very finely bedded tuff, cut by small faults. (RF167). x2. Drawing of hand specimen.

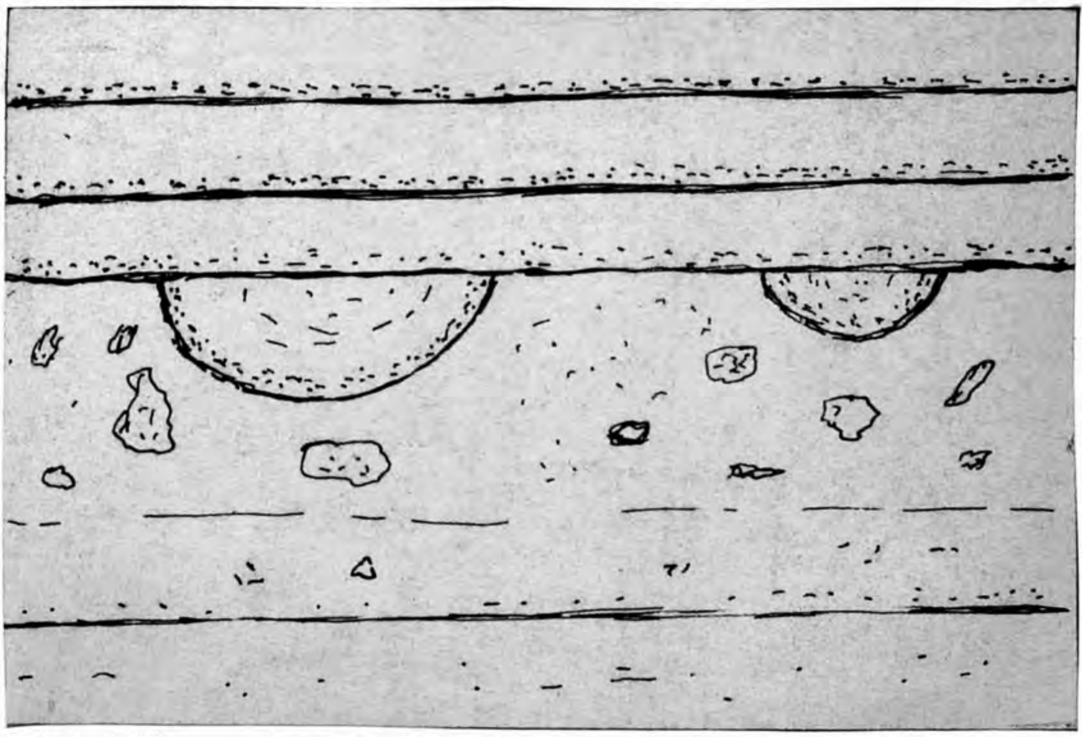


Plate 124. Accretionary lapilli truncated by a layer of Bedded Tuff. (RF10). x5. Drawing of hand specimen.

matrix of RF 20 is made up of angular particles, and the top of one lapillus is planed off; also the whole rock is reddy brown, unlike the true Banded Tuff. In RF 10, two small lapilli are cut in half by a thin flat layer of Bedded Tuff (plate 124). RF 69 and RF 90 have bands containing lapilli interspersed with Bedded Tuff.

The occurrence of the mixed tuff is widespread though infrequent, and it is found within the areas of distribution of both types of tuff.

(4) CARBONATE CONTENT OF THE TUFF GROUP.

As the descriptions show, the rocks in the Tuff Group are rich in carbonate, but only the Bedded Tuff contains felspars as well. As with the Lower Agglomerate, the weight percentages of CO_2 were found in ten specimens, and these were converted to weight percentages of $CaCO_3$, since most of the carbonate is calcite, and the results are:-

RF 84	23.58%
RF 166	25.22%
RF 134	26.39%
RF 297	28.09%
RF 129	28.14%
RF 159	28.39%
RF 96	29.98%
RF 162	30.66%

RF 170	30.89%
RF 208	63.83%

But for RF 84, which is a specimen of comparatively unweathered Bedded Tuff, and RF 208, which is from near the Mwisasu Carbonatite, the range of values is even smaller than those of the Lower Agglomerate. As the values for the tuff are lower though it occurs inside the Lower Agglomerate, it is unlikely that the carbonation came from a central source. Besides, the fact that RF 208 contains 63.83% carbonate shows the effect of proximity to a large carbonatite, while otherwise there is little variation over the entire width of outcrop of the Tuff Group.

In the specimens which have a matrix of white carbonate (RF 134, RF 162 and RF 171), there are patches of clear, angular calcite crystals, generally radiating from points near the edges of the fragments and extending inwards (plate 106). Elsewhere, the carbonate occurs as a background mosaic. It is thought that in both cases the carbonate must have been present when the rock was formed, and has crystallised or recrystallised since then from the ash and glass, but where the matrix is specially rich in carbonate it has introduced more carbonate into the fragments.

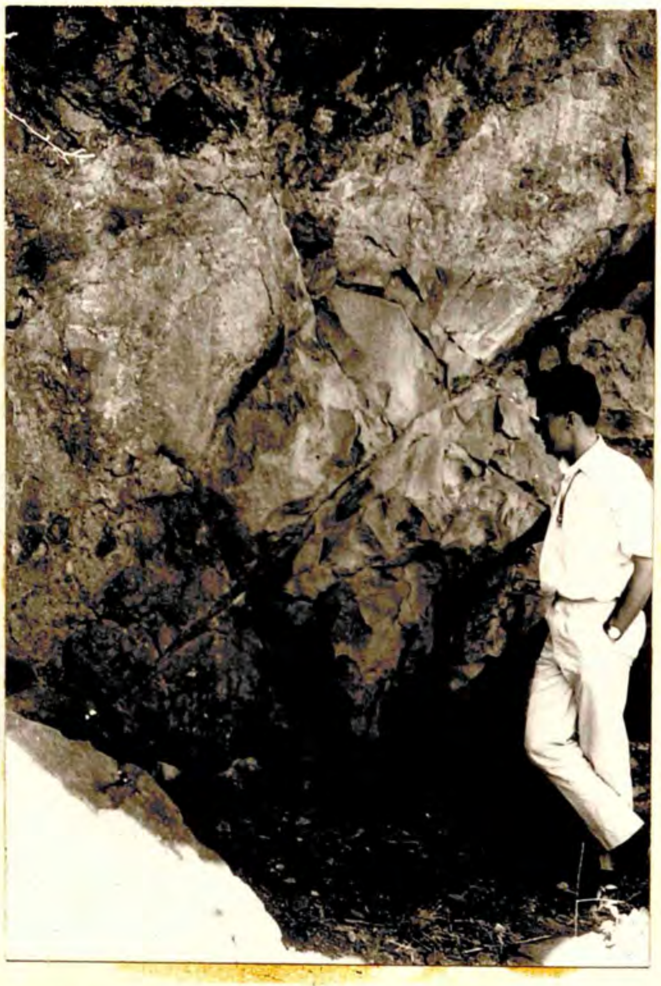
C. UPPER AGGLOMERATE.

The Upper Agglomerate is generally poorly exposed and highly weathered; hence it is more problematical than the other pyroclastic groups. To understand its nature properly, it is necessary to see a very large exposure, and these only occur on the cliffs north west of Kinyathengo, which are up to 30 ft. high. They have a rubbly appearance, and consist of large closely-packed boulders ranging from 10 cm - 5 m in size (plates 125 and 126). The fragments are subrounded, and show no sign of bedding, banding, sorting or orientation. It is often difficult to spot the boundaries of the fragments, as there is so little matrix, and it has the same hardness as most of the fragments. Elsewhere within the boundaries of the Upper Agglomerate, the ground is scattered with loose blocks, as well as a few highly weathered exposures.

It is hard to tell how much of the fine-grained material is matrix to the Upper Agglomerate, and how much belongs to the agglomerate or tuff fragments in the rock. The undisputed matrix from the cliffs mentioned above only occurs as a very thin packing, and contains both small chips of previously formed agglomerate and tuff, and some original blobs similar to those in the Lower Agglomerate (RF 24, plate 127); it is stained brown, and rich in carbonate.

Fragments found in the Upper Agglomerate are:- Bedded Tuff, Banded Tuff, agglomerate (probably Lower Agglomerate), granite, nephelinite (dyke rock), ijolite, melteigite, biotite pyroxenite, biotite uncompahgrite. Most of the large fragments are of previously formed pyroclastic rocks, and Bedded Tuff (RF 116),

Plate 125. Large fragment of tuff in the Upper Agglomerate, from the cliffs between Sindo and Roo.



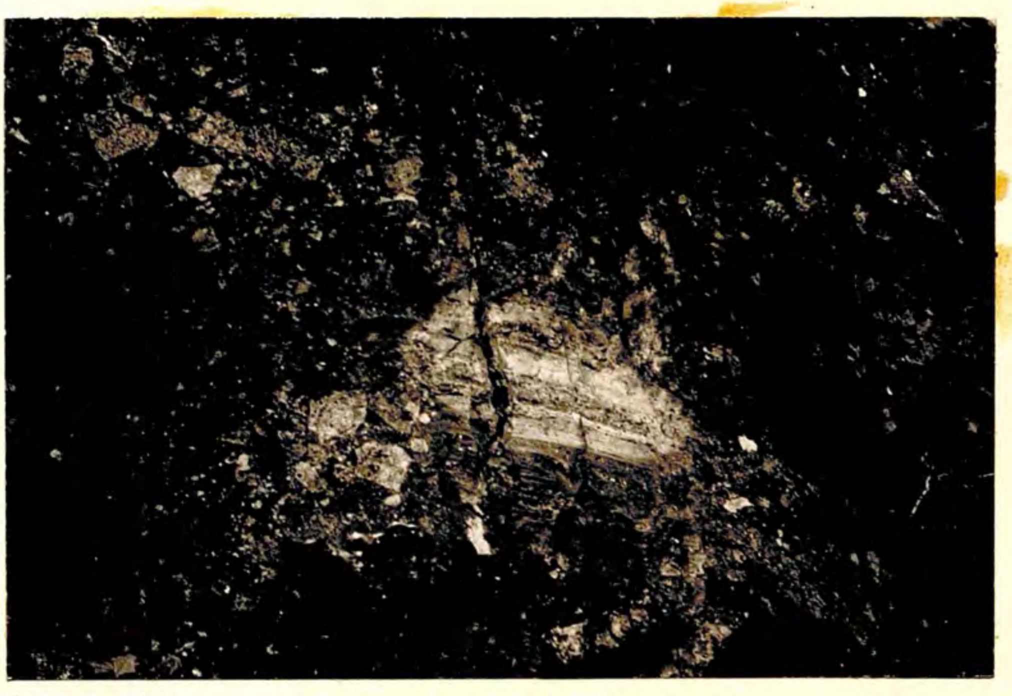


Plate 126. Small fragment of tuff and some Basement fragments in the Upper Agglomerate, from the cliffs between Sindo and Roo.

Plate 127. The matrix of the Upper Agglomerate (negative). (RF24). x5.

Plate 128. A fragment of tuff in which the bedding has been bent in the Upper Agglomerate. (RF124). x½.

Banded Lapilli Tuff (RF 24) and finer-grained agglomerate (RF 29) occur frequently. Normally they appear unaltered but sometimes they have been twisted and partly shattered by the formation of the agglomerate; this is evident in some of the tuff fragments (RF 124, plate 128). The presence of Bedded Tuff fragments is useful, as there are so many of them that they show definitely that the rock is a very coarse agglomerate; even in the most weathered outcrops, their bedding is prominent, and any large exposure has tuff fragments whose bedding dips in different directions.

Basement and plutonic fragments are infrequent, and have many of the same features as those in the Lower Agglomerate. Most of them are rounded, and never bigger than 20 cm across. Some may be parts of Lower Agglomerate fragments, but most of the ones collected from the cliffs below Kinyathengo are thought to be original. RF 33 contains several fenitised granite fragments, which are felspathised round the edges, and are surrounded by felspathised chips; as in RF 61 and RF 102 in the Lower Agglomerate, the granite is closely associated with coarse nephelinite in which the pyroxenes survive. Specimens of ijolite (RF 304), melteigite and biotite pyroxenite (RF 30) are unaltered. Melilite in the biotite uncompahgrite is changed to noncrystalline material as in the Lower Agglomerate although the other minerals are fresh.

The extent and nature of the Upper Agglomerate are reasonably certain, but the specimens collected are not representative of the whole area of outcrop. For this reason, the work accomplished is not as detailed or comprehensive as what was possible for the other pyroclastic groups.

3. THE STRUCTURE OF THE PYROCLASTICS.

The pyroclastics form a distinct structural unit, as do the surrounding plutonics and basement. It will be shown in the next chapter that the emplacement of the small carbonatite conesheets and the central carbonatites was later than the events which caused the structures in the pyroclastics. Although carbonatite conesheets and radial dykes occur throughout the pyroclastics, they belong to a different structural episode.

As elsewhere on Rangwa, it is impossible to account for the structures in isolation; so in the section that follows the structure is fitted into a broader framework.

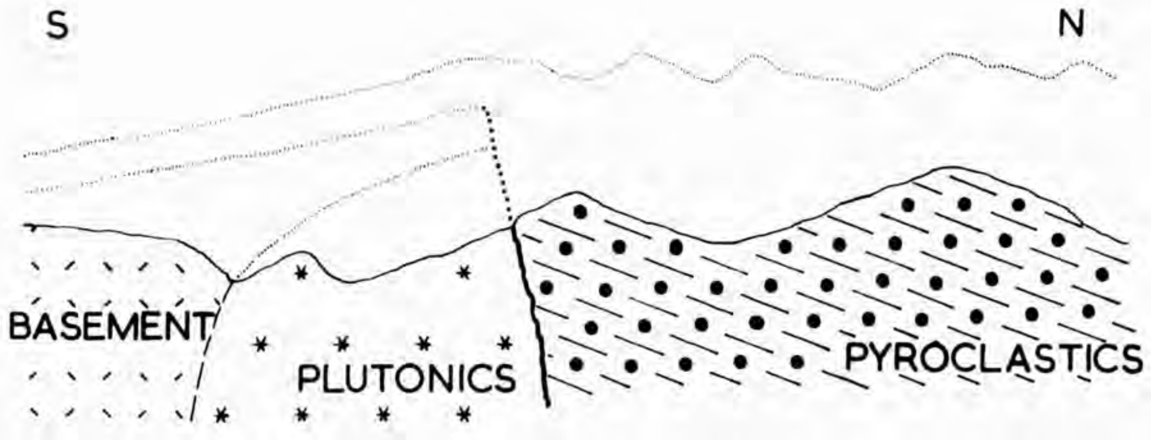
A. THE OUTER BOUNDARY.

The boundary is vertical and has an almost perfect oval form. Across it, there is a change of rock type from plutonics and basement to extrusive pyroclastics. The nature and cause of this vertical boundary are not immediately clear, and it is necessary to consider the alternative explanations and eliminate the improbable ones (Figure 15).

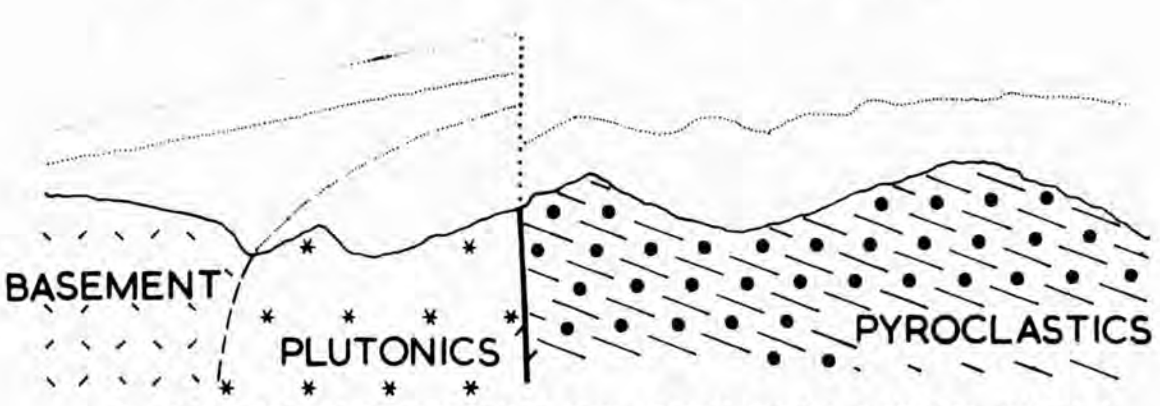
McCall (1958) supposed that the contact is the original lip of the crater of the volcano (see his series of diagrams showing the evolution of the Kisingiri Volcano). This view is thought to be untenable for several reasons. To the south east of Rangwa, Banded Tuff is exposed within ten yards of the biotite uncompahgrite, which would have been very close to the vertical cliff that would have been the edge of the crater at the time of deposition of the subaerially formed Banded Tuff. However, although a zone of alteration exists in the melilite, the uncompahgrite does not show the weathering or corrosion which would be expected had it been exposed in a volcanic environment. Also, if the crater had been bounded by vertical cliffs of alkaline plutonic rocks, the tuff exposed round the edge of Rangwa would contain large angular lumps of wall rock which had slipped down; none have been found. The most compelling reason for rejecting this explanation is that the Lower Agglomerate, which was formed by flow rather than air fall, is far too low at its present level to have given rise to its probable counterparts at Gingo and on Rusinga and Mfwangano, even allowing for the reversal of the Mfwangano Fault (this relationship will be clarified in Part III). Besides, as will be explained later, the size of the whole of Rangwa is considered to be far bigger than that of a normal volcanic vent.

Therefore the outer boundary of the pyroclastics must be the

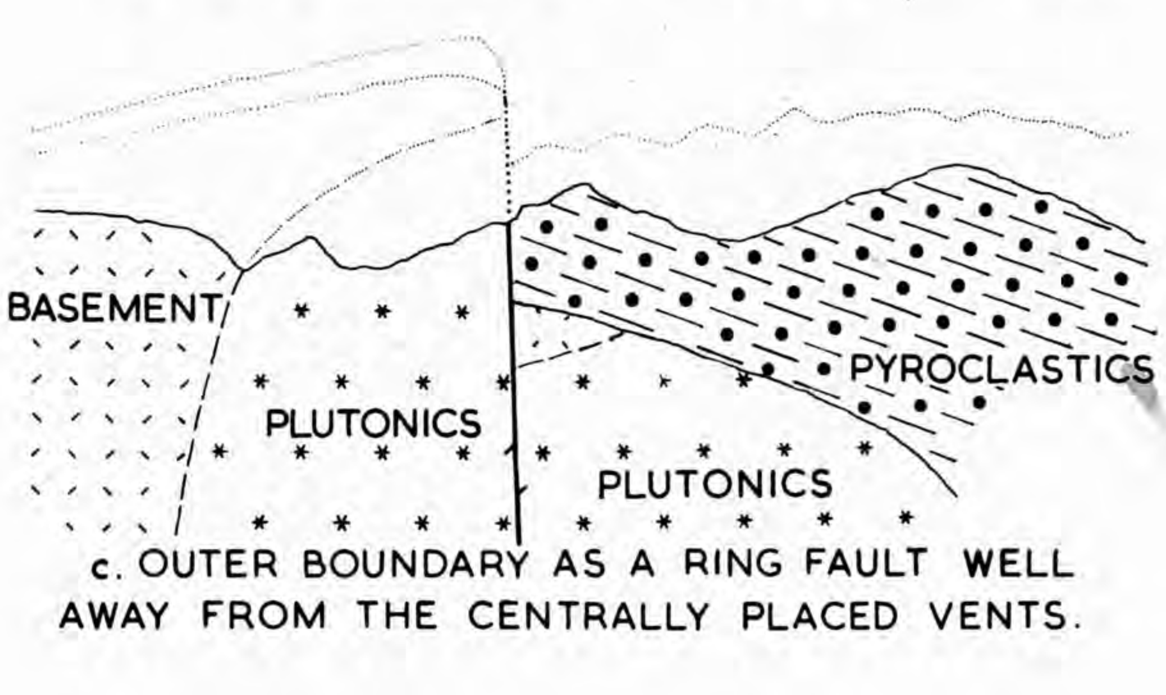
THE SECTIONS DO NOT INCLUDE THE MAIN NEPHELINITES.



a. OUTER BOUNDARY AS VENT WALL.



b. OUTER BOUNDARY AS FAULTED VENT WALL.



c. OUTER BOUNDARY AS A RING FAULT WELL AWAY FROM THE CENTRALLY PLACED VENTS.

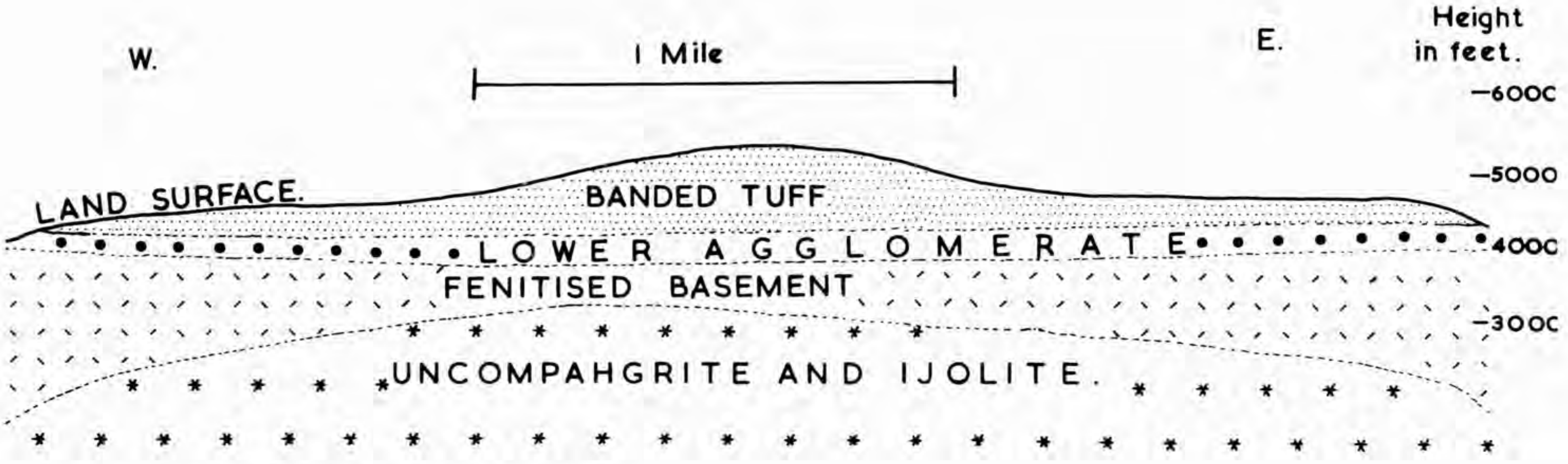
FIGURE 15. ALTERNATIVE INTERPRETATIONS OF THE FORM OF THE OUTER BOUNDARY OF THE PYROCLASTICS.

line of a ring fault with the downthrow to the inside. McCall (1963) arrived at this conclusion; he follows Von Eckermann's theories for the alkaline centre at Alno (Von Eckermann 1948 and 1958), and supposes that the carbonatite dykes on Rangwa come from a later and higher centre of activity than the alnoite dykes round about, and that the whole of Rangwa has subsided because the carbonatites are now at a lower level than they were originally. So McCall (1963) accepts that Rangwa must have been downfaulted along its outer boundary, but it will be shown below that most of the subsidence occurred prior to the emplacement of the Rangwa carbonatites.

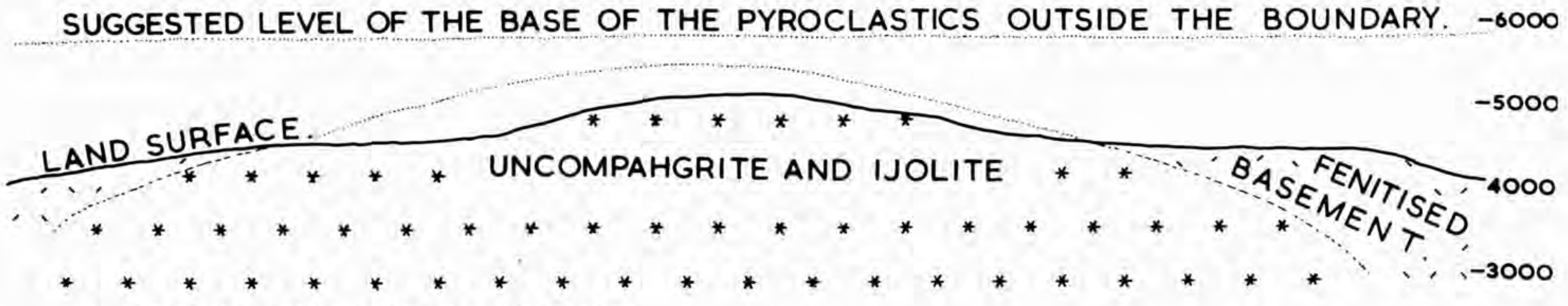
Granted that the outer boundary of Rangwa is a vertical fault, it could have two possible relations with the original vent which must have existed on the site occupied by Rangwa today. Either Rangwa could be the size of the vent, in which case faulting and subsidence would have taken place along the vent walls, or Rangwa could be considerably larger than the vent; in the latter case the pyroclastics exposed at the present would represent the top of a funnel shaped vent, after it had splayed out and the pressure is dissipated sideways as well as upwards (Figure 20). The former alternative can be ruled out for most of the same reasons as the hypothesis that the pyroclastics are the vent filling in their original position, as there would be more alteration and penetrating tongues of vent rock in the adjacent uncompahgrite.

So the only possible conclusion is that the ring fault, which is the boundary between the plutonics and pyroclastics at the surface becomes, lower down, the boundary between two different levels of plutonics and basement.

The throw of the boundary fault cannot be deduced with any accuracy, because it is impossible to match any rock types across it, but some limits to its size can be set. Figure 16 is a long section along the fault plane, to the south east of Rangwa; on it the present land surface is marked, together with the rocks on either side of the fault plane, and their hypothetical extension upwards and downwards. It shows that, even though the fault has a big throw, the base of the tuff is at a fairly constant level, and is a smooth line, whose height ranges from 4,200 ft. in the north to 4,600 ft. in the south. Since it is thought that the original base level of the tuff must have been almost the same all the way round, the throw of the fault does not vary much. The thickness of the Lower Agglomerate is not known, as the base of it is never seen, but it is assumed that there are always several hundred feet of it beneath the tuff. So at the south of Rangwa the base of the Lower Agglomerate is probably below 4,300 ft; when formed, this would have been higher than the highest of the uncompahgrite, presumably capped by ijolite, fenite and basement. The highest surviving exposure of uncompahgrite is at 5,300 ft. and it must have been covered by at least 500 ft. of



a. WITHIN THE BOUNDARY FAULT.



b. OUTSIDE THE BOUNDARY FAULT.

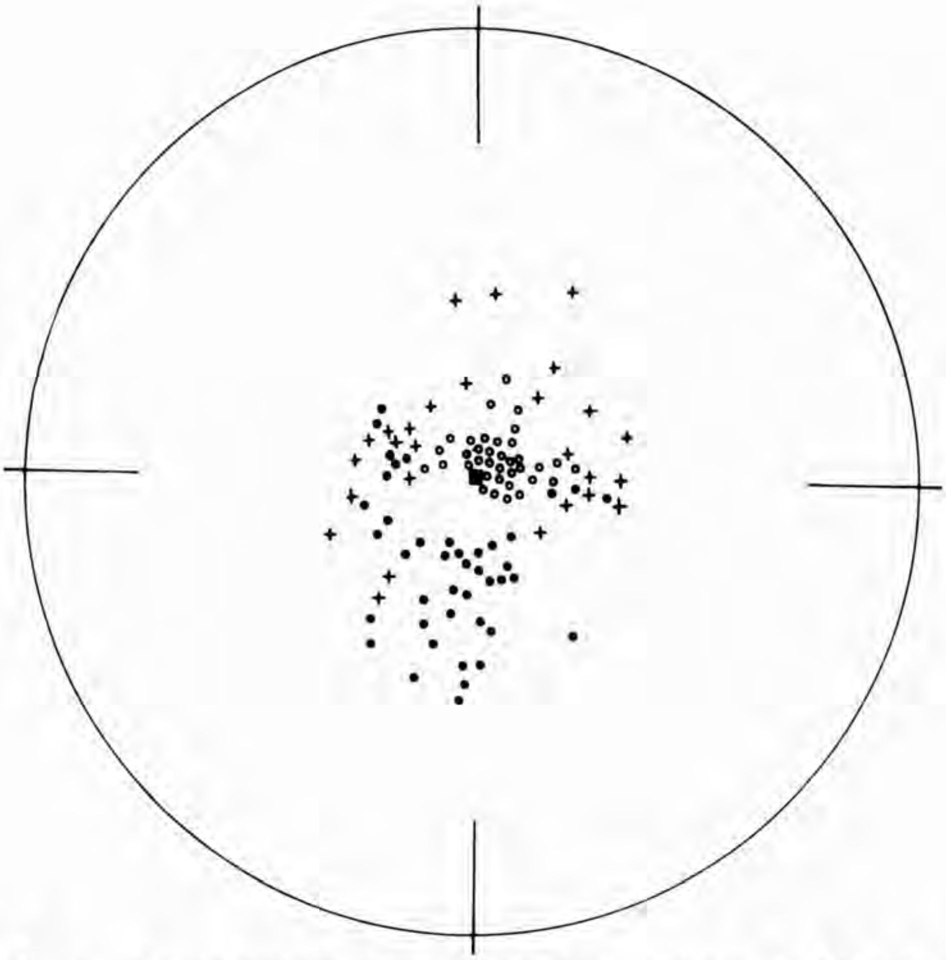
FIGURE 16. SECTION ALONG THE SOUTHERN PART OF THE BOUNDARY OF THE PYROCLASTICS SHOWING THE ROCKS AND THEIR PROPOSED EXTENSIONS ON EACH SIDE OF THE BOUNDARY.

plutonics and basement; so the height of the base of the Lower Agglomerate, which now stands at below 4,300 ft. was once above 5,800 ft. so that there was movement of over 1,500 ft. at the fault plane. It is emphasised that this is a minimum figure, as there are at least two imponderables; the thickness of the covering of basement over the plutonics is unknown, and it is impossible to tell how much of it was eroded away before the emplacement of the Lower Agglomerate, and how much was blasted out during the formation of the vent.

Except in the west, where the edge of Rangwa is indented by erosion, the boundary fault is continuous and well-marked, although never well enough exposed to show any fault breccia. The excessive erosion in the west may well be the effect of several smaller faults (plate 6), but elsewhere only one large fault exists.

B. THE INWARD DIPS IN THE PYROCLASTICS.

All the types of layers in the pyroclastics, both the flow banding in the Lower Agglomerate and the bedding and banding in the Tuff Group tend to dip towards the centre of Rangwa (stereogram - Figure 17). Figure 28 shows the dips plotted at their correct height and distance from the centre of the complex. It will be seen when their modes of formation are discussed that not many of the present day dips could have been original. When deposited, the Bedded Tuff must have been nearly horizontal, and not dipping in



\+ POLE TO A BANDING PLANE IN THE LOWER AGGLOMERATE.

∘ POLE TO A BEDDING PLANE IN THE BEDDED TUFF.

• POLE TO A BANDING PLANE IN THE BANDED TUFF.

FIGURE 17. STEREOGRAPHIC PROJECTION OF THE POLES TO THE BEDDING AND BANDING PLANES IN THE PYROCLASTICS.

any set direction, but now it has an average dip inwards of 14°, and the stereogram shows that except for the very small dips in the north, the dip does not vary significantly from the average in the entire area of exposure of the Bedded Tuff, but this only extends through an arc of 150°. The Banded Tuff is a subaerial ash deposit, and could have been laid down with any dip less than the angle of rest of the tuff; there is no evidence what that angle was, but it must have been less than 40°. However, at a few exposures it has a dip of more than 45°, and the average dip is 28°. On the stereogram the dips show no trend away from the average, and the trend of the dips of the Bedded Tuff is not a continuation of that of the Banded Tuff. If it is assumed that the Bedded Tuff was approximately horizontal when deposited and that the two types of tuff have undergone the same amount of tilting, the average original dip of the Banded Tuff can be corrected from 28.0° to 15°.

It was impossible to measure as many dips of the flow banding in the Lower Agglomerate. The average of the dips measured is 25°, but the measurements are so scattered on the stereogram that there are no concentrations. Since the Lower Agglomerate underlies the Bedded Tuff, the average original dip must have been 13°. The Upper Agglomerate has no recognizable banding or bedding, and there is no evidence with which to fit it into the structural pattern.

Tantalizingly, nearly all the measurable dips are within several hundred yards of the edge of Rangwa; so the structural picture for the rest of the pyroclastics has to be deduced from the structures round the edge and from analogous situations elsewhere.

C. FAULTING.

McCall (1958) marks several faults on the west and north west parts of his large scale map of Rangwa, but does not mention them in the text, and the amount of throw is not indicated. These were not found in the field, and, except for the fact that most of them follow valleys, they are not marked by features on the air photographs. All of them are shown to extend from the outer margin of the pyroclastics to the breccia associated with the central carbonatites. The breccia is caused by disruption of previously formed rocks, and could easily be mistaken for a fault breccia.

The only large fault proved in the field runs north-south for at least half a mile on the northern slopes of Kinyathengo. It is a normal fault, throwing about 200 ft. to the west, and it displaces the Bedded Tuff and both the Agglomerates. There is no way of showing whether it occurred before or after the emplacement of the carbonatites. Other faults may exist, but as most of the boundaries between the rock types are ill-defined it is impossible to prove minor displacements.

Minor faults are common throughout. The Lower Agglomerate is often cut by sharp faults with throws of up to 1 cm; the direction is random, and there is no shattering regardless of whether they cut volcanic or basement fragments, and it is not known when the faulting happened. The tuff shows minor faulting too. RF 167 (plate 123) has numerous small faults normal to the bedding. In RF 174 , some fine-grained beds show faulting, which does not extend to the coarser beds beneath; although smaller, these faults are similar to ones described by Cotton (1944) in tuff from Lake Pupuke in New Zealand, and are caused by penecontemporaneous differential settling. In RF 90 faulting occupies a vertical zone between 1 and 2 cm thick, across which the banding has been bent in the direction of the throw of the faulting; this too must have occurred when the tuff was still unconsolidated.

4. GENESIS AND HISTORY.

A. THE LOWER AGGLOMERATE.

It can be shown that the Lower Agglomerate is extrusive, because it is succeeded conformably by extrusive tuff. The banding indicates that the rock has flowed (plates 71 and 72), and is not unlike the flow banding found in ignimbrites. Although there is no sign of welding, the rock was very hot when it was formed, as much of the volcanic component must have been liquid at that time. All the banding dips towards the centre of Rangwa, and it has been shown that the original dip was between 10° and 15°. However, the direction of flow is away from the centre; so the neck responsible for the pyroclastics must have been centrally placed with its top slightly below the level of the Lower Agglomerate, and it was far smaller than the present day area of Rangwa (Figure 21). Therefore the Lower Agglomerate was forced up hill under pressure.

From evidence at other igneous centres, too, this explanation seems most likely. Volcanic necks which survive are seldom more than half a mile across, and the relationship between the pyroclastics on Rangwa and the neck that gave rise to them is illustrated by Howel Williams' classification of the vents in the Navajo-Hopi country in the western United States (1936) into the "Navajo" and "Hopi" types. The former are narrow necks formed from tuff breccia, and the latter are broader structures with inward dipping pyroclastics at their bases. Williams supposes that the two types are different erosion levels of the same kind of vent, and the Lower Agglomerate on Rangwa exemplifies the latter type.

The Lower Agglomerate shows many of the symptoms listed by Reynolds (1954) of rocks that have been caused by fluidization.

The following are the most common:-

(a) Mixing of different rock types.

(b) Rounding of fragments.

(c) Break-up of fragments in situ.

(d) Intense alteration round fragment edges.

(e) Fragments that have not moved far.

(f) Streaming of the matrix round the fragment edges.

All these characteristics are recorded widely in the literature on both intrusive and extrusive fluidized agglomerates and tuffs. Since the Lower Agglomerate is extrusive, but has not moved far from the actual volcanic neck, it shows features of both intrusive and extrusive bodies of fluidized rock. Cloos (1941) describes how the intrusive tuff pipes in Swabia contain a mixture of fragments of Jurassic country rock and lapilli of melilite basalt, and how the country rock fragments become larger and more numerous towards the edges of the pipes, where they are seen not to have moved far. The basement and plutonic fragments in the Lower Agglomerate have not moved far either, as they can be matched with in situ exposures, and apart from their rims they have not been altered much, but the agglomerate cannot be zoned by the proportion of country rock fragments, because, having been pushed out of the neck, they are too much disturbed. As in the Swabian pipes, the country rock fragments are rounded and have chemical reaction rims, and the larger ones are often broken down almost in situ.

The nature of the volcanic component is broadly comparable with that at many other centres, and the lava blobs with skins formed by attrition between fragments are of widespread occurrence. Bailey (1960) describes lava pellets rounded by attrition in the tuff and agglomerate at the Chasweta vent in the Rufunsa Valley. Holmes mentions lapilli of katungite with skins, which formed as lava droplets in the crater at Katwe in western Uganda (1956). On Rangwa the lava component is highly carbonated nephelinite, which suggests that the vent was drilled by carbonate-rich gas. This is expected, since the drilling was preceded and followed by carbonatite episodes. The carbonate and alkalis that were present in the fluidization column were trapped in the agglomerate as it cooled, to cause the carbonation and felspathisation.

Apart from a possible unconnected lava episode, the break through of a fluidized vent was the earliest extrusive event on Rangwa, and it pierced the dome of basement and plutonics near the top slightly to the north. The position in relation to the dome is hypothetical, but the north side is suggested for two reasons; the centre of Rangwa is north of the centre of the contoured dome, and the main extrusive products at a distance from the vent are to the north. When the fluidized column reached the surface, it formed a large crater round itself, partly by avalanching of the sides, and partly by outward blasting by the gases in the column, a phenomenon that could only happen to any great extent near the surface of the dome, where the basement would be less resistant to outward pressure.

Layers of Lower Agglomerate interspersed with occasional layers of ash accumulated in the crater, and were forced up its sides by the outward pressure. As will be described when the history of the whole volcano is outlined, the fluidized flows escaped from the crater where the sides were lowest. This is similar to the "boiling over" described at some of the fluidized vents in western Uganda by Holmes (1956).

B. TUFF GROUP.

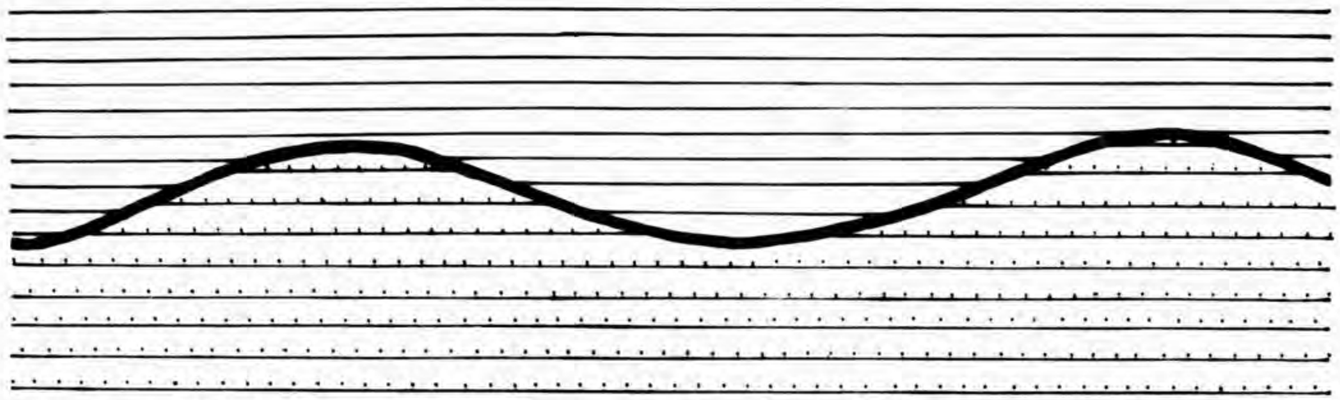
The two types of tuff are composed of similar material. The main differences are that one is finely bedded and the other is roughly banded, that the Banded Tuff contains lapilli, and that the Bedded Tuff is far more highly altered. They both consist of carbonate-rich ash, glass and lava together with crystals of minerals typical of alkaline rocks. Both occur at the same stratigraphic level on the mountain, and they interfinger. So it is thought that they originated as the same air fall tuff, but that they fell into different environments. The three environments that must be considered are:-

(a) Ash falling into a dry environment.

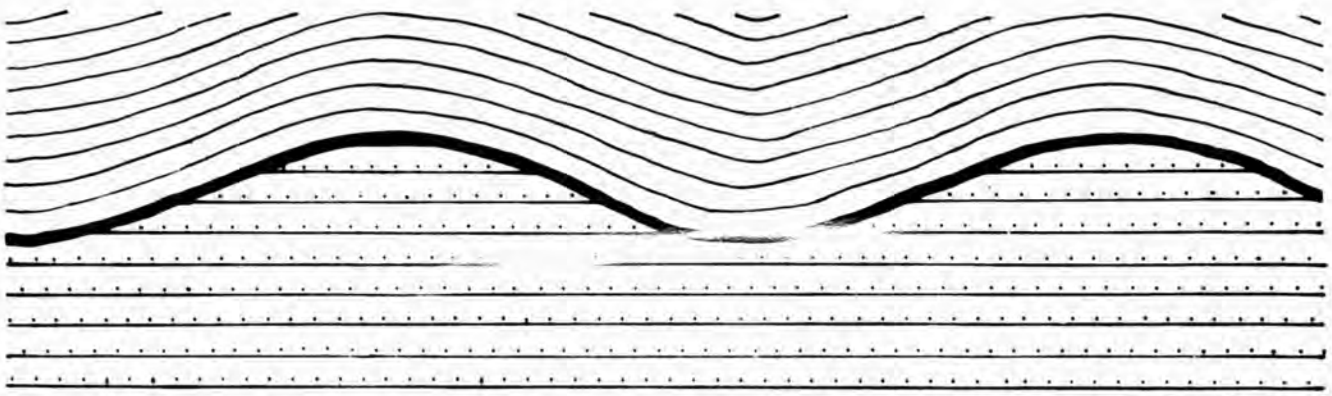
(b) Ash falling into water and being reworked extensively.

(c) Ash falling into shallow water.

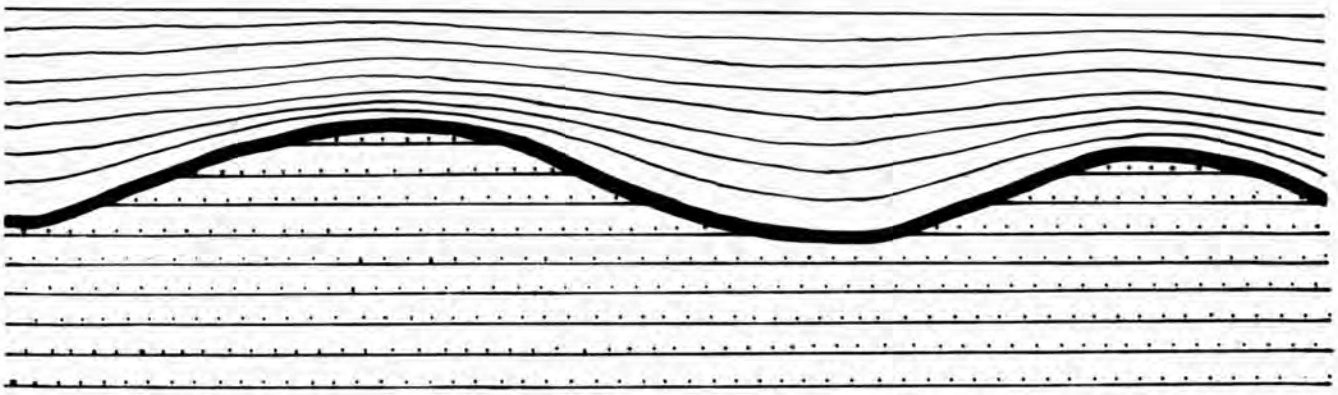
In the case of the Bedded Tuff, the first alternative is unlikely, since the erosion surfaces are not the right shape to have been caused by either wind or running water. Besides any irregularities caused by the erosion surfaces would be maintained by succeeding beds, until, after several erosion surfaces, the beds would become very irregular, as one bed would be the same thickness throughout regardless of the surface it was laid upon, (Figure 18 shows the type of bedding that would occur above an erosion surface in each of the three environments). The second environment is ruled out too. Although there is grading, the sorting is not good enough for a finely bedded waterworked deposit, and the configuration of the beds above the erosion surfaces is wrong, as the lowest ones should fill only the hollows, whereas in fact they are continuous. The last alternative is the only one that fits all the facts. Each bed is a single ash fall. The environment would have allowed heavier fragments to sink into the tops of the beds below, and rough grading would have been caused by the larger fragments falling first, as with ash falling into a dry environment. In water only a little agitation would have been needed to cause the beds above the erosion surfaces to thicken into the hollows and thin out over the humps occasionally disturbing the partly consolidated beds below, until the surface became level again. The beds are normally continuous, but the erosion surfaces were formed by gently moving water during a lull in the falls of ash.



a. WHEN ASH HAS BEEN CARRIED AND DEPOSITED BY WATER.



b. WHEN ASH HAS FALLEN INTO A DRY ENVIRONMENT.

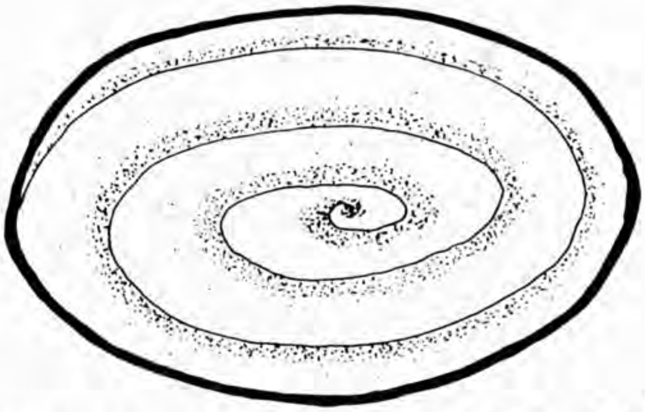


c. WHEN ASH HAS FALLEN INTO SHALLOW WATER.

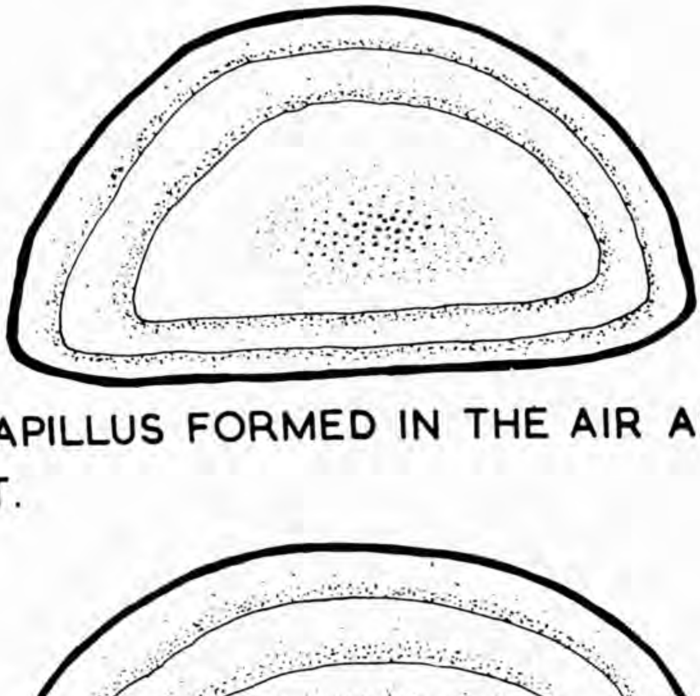
FIGURE 18. ALTERNATIVE METHODS OF FORMATION OF EROSION SURFACES IN BEDDED TUFF.

The Bedded Tuff was deposited in a shallow lake, but the Banded Tuff is the product of a dry environment. The rough banding and lack of bedding structures indicate this, but the most positive evidence is the presence of accretionary lapilli. The origin of the lapilli is important, as it helps to show how the tuff on Rangwa was deposited, and how much compaction it has suffered. McCall (1958) says that they are secondary features, because the material inside them and the matrix of the tuff are the same; but the large number of broken lapilli, most of which were broken before the tuff was formed, proves that they are not. Therefore the lapilli were deposited at the same time as the rest of the rock.

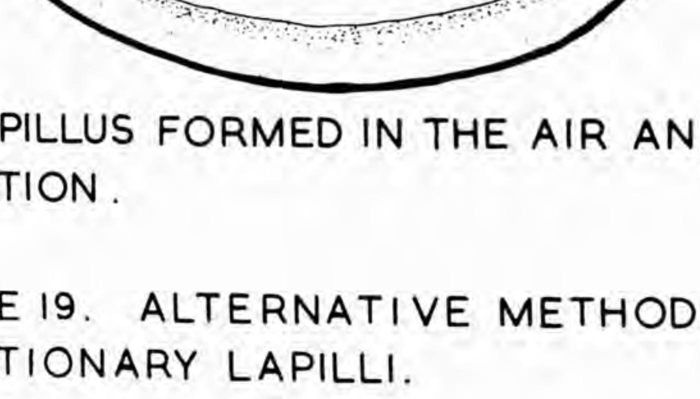
They were not formed under water, as any lapilli formed there would not have continuous rings, but would be surrounded by spirals (Figure 19), as a result of rolling. For the same reason the lapilli were not formed by rolling of balls of ash. None of the lapilli would survive unbroken if they had been ejected from the vent with the ash; so they formed in mid-air. The flattening of the lapilli always follows the banding, unlike the biotite crystals in the tuff, which are unorientated. This shows that the flattening is a post-deposition feature, as if they were flat when they landed their orientation would be random. Since there is the same amount of flattening at the tops and bottoms of the lapilli, it was due to compaction of the whole rock rather than impact at



a. A LAPILLUS FORMED BY ROLLING.



b. A LAPILLUS FORMED IN THE AIR AND FLATTENED ON IMPACT.



c. A LAPILLUS FORMED IN THE AIR AND FLATTENED BY COMPACTION.

FIGURE 19. ALTERNATIVE METHODS OF FORMATION OF ACCRETIONARY LAPILLI.

the time of deposition; hence the environment into which the lapilli fell must have been softer than the lapilli themselves.

Most of the lapilli are oval today, and they started as spheres of ash in mid-air. Some broke presumably by knocking against each other or against other fragments. As the broken ones tend to occur in layers, and their number does not vary with the number of whole ones or other fragments, another factor, such as periodic violent agitation in the atmosphere, must be involved too.

Few lapilli have grown round nuclei, and their centres usually consist of ash similar to the matrix of the rock. It is thought that water was the agent responsible for holding the material together in the air. Volcanic eruptions are accompanied by large quantities of steam, which condense into droplets as it cools, and ash could have coagulated round these to form the lapilli in the tuff at the volcanic centre. The decrease in grain size towards the edges was caused by a decrease in temperature and humidity, when the lapilli were forced upwards and away from the vent. Those with several rings, across which the grain size decreases, occur in bands, and were formed in turbulent air conditions, when the lapilli were pushed up and down more than once; this is analogous to the rings that accumulate round hail stones, when they are jostled up and down in thunder clouds. So the lapilli were formed from clots of wet ash soon after leaving the vent, and the fact that the size of material that could stick to them became less with decreasing humidity caused the fine grained margins and rings, and ensured that the rings are always continuous.

Although this appears to be the first documented occurrence of accretionary lapilli from a carbonatite centre, they are not a unique phenomenon. They have been observed to fall with rain through volcanic ash, or have been seen soon afterwards at some recent eruptions. They have been recorded by Scrope (1829) and Jaggar (1921) at Vesuvius, and at Hawaii by Perret (1913), Stearns (1925) and Macdonald (1949). Moore and Peck (1962) give a summary of occurrences of all ages in the United States, and their conclusions are in general accepted, as the lapilli on Rangwa have similar characteristics. They say that lapilli occur in poorly stratified air fall tuff, a definition that fits the Banded Tuff on Rangwa well. The size range they give for the major axis is between 2 and 10 mm, with the majority between 2 and 4 mm; the ones found on Rangwa are rather larger, and many have long axes of over 10 mm. Their ratio of major to minor axes is between 1:1.40 and 1:1.70, and the ratios on Rangwa fall between 1:1.30 and 1:2.20, with an average of 1:1.60. In their examples, there are more broken lapilli when the matrix of the tuff is coarse, a feature which was not noticed on Rangwa. Their textural description tallies well, and they give the cause as condensation of volcanic steam or showers of rain falling into clouds of ash. They do not think that the lapilli were cohesive enough to survive falling into water.

The lapilli give useful information concerning the amount of compaction in the tuff. The average length of the minor axes relative to the major ones is 62% (or 1:1.60) for the samples collected. Although sampling was obviously by no means complete, this figure is probably near to the true average, as half the specimens with lapilli have minor axes that are between 56% and 67% of the major ones. It has been shown that the larger the other fragments in the tuff, the less the compaction; the reason is that large fragments which were rigid when the tuff was deposited provide a framework that prevents compaction. The total thickness of Banded Tuff at the southern part of Rangwa today is at least 4,000 ft., and prior to compaction there must have been a thickness of up to 7,000 ft. Presumably some of it happened penecontemporaneously, but more must have been due to the weight of succeeding volcanics, and it is a potential source of gradual subsidence.

All the tuffs were erupted from a central source, and represent a waning phase of activity from the vent of the Lower Agglomerate (Figure 21). The ash falls covered the whole area of the crater caused by the Lower Agglomerate, falling into a crater lake in the northern part, and into a dry environment in the south, so that, though ash with lapilli fell throughout, the lapilli were destroyed by the water in the north. The interfingering between the two types of tuff shows that the size of the lake varied, and occasionally it must have dried up, as there are some exposures of lapilli tuff to the north (RF 20), but they are red and altered, because water has percolated down to them, and they are succeeded by Bedded Tuff, which may break the lapilli below (RF 10), or pick up bits of them (RF 47). RF 167 demonstrates that the lake sometimes penetrated to the south of Rangwa, as Bedded Tuff is seen to flow over Banded Tuff. As it is today, the base of the Banded Tuff must have been slightly higher than the Bedded Tuff, and it tended to be banked up against the wall of the crater, to give it an original inward dip of about 15°, whereas the Bedded Tuff was always more or less level.

It will be shown in Part III that the only tuffs equivalent to the Tuff Group that survive away from Rangwa are to the north, and their deposition depended on the prevailing wind direction.

C. UPPER AGGLOMERATE.

The Upper Agglomerate was formed after the consolidation of the Tuff Group, as it consists largely of fragments of Bedded Tuff. It contains a few fragments of matchable basement and plutonic rocks, and its area of outcrop is to the north of the centre of Rangwa; so presumably it was caused by a vent that pierced the country rock in a new place (Figure 22).

The incipient rounding of even the largest tuff fragments, and the reaction rims round the basement fragments suggest that, as for the Lower Agglomerate, the mechanism of emplacement was gas drilling. The amount of material that was pushed out from the vent is small, as not much survives away from Rangwa, and the vent is still cluttered up with the rocks that were there prior to the drilling and have not been moved far.

The outcrop pattern shows that the boundary dips inward steeply, and the originally circular vent was about a mile across. Inward-dipping flow banding is not present. These features indicate that the Upper Agglomerate represents a lower level in the fluidisation column than the Lower Agglomerate, and the vent is, therefore, closer to Williams' "Navajo" than "Hopi" type. Presumably lower down the vent narrows farther.

D. SUBSIDENCE OF THE PYROCLASTICS.

The subsidence of the pyroclastics is one of the most enigmatic events in the history of Rangwa. It has been shown in the structural section that the pyroclastics are surrounded by a ring fault, which threw their outer boundary at least 1,500 ft. down, and dips round the edge have been steepened by more than 10°. The faulting and steepening of dips must have preceded all the carbonatite intrusions within the pyroclastics for these reasons:-

1. If the steepening of the dips had been later than the intrusion of the small carbonatite conesheets and dykes, the dips of the conesheets would have been steepened too; by correcting them (Figure 30) and reversing the fault, their foci of origin would be impossibly high in the volcanic superstructure.

2. If the faulting had postdated the intrusion of the carbonatite conesheets and dykes, the basement and plutonic rocks to the southeast of Rangwa would have been at a lower level with relation to the carbonatite intrusions than they are now; therefore many more small intrusions of late carbonatite would be expected in them.

Away from the edge of Rangwa, few dips could be measured in the pyroclastics, and those that were are ambiguous. So, although the stage in the evolution of Rangwa at which the subsidence took place is relatively certain, the nature and cause of the subsidence are conjectural.

Subsidence of an area the size of Rangwa must have caused the formation of a caldera, the reverse of today's relief pattern. If the subsidence is related to the explosive eruptions of nephelinite agglomerate at the centre, it has affinities with Williams' Krakatoan type of caldera (1941). This relationship cannot be proved, but some features do occur on the Kisingiri Volcano, which are similar to those associated with calderas elsewhere (Holmes 1965, pp 339 - 344):-

1. The size of Rangwa ($4\frac{1}{2}$ x $3\frac{1}{2}$ miles) is not far different from that of many other calderas. It is rather larger than Kilauea (3 x 2 miles), about the same size as Krakatoa ($4\frac{1}{2}$ x 4 miles) and smaller than Crater Lake, Oregon ($6\frac{1}{2}$ x $6\frac{1}{2}$ miles).

2. Most of the material on the caldera floor (i.e. the Rangwa pyroclastics) has not been blasted out. About 80% of the area of Rangwa is covered by pyroclastics which were there prior to the subsidence.

3. Sometimes, as in the case of Lake Toba in Sumatra, caldera formation is preceded by doming of the surrounding area. This happened around Rangwa at a very much earlier stage, prior to most of the volcanic activity.

4. As at Krakatoa, volcanic activity (the higher nephelinites, some of which contain carbonatite fragments) was resumed after the subsidence, and the possibility of several episodes of subsidence must not be overruled.

5. Steepening of dips at the edges of subsided blocks has been observed at other centres. For example, in three of the cauldrons in the Oslo area (Oftedahl in Reynolds 1956), and at Glencoe (Bailey and Maufe 1916), marginal lavas have been tilted, and, in some cases, overturned.

However, some features often associated with cauldron subsidence and calderas (Reynolds 1956) are either obscured or lacking. No fluidised breccias are exposed along the fault plane, and few radial faults cut the subsided pyroclastics.

The dip of the plane of the boundary fault cannot be determined, and the mechanism of subsidence is not known. It may be supposed that Rangwa subsided when its support from the magma chamber below was removed, and this probably happened when nephelinite agglomerates were erupted from the centre on a large scale.

It cannot be proved that the centres of any of the other alkaline volcanoes in Western Kenya or Eastern Uganda subsided in the same way as Rangwa. The older centres in Uganda, Tororo, Bukusu, Sukulu and Toror are too deeply eroded for subsidence to be recognized if it occurred. Elgon (Davies 1952) and Tinderet (Binge 1962) are both far less eroded than the Kisingiri Volcano. If the centres of either of these volcanoes subsided, any evidence for subsidence would be hidden beneath nephelinite agglomerates and lavas. Of the volcanoes where the amount of erosion is intermediate, no subsidence can be proved at Mount Moroto within the comparatively small erosion caldera (Varne 1963), and of the two tectonic interpretations of Napak King (1948) does not give any evidence for subsidence, whereas Trendall (1961) believes that most of the area within the inward-facing volcanic scarps subsided. If Trendall's interpretation is correct, a quite different type of subsidence must have happened at Napak, since only a small part of the area within the volcanic scarps subsided on the Kisingiri volcano.

Elsewhere in East Africa, calderas have been formed at alkaline volcanoes of a very wide range of types, ranging from nephelinitic to trachytic, and from predominantly lava to pyroclastic. The most spectacular ones are the Giant Craters of the Eyasi Rift of which the largest is Ngorongoro (Wilcockson 1964), and Suswa and Menengai in the Gregory Rift; both the latter calderas are associated with eruptions of ignimbrites (McCall 1963). It is concluded that the level of erosion on Rangwa is unusual rather than the occurrence of subsidence.

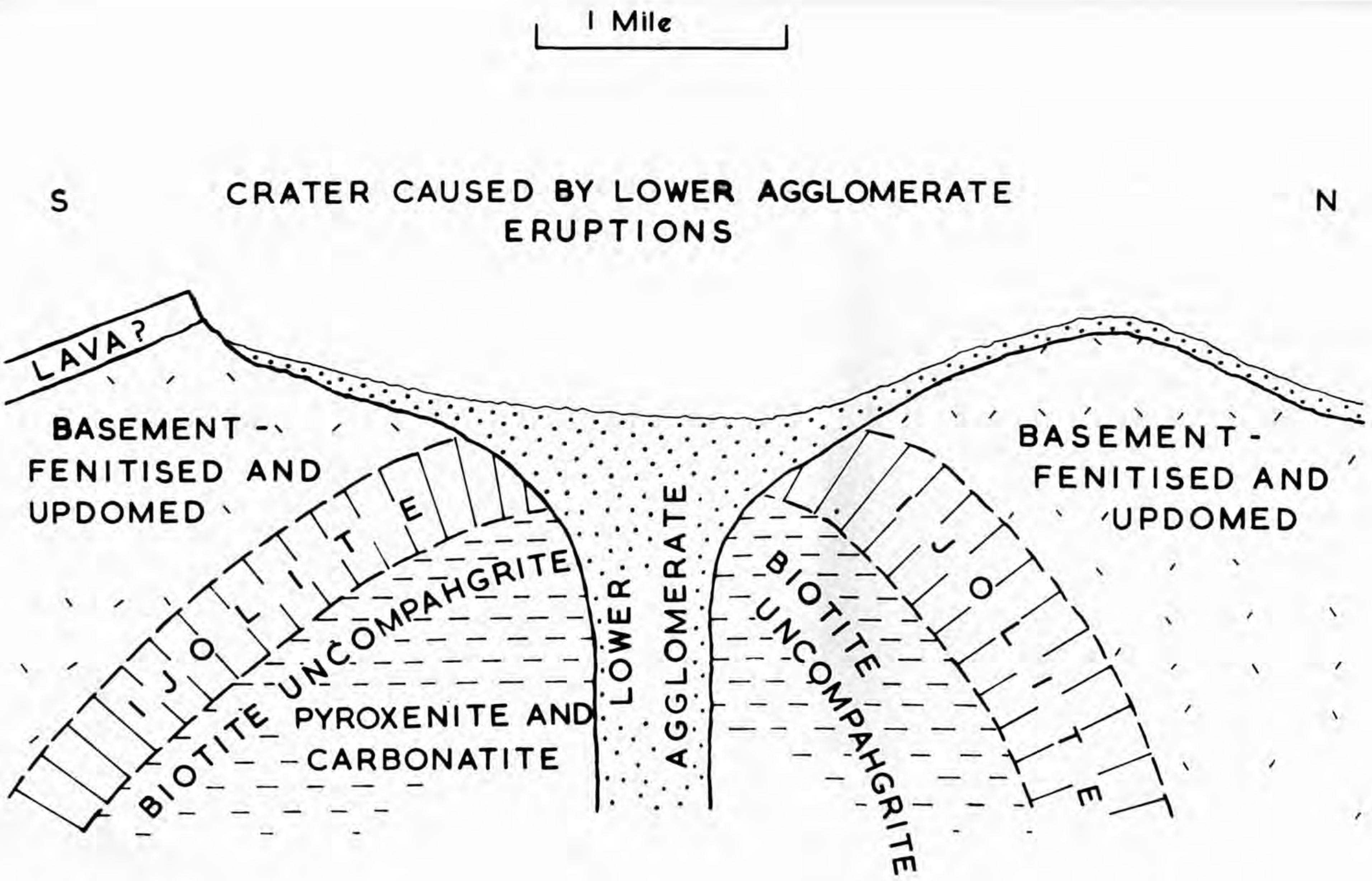


FIGURE 20. PROBABLE SECTION ACROSS RANGWA AFTER THE ERUPTION OF THE LOWER AGGLOMERATE.

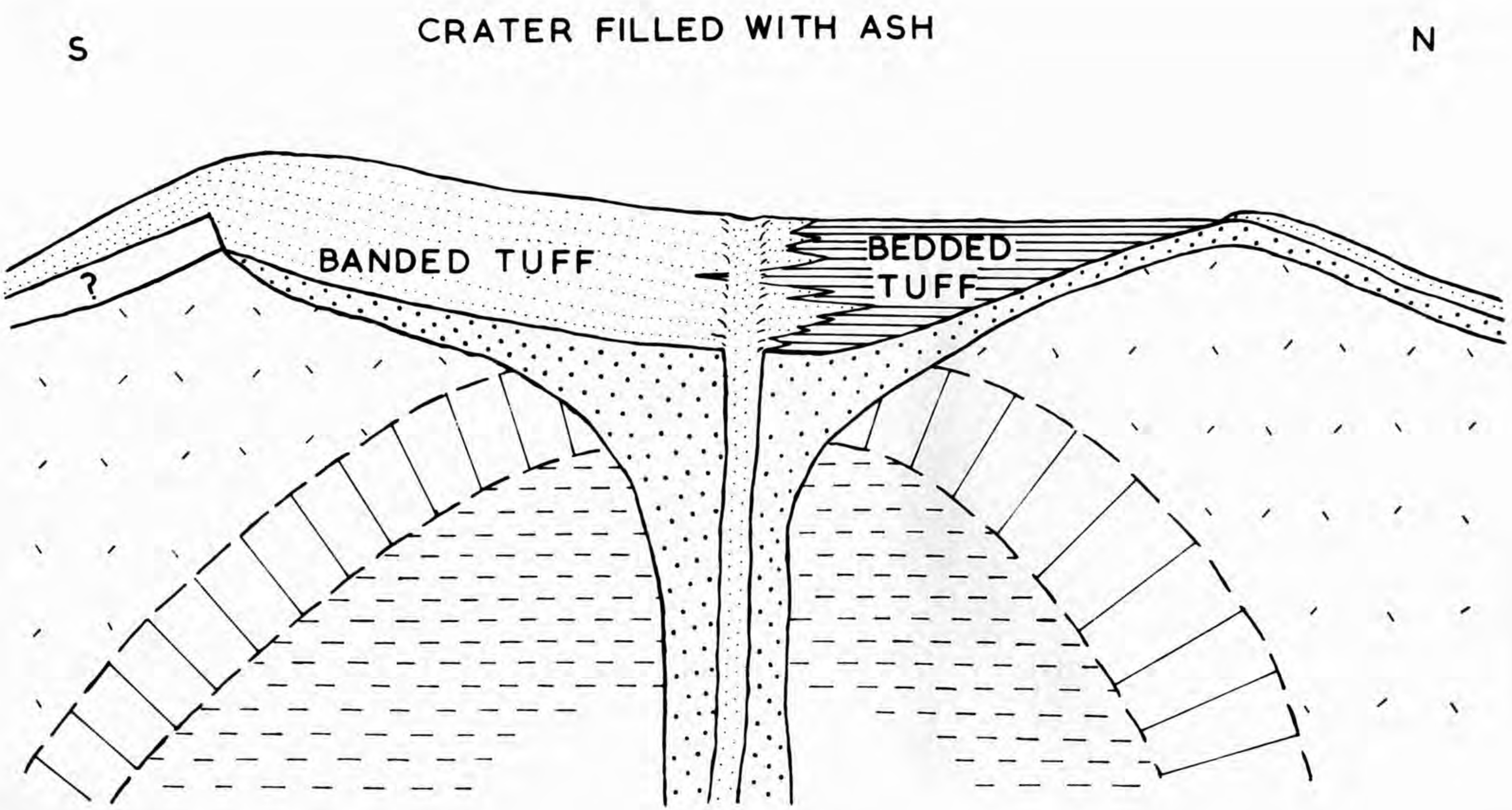


FIGURE 21. PROBABLE SECTION ACROSS RANGWA AFTER THE ERUPTION OF THE TUFF GROUP.

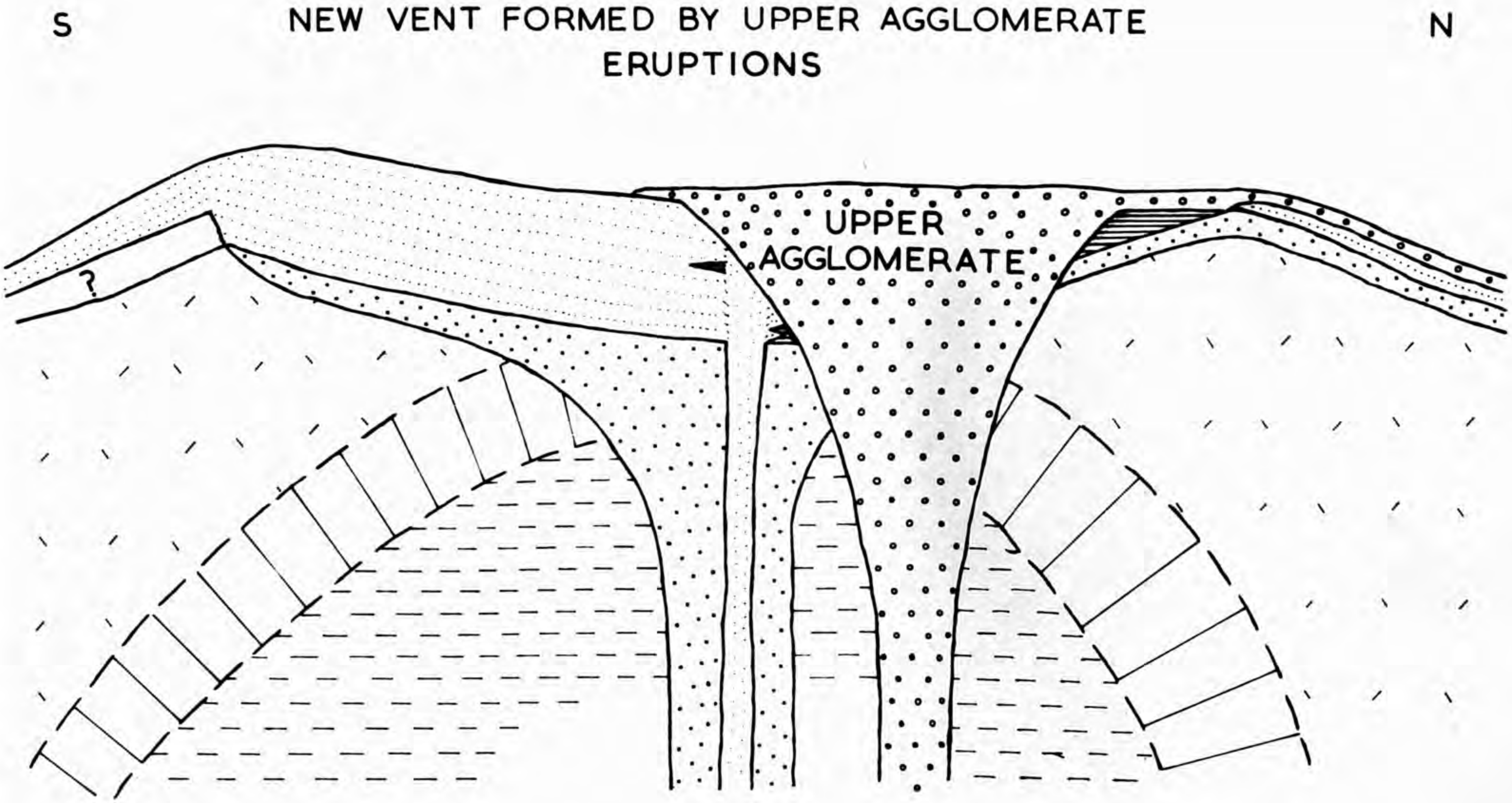


FIGURE 22. PROBABLE SECTION ACROSS RANGWA AFTER THE ERUPTION AND EMPLACEMENT OF THE UPPER AGGLOMERATE.

THE EXTENT OF SUBSIDENCE IS PROBABLY EXAGGERATED.

SUBSIDENCE OF THE CENTRE OF THE VOLCANO ACCOMPANIED BY THE ERUPTION OF SOME NEPHELINITE AGGLOMERATE

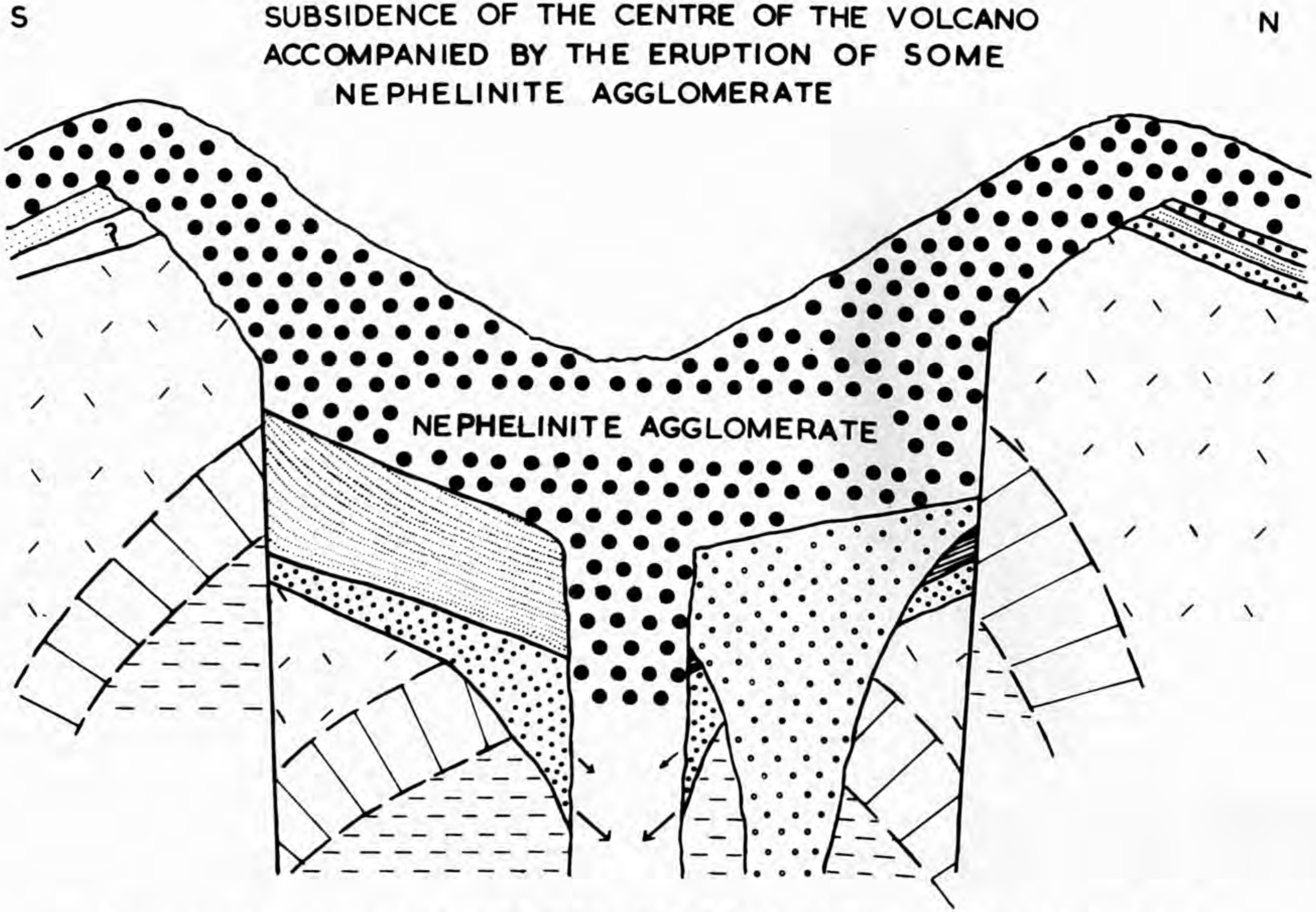


FIGURE 23. INFERRED SECTION ACROSS RANGWA AFTER THE MAIN SUBSIDENCE.

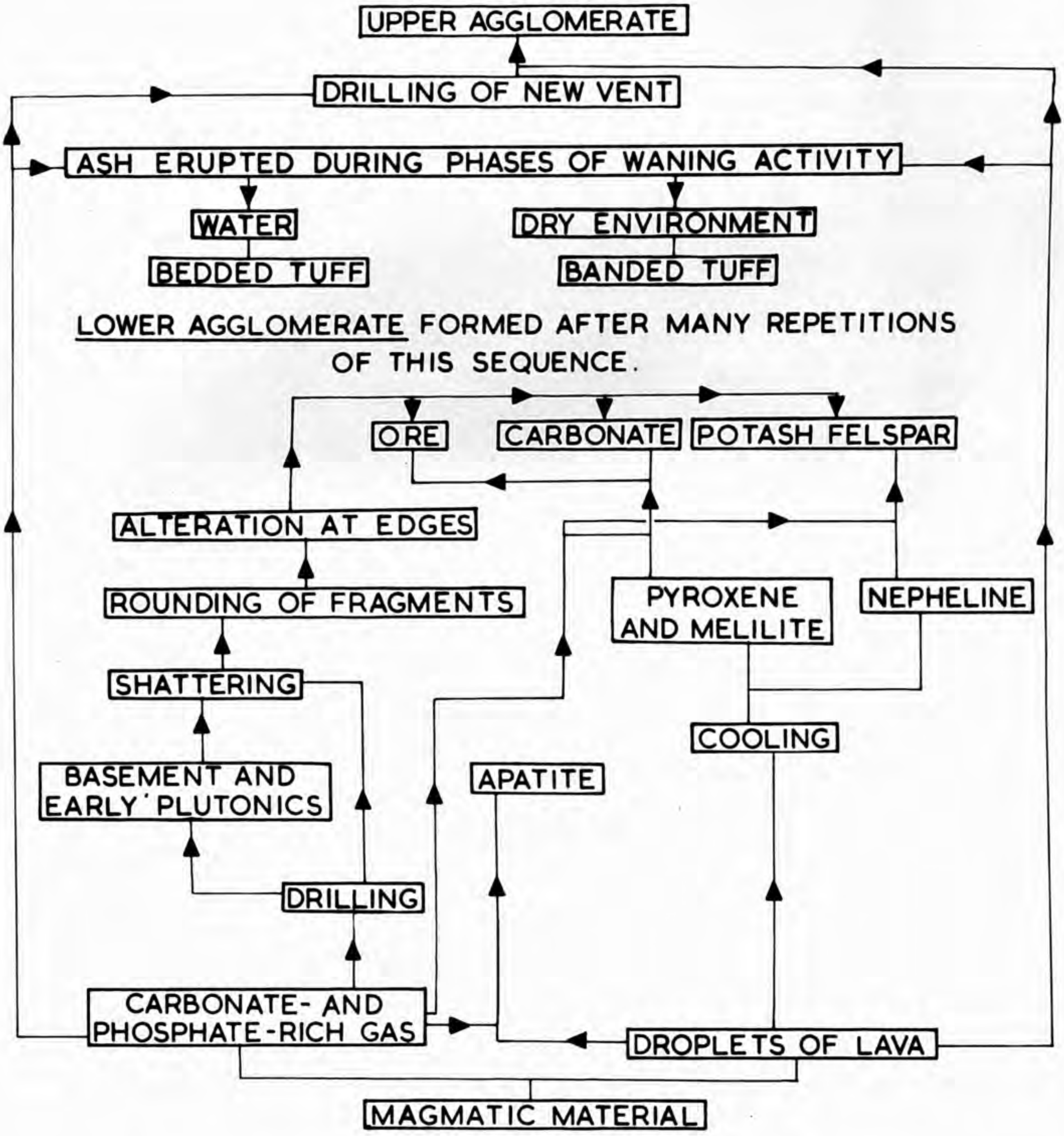


FIGURE 24. DIAGRAMMATIC REPRESENTATION OF THE MODES OF FORMATION OF THE PYROCLASTICS.

VIII

THE LATE CARBONATITES

Carbonatites and the rocks which have been altered or brecciated by them comprise the only major group of rocks on Rangwa apart from the pyroclastics. Including the areas of presumed carbonatite and breccia that are covered by the alluvium and gravel on the floor of Nyakirangacha, they account for nearly 20% of the area of Rangwa. Their field relations and appearance in hand specimen enable them to be divided into three groups:-

Small conesheets and radial dykes.
Ekiojango Carbonatite and Breccia.
Kinyamungu Carbonatite and Breccia.

The divisions are partly related to the history of emplacement of the carbonatites, and it will be shown that most of the small dykes and conesheets were emplaced before the Ekiojango Group, and the Ekiojango Group before the Kinyamungu Group (Figure 25). However, not all the dykes and conesheets are early, and there is a late episode of red dykes, which will be described with the Kinyamungu Group. The petrographic distinction between the two groups is sometimes blurred, and each one may well be split into several episodes.

The groups used are the most convenient and logical sub-divisions available, but they are not sharply defined and their

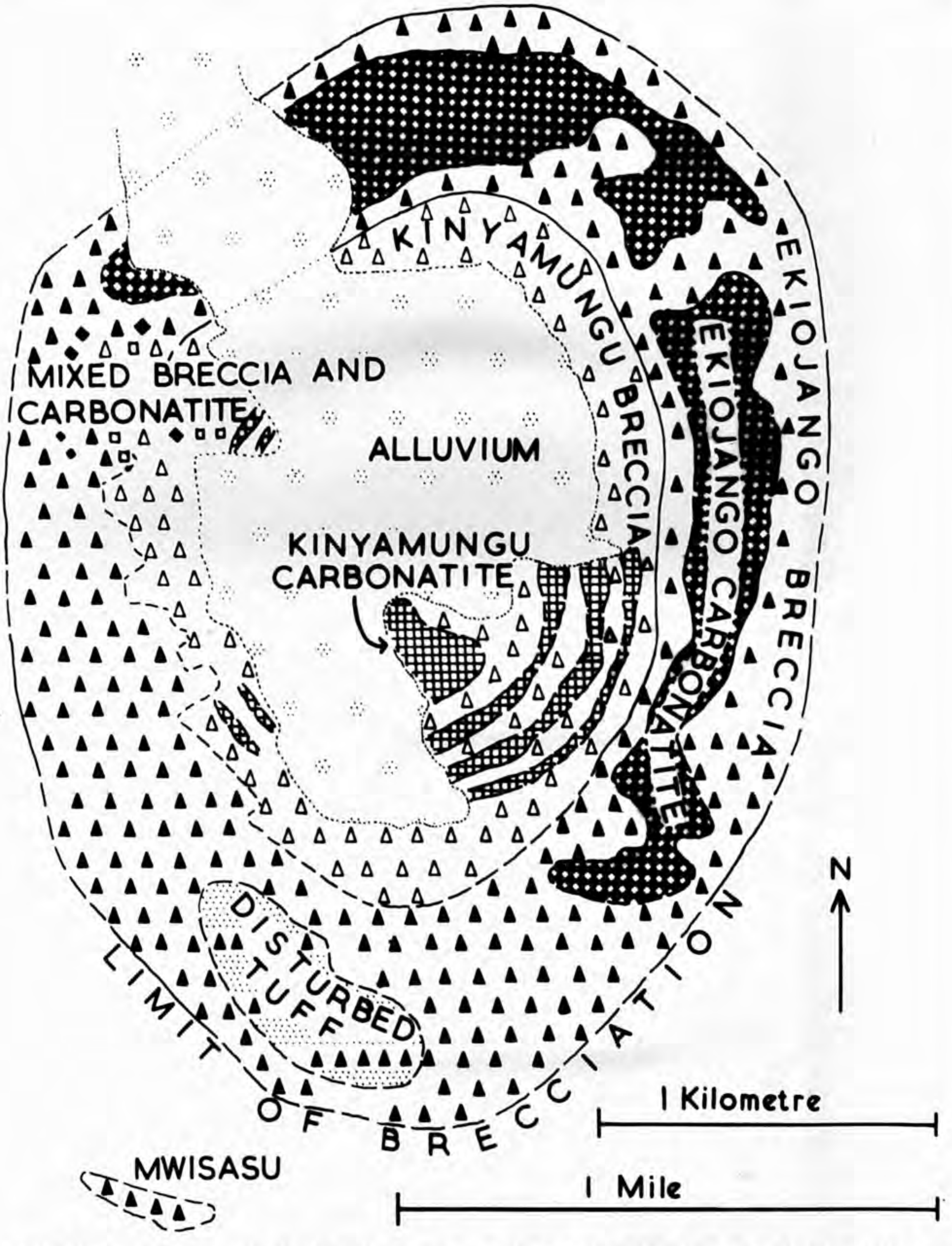


FIGURE 25. SIMPLIFIED GEOLOGICAL MAP SHOWING THE OUTCROP PATTERN OF THE BRECCIAS AND CARBONATITES IN NYAKIRANGACHA.

limitations will be discussed in the section on age relations.

1. DISTRIBUTION.

Apart from the small conesheets and dykes and the carbonatite on Mwisasu, all the carbonatites and breccias caused by them occur in and around Nyakirangacha. The shape of their area of outcrop is a rough oval, which is $1\frac{1}{4}$ miles from north to south, and $\frac{3}{4}$ of a mile from east to west. It is slightly to the north of the centre of the larger oval formed by the outcrop pattern of the pyroclastic groups (Figure 25).

A. THE SMALL CONESHEETS AND RADIAL DYKES.

The small conesheets and radial dykes are seen among the pyroclastics almost wherever the exposure is good, and over two hundred of them were found on Rangwa. Since they are discontinuous and seldom more than 10 cm across, and their hardness is much the same as that of the host rock, they are not prominent, and the distribution pattern which survives is by no means complete.

They occur all along the northern and eastern boundary cliffs of Rangwa, and they are especially frequent on Kumuthua and Muitherere, the northern slopes of Kinyathengo, and the tops of Kurugitho and Ikiwathi. The only extensive exposures of pyroclastics where few small conesheets and dykes occur are those of Banded Tuff at the south east and south.

B. THE EKIOJANGO CARBONATITE AND BRECCIA.

The Ekiojango group forms a discontinuous ring round Nyakirangacha. In the northeast and east the ring is well formed, in the south and west it is disrupted by faulting and partly cut out by the Kinyamungu Group, and, in the northwest it is covered by alluvium at the outlet of Nyakirangacha. The ring is widest near Mwisoma, where its width is 450 yards.

The carbonatite is flanked on both sides and sometimes capped by the associated breccia, and it normally occupies relatively lower ground than the breccia. This will be evident if the rock types and topography they cause are followed in a clockwise direction, starting in the north. Breccia and carbonatite are closely involved together, and for purposes of mapping, a rock containing more than 50% carbonatite was classified as carbonatite, and less than 50% as breccia. The top of Ikiwathi and its south facing cliff are breccia; so is the steep ridge of Kisoi, but the valley between them is floored by carbonatite. The rocky breccia hill of Mwisoma rises at the head of the valley (plate 129), and its base is surrounded by carbonatite at much the same level all the way round. Apart from some outward facing cliffs south of Omwoyo, the transition from pyroclastics to their brecciated counterparts is not marked by any topographical feature, but the inner boundary of the inner zone of breccia is a curved scarp, running from Kisoi to south of Ekiojango (plate 130). The breccia tends to form cliffs on either side of the carbonatite. These constitute the irregular scarp round the upper slopes of Nyakirangacha, and the outward facing cliffs on the two dykelike features on Ekiojango. Kinyuka is a rocky capping of breccia like Mwisoma.

North of Erikende, the carbonatite disappears beneath the breccia, and an irregular patch of carbonated tuff several hundred yards across rests on the breccia but has little topographical expression. North of Mwisasu, the outer boundary of the breccia is marked by several large cliffs, and the connecting ridge between Erikende and Kumuthua as well as the tops of Kumuthua and Muitherere are composed of breccia. No large outcrops of carbonatite were found south or west of Nyakirangacha. On Eriauruma, the Ekiojango Group is cut out by the Kinyamungu Group, so that the ring is broken.

The top of Mwisasu, half a mile to the southwest of the main ring, is a ridge of carbonatite and breccia, similar to those of the Ekiojango Group, with which its rocks will be described. The outcrops form an arc that is concentric with the main ring and about 200 yards long.

C. THE KINYAMUNGU CARBONATITE AND BRECCIA.

The Kinyamungu Group probably occupies the floor of Nyakirangacha, but it only projects above the present day level of

Plate 129. The valley between Ikiwathi and Kisoi from the west. Carbonatite is exposed in much of the valley; the cliffs on either side and Mwisoma in the background consist of breccia.

Plate 130. Mwisoma and Kinyuka from the south. Both are rocky hills of breccia underlain by carbonatite.

Plate 131. The north east part of Nyakirangacha. Engima is at the bottom right. The inner boundary of the Ekiojango Breccia is a discontinuous line of cliffs. The Ekiojango Carbonatite occurs behind them; the cliffs higher on the slope mark the outer boundary between carbonatite and breccia. The pyroclastics of Kinyathengo and Kurugitho occur in the background.

Plate 132. The south east part of Nyakirangacha. Kinyamungu is in the foreground. The inner boundary of the Ekiojango Breccia is marked by cliffs. Kurugitho, Kithamweni and Erikende occur in the background.

Plate 133. Engima from the north east. Muitherere and Eriauruma are in the background.

Plate 134. The cliffs on Muitherere, which are thought to be fault scarps.

the alluvium at several places. The two small hills, Kinyamungu and Engima are composed almost entirely of carbonatite. Kinyamungu is a north-west-south-east ridge, which joins the side of Nyakirangacha in the south where it rises to about 250 ft. above the valley floor, and has cliffs on each side (plate 132). Engima is a collection of several carbonatite knobs 300 yards north of Kinyamungu, 150 ft. high and precipitous on all sides (plate 133). Several isolated exposures of Kinyamungu Carbonatite and Breccia poke up through the alluvium between Kinyamungu and Engima, south of Kinyamungu and at the bases of Kumuthua and Eriauruma. At these exposures, breccia is interspersed with carbonatite. The floor of Nyakirangacha is littered with loose blocks of both.

The only outcrops of the Kinyamungu Group which are away from the valley floor are on Eriauruma, a rocky hill that consists of an intimate mixture of carbonatite and breccia of both groups [illegible].

2. DESCRIPTION OF THE ROCK TYPES.

A. THE SMALL CONESHEETS AND RADIAL DYKES.

With a few exceptions, the conesheets are 2 - 8 cm thick (plate 135), and dip towards the centre of Rangwa at $15^\circ - 40^\circ$; the dykes are the same thickness, and are normally radial and within 10° of the vertical. The conesheets often follow the banding and bedding planes of the pyroclastics, but sometimes they are partly transgressive, so that they have a zigzag appearance (plate 136). The dykes always cut the conesheets, but are not so frequent. Both usually occur singly, although on Muitherere and Ikiwathi, there are swarms of conesheets, which merge and split over short distances (plates 137 and 138). Except on Ikiwathi, where they tend to be rather thicker, and one dyke can be traced for over a hundred yards, the conesheets and dykes cannot be followed from exposure to exposure.

On weathered surfaces they are pale grey in contrast to the darker pyroclastics (plate 135), but weathering affects both of them at the same rate. It is often possible to see that they are multiple, and later ones tend to occur in the middle of earlier ones; there is one case of a dyke that has been emplaced in three stages.

(1) THE NORMAL TYPE.

The normal type includes the whole group but for three large radial dykes on Ikiwathi. Petrologically the conesheets and radial dykes are similar; both are composed of carbonate and noncrystalline brown material. The carbonate is a mosaic of cloudy anhedral crystals, whose size varies between .2 and .4 mm, and which seldom have parallel orientation or show straining. In marked contrast to the Ekiojango Carbonatite, the cleavage planes are not seen, and

Plate 135. A carbonatite conesheet, with included fragments of agglomerate on Manganga.

Plate 136. A carbonatite conesheet, partly following the bedding of the Bedded Tuff on Manganga.

Plate 137. A radial carbonatite dyke cutting a carbonatite conesheet on Manganga.

Plate 138. A radial carbonatite dyke cutting a carbonatite conesheet, which intrudes one of the large carbonatite dykes on Ikiwathi.

Plate 139. Small cross-cutting carbonatite dykes and conesheets on Ikiwathi.

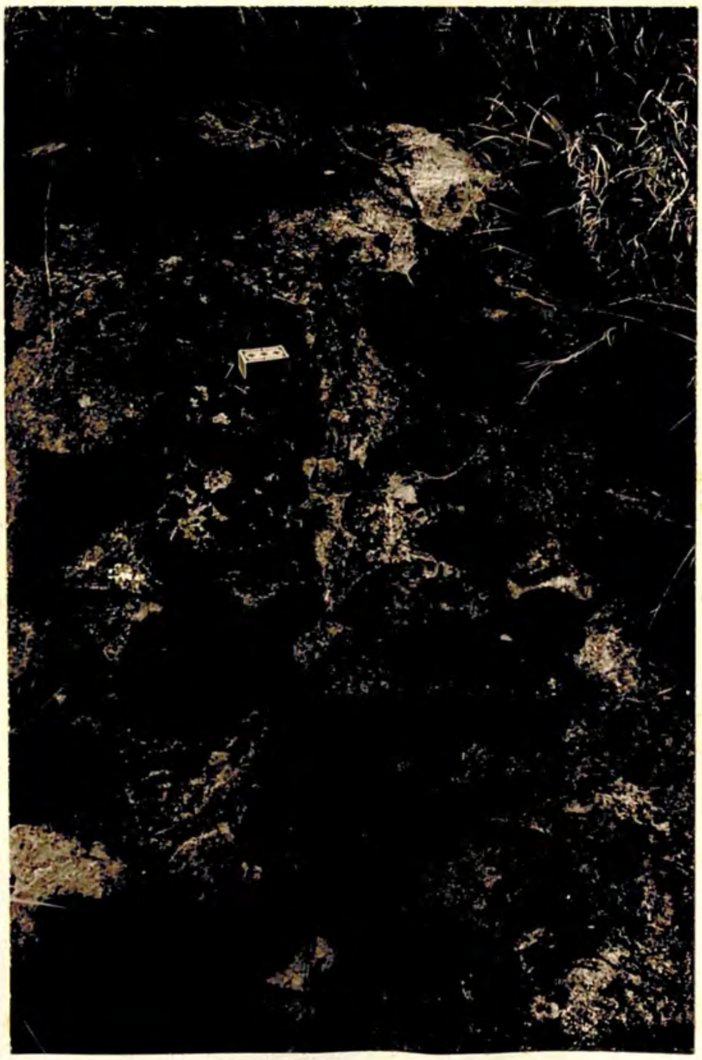


Plate 140. Breccia with a carbonatite matrix at the edge of a large carbonatite dyke on Ikiwathi.

twinning is rare.

The amount of brown material varies systematically which gives the rock a banded appearance in the field (plate 137), where rough parallel streaks of brown and pale grey can usually be seen. The brown material is present either as rims round carbonate crystals (RF 28, plate 141), or as small schlieren up to 3 mm long (RF 33, plate 142). Since most of the specimens are fresh, and the brown zones are well-defined, it is unlikely that they were caused by weathering.

Apart from patches of felspathised wall rock, which will be described presently, and the occasional apatite crystal, the carbonate contains no other recognizable minerals or pseudomorphs.

Specific gravity measurements on the purer specimens, most of which fall between 2.60 and 2.70, and staining with alizarin sulphonate did not reveal any carbonate other than calcite; so the rock type is alvikite.

There is no change in texture or crystal size at the margins of the dykes or conesheets, and the rock has an even texture right up to the boundaries between the phases in the multiple ones (RF 65, plate 143). The main distinction between the phases is that the later are normally less brown than the earlier, a feature shown by RF 65, in which a banded brown rock with slightly strained and orientated carbonate crystals is cut by paler carbonate. The boundary appears sharp in hand specimen, but is in fact blurred by the growth of carbonate crystals across it.

(2) THE DYKES ON IKIWATHI.

On and close to Ikiwathi, two unusual varieties of carbonatite occur as dykes. One of them forms two vertical radial dykes near the top of Ikiwathi. Both have variable widths which may be as much as 100 yards, and they can be followed for several hundred yards. They run north-south, and are traceable right up to the Ekiojango Breccia. They cut some of the small conesheets and are cut by both dykes and conesheets (plates 138 and 139). The wall rock is brecciated, and, in places, fragments of it are engulfed, but the dykes themselves are brecciated close to the Ekiojango Carbonatite (plate 144). In the field they have a "porphyritic" appearance with large white carbonate crystals protruding from a brown matrix. These crystals are up to 15 mm long, and are anhedral, with ragged edges, as if they are partly absorbed by the matrix (plate 145). They are strained and show twinning. The matrix consists of fine-grained carbonate often rimmed with brown material and is similar to the normal type. Both matrix and large crystals were proved to be calcite by staining with alizarin sulphonate.

The second variety is represented by one wide vertical dyke, which can be traced for a limited distance below the western slopes of Ikiwathi. It runs north-west-south-east, and is responsible for

Plate 141. Carbonate crystals rimmed by brown material in a small carbonatite dyke. (RF28). x55

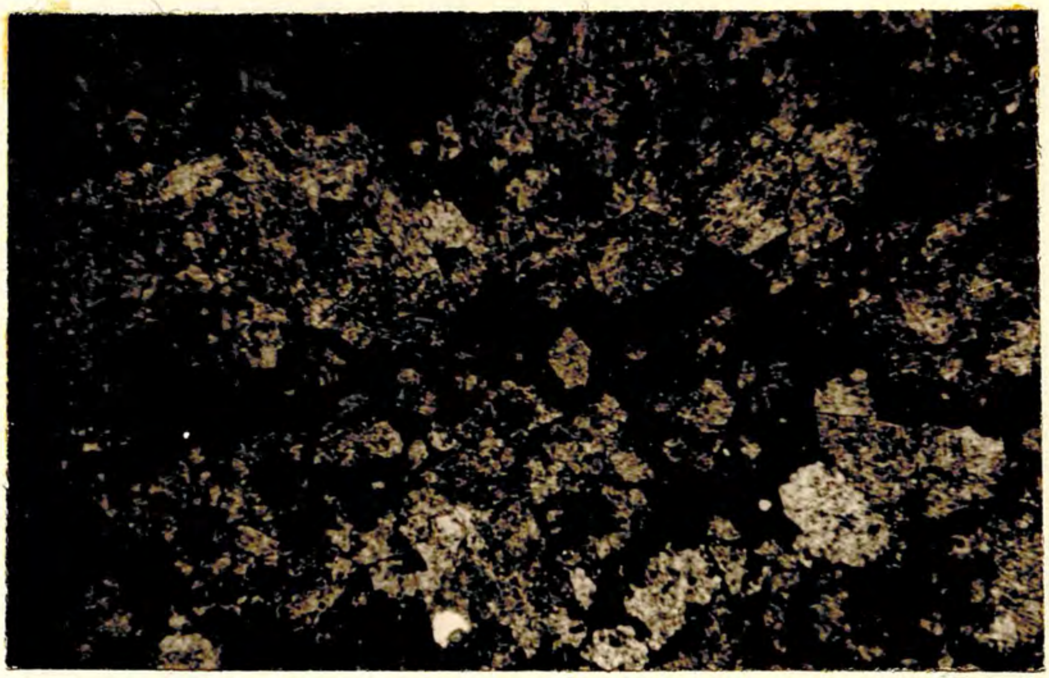


Plate 142. Carbonate crystals with schlieren of brown material from a carbonatite conesheet. (RF33). x85.

Plate 143. Boundary between phases in a multiple carbonatite conesheets. The pale carbonate is intrusive into the dark. (RF65). x25.

Plate 144. Brecciated carbonatite dyke on Ikiwathi.

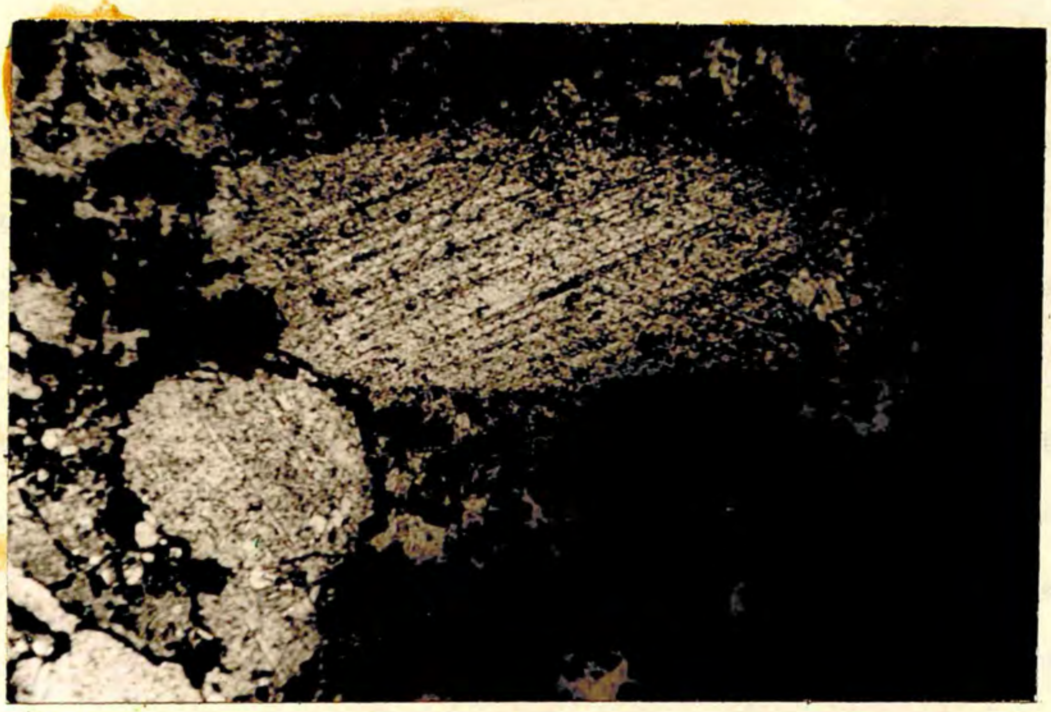


Plate 145. Ragged large carbonate crystals surrounded by fine-grained carbonate from one of the large carbonatite dykes on Ikiwathi (RF314). x25.

Plate 146. Euhedral brown-rimmed carbonate crystals, surrounded by fine-grained carbonate, from the carbonatite dyke west of Ikiwathi. (RF315). x25.

the only exposures of rock in the gap between Ikiwathi and Mbuwi. It, too, is "porphyritic" and contains large carbonate crystals, some of them over 20 mm long, which are rimmed by dark red-brown borders of noncrystalline material up to 2 mm thick (plate 146). Staining shows that the large crystals are calcite, but it is thought that they have been altered from carbonate containing iron or magnesium which has accumulated round the edges. The matrix is an intergrowth of clear carbonate crystals with an average grain size of 2 mm. Age relations of this dyke are unclear, as it is not seen in conjunction with any other rock type. The only other exposure of carbonatite with similar, though smaller, "porphyritic" crystals coated with brown material that was found occurs within the Ekiojango Carbonatite, north of Mwisoma.

(3) ALTERED WALL ROCK AND INCLUDED FRAGMENTS.

The conesheets and dykes have a noticeable effect on the agglomerate and tuff into which they were intruded. The alteration takes the form of intense felspathisation combined with indiscriminate spreading of amorphous brown material. Despite the previous felspathisation and carbonation of the pyroclastics, the textures of the original rocks are preserved elsewhere, but this superimposed alteration destroys them.

Normally felspathisation affects the wall rock up to 30 mm away from the carbonatite. The nearest few millimetres are converted to a rock that contains over 80% felspar, as well as some brown material; further from the carbonatite, the patches of brown material become more prominent, until they are identifiable as actual fragments in the agglomerate or tuff (RF 40, RF 44, RF 120, plate 147). Fragments of wall rock within the carbonatite normally suffer the same treatment, and become entirely felspathised. Their edges become ragged and indeterminate, and it is impossible to identify any pseudomorphs (RF 44). Occasionally, fragments become carbonated.

The felspathised pyroclastics are invaded by a network of crosscutting veisn of felspar which, in turn, are cut and displaced by carbonate veins (RF 40, plate 148). Since the veins of felspar extend into unfelspathised pyroclastics, the wholesale felspathisation must have been caused directly by the carbonatite at an earlier stage than the veins.

Generally, a thin band of carbonate, .5 mm wide, and the thickness of one crystal, runs between the wall rock and the carbonatite. It does not follow the boundary exactly, but strays indiscriminately for up to 2 mm on either side of it. It is presumably a late feature unrelated to the emplacement of the carbonatite.

The felspar that forms is uniform, fine-grained material; it is barely crystalline, and extinguishes patchily. It has been shown by staining to contain potash and its x-ray diffraction pattern

Plate 147. The contact at the edge of a carbonatite conesheet. The texture of the wall rock has been destroyed; the white material in it is fine-grained felspar. (RF44). x80.

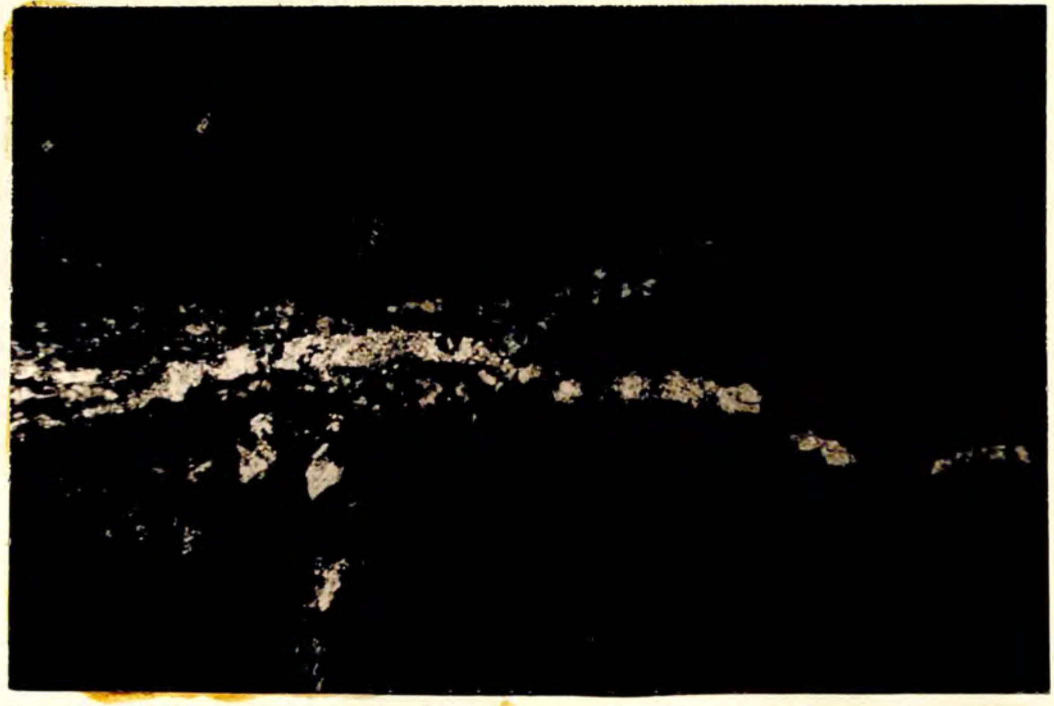


Plate 148. Veins of fine-grained felspar, cut by vein of carbonate near the edge of a carbonatite conesheet (under crossed polarisers). (RF40). x80.

is that of orthoclase, with, occasionally, lesser amounts of microcline. Sometimes it encloses tiny colourless needles of high relief which are thought to be pyroxene.

The importance of the alteration caused by the small carbonatite intrusions is that all stages in the process are shown. In the breccias caused by the central carbonatites, only the end product exists, and it is analogous to the rocks nearest to the dykes and conesheets.

B. THE EKIOJANGO CARBONATITE AND BRECCIA.

The carbonatites and, to a lesser extent, the breccias of this group can generally be distinguished easily from those of nearby exposures of the Kinyamungu Group. However, to the west of Nyakirangacha a gradation exists between the two groups. Parts of the carbonatite on Eriauruma are petrographically similar to the typical Ekiojango Carbonatite, but these grade into carbonatite of Kinyamungu type which contains fragments of Ekiojango carbonatite. The gradational boundary is unmappable here, but the proportion of Ekiojango carbonatite increases outwards and towards the top; the accompanying breccia varies in the same way, and it is impossible to tell to which type much of the breccia on Muitherere and Kumuthua belongs.

(1) CARBONATITE.

The Ekiojango Carbonatite as it normally occupies lower ground

EKIOJANGO CARBONATITE.	KINYAMUNGU CARBONATITE.
COARSE.	FINE.
WHITE.	BROWN AND DIRTY.
CALCITE.	CALCITE AND A LITTLE ANKERITE.
CONTAINS MICA AND APATITE.	CONTAINS MAGNETITE AND PYROCHLORE.
BRECCIATED.	UNBRECCIATED.
BANDING PATTERN DESTROYED.	CONCENTRIC BANDING.
BRECCIA WITHOUT MATRIX.	BRECCIA WITH MATRIX.
CARBONATITE FRAGMENTS IN BRECCIA.	CARBONATITE MATRIX TO BRECCIA.
PYROCLASTIC FRAGMENTS IN BRECCIA.	FEW PYROCLASTIC FRAGMENTS.
LITTLE NEW MATERIAL IN BRECCIA.	PROBABLY MOSTLY NEW MATERIAL.
FELSPATHISATION OF BRECCIA.	FELSPATHISATION AND CARBONATION.
IRREGULAR FINE ORTHOCLASE.	SUBHEDRAL COARSER ORTHOCLASE AND ANORTHOCLASE.
NO INTRUSIVE RELATIONSHIPS.	CARBONATITE INTRUSIVE.

FIGURE 26. THE MAIN DIFFERENCES BETWEEN THE EKIOJANGO AND KINYAMUNGU CARBONATITES.

than the breccia on either side of it, is poorly exposed, and covered with soil. Carbonatite was never found in situ on Mwisasu but is represented by a few boulders from the undergrowth beneath the breccia cliffs. Because of the large amount of brecciation on Mwisasu, a carbonatite mass probably extends under the hill.

The carbonatite is white or yellow and, where it is exposed, it is unweathered. A rough banding is often seen, but the fact that it changes its direction over short distances gives the rock a brecciated appearance. The banding consists of streaks of orientated crystals, particularly mica and sometimes apatite, normally accompanied by disseminated brown material (plate 149). The carbonatite contains varying proportions of angular felspathised fragments (plate 150).

In thin section, the carbonatite is seen to be composed predominantly of large crystals of carbonate, which can be up to 75 mm long (RF 285) but have an average length of 5 mm and are clear, anhedral and highly cleaved. Many of the crystals show polysynthetic twinning. They are seldom strained, but some individual crystals are strained so that the extinction takes up to 20° to move across them (RF 253), or large crystals are broken into pieces by twisting (RF 199). This coarse clear carbonate composes from 60% to 90% of most of the specimens that were examined.

Some fine-grained carbonate, with a grain size of up to .5 mm, occurs in varying quantities between the large crystals and in small

Plate 149. Banding in the Ekiojango Carbonatite, east of Nyakirangacha.

Plate 150. Ekiojango Carbonatite with partly absorbed felspathised fragments, from east of Nyakirangacha.

veins cutting them (RF 199 and RF 285, plate 151). It forms intergrowths of cloudy anhedral crystals which normally occupy continuous veins or streaks, and is therefore thought to be mainly intrusive into the coarse carbonate. However, the coarse material is sometimes partly replaced by the fine (RF 252 and RF 296). Most of RF 296 consists of very fine-grained carbonate with a grain size of only .05 mm, but there are groups of large crystals, whose boundaries against each other are clean, though their outer boundaries are corroded and indented by engulfing fine-grained carbonate. The fine-grained material is arranged in such a way that there are parallel lines of crystals which show similar extinction. In hand specimen, the whole rock appears to be coarse grained, and it seems that the parallel orientations of the small crystals are a relic feature of replaced large ones.

Once (RF 314, plate 152) subhedral crystals of clear calcite with red-brown rims occur in a finer-grained ground mass. Although smaller, they are similar to the ones in the large carbonatite dyke west of Ikiwathi.

Both specific gravity measurements and staining show that most of the carbonate is calcite in all the Ekiojango Carbonatite, and the rock can properly be called sovite.

Of the other minerals in the Ekiojango Carbonatite, apatite is ubiquitous and is formed in two generations. The first generation crystallized earlier than the carbonate, and is often poikilitically

Plate 151. Fine-grained carbonate between large crystals of carbonate in the Ekiojango Carbonatite. (RF199). x25.

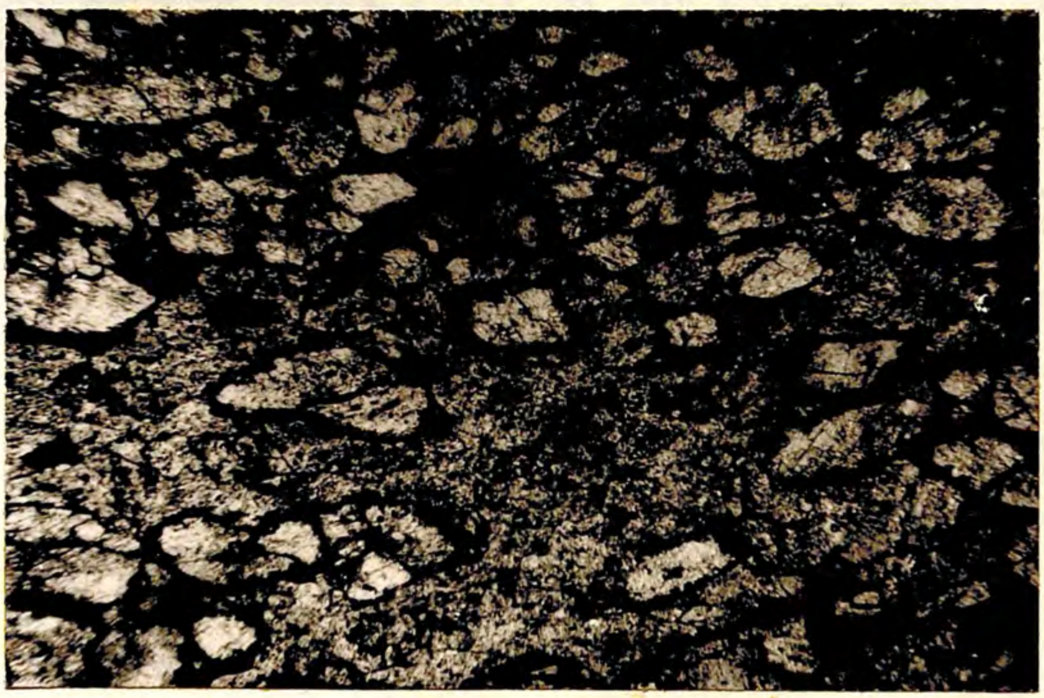


Plate 152. Brown-coated subhedral carbonate crystals in a matrix of finer carbonate from the Ekiojango Carbonatite. (RF314). x25.

enclosed by it. The crystals are between .1 and .4 mm long, and are clear, without inclusions. Both the length and cross sections occur characteristically as ovals, and frequently those near to each other have the same orientation (RF 243 and RF 285, plate 153). The amount of early apatite is seldom great, and RF 243 which contains 5% of it, is an exception. The second generation of apatite is equally widespread, but its habit is different; it formed late, and always occurs interstitially in groups of crystals or irregular veins. The crystals are subhedral, and nearly always have straight edges with each other (RF 246, plate 154). They are up to 1 mm long, and most of them have parallel lines of small inclusions which are normally brown and noncrystalline. RF 285 which includes nearly 10% of the late apatite, contains early apatite also.

Phlogopite is found widely in the group, and is recognizable in the field, since it causes the banding. However, the crystals are very altered, as they normally have ragged edges, and their cleavage planes are bent (plate 155). They are pale brown or almost colourless, and show little pleochroism. The axial angle is very small. Although occurring in distinct bands, the crystals of phlogopite lack any preferred direction of orientation.

Sometimes pyroxene crystals or pseudomorphs occur closely associated with the phlogopite. In RF 246, there are subhedral relics of pyroxenes up to 1 mm long which show characteristic

Plate 153. Rounded apatite crystal in the Ekiojango Carbonatite. (RF243). x155.

Plate 154. Subhedral apatite crystals from a vein in the Ekiojango Carbonatite. (RF246). x155.

Plate 155. Phlogopite crystal with bent cleavage flakes in the Ekiojango Carbonatite. A rounded apatite crystal occurs at the top of the picture. (RF243). x55.

Plate 156. Pseudomorph, possibly after pyroxene, in the Ekiojango Carbonatite. (RF251). x55.

cleavage, but are altered almost entirely to small carbonate crystals and brown material. The pyroxenes never survive completely unaltered, but from the evidence of extinction angles of unaltered patches, it is thought that they originated as aegirine-augite. Usually the alteration is carried so far that none of the original pyroxene survives, and there are some pseudomorphs which defy identification (plate 156).

Pyrochlore is an occasional constituent (RF 312, RF 313, plate 157). Its crystals are seldom longer than .3 mm, and are euhedral-subhedral, showing the cubic or octahedral form, or both. They are mottled and pale brown and have very high relief. The distribution of pyrochlore is sporadic, and does not seem to depend on that of any other mineral, or on any special feature in the carbonatite.

Magnetite was never found, although limonite pseudomorphs after magnetite do occur.

Felspars similar to those associated with the small dykes and conesheets occur both in distinct patches or inclusions in the carbonatite, and in small veins. The former may be of any size and consist of an intergrowth of tiny crystals combined with much brown material. In their composition and lack of texture, these patches bear a marked resemblance to much of the fragmental material in the Ekiojango Breccia, and they are considered to be altered fragments engulfed by the carbonatite. Single zoned felspars occur also

Plate 157. Pyrochlore crystal from the Ekiojango Carbonatite. (RF312). x155.

Plate 158. Zoned felspar crystal from the Ekiojango Carbonatite. (RF243). x155.

(RF 243). The small veins of felspar formed late and intrude the carbonate.

(2) BRECCIA.

The Ekiojango Breccia has a similar relationship with the Ekiojango Carbonatite as the altered wall rock has to the small carbonatite dykes and conesheets. It consists of fragments which have normally been altered beyond all recognition by the action of the carbonatite and they are sometimes surrounded by carbonate or felspar.

In the field, differential weathering shows that the breccia consists of a haphazard mass of closely packed angular fragments. They are often elongated and chip-shaped; their size is variable, but they are normally less than 20 cm in length. There is no orientation or sorting by fragment size. Variable quantities of coarse white carbonate are present as tongues between some of the fragments. A diagnostic feature of the breccia in the field is that even where the boundaries between the other fragments are unclear, angular pieces of carbonatite similar to that of the dykes and conesheets are present, (plate 144).

The fact that most of the fragments are highly altered gives rise to considerable difficulties in the description of the rock. An attempt has been made to describe it in terms of fragments and interstitial material but much of the rock is an obscure mixture of felspars, carbonate and brown material, which it is impossible to subdivide.

(a) FRAGMENTS.

Because of the intense alteration, it is necessary to use rather indirect methods to establish what the fragments were before brecciation. Since the boundary of the brecciation is gradational, the rocks into which the breccia grades, both outwards and upwards, can be seen. Round its outer edge, the breccia merges into shattered pyroclastics, which are generally very weathered. Far more revealing are the outcrops of altered tuff on top of the carbonatite on Mwisasu, and the "island" of tuff that covers some of the breccia north of Erikende. The tuff on Mwisasu has been carbonated; the rock is grey, and still retains the appearance of the Banded Tuff (RF 208), but much of its texture has been destroyed by the invasion of carbonate. This accounts for the high carbonate value obtained from RF 208, which contains 63.83% calcium carbonate, over twice the average for the Tuff Group. The alteration suffered by the tuff on the "island" has been different, as there has been felspathisation rather than carbonation, and the process is gradational. Some of the tuffs are comparatively unaltered, and still retain their banding (RF 270), although the direction of dip may have been changed. However, in most of it (RF 265, plate 160), the banding has been destroyed, the rock has been invaded by veins

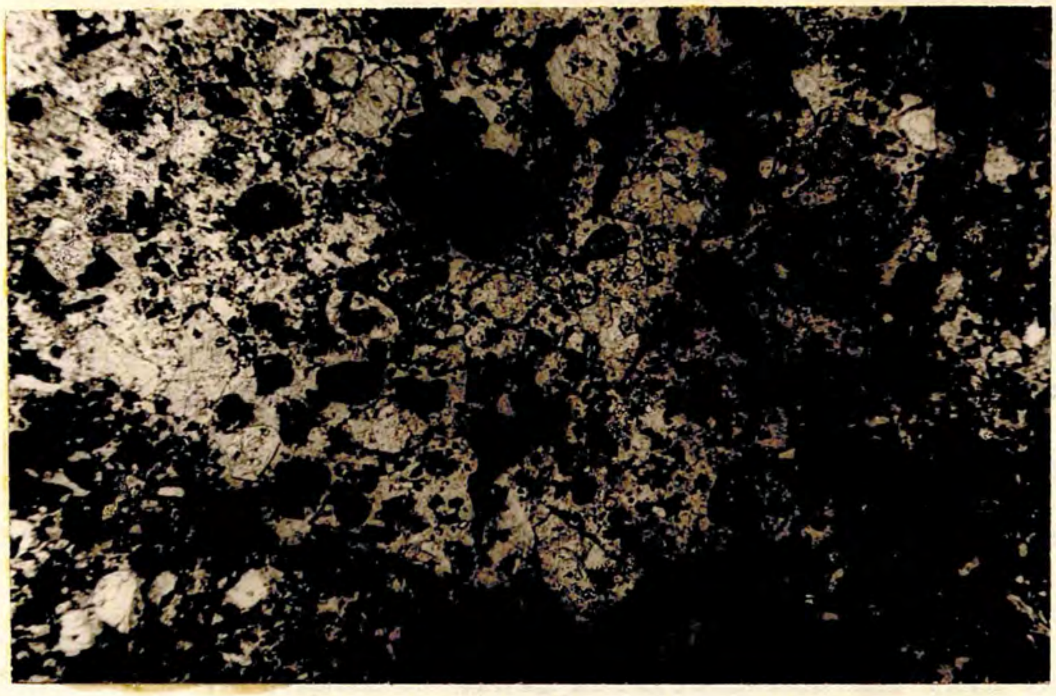


Plate 159. Partly felspathised pyroclastics from the Ekiojango Breccia. The pale material is very fine-grained felspar. (RF265). x55

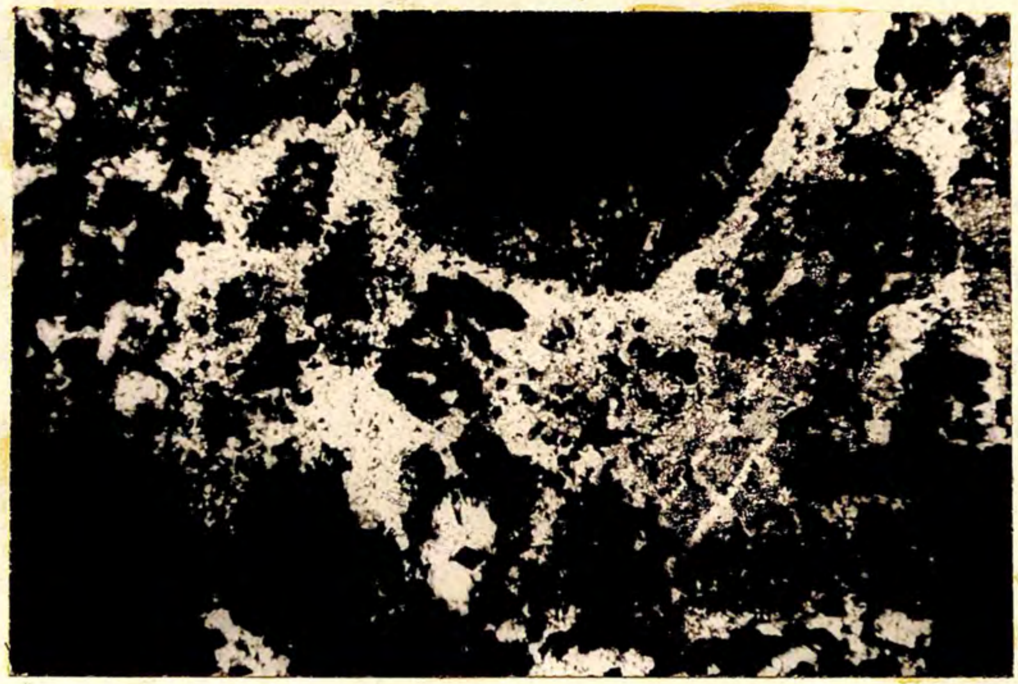


Plate 160. Partly felspathised agglomerate blobs from the Ekiojango Breccia. The pale material is very fine-grained felspar. (RF249). x155.

of felspars, and the fragments have been converted to patches of felspars some of which are distinct and some diffuse. Also much of the matrix has been turned to opaque brown material.

As this transition from normal pyroclastics to brecciated and altered fragments in the Ekiojango Breccia is seen to take place, it is reasonable to conclude that much of the breccia consists of highly altered fragments of pyroclastics. A few fragments show relic texture from either agglomerate or tuff; RF 249 is typical of these. In hand specimen, it appears to be composed of homogeneous fine-grained brown material, but the thin section shows it to consist of angular fragments and within them it is possible to trace the boundaries of smaller rounded fragments (plate 160). The material on either side of the boundaries is so heavily felspathised that under crossed nicols, it is impossible to see the boundaries. The small rounded fragments are thought to be derived from the agglomerate, though the typical flow structures and pseudomorphs do not survive. The fragments consist of over 70% fine-grained felspar and the remainder is composed of dispersed noncrystalline brown material, with a few crystals of turbid carbonate and a little apatite.

Occasionally, plutonic fragments survive little altered from the agglomerate. On Eriauruma, fragments of melanite ijolite with beautifully zoned melanites and felspar rock which contains over 90% subhedral orthoclase and is similar to the felspar rock from Kiako that was described in Chapter VI occur close to the boundary with the Lower Agglomerate.

The most common sort of fragment is carbonatite, with varying degrees of purity and grain-size. Since felspathisation is the dominant form of alteration in the Ekiojango Breccia, it is thought that most of them are original carbonatite rather than carbonated agglomerate. Some are fragments of the small dykes of both the normal and Ikiwathi types, and some are fragments of Ekiojango Carbonatite, which shows the close relationship between the carbonatite and the breccia, as the carbonatite itself is normally brecciated. Also there are fragments of carbonatite of types unrepresented elsewhere on Rangwa. The recognizable fragments of small dykes and conesheets are composed of normal fine-grained cloudy carbonate, with orientated streaks of brown material (RF 225). Very few undisturbed carbonatite dykes or conesheets cut the breccia, and any that do are of the dark red-brown type described with the Kinyamungu Group. Since most of the Ekiojango Carbonatite is brecciated, the distinction between the breccia and carbonatite depends on the proportion of coarse carbonatite present in the rock, but fragments of Ekiojango Carbonatite frequently occur in the breccia at a distance from main areas of carbonatite. The cliffs below Kurugitho contain boulders of Ekiojango Carbonatite set in breccia (RF 283). The large crystals of carbonate sometimes survive, but normally (RF 301), what appear to be large crystals in hand specimen, are in fact, intergrowths of very small ones, and the outlines of the original large crystals survive as thin brown lines. Several fragments of carbonatite were found containing up to 20% apatite (RF 245. The rock is a coarse clear carbonatite, and rounded crystals of apatite are enclosed by the carbonate. The rock type is broadly similar to the Ekiojango Carbonatite, but none was found containing so much apatite.

As well as the fragments of pyroclastics and carbonatite, some new material, not represented elsewhere on Rangwa, was found in the breccia. The occurrence of this is widespread, and it exists both altered and unaltered. Although it is itself fragmental, it normally occurs within distinct fragments. The predominant minerals are biotite, pyroxene (usually aegirine-augite with a maximum extinction angle of 38°), and nepheline or pseudomorphs after nepheline in felspar, with, occasionally, magnetite, apatite, perovskite and pyrochlore. In its most striking form, the material consists of large crystals or pseudomorphs, surrounded by skins of fine-grained matter (RF 255 and RF 292, plates 161 and 162). Unaltered plates of biotite, up to 20 mm long and with rounded corners, are frequent, and there are occasional rounded and partly calcified crystals of aegirine-augite. Often large crystals of biotite surround and include remnants of pyroxene crystals, and one plate of biotite may include several specks of pyroxene, each with the same orientation, as though a single pyroxene crystal has been

Plate 161. Matrix and droplets of pseudomorphed lava in the new igneous material in the Ekiojango Breccia. The picture includes a large biotite crystal. (RF255). x25.

Plate 162. Pyroxene and biotite crystals enclosed in a droplet in the new igneous material in the Ekiojango Breccia. (RF255). x25.

partly altered to biotite, but sometimes the enclosed pyroxene is euhedral (RF 255, plate 161). The pyroxene may contain small crystals of perovskite which is sometimes altered to ilmenite (RF 292). A few square and rectangular patches of felspar with possibly pseudomorph nepheline occur and there are some areas of clear carbonate crystals. The minerals are surrounded by skins of partly crystalline carbonated material, which are up to 2 mm thick, and protrude on weathered surfaces. They contain concentrically arranged needles of carbonate which are up to .2 mm long. The groundmass is an opaque grey material, and contains similar needles. It is thought that both the skins and the groundmass are carbonated lava, and that the xenocrysts and their pseudomorphs were at first coated by lava and were then swept up by it. The altered lava is texturally similar to some of what occurs in the Lower Agglomerate (RF 35, plate 75).

The same material exists widely in an altered form, both as large fragments and as isolated pseudomorphs in the breccia matrix. In the matrix of RF 198, there is a pseudomorph after biotite consisting of opaque brown material with a marked relic cleavage; it includes several cloudy carbonate crystals which could have replaced a pyroxene. In RF 224, a few subhedral crystals of unaltered nepheline occur as well as some partly felspathised ones, all in the matrix of the breccia. RF 245 contains a large angular fragment of fragmental material which includes the apatite carbonatite described above; also there are biotite crystals with ragged edges which are closely associated with large carbonated pyroxene, apatite, euhedral perovskite grains, one of which measures 1.5 mm across, subhedral melanite and a little pyrochlore; these are scattered in a groundmass of brown material with small needles of carbonate.

A fragmental rock of a slightly different type was found once (RF 290); many of the same minerals occur, but the rock does not contain any skins or groundmass of altered lava. It is uncertain whether this occurrence is an individual large fragment made up of smaller ones, or part of the matrix of the breccia that is packed with crystals and fragments which are less altered than the average. These include small crystals of slightly carbonated aegirine-augite with a maximum extinction angle of 32°, pale phlogopite, which sometimes shows a uniaxial interference figure, melanite, in euhedral-subhedral crystals that often enclose small subhedral pyroxenes, large crystals of calcite with ragged and brown edges, apatite and minor amounts of pyrochlore and perovskite. Pyroxene crystals may be enclosed and partly absorbed by calcite (plate 163). Also there are small nodules of unaltered pyroxenes. The largest rock fragment consists of magnetite, pyrochlore and phlogopite, and is only 3 mm across.

The details of the few specimens that contain recognizably new material have been given at some length, because of their importance in showing part of the mineral assemblage which must be associated with the central carbonatites.

(b) THE INTERSTITIAL MATERIAL, VEINING AND SHATTERING IN THE BRECCIA.

The Ekiojango Breccia seldom has a true matrix. Although the Breccia is associated with the Ekiojango Carbonatite, the brecciation is not caused by disruption due to the intrusion of carbonatite, and the breccia does not often have a matrix of coarse carbonate. Rather the fragments in the breccia are separated from each other by narrow and fairly straight cross-cutting veins, which are occupied by felspar, carbonate or quartz, and from which alteration has spread into the fragments.

Felspars are the commonest interstitial material and alteration product; they are all of the same type, and their form is similar to that of those which occur in the pyroclastics and as an alteration product along the small carbonatite dykes and conesheets. The veins of felspar are of uneven thickness, with a maximum of 3 mm (RF 268 and RF 284, plate 164). It is doubtful whether they have caused any alteration to the breccia fragments, since the amount of felspathisation in the fragments, though high throughout, does not increase towards the felspar veins.

The carbonate found in veins is either coarse or fine, and the veins are often thicker than the felspathic ones, as they may be at least 5 mm thick. They can cause brecciation on different scales; in RF 292, carbonatite is broken into angular fragments with a width of over 20 mm, but at the other extreme, coarse carbonatite in RF 277 has recrystallized into a finer-grained rock, and fine-grained carbonate has penetrated along the original boundaries of the large crystals. Not all the fragments that are veined by carbonate are of carbonatite, and in RF 284 (plate 165), fine-grained carbonate provides interstitial material for angular fragments of brown felspathised agglomerate, and the amount of felspathisation increases markedly towards the edges of the fragments. The carbonate often contains irregular patches of felspar and the carbonate sometimes causes carbonation as well as felspathisation (RF 302). Where the coarse-and-fine-grained carbonate veins occur together, the fine cuts and replaces the coarse. In fact this is the same relationship as is found in the Ekiojango Carbonatite. Because of the ease with which carbonate recrystallizes and the fact that there is no proof that some of the veining is not secondary, little reliance is placed on evidence from the veins.

Quartz veins occur very rarely along the edges of fragments, but their nature is different from that of the felspar, and carbonate veins. Instead of separating originally contiguous fragments, they fill gaps between fragments and felspathic interstitial material, or between fragments of different sorts (RF 198, plate 166). The veins are normally about .03 mm wide and

Plate 163. A carbonate crystal surrounded by pyroxenes in the Ekiojango Breccia. (RF290). x55.

Plate 164. Diffuse veins of fine-grained felspar in the Ekiojango Breccia. (RF284). x85.

Plate 165. Carbonate causing felspathisation in a fragment in the Ekiojango Breccia. Between the carbonate and the fragment boundary, there is an irregular zone of ore. Within the boundary, the pale material is fine-grained felspar. (RF284). x80.

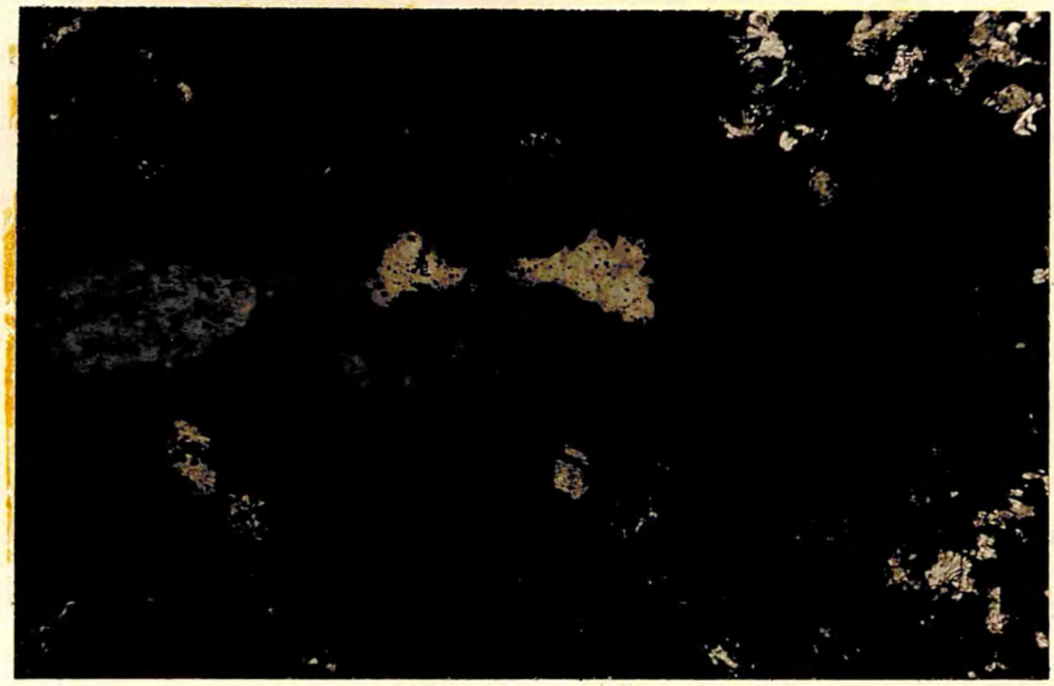


Plate 166. Quartz vein in the Ekiojango Breccia (under crossed polarisers). (RF198). x155.

one crystal thick. The quartz is clear and slightly strained. The quartz veins are probably a late feature, although in RF 256, quartz is partly absorbed by felspar.

The directions of the veins appear to be random from exposure to exposure and successive episodes of brecciation have destroyed any pattern which may have existed.

C. THE KINYAMUNGU GROUP.

As with the Ekiojango Group, it is possible to split the Kinyamungu Group into a carbonatite and an associated breccia, and the distinction is sharper, since the carbonatite contains fewer extraneous fragments and the breccia has a well-defined matrix. The carbonatites on Eriauruma are described with this group, as are the late fine-grained red-brown dykes, which occur mostly within the main Kinyamungu Carbonatite. It was explained earlier the two types of breccia are distinctive and well-defined to the east of Nyakirangacha, but they merge into one another to the west. Gradational types are described with the Kinyamungu Breccia.

(1) CARBONATITE.

The Kinyamungu Carbonatite, being fairly pure carbonate, shows features of normal limestone weathering. On the tops of Kinyamungu and Engima, it is well-exposed, and the surface is fluted with sharp edges, which are often parallel. The edges are a weathering feature, and differ from the compositional banding in the carbonatite (plate 167). The bases of many of the cliffs are plastered with secondary carbonate, and are often undercut and polished by baboons.

The rock is normally banded, and sometimes irregular streaks of magnetite crystals can be seen in the field. The bands are within 10° of the vertical, and part of the abrupt southwest-facing cliff on Kinyamungu is caused by differential weathering along a band. Although the rock is brown-dark-brown, it weathers pale, in contrast to the breccia associated with it. Even the small deep red-brown carbonatite dykes are pale on weathered surfaces (plate 169). Because of good exposure and the pale colour, the distinction and relations between the carbonatite and breccia is shown well on Eriauruma (plates 167 and 174).

Since it is fine-grained, the carbonatite does not reveal much in hand specimen. Nevertheless it is noticeable that the more large magnetite crystals the rock holds, the paler the carbonate becomes. Otherwise the carbonate is homogeneous.

In thin section, the carbonate is seen to have a grain-size which seldom exceeds .1 mm. The crystals are cloudy, and have indeterminate edges, so that most of the rock is a turbid mosaic, and it is only possible to pick out where the crystal boundaries are under crossed nicols (RF 227, plate 175). Any twinning or cleavage is masked by the brown cloudiness, an effect which is probably caused by very finely dispersed iron ore throughout the rock. The brown material is occasionally organized into parallel

Plate 167. Fluted Kinyamungu Carbonatite from the top of Engima.

Plate 168. The undercut base of a cliff of Kinyamungu Carbonatite, plastered with secondary material and polished by baboons.

Plate 169. Late red-brown carbonatite dyke cutting the Kinyamungu Carbonatite, on Kinyamungu.

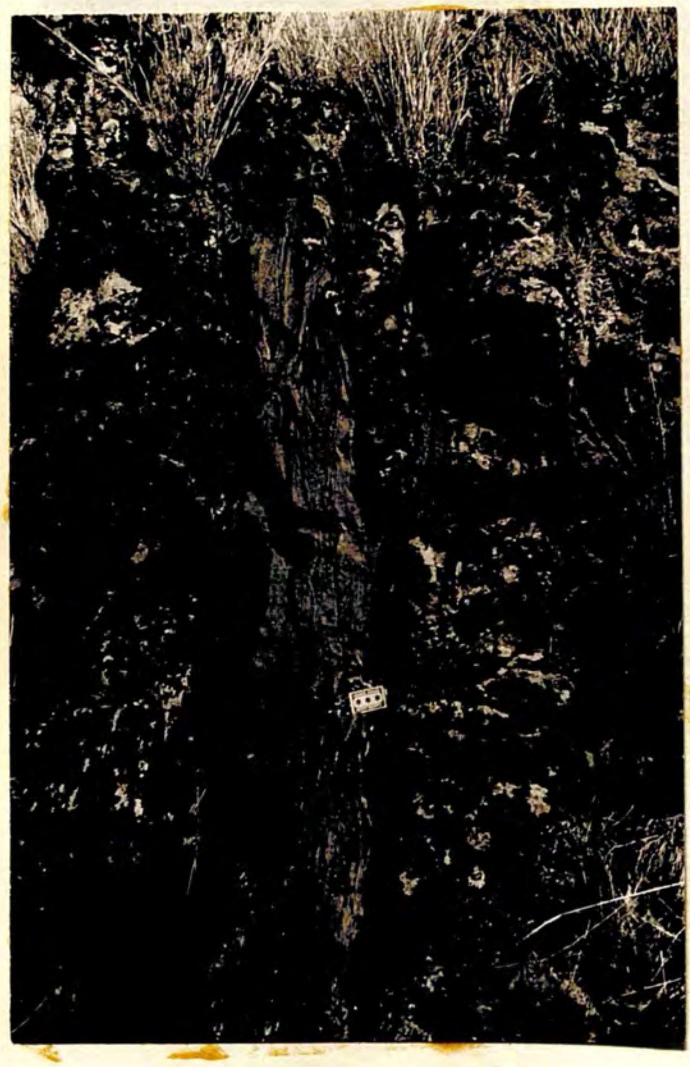
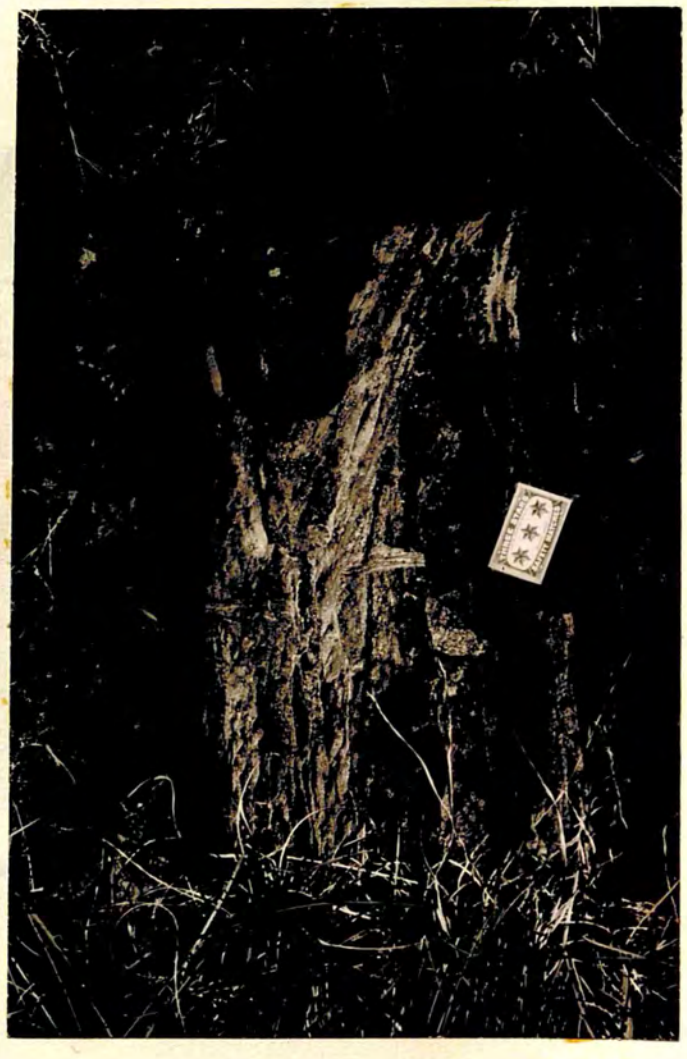


Plate 170. Intrusive tongue of Kinyamungu Carbonatite on Eriauruma.

Plate 171. Kinyamungu Carbonatite penetrating between brecciated fragments on Eriauruma.



late 172. Tongue of Kinyamungu Carbonatite with its end displaced on Eriauruma. Two phases of intrusion are visible.

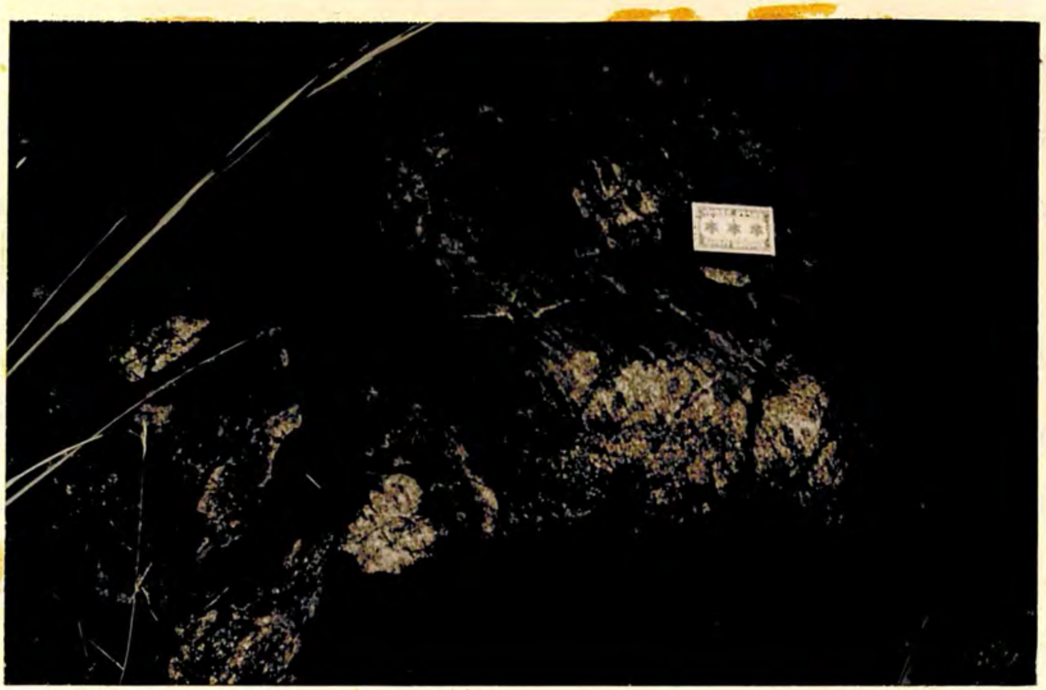


Plate 173. A fragment of Kinyamungu Carbonatite from breccia on Eriauruma.

Plate 174. Kinyamungu Breccia from near Engima. The fragments are set in a carbonatite matrix.

noncrystalline streaks as in RF 238 (plate 176); although this specimen is from a large outcrop of massive carbonatite, it is petrographically similar to many of the small conesheets and dykes.

The specific gravity of several specimens of this type of carbonatite was measured, and they all gave readings that are well under 2.71. Staining was inconclusive, because of the brown material and the small size of the carbonate crystals, but x-ray diffraction work has shown that the carbonatite is predominantly calcite with minor amounts of ankerite.

Generally, the carbonatite includes small patches of long radiating carbonate crystals (RF 228, plate 177). They are up to 2 mm long, and are strained so that the extinction always forms an irregular cross. They are clear and the edges between crystals are often straight, but the outlines of the patches are ragged and enveloped by a thin line of brown material. There seems to be no way of telling whether these features are caused by fine-grained carbonate invading coarse or vice versa, or by recrystallization.

Magnetite is almost ubiquitous in the Kinyamungu Carbonatite. Normally subhedral crystals, whose size varies from 1 to 15 mm, occur, and they are found in rough bands, the centres of which may contain 90% magnetite or haematite (RF 228 and RF 229, plate 178). But the very rich bands are never more than 40 mm thick. The crystals show no orientation, and, except in the very iron-rich

Plate 175. Typical texture in the Kinyamungu Carbonatite. It includes small grains of magnetite. (RF227). x85.

Plate 176. Streaks of ore in the Kinyamungu Carbonatite. (RF238). x55.

Plate 177. Radiating crystals of carbonate in the Kinyamungu Carbonatite (under crossed polarisers). (RF228). x85.

Plate 178. Subhedral magnetite crystals in the Kinyamungu Carbonatite. (RF228). x25.

bands, they tend to occur singly rather than in clusters. The other minerals in the carbonatite are normally associated with bands that contain magnetite. The commonest of these is mica; it occurs in unorientated plates up to 15 mm long (RF 227, plate 179). It was probably biotite or phlogopite originally, but has been altered to a cloudy brown substance which retains a pronounced cleavage but is hardly pleochroic. Carbonate has invaded the cleavage planes, and most of the cleavage flakes are very bent. The degree of alteration of the mica is considerably more than in the Ekiojango Carbonatite.

Occasional small rounded apatite crystals occur, but they are far less common than in the Ekiojango Ekiojango Carbonatite. They are sometimes entirely enclosed by single carbonate crystals.

Within the iron-rich bands, there may be at least 5% pyrochlore. This may occur within the haematite (RF 233, plate 180), or in the material that is interstitial to the ore. It forms subhedral or broken cubic or octahedral crystals up to .5 mm across. Pyrochlore seldom occurs among the normal carbonate.

The ore in the iron-rich bands has normally turned to haematite, and the masses of ore have borders of brown material which must be a further alteration to limonite. Between the ore, there are irregular bodies of analcite, and subhedral crystals of quartz and barytes, both of them up to .8 mm long, which frequently contain streaks of brown ore.

Plate 179. Altered mica in the Kinyamungu Carbonatite. (RF227). x25.

Plate 180. Pyrochlore crystal surrounded by ore in the Kinyamungu Carbonatite. (RF233). x80.

Felspar is an occasional constituent, and forms irregular cloudy crystals of orthoclase with clear margins of albite. They are untwinned.

The carbonatite on Eriauruma is coarser grained, and includes many more of the groups of long radiating crystals of coarse carbonate. The red-brown dykes are very much darker, and largely noncrystalline; their x-ray diffraction pattern is predominantly that of ankerite with smaller amounts of calcite.

(2) BRECCIA

In its field appearance, the Kinyamungu Breccia contrasts with the Ekiojango Breccia in that it really looks like a breccia; well-defined angular fragments stand out from a paler matrix (plate 174). The main exposures occur close to the carbonatite on Eriauruma and both on and around Kinyamungu and Engima. Sometimes, especially on Engima, it is exposed as a skin over carbonatite, but unlike the Ekiojango Breccia, it never has any topographical expression at the expense of the carbonatite.

(a) FRAGMENTS.

The fragments are angular, and their size varies up to about 20 cm long. As in the Ekiojango Breccia, most of them are so altered that it is impossible to see what they were originally, but apart from the carbonatite there are no unbrecciated rocks nearby with which any of the fragments can be matched, and the type of alteration tends to be different from what occurs in the Ekiojango Breccia.

The most common sort of fragment consists largely of an obscure aggregate of fine-grained cloudy carbonate and brown material. The fragments generally lack distinct texture, and there are seldom any recognizable pseudomorphs (RF 234). On cut surfaces and thin sections, the overall colour effect is grey. Besides the carbonate, these fragments contain a wide variety of minerals in small quantities.

The fragments in most specimens include at least 5% felspar, and RF 259 contains up to 20% felspar. It is usually very cloudy anhedral or subhedral potash felspar which occasionally shows simple twinning, and occurs in crystals up to .5 mm long (RF 234, plate 181). The potash felspar has a 2 V of 10° - 20° which is appreciably lower than that of normal orthoclase, so that the felspar is probably sanidine. Sometimes it is surrounded by a rim of clearer anorthoclase which shows very fine polysynthetic twinning (RF 259). Occasionally, as in RF 259, the potash felspar occurs in far larger subhedral plates that are up to 5 mm across. Normally the felspar is surrounded by carbonate, but sometimes its edges are corroded and replaced by very fine-grained amorphous felspar. The felspar, because of its frequently unaltered state and its common association with veins of carbonate, is considered normally to be a secondary product, though what it altered from is not known.

Plate 181. Subhedral potash felspar in the Kinyamungu Breccia. (RF234). x80.

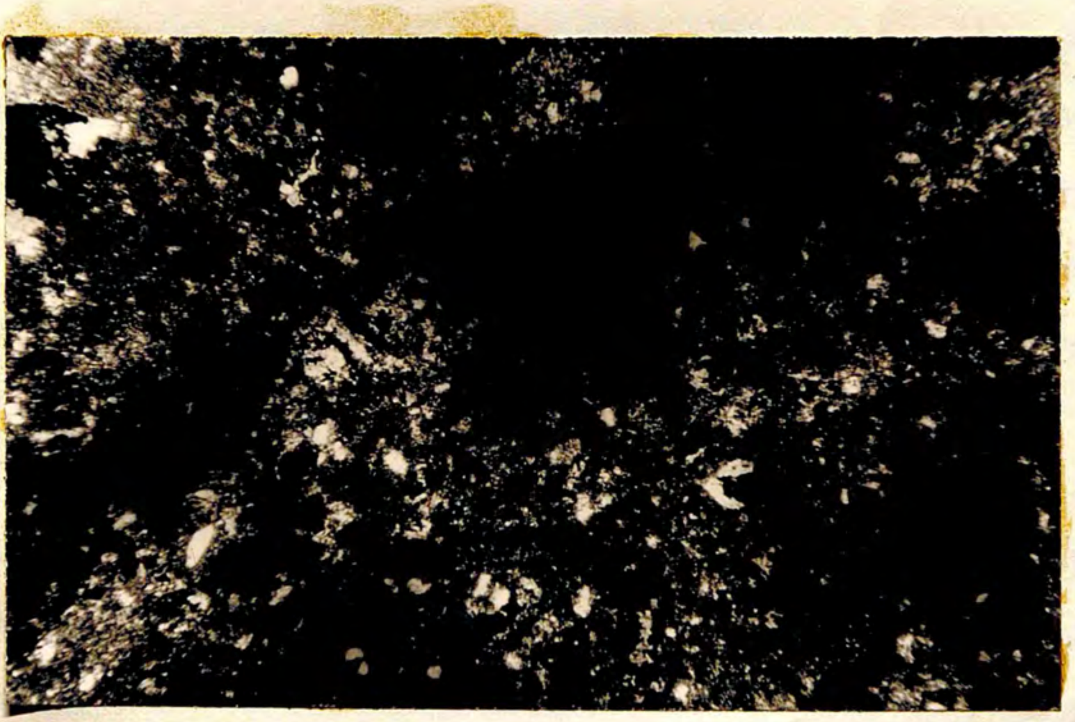


Plate 182. Part of a fragment from the Kinyamungu Breccia. The white material is potash felspar, and the grey, speckled material is carbonate. (RF259). x25.

Since there is not much fine-grained felspar in the Kinyamungu Breccia, a basic difference between the two sets of carbonatite and breccia is that the Ekiojango Carbonatite is associated with alteration to small, poorly formed potash felspar, whereas the Kinyamungu Carbonatite is associated with alteration to coarser subhedral felspar and carbonation.

Fine-grained felspar does occur sporadically in the groundmass of the fragments, but there is never indiscriminate alteration to them. Felspar and analcite form irregular patches with distinct outlines (RF 288 and RF 330). By analogy with the mode of occurrence of felspar in the pyroclastics, these could well be highly distorted pseudomorphs after nepheline.

Apatite is, as in most of the other groups of rocks, a common constituent, and occurs both as tiny rounded crystals, and as larger subhedral ones which are up to 1 mm long (RF 250). It is thought that, as in the Ekiojango Carbonatite, the rounded ones are early and partly resorbed, and the subhedral ones are late, and may have been formed during brecciation and alteration.

Other minerals are found less frequently. Large crystals of zoned aegirine-augite up to 5 mm long (RF 250 and RF 330) occur with pronounced carbonation along the cleavage planes, as in the pyroxenes in the Ekiojango Breccia, and occasionally pyroxene is pseudomorphed by carbonate (RF 234, plate 184). Melanite was found in one specimen, in clusters of euhedral crystals, which are dark brown and beautifully zoned (RF 250, plate 183). Ragged and cloudy plates of biotite occur in RF 329. RF 250 contains subhedral magnetite with corroded edges.

As many of the fragments contain minerals that are not found unaltered in the pyroclastics, it can be said safely that they are not brecciated fragments of pyroclastics. The minerals are the same as some of those found in the newly formed material that occurs in the Ekiojango Breccia. It will be shown in Part 3 that Nyakirangacha is probably the site of the vent that gave rise to the nephelinite agglomerate on the Kisingiri Volcano, as well as some of the lavas. So it is a reasonable deduction that many of the fragments, especially the ones towards the centre of Nyakirangacha, are highly carbonated and felspathised pieces of volcanic or subvolcanic material.

All of the other fragments are of carbonatite. A few are similar to the Ekiojango Carbonatite, and are pure and coarse-grained, or have been partly replaced by fine-grained carbonate (RF 317). More frequently found are fragments of fine-grained cloudy carbonatite, which resemble the Kinyamungu Carbonatite and normally contain apatite (RF 250). In one specimen (RF 288), fragments of carbonatite are surrounded by rims of fine-grained felspar, even though the matrix of the rock consists of carbonate.

Plate 183. Zoned melanite crystal from the Kinyamungu Breccia. (RF240). x155.

Plate 184. Possible pseudomorph after zoned pyroxene in fine-grained, cloudy carbonate. The pseudomorph is ringed by fine-grained felspar. (RF234). x80

(b) MATRIX.

The intensive veining found in the Ekiojango Breccia seldom occurs in the Kinyamungu Breccia, and, when it does, the composition of the veins is different and they are not so regular or straight. In RF 234, a set of veins of fine-grained carbonate is cut by at least two sets of dark brown veins, which contain small apatite crystals. Both types cause carbonation and a minor amount of felspathisation.

Normally, the breccia has a matrix that is similar to the Kinyamungu Carbonatite, although without the magnetite-rich bands and many of the usual accessory minerals. Where exposures of the breccia occur close to the carbonatite, as on Eriauruma and Engima, it can be shown that the matrix of the breccia is continuous with nearby carbonatite (plate 171). The matrix is composed of cloudy fine-grained carbonate, with a grain-size of up to .5 mm and containing very little interstitial noncrystalline material. There are some rounded crystals of apatite, and black specks which may be magnetite. The matrix in RF 239 contains small amounts of blue-green amphibole, a mineral that was not found in the carbonatite. It occurs as small bundles of fibres, never more than .04 mm long; the fibres have more or less straight extinction, though they are wavy and it is hard to find the exact extinction angle. They are length fast. The mineral is pleochroic from blue to colourless along the length of the fibres, and the polarisation colour is normally blue, and an anomalous yellow is shown just before the fibres go into extinction. It is not unlike the fibrous amphibole which forms round some of the pyroxenes in the ijolite, and is probably arfvedsonite or magnesioarfvedsonite.

The description of the matrix pinpoints one of the main differences between the two groups of carbonatite and breccia (Figure 26). The Ekiojango Breccia was formed after the intrusion of the carbonatite, when both the carbonatite and the surrounding rocks were brecciated, possibly in several stages, whereas the Kinyamungu Breccia was caused by the intrusion of the Kinyamungu Carbonatite, although in fact, this happened in more than one episode, as the blocks of Kinyamungu Carbonatite in the breccia show.

3. SUMMARY OF AGE RELATIONS.

The petrological descriptions illustrate one of the biggest problems in determining age relations between different types and episodes of carbonatite. The rock type is not necessarily evidence of the phase of activity to which the carbonatite belongs, both because the form that crystallization has taken depends on local conditions, and because recrystallization of the carbonate has often modified or destroyed the original texture and grain-size. However, it is possible to establish age relations between the carbonatite groups and sometimes within them.

All the carbonatites found on Rangwa post-date both the agglomerates and the Tuff Group. This is clear for two reasons; very few carbonatite fragments occur in the pyroclastics, and these could well be from an earlier carbonatite centre which was broken up by the drilling of the pyroclastic vent. Small carbonatite dykes and conesheets of similar type cut all three groups of pyroclastics alike. It will be shown in the section on structure that the dykes and conesheets post-date the main subsidence also.

Within the small dykes and conesheets, there were several phases of intrusion, although the normal rock type does not vary much. Wherever radial dykes and conesheets cross, the dyke always cuts the conesheet; some of them are multiple, but none of these were found which showed crosscutting relationships. The fact that radial dykes normally succeed conesheets is well-documented at other alkaline centres (Tororo, Williams 1952; Chilwa, Garson and Campbell Smith 1958 and Tundulu, Garson 1962). The large dykes on Ikiwathi were intruded at some stage during the conesheet and dyke intrusions, since they both cut and are cut by them.

The Ekiojango Breccia includes fragments of the small dykes and conesheets, and, as one approaches the area of brecciation on Ikiwathi, one of the larger dykes can be seen in the process of disintegration. Compared with the large number that occur immediately outside it, few small dykes or conesheets cut the

Ekiojango Breccia or Carbonatite, and the ones that do belong to the red-brown type, which occurs mostly within Nyakirangacha. So the Ekiojango Breccia and, by implication, the Ekiojango Carbonatite, are later than the majority of the small dykes and conesheets. This is an unusual order of intrusion, since normally the large intrusions precede the small ones (King and Sutherland 1960). However, the order possibly fits in well with the sequence of events which occurred at the centre.

The emplacement of the Ekiojango Carbonatite happened in two distinct stages. The carbonatite was intruded as a ring-shaped body, causing extensive alteration to fine-grained felspar in the wall rock. Then both the carbonatite and the wall rock were brecciated together. So much is clear from the field relations and petrography, but each stage may well have had several episodes, and there is no indication whether any brecciation occurred with the intrusion or not.

That the Kinyamungu Carbonatite post-dates the Ekiojango one is harder to prove, and can only be shown at a few exposures. In the Kinyamungu Breccia at the base of Engima, there are large fragments of Ekiojango Carbonatite. Again, on Eriauruma, Kinyamungu Carbonatite can be seen to displace and brecciate Ekiojango Carbonatite. The latter evidence is doubtful, as most of the carbonatite on Eriauruma is of a transitional type, but in general, finer-grained carbonatite post-dates coarser carbonatite. Crystals of the Ekiojango Carbonatite are often cut and separated from one another by finer-grained carbonate, and the Kinyamungu Carbonatite contains "phenocrysts" of coarse-grained carbonate, but this is not conclusive either, as the carbonate could have recrystallized under different conditions. The order established for Rangwa occurs on Ruri also, where fine-grained magnetite-rich carbonatite is often seen to cut a coarser type (personal communication, Mr. B. Collins).

In thin section, it is difficult to see different phases within the Kinyamungu Carbonatite, but in the field it can be shown that there were several phases of intrusion, often accompanied by brecciation, carbonation and alteration to coarse felspar. Sometimes, a sequence of several intrusions can be seen at one exposure, and the breccia frequently contains fragments of Kinyamungu Carbonatite. The breccia and carbonatite form an oval composite mass, whose boundary roughly coincides with the steepening of the slope round the edge of Nyakirangacha.

Small red-brown conesheets and dykes were the last carbonatitic episode on Rangwa. Again the dykes cut the conesheets. They represent waning carbonatite activity, as very few of them were found, and they seldom extend beyond the bounds of the Kinyamungu Carbonatite and Breccia.

4. STRUCTURE.

Each of the main carbonatite groups has a structural unity of its own, and the structure and events which caused them can be separated.

A. THE SMALL CONESHEETS AND DYKES.

The dips and strikes of over 200 small carbonatite conesheets and dykes were measured, and the structural pattern or lack of pattern is of great interest, since it can be compared with that obtained by others who have worked on the structural pattern caused by conesheets and dykes (Anderson 1936, Von Eckermann 1948 and 1958, and Garson 1958, 1959 and 1962). It can be established that most of the dykes and conesheets on Rangwa radiate from the vicinity of Nyakirangacha. The conesheets dip inwards at angles of between 5° and 55°, and the dykes, whose dip is seldom more than 15° from the vertical, strike towards the centre of Rangwa (Figures 27 and 28). The stereogram on which the dips and strikes of all the small carbonatite intrusions on Rangwa are plotted shows that most of them fit into these two types, and that there are few intermediate ones (Figure 29). On Figure 27, all the conesheets are plotted at their correct distances and heights from the probable centre, and their dips are extended to the centre line without regard to any change of dip which may occur at depth. On this basis, the inferred depths of the foci from which the conesheets originated vary between

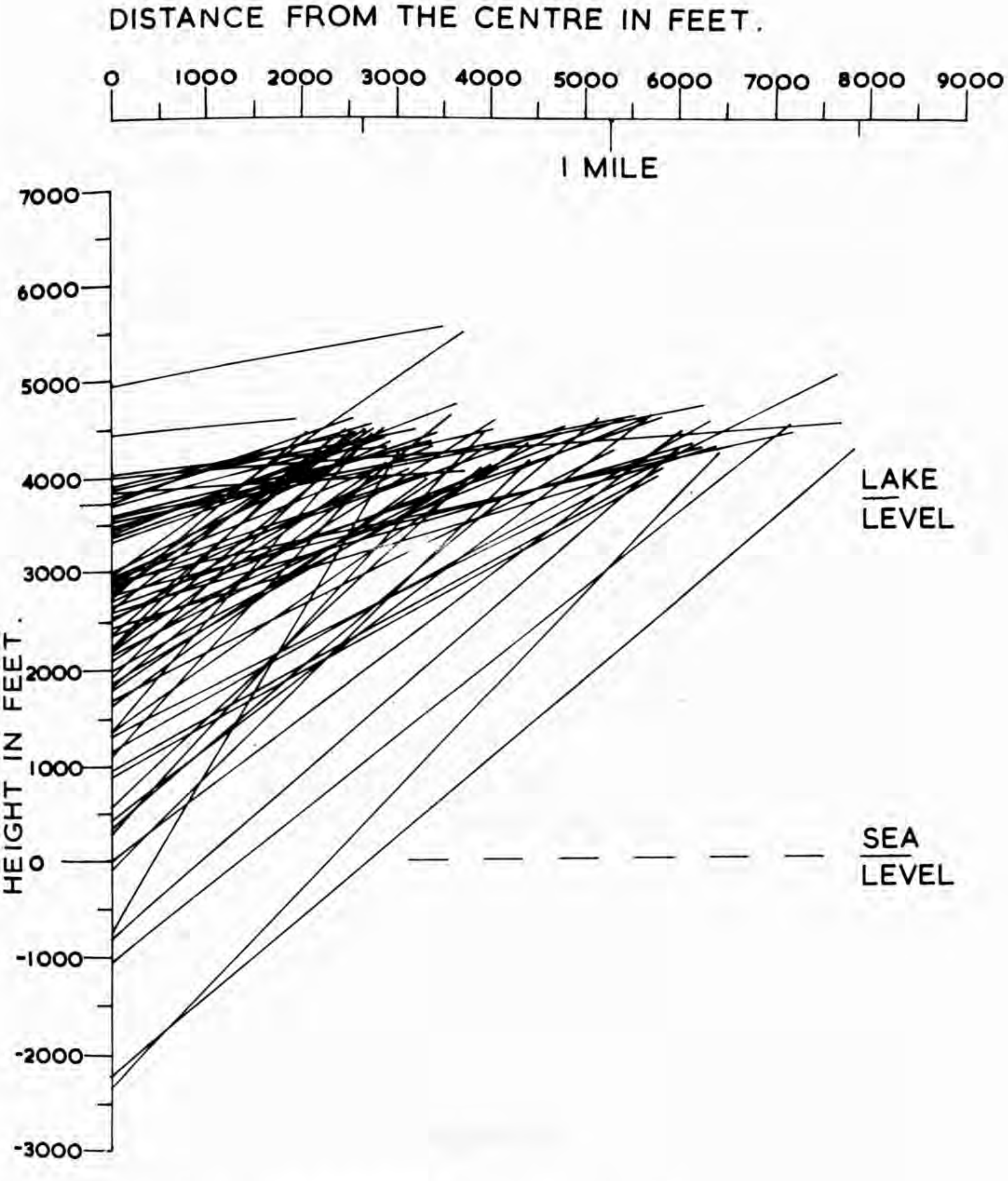
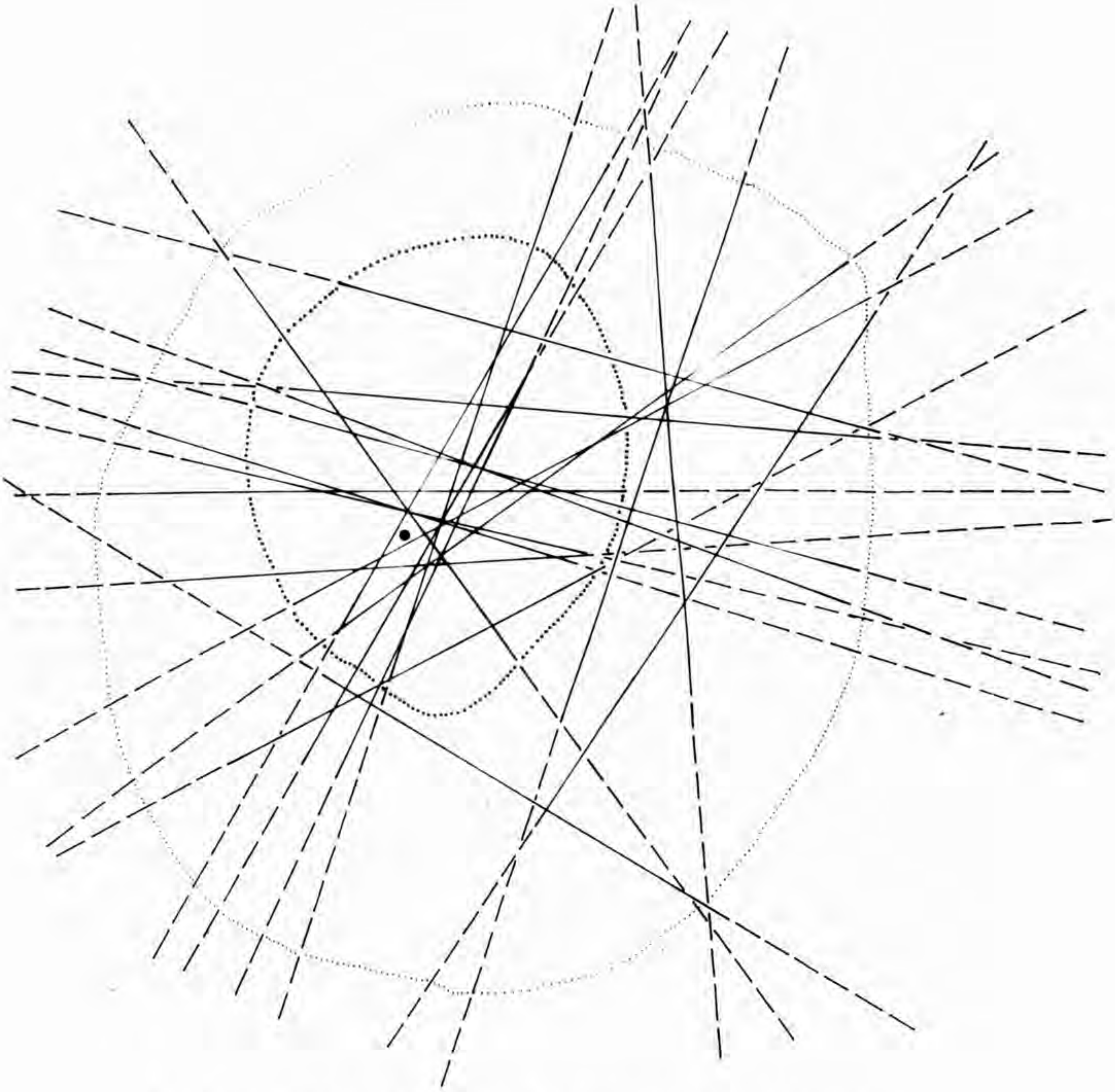


FIGURE 27. DOWNWARD AND INWARD PROJECTION OF THE DIPS OF THE CARBONATITE CONESHEETS ON RANGWA.

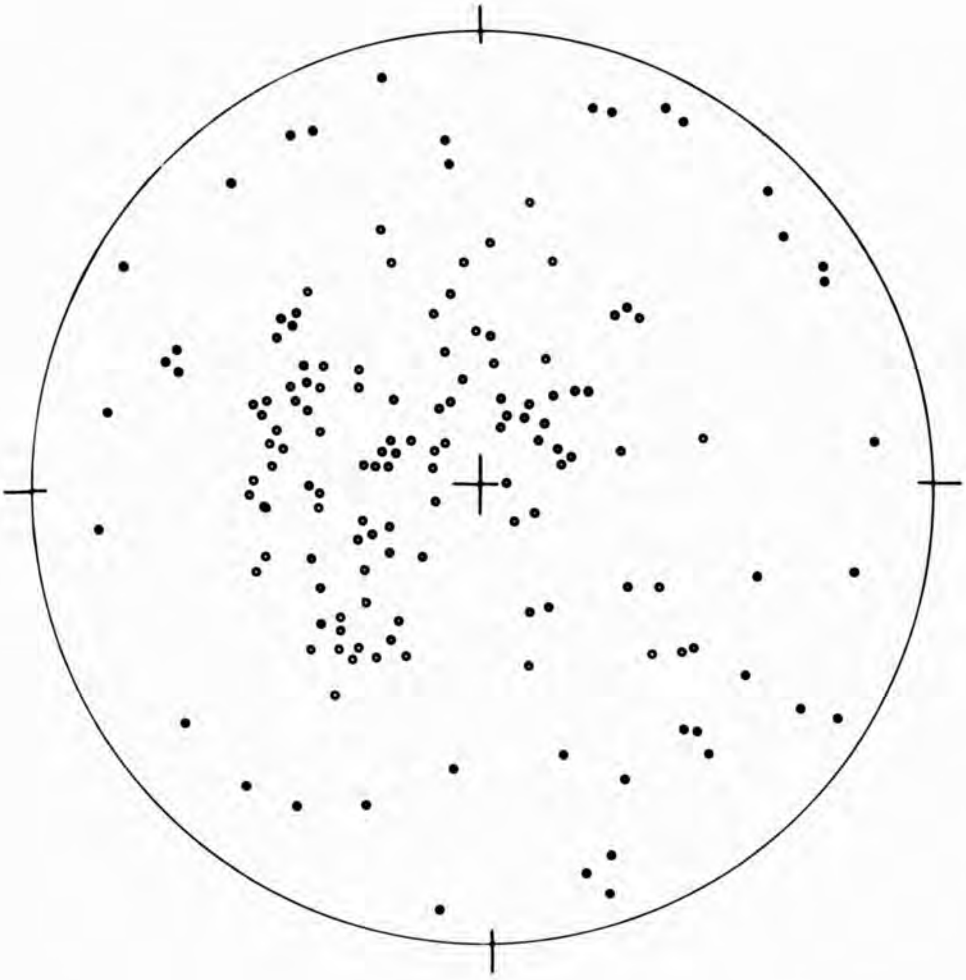


········ OUTER BOUNDARY OF THE PYROCLASTICS.

·········· BOUNDARY OF CENTRAL BRECCIAS AND CARBONATITES

● CENTRE ROUND WHICH THE BANDING OF THE KINYAMUNGU CARBONATITE IS CONCENTRIC.

FIGURE 28. INWARD PROJECTION OF THE STRIKES OF THE VERTICAL AND NEAR-VERTICAL CARBONATITE DYKES ON RANGWA.



◦ POLE TO THE PLANE OF A CONESHEET.

• POLE TO THE PLANE OF A RADIAL DYKE.

FIGURE 29. STEREOGRAPHIC PROJECTION OF THE POLES TO THE PLANES OF THE SMALL CARBONATITE CONESHEETS AND RADIAL DYKES.

2,500 ft. below sea level to 5,000 ft. above sea level, with a peak occurring between 1,000 ft. and 4,000 ft. The dips measured in the field do not change with the distance of the exposures from the centre.

Since most of the carbonatite dykes and conesheets are of broadly similar rock type, which does not vary with the inferred levels from which they were emplaced, it is thought that they were all intruded in one related series of events. The fact that there is not more than one concentration of projections along the centre line could mean that the conesheets are all related to one focus. It is unlikely that the extensive scatter was caused by later disruption of the pyroclastics into which the conesheets were intruded, as no evidence for this was found. It is probable that the scatter was caused partly by local distortion of dips, influenced by the inward-dipping pyroclastics. The courses followed by the conesheets which intrude the Bedded Tuff are rarely straight, as they sometimes follow the bedding, and sometimes move from bed to bed. A further reason for the scatter may be that the conesheets were intruded from many different levels.

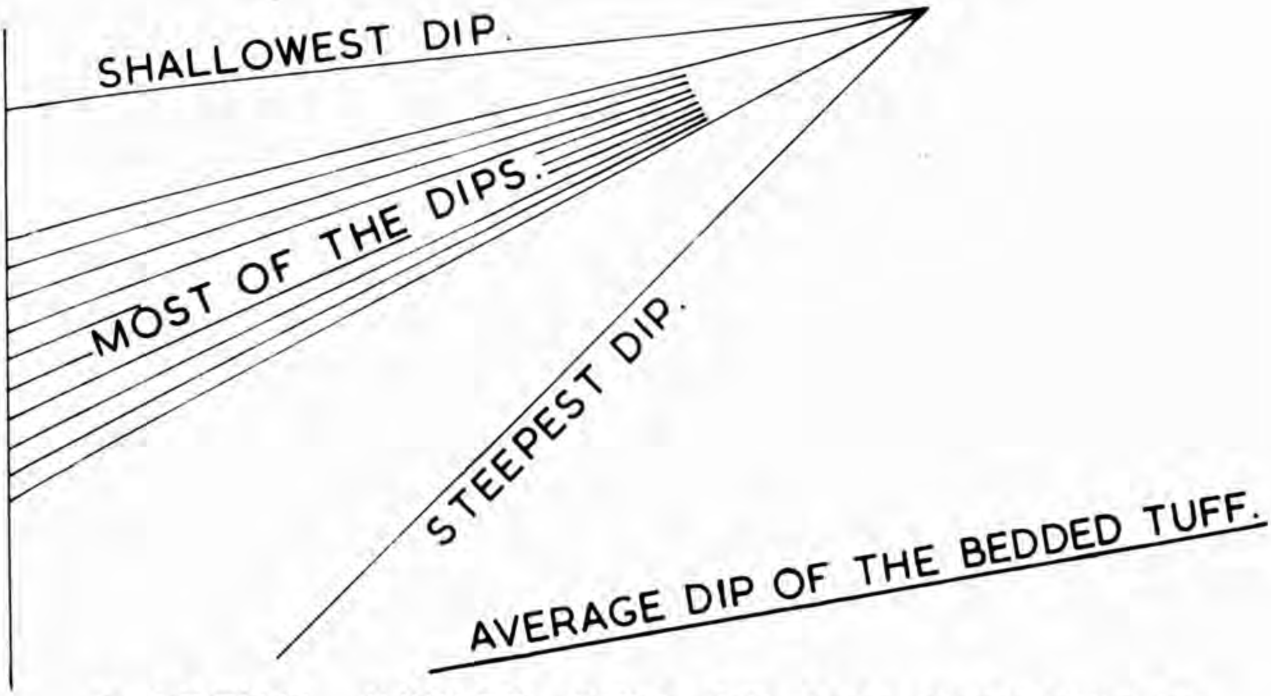
If the conesheets did in fact originate from different levels, it can be explained in terms of the volcanic events at the nephelinite vent which probably existed on the site of Nyakirangacha. It will be shown in Part 3 that the main nephelinite vent was from time to time, blocked by carbonatite, and it is suggested that conesheets were intruded at times when the vent was blocked.

The radial dykes are nearly always later than the conesheets, a phenomenon which is observed at Alno (von Eckermann 1948 and 1958), Chilwa (Garson and Campbell Smith 1958), and Tundulu (Garson 1962), and are presumably the result of late radial pressure.

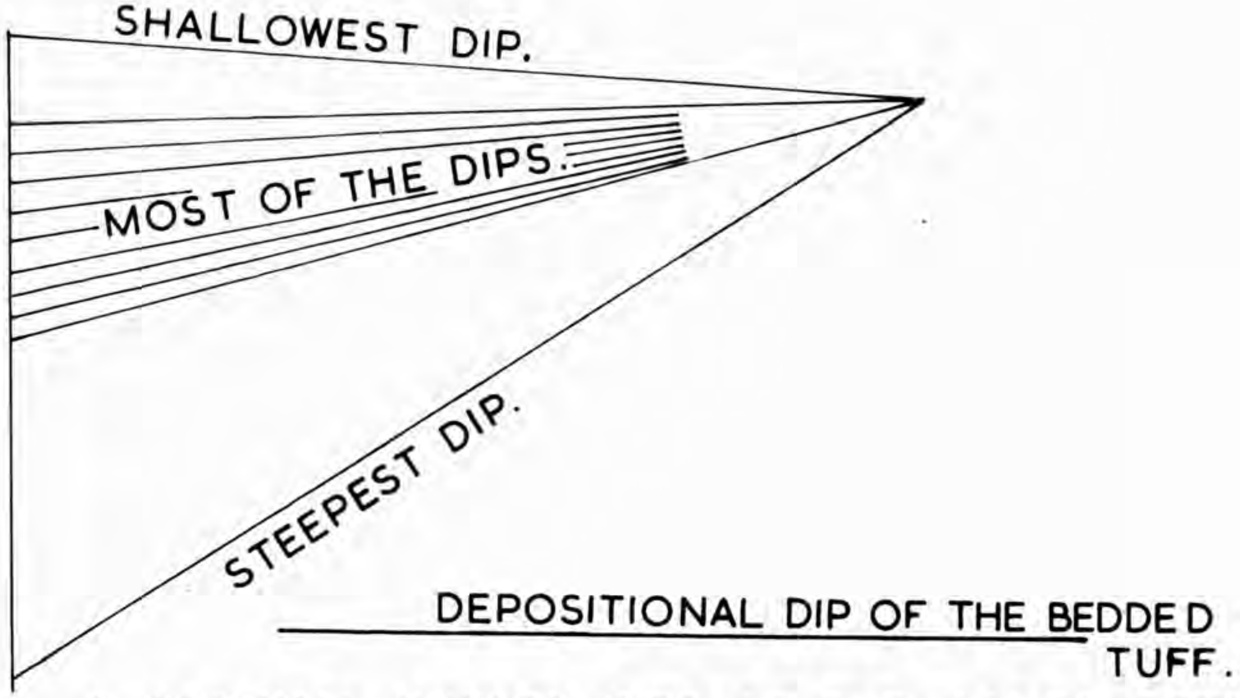
The pattern of carbonatite conesheets and radial dykes on Rangwa is the main proof that the subsidence and steepening of the dips in the pyroclastics happened prior to the intrusion of the small carbonatite conesheets. Figure 30 shows the greatest and smallest dips measured in the carbonatite conesheets and the equivalents of these if the conesheets had been intruded before the steepening. If that had happened, many of the conesheets would have dipped outwards from their centre of origin, and most of the rest would have dipped inwards at a low angle, an impossibility if the conesheets are filling tension cracks caused by pressure from below.

B. THE EKIOJANGO CARBONATITE AND BRECCIA.

The Ekiojango Carbonatite and Breccia have the form of an irregular ring dyke. Anderson (1936) supposed that most ring dykes delimit areas of subsidence, as in the case of the Loch Ba Felsite on Mull, which has been intruded along a fault plane with a throw of at least 3,000 ft. However, it is unlikely that subsidence occurred within some large ring dykes (Richey and Thomas 1930, p 211). None can be proved along the line of the Ekiojango Carbonatite and



a. ACTUAL INWARD DIPS OF THE CONESHEETS.



b. ORIGINAL INWARD DIPS OF THE CONESHEETS BEFORE SUBSIDENCE HAD THEY EXISTED THEN.

FIGURE 30. DIAGRAMS SHOWING THE EFFECT OF SUBSIDENCE ON THE DIPS OF THE CARBONATITE CONESHEETS IF THEY HAD BEEN EMPLACED EARLIER.

Breccia.

The descriptions have shown that there is no clearcut boundary between the breccia and the carbonatite, and much of the brecciation occurred after the intrusion of the carbonatite. Both are cut by many cross-cutting veins of carbonate and felspar, which have a haphazard arrangement, and it is likely that several phases of brecciation occurred. The rocks within the ring of the Ekiojango Carbonatite and Breccia are mainly of later origin than the pyroclastics outside them, and any comparatively unaltered fragment in the Kinyamungu Breccia is of volcanic or subvolcanic material, quite different from the fragments in the pyroclastics.

The Ekiojango Breccia contains fragments of both the pyroclastics and new igneous material, and as a vent is thought to have occupied the central part of Rangwa (pp 235) the fragments in the Breccia may have come from both the vent and its wall. Since the carbonatite and Breccia have the form of a ring, it is possible that carbonatite was forced up the edge of the vent at times when the vent was plugged, and that brecciation was caused by subsequent activity at the vent.

C. THE KINYAMUNGU CARBONATITE AND BRECCIA.

The Kinyamungu group forms an oval body, whose boundary is probably nearly vertical. The breccia has a matrix of carbonatite similar to the main carbonatite, which has seldom been brecciated.

Most of the Kinyamungu Carbonatite is banded; the dips of the bands, which are composed mainly of ore, are generally within 15° of the vertical, and, strikes measured on the sporadic exposures are concentric around a centre, which shows no exposure, several hundred yards west of Kinyamungu. Near this centre, the banding tends to dip inwards, and near the boundary of the carbonatite, it dips outwards. Except for the breccia it contains and grades into, and the areas in which it is involved with Ekiojango Carbonatite, the Kinyamungu Carbonatite is fairly homogeneous, and no internal boundaries were found; the upper surface of the carbonatite is irregular, as the level of the coating of breccia, where it is present, varies considerably, but it is not known whether the carbonatite was emplaced as one body or as a series of dykes.

The central carbonatite plug at Tororo (Williams 1952), which is very much better exposed, has the same sort of banding as the Kinyamungu Carbonatite. Near the middle the bands dip inwards at a very high angle, and further out the angle decreases. Williams supposed that the inner parts were emplaced first, and that the outer bands were pushed along the boundary between the inner carbonatite and the wall as "collars". Such a clear picture cannot be obtained on Rangwa, but, because the carbonatite sometimes outcrops as irregular dykes separated by breccia, and sometimes as large, apparently homogeneous masses (as on Kinyamungu itself), it is thought likely that the Kinyamungu Carbonatite is a large body, which splits into tongues at the top; both these phases are visible at the present erosion level.

Some late faults, mainly to the west of Nyakirangacha, cut both the Ekiojango and Kinyamungu Carbonatites and form clean scarps (plate 134). Most of them are radial to the centre of Rangwa, and sometimes there are persistent joints parallel to them. The types of carbonatite and breccia are so mixed there that it is not possible to determine throws on the faults.

5. MODE OF ORIGIN.

The small conesheets and dykes of carbonatite show an obvious intrusive relationship to the pyroclastics.

Because it occurs within the intensively brecciated Ekiojango Group, the Kinyamungu Carbonatite does not often have clear contacts. However, on Eriauruma, large irregular tongues of carbonatite intrude previously formed breccia (plates 170 and 171). Moreover, carbonatite forms a matrix for the breccia that is associated with it. The banding that occurs in the Kinyamungu Carbonatite is not in itself a criterion of emplacement as a liquid, since it cannot be proved that it is due to magmatic flow. The evidence from Eriauruma, where the tops of some of the tongues of carbonatite have been broken off (plate 172), suggests that, at any rate round the edges, parts of the Kinyamungu Carbonatite have been moved after solidification.

Being itself brecciated and mixed with fragments of carbonated and felspathised breccia, all the Ekiojango Carbonatite must have reached its present position after it solidified; in deciding whether it was originally emplaced as a liquid, a distinction must be drawn between the actual carbonatite, a coarse white rock, rich in mica and apatite and frequently banded, and the carbonated breccia fragments, which are composed of far finer-grained carbonate, with some felspar, and which sometimes retain relic textures from the pyroclastics. Even for the true carbonatite there is no direct evidence of liquid emplacement, but the banding and typical assemblage of accessory minerals can be compared with that of carbonatite which originated as a liquid from other localities.

From what sort of liquid did many of the carbonatites crystallize? Nearly all the carbonate is calcite, except for some ankerite in the late red-brown dykes, but even in these calcite predominates. Sometimes, especially in the "porphyritic" dykes on Ikiwathi, and in the Ekiojango Carbonatite (RF 314), which have been proved by staining and X-ray diffraction to consist entirely of calcite, large euhedral crystals of calcite are rimmed by noncrystalline red and brown material, which may penetrate along the cleavage planes. It is suggested that these are akin to the exsolution textures described from Loolekop by Verwoerd (1966), and similar to the pseudomorphs after siderite and ankerite found in the carbonatite at the second centre at Tundulu (Garson 1962) and at many other localities. This implies that the original dolomite or ankerite crystals were included in a predominantly calcitic liquid, which always cooled on the calcite side of the solvus curve between calcite and the solid solution series between dolomite and ankerite (Goldsmith and Heard 1960). Probably the streaks of brown noncrystalline material which occur between the carbonate crystals in the small dykes and conesheets and in the Kinyamungu Carbonatite represent iron and magnesium exsolved during cooling from calcite which could not accommodate them at lower temperatures.

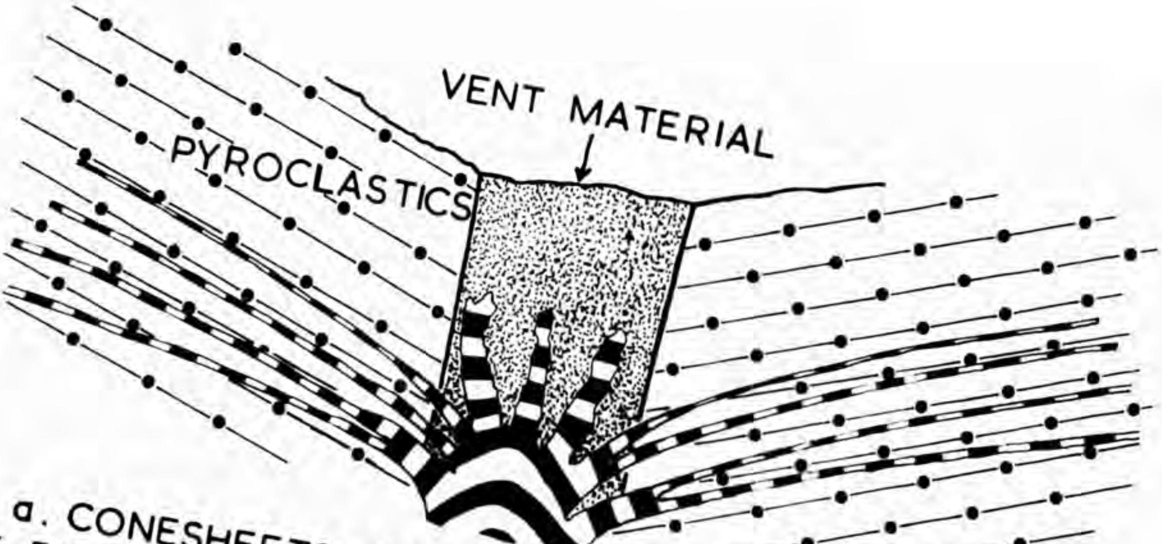
What else did the carbonatite liquid contain besides lime, carbon dioxide, and a little magnesia and iron? Niggli (1937 in Wyllie and Tuttle 1960) established that carbonate would be molten at comparatively low temperatures if it contained at least 50% of sodium and potassium carbonate, and some of the early protagonists of a carbonatite magma (von Eckermann 1948) assumed that the original magma did contain large amounts of potassium carbonate, which was dispersed to cause the potash enrichment involved in fenitisation. Wyllie and Tuttle (1960) showed that a carbonate liquid can exist at pressures of between 27 and 4,000 bars, at temperatures of 685° - 640° C, provided that it contains excess water and carbon dioxide. All the carbonatites on Rangwa cause felspathisation, and orthoclase or homogeneous soda-potash felspar is the most common felspar to form. This process has been followed at the edges of the small conesheets and dykes from a rock that contains a little potash felspar to one that consists almost entirely of it, and it must involve an increase in potash, which could only come from the carbonatite. So it is reasonable to assume that the carbonatite liquid did contain some alkaline carbonates. Water was probably present in the magma too, and it seems that variations in the water content might account for the different textures in the carbonatites and associated breccias of the Ekiojango and Kinyamungu Groups.

Variations in water content of the magma might also explain the different modes of occurrence and forms of brecciation associated with the two groups of carbonatite (Figure 26); for example, large, subhedral homogeneous potash-soda felspar has formed in the Kinyamungu Breccia, whereas small, cloudy felspars occur in the Ekiojango Breccia; the former has a matrix of carbonatite which has flowed round the fragments, and the latter scarcely has a matrix. The Kinyamungu Carbonatite sometimes penetrates its wallrock in long tongues, without causing brecciation, whereas the Ekiojango Carbonatite is always associated with brecciation. If the differences between the two types of carbonatite are caused by a slight difference in the water content of their magmas, the occurrence of gradational types of carbonatite, as on Eriauruma, is to be expected because of variations in local conditions at the time of formation, and the apparent anomaly of occasional reversed age relations between the two groups can be explained in the same way.

Although, unlike some complexes, Chilwa for example, the carbonatites on Rangwa do not show a marked trend of differentiation, each group carries a characteristic assemblage of accessory minerals. The Kiako Carbonatite and, possibly, the carbonatite which once existed in the middle of the alkaline plutonic complex, contain aegirine and magnetite, the Ekiojango Carbonatite contains phlogopite, and the Kinyamungu Carbonatite, magnetite, pyochlore and a little phlogopite. All carry felspar and apatite; the Ekiojango Carbonatite is especially rich in apatite.

Phosphate was evidently one of the components of the original liquid, since more than one generation of apatite is often found. For example, in the Ekiojango Carbonatite, apatite crystallized both early and late; the early phase is partly resorbed by the carbonate, and the late phase, which is found in veins, crystallized from the residual solutions. Of the other minerals, some have been altered by the carbonate, and some are not in equilibrium with it. The aegirine is partly carbonated and altered to ore. The phlogopite, which possibly originated as biotite, is cloudy, especially in the Kinyamungu Carbonatite, and its cleavage flakes are bent and often broken. Occasionally even the magnetite is partly replaced by carbonate. It is not certain how many of these alterations are later changes, but many of the minerals have the appearance of xenocrysts. Most of them are probably from the subvolcanic mineral assemblage at the time the carbonatite which contains them was emplaced; the felspar may represent altered and broken-up fragments of wall-rock, or it may have crystallized from the carbonatite liquid.

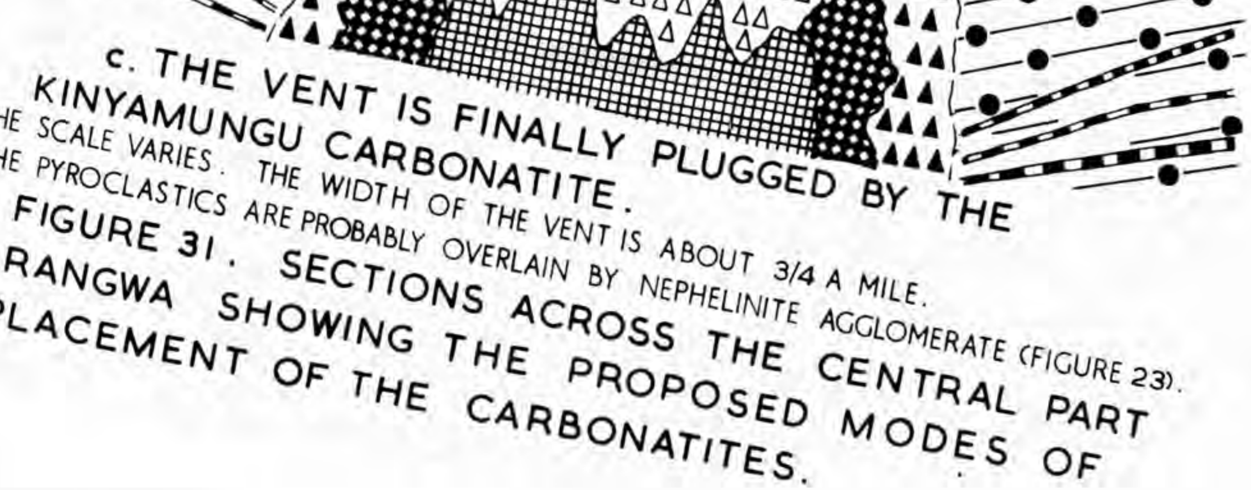
Finally, although the carbonatite is closely associated with altered alkaline silicates, why is there no gradation in composition and texture between carbonatite and alkaline silicates? The experimental work of Koster van Groos and Wyllie (1963) hints at an answer; in the experimental system albite-sodium carbonate, with 10% water added, the albite and sodium carbonate melts were found to be immiscible at temperatures of over 650° C at a pressure of 1,000 bars. So possibly alkaline silicate and carbonate melts of other compositions are immiscible at magmatic temperatures.



a. CONESHEETS AND DYKES ARE INTRUDED INTO THE PYROCLASTICS FROM FOCI BELOW THE VENT WHEN THE UPPER PART OF THE VENT IS BLOCKED.

b. THE EKIOJANGO CARBONATITE IS FORCED UP THE WALL OF THE BLOCKED VENT.

PROBABLY BOTH a AND b HAPPENED IN SEVERAL STAGES DURING LULLS IN VOLCANIC ACTIVITY.



c. THE VENT IS FINALLY PLUGGED BY THE KINYAMUNGU CARBONATITE.

THE SCALE VARIES. THE WIDTH OF THE VENT IS ABOUT 3/4 A MILE.
THE PYROCLASTICS ARE PROBABLY OVERLAIN BY NEPHELINITE AGGLOMERATE (FIGURE 23).

FIGURE 31. SECTIONS ACROSS THE CENTRAL PART OF RANGWA SHOWING THE PROPOSED MODES OF EMPLACEMENT OF THE CARBONATITES.

IX

LATE ALKALINE DYKES

The rocks that are described in this chapter are of several distinct types, and, as was explained in the introduction to Chapter VI, some of them can be proved to be later than all the other alkaline rocks by their cross-cutting relationships, whereas others are thought to be late by inference. Dykes of some of these types have been found on Rusinga and Mfwangano (Kent 1936 and 1944, McCall 1958, Shackleton 1951 and Whitworth 1958); they will be mentioned, but specimens of them were not collected during the present work.

Rocks of these types were found:-

1. Phonolite.
2. Lamprophyres.
3. Felspathised ijolite.
4. Collophane rock.
5. Concretionary Carbonate.
6. Late hydrothermal veining.

1. DISTRIBUTION.

Since the dykes are seldom more than 10 cm thick, they were found only where the rocks they cut are exposed; so the outcrop pattern, though wide-ranging, is necessarily far from complete.

One phonolite dyke was found, striking north-east south-west on Kiawindo (RFP 96); a loose block of phonolite was collected from Kiako (RFP 157), and another from near the contact between the basement and volcanics south-west of Kiawindo.

Most of the late dykes in the Rangwa area are considered to be lamprophyres of various sorts. They cut the pyroclastics, early plutonics, basement and volcanics, and they were found at these localities. Loose blocks of lamprophyre were collected from among the pyroclastics to the west of Manganga (RF 42). A dyke cuts the uncompahgrite (RF 220), and another occurs among the talus to the west of the uncompahgrite (RFA 28). Three vertical dykes outcrop on Kiawindo (RFA 86, RFA 87 and RFA 89), and they are cut by a conesheet which has a north-south strike and dips towards the centre of Rangwa at 20° (plates 185 and 186). Four dykes of lamprophyre were found on Kiako (RFP 61, RFP 156, RFP 159 and RFP 164); these cut the basement, felspar rock, carbonatite and nepheline syenite, and they all strike towards the centre of Rangwa or slightly north of it. A dyke cuts the nephelinite lava 300 ft. above its base on Kiodiga, 3½ miles south-east of Rangwa (RFP 3).

Dykes of felspathised ijolite are confined to Rangwa, where six were found. They cut both the pyroclastics and the carbonatites, and they do not seem to conform to any structural pattern.

One dyke of collophane rock cuts the breccia near the top of Kumuthua; it dips 5° to the north, although this may not be its original dip.

Plate 185. Dyke of lamprophyre intrusive into granite on Kiawindo.

Plate 186. Lamprophyre conesheet cutting lamprophyre dyke, intrusive into granite, on Kiawindo.

Several occurrences of banded and apparently concretionary carbonate were found on and around Rangwa.

2. DESCRIPTION OF THE ROCK TYPES.

A. PHONOLITE.

In hand specimen, the phonolite is seen to have a dark grey matrix, packed with orientated felspar laths, which may be 3 cm long, and are often split down the middle. As well as the felspar, the rock contains subhedral phenocrysts of hornblende and pyroxene which are seldom more than 2 mm long, and the matrix is very fine-grained and felspathic.

The felspar is either orthoclase or anorthoclase; in RFP 96, where it is relatively fresh, it has a 2 V of $35^\circ - 45^\circ$, and shows simple twinning (plate 187). Imposed on this there is extremely fine multiple twinning on the albite law, and occasionally on the pericline law. In RFP 157, only the simple twinning is evident, as the multiple twinning is normally obscured by cloudiness. The felspar may be replaced patchily by calcite.

Hornblende is generally zoned, and has darker edges; it is pleochroic:- Z = chocolate brown, Y = light brown, X = buff. Twinning is common. Frequently the darker borders of the crystals contain tiny specks of ore (plate 188), and prisms of apatite sometimes occur within the hornblende.

Plate 187. Euhedral potash felspar in phonolite. (RFP96). x25.

Plate 188. Euhedral zoned hornblende in phonolite. The phenocrysts at the bottom are partly altered pyroxenes. (RFP96). x55.

Pale green aegirine augite with darker green, slightly pleochroic borders of aegirine forms small phenocrysts, although these are less common and tend to be more highly altered than the hornblende. In RFP 157, most of the pyroxenes are pseudomorphed by specks of ore and pale noncrystalline material. No unaltered nepheline was found either as phenocrysts or in the groundmass.

Small prisms of apatite occur as phenocrysts and as inclusions in both the felspar and hornblende phenocrysts. It is normally euhedral. Euhedral crystals of hornblende may also be included in the felspar phenocrysts.

Euhedral sphene and subhedral magnetite both occur as accessories.

The matrix, which composes at least 65% of the phonolite is highly altered. It consists of unorientated needles of cloudy felspar and carbonate. The felspars are too small and altered to allow their optics to be determined, but some of those in RFP 96 show simple twinning, and they are thought to be orthoclase. No nepheline was found in the matrix.

B. LAMPROPHYRES.

The rocks in this category contain a wide variety of minerals:- biotite, magnetite, perovskite, sphene, melanite, apatite, pyroxene, hornblende and probable pseudomorphs after melilite and nepheline. These all tend to have ragged and altered edges, and they are set in a matrix that is predominantly fine-grained dirty brown carbonate with, occasionally, small amounts of very fine felspar. They are considered as a group, because they have related textures, modes of alteration and mineral assemblages. Because of the large amount of alteration and the possibility of unrecognized or misidentified pseudomorphs, it is difficult to give them specific rock names. Nearly all of them contain biotite and pyroxene phenocrysts and pseudomorphs after melilite. Except for the fact that no olivine psuedomorphs were found, the mineral assemblage and texture are those found in alnoite (Johannsen 1938, Volume 4 pp 385 - 387). Although belonging to the same suite of rocks, individual dykes have modal compositions which are those of other named types of lamprophyre; some dykes are mica-free (RF 220 and RFP 89), and have the modal compositions of melilite-fasinites (Johannsen 1938, Volume 4 p 377), (RFP 61 and RFP 86), and dykes in which brown hornblende predominates over pyroxene are more akin to farrisite (Johannsen 1938, Volume 4 p 389).

The lamprophyres are grey or dark grey in hand specimen, and apart from trains of small vesicles filled with zeolites (specially in RFP 3), they are homogeneous and fine-grained. The hard and massive appearance of the rock implies that very little of the alteration that permeates it is the result of weathering. Normally over half the rock is matrix and indeterminate pseudomorphs, and unorientated phenocrysts, both unaltered and altered, generally with ragged edges, and never more than .5 mm long, are scattered through it.

Biotite forms the most prominent phenocrysts. It is pleochroic from brown to pale yellow, and shows a pseudo-uniaxial interference figure, so that it is not unlike the biotite of the biotite uncompahgrite. It occurs as plates which nearly always have paler rims, and are sometimes altered to specks of ore (RFP 88). The plates are frequently broken, and the pieces are twisted relative to each other, so that much of the biotite has the appearance of xenocrysts.

Magnetite occurs widely as subhedral crystals and irregular specks, some of which may be alteration products. Perovskite is only found occasionally, sometimes as separate grains, but more often it is associated with magnetite and biotite, and the three minerals have the same sort of interrelationship as they do in the uncompahgrite; biotite may partly surround intergrowths of magnetite and perovskite (RFP 87; plate 190). In RFP 88, groups of magnetite and biotite crystals are surrounded and partly replaced by brown and pale brown zoned melanite, another relationship found in the early plutonics. Euhedral sphene is a common accessory, and, although it does not occur together with the magnetite, biotite and melanite, there is more of it in the melanite-bearing dyke. Biotite also replaces pyroxene (RFP 86).

Where the pyroxene has not been pseudomorphed, it is pale

Plate 189. Magnetite and biotite in a predominantly carbonate groundmass from a lamprophyre dyke. (RFP87). x55.

Plate 190. Magnetite partly rimmed by biotite from a lamprophyre dyke. (RFP87). x160.

green aegirine-augite, with a maximum extinction angle of 36°. It is commonly rimmed by darker green aegirine which is often obscured by alteration products. The pyroxene is anhedral and appears to have been replaced considerably by the matrix, as the crystal edges are embayed (RFA 28) and spotted with ore; the matrix round the pyroxenes contains spots of ore too. This feature is regularly shown by the large pyroxenes in the nephelinite lavas. Small fragments of pyroxenite occur occasionally (RFA 28 and RFP 61), and in RFP 61, small crystals of wollastonite were found with the pyroxene.

Hornblende is present in two dykes (RFP 61 and RFP 86); its pleochroic scheme is Z = dark brown, Y = reddish brown and X = yellow, which is similar to that of the hornblende in the phonolite dykes, but unlike any from the basement. It forms subhedral phenocrysts, and replaces pyroxene; in RFP 61, a large, irregular hornblende crystal encloses blebs of pyroxene that have the same orientation.

Apatite is a normal accessory as phenocrysts, and, as in the phonolite, it sometimes forms inclusions in other minerals.

No unaltered melilite was identified, but pseudomorphs can be interpreted with varying degrees of certainty as being after melilite in most of the dykes. These are generally small laths, but RFP 61 contains pseudomorphs after tabular melilite which are up to 1 cm across. The main pseudomorphing minerals are pale but cloudy carbonate, and a mineral that has been identified tentatively as cebollite. The latter is composed of minute fibres which have straight extinction and are length slow, and whose refractive index is slightly higher than that of Canada Balsam; the cebollite that alters the melilite in the uncompahgrite has similar characteristics. The fibres form a mesh, and are aligned in two predominant directions at right angles, which probably correspond to the cleavage directions of the melilite (RFP 89, . Sometimes (RFP 3), minute crystals of carbonate form aligned fibres, possibly a replacement after cebollite. Most of the pseudomorphs are laths with indeterminate edges; occasionally, they have a median crack which is characteristic of the unaltered melilites in the lavas. In RF 220 and RF 53, there are darker needles of fine-grained carbonate, and it is uncertain whether these pseudomorph melilite or pyroxene.

Pseudomorphs after nepheline are fewer and more dubious. RFA 28 contains small euhedral nephelines which have been almost completely cancrinitised. Otherwise the only possible nepheline pseudomorphs are small patches of fine-grained homogeneous felspar, which is cloudy and untwinned and extinguishes irregularly. It is not unlike much of the potash felspar which occurs both interstitially and as pseudomorphs throughout the pyroclastics. The patches of felspar are generally angular and have clearcut edges, but their shapes are not specially characteristic of unaltered nepheline.

The matrix of the lamprophyre is cloudy and apparently noncrystalline under low power. It is in fact a mosaic of very dirty, small carbonate crystals with streaks and patches of brown noncrystalline material and black ore. It contains some small colourless crystals of low relief which are an indeterminate felspar or zeolite, and a lot of finely disseminated biotite. Tiny colourless needles of high relief are superimposed on both the matrix and phenocrysts; their thickness is generally less than that of the slice, so that their optics cannot be determined, but they could be pyroxene or amphibole.

C. FELSPATHISED IJOLITE.

The felspathised ijolite is normally deeply weathered, and is yellow with thin red-brown stripes. In this state it is soft and studded with vesicles, and few of the original minerals survive. The one fresh specimen collected is greenish grey, unbanded and nonvesicular. Pyroxene and nepheline crystals are prominent on the surface.

The rock is coarse-grained, and prior to alteration it must have consisted predominantly of euhedral nepheline and zoned pyroxene, both forming crystals up to one millimetre across. Felspar has replaced much of the nepheline so that nearly half of the rock is composed of it. The pyroxenes have overgrowths of aegirine and blue-green amphibole which are often larger than the crystals themselves, and calcite has crystallized interstitially.

The surviving nepheline is water clear, and numerous perfect six-sided cross-sections are preserved. They are zoned concentrically by layers of minute colourless inclusions, and remnants of euhedral nepheline crystals tend to occur in groups; so nepheline was probably the main mineral before alteration (plate 191). The felspar that has replaced nepheline is cloudy and untwinned, and has a refractive index slightly lower than that of nepheline, but its birefringence colours are slightly higher. It is negative with a high 2 V. From these properties it is thought to be orthoclase. It forms irregular crystals up to 5 mm across, which replace the nepheline patchily, and unconnected areas of felspar often show the same extinction. The extinction moves across the felspar fan-wise.

It is difficult to tell what the original pyroxene was, as every gradation exists between augite and aegirine. It is zoned, but not regularly, and patches of aegirine-augite with similar orientation are frequently enclosed in a more aegirine-rich pyroxene, with gradational boundaries and continuous cleavage from one to the other (plate 192). The aegirine-augite is pale green, and the aegirine is pleochroic between dark green and paler yellow-green. The blue-green amphibole is only slightly pleochroic between green and blue -green. Aegirine-augite, either zoned or showing hour glass texture, is rimmed irregularly by aegirine, which either

Plate 191. Euhedral nepheline replaced marginally by potash felspar in felspathised ijolite. (RF248). x55.

Plate 192. Needles of aegirine (dark) and sodic amphibole (paler) penetrating potash felspar in felspathised ijolite. (RF248). x85.

overgrows the original pyroxene crystal, or has a separate orientation and engulfs several pyroxenes. The aegirine protrudes into the surrounding felspar and, sometimes, nepheline, either as globular growths or as spikes. Both round the pyroxene and within the felspar and nepheline, fibrous aegirine and blue-green amphibole grow in bundles, intergrown or with the blue amphibole occurring outside the aegirine.

Large crystals of carbonate with very irregular edges occur throughout as a replacement mineral, especially within the pyroxenes.

D. COLLOPHANE ROCK.

The collophane rock is a vesicular rock of concretionary appearance, with subparallel white and brown bands. In hand specimen, no crystalline minerals are visible. In thin section, it is seen to consist of bands, each about .1 mm thick, of dahllite, whose length is always perpendicular to the plane of banding (plate 193). The crystals are very small, and crystal boundaries are obscure. The dahllite rims larger rounded areas of similar relief, which are opaque under crossed polarisers and apparently noncrystalline. This is thought to be collophane, as staining with ammonium molybdenate shows that the rock consists mainly of phosphate. Within the opaque areas, and between dahllite bands, there are small vesicles, generally streaked out in the direction of banding, and sometimes lined with crystalline carbonate. Obscure patches of brown ore are scattered through the rock.

Only one dyke of collophane rock was found on Rangwa.

E. CONCRETIONARY CARBONATE.

Although more compact and definitely forming a dyke, the concretionary carbonate looks not unlike tufa. It occurs in a small dyke, 10 cm across and radial to the centre of Rangwa, which cuts the ijolite on Sagurume, without causing any brecciation or alteration in it. The dyke is composed of very fine laminae of yellow and brown carbonate which, though mamillated, are roughly parallel with plane of the dyke (plate 194).

The size of the crystals of carbonate is variable, but normally they are less than 1 mm across; within one band they are about the same size, except that the outer edge of each band is composed of carbonate of fibrous appearance. The carbonate is clear at the inner parts of the bands, and becomes cloudy towards the edges; each band is a separate unit, and they are always continuous, although their form is very tortuous. Shattered crystals of analcite up to 2 mm long occur within the carbonate, which tends to vein them. Between the bands, patches of tiny quartz crystals occur and boundaries between them and the carbonate are often straight.

F. HYDROTHERMAL VEINING.

Several instances of late-stage veining following zones of

Plate 193. Bands of dahllite with collophane (black) in collophane rock (under crossed polarisers). (RF272). x125.

Plate 194. Banded concretionary carbonate. (RFP84). x25.

brecciation were found on the cliffs that bound Rangwa. On Manganga, a vertical gulley, which runs 150 ft. up the cliff face is caused by a zone in which euhedral crystals of pure calcite up to 1 cm long have grown between brecciated fragments of agglomerate.

3. THE LATE DYKES ELSEWHERE ON THE KISINGIRI VOLCANO.

Kent (1936 pp 93 - 102) lists 36 dykes which cut the sequence on Rusinga. Their average thickness is 4 ft., and they can be traced for long distances, a mile in one case. The main rock type is "a moderately coarse-grained" rock, which "resembles a rotten schist when weathered". One nephelinite dyke was found. They are nearly vertical, and their main strike is north-south, tending towards northeast-southwest in the east of the island. Most of them postdate the faulting and slumping there, and some show crosscutting relations. Shackleton (1951) marks several dykes with a north-south strike on his map of Kiahera Hill, and in the key, he splits them into micaceous, basaltic and carbonate dykes. McCall (1958 p 57) mentions a swarm of red melanite nephelinite dykes on Kiahera Hill which strike north-south.

Whitworth (1962 p 175) recorded 22 dykes from the eastern part of Mfwangano, most of which strike northwest-southeast. He splits them into two types, alnoitic and augititic. In the former, melilite occurs both as euhedral phenocrysts and in the matrix, and biotite forms prominent phenocrysts, sometimes enclosing magnetite, which is a constituent of the matrix as well. Apatite and perovskite are often present. The augititic type, which is found less often, contains about 45% of euhedral augite in a very fine-grained, colourless matrix, which shows first order grey, and is thought by Whitworth to be zeolitic.

McCall (1958 pp 55 and 56) describes nephelinitic and alnoitic dykes which cut the nephelinite lavas and agglomerates at many localities, mostly striking radially to Rangwa. The nephelinitic dykes contain phenocrysts of augite, pseudomorphs after melilite and a little biotite in a highly altered zeolitic groundmass. The alnoitic dykes contain the same mineral assemblage as the lamprophyre dykes described in this work, only without prominent pyroxene phenocrysts.

Of the above, the only petrographic descriptions are those of Whitworth and McCall; the alnoitic dykes described by both of them are similar and the nephelinite dykes of McCall and the augititic dykes of Whitworth can probably be correlated also. The alnoitic dykes are certainly the same as the lamprophyres described in this work, and possibly some of the nephelinite and augititic dykes are too, although no dykes were found near Rangwa which carried as much as 45% of pyroxene.

From their descriptions, it seems likely that Kent's main type of dyke and Shackleton's micaceous dykes are alnoitic, and Shackleton's basaltic dykes may be the same as McCall's red melanite nephelinite ones. Shackleton's carbonate dyke is composed of very fine-grained homogeneous carbonate, and is probably of hydrothermal origin.

4. MODE OF ORIGIN.

Nearly all the late dykes from Rangwa's immediate surroundings and from farther afield have a strike that is almost radial to Rangwa, and the only conesheet that was found dips towards Rangwa. So it is likely that most of them originated from a centre beneath Rangwa. The lack of conesheets does not allow the depth of the focus to be determined. The fact that the dykes sometimes cross each other (as at Kiawindo, and at several localities on Rusinga and Mfwangano) shows that they were emplaced in more than one stage although no trends of differentiation can be detected.

The age relations of the phonolite cannot be determined. Only two examples of felspar-bearing lava have been found on the Kisingiri Volcano so far (within the melanite nephelinite agglomerate); the large anorthoclase phenocrysts of the phonolite have not been found elsewhere except in some of the felspathised rocks, and the same zoned brown hornblende only occurs in the lamprophyres and in some fragments of hornblende rock in the conglomerates on Rusinga. It is not known whether the phonolite originated from the Rangwa centre or whether it is part of the large suite of phonolitic rocks whose occurrence extends eastwards along the Kavirondo Rift.

The lamprophyres contain nearly all the same minerals, often with the same relations with one another, for example magnetite, perovskite and biotite, as the alkaline plutonics. It is difficult to decide whether the phenocrysts in the lamprophyres are xenocrysts picked up from alkaline plutonics, or whether they are newly formed minerals. Brown hornblende is the only mineral in the lamprophyres not found in the alkaline plutonics, and it is often seen to have a replacement relationship with pyroxene. The fact that the lamprophyre dyke which cuts the uncompahgrite (RF 220) does not contain appreciably more melilite or biotite than any of the other dykes indicates that any xenocrysts must have been incorporated at depth. Also the absence of basement xenocrysts in the dykes which outcrop away from the centre shows that most of the xenocrysts must all have come from near the focus of origin. The matrix is so highly carbonated and the edges of the phenocrysts so corroded that the magma must have been very rich in volatiles. It is probable that this magma, which was trapped at depth after the vent had been blocked, pushed its way outwards along cracks caused by explosive activity, carrying with it crystals and fragments from deep-seated plutonic rocks. Lamprophyres, especially alnoites, are a normal late feature of carbonatite complexes (Chilwa, Garson and Campbell Smith 1958, and Alno, von Eckermann 1948).

The felspathised ijolite dykes on Rangwa itself were only intruded close to the carbonatite centre, after carbonatite activity had ceased. Their relations with the lamprophyres are not known.

The concretionary carbonate, collophane rock and veins of carbonate are all manifestations of late hydrothermal activity, and they could have occurred at any time between the end of the volcanic activity and today. The presence of poorly consolidated tufa on Rangwa shows that hydrothermal activity has continued there until recently, and there are still hot springs on Homa Mountain today.

X

LATE SEDIMENTARY AND SECONDARY DEPOSITS

1. DESCRIPTION OF THE DEPOSITS.

The late deposits on Rangwa can be split into 4 groups:-

1. Cemented gravel.
2. Secondary breccia.
3. Tufa.
4. Alluvium, uncemented gravel and soil.

The groups are not necessarily connected with each other, except in the sense that they were all deposited or formed after the main igneous activity on Rangwa and after most of the erosion of the Kisingiri Volcano.

A. CEMENTED GRAVEL.

Two small outcrops of cemented gravel were found, one half way between Sindo and Sindo School, and the other near the lake 400 yards east of Rowo School. Both are at a height of about 20 ft. above the level of the lake, and can be seen as patches of crumbling white material, at the same level as the surrounding red alluvium.

Several centimetres under the surface, the white material is more consolidated, and provides a matrix to closely-packed rounded pebbles, whose diameter varies between 1 and 4 cm. The rock is roughly bedded, and, although no measurements were taken, an impression was gained that the long axes of the pebbles were normally in the horizontal plane.

The matrix is calcareous, and dissolves away almost entirely in hydrochloric acid. The pebbles consist mostly of the rock types found round Rangwa, and the majority are of fenite and granite, as well as some lava, agglomerate and ijolite. No fragments of uncompahgrite or carbonatite were found, although only a cursory search was made.

Although many of the gulleys on and around Rangwa were examined, no outcrops of cemented gravel were found in them. However, the two small occurrences mentioned above must be the remnants of sediments from a far larger area of deposition. The sediments are waterlaid, since no other agency could round, transport and deposit the fragments, and the matrix originated as very fine calcareous mud, similar to what occurs on the floor of Kaksingiri Bay at the present. If the deposits that survive are extended laterally, it becomes apparent that a lake existed to the north of Rangwa, and possibly partly surrounding it, and that pebbles were washed into it from Rangwa itself and the country round it. There is no evidence on which to decide whether the fact that both outcrops are at heights of 20 - 30 ft. above lake level is due to their having been planed down to the same level as the alluvium that encircles them, or whether they reach the original maximum height of the cemented gravel. So the original size of this early lake is problematical.

B. SECONDARY BRECCIA.

Outcrops of the secondary breccia are widespread. It occurs at the bases of most of the cliffs which bound Rangwa, and under a few of the cliffs above Nyakirangacha, although it is not so frequent there, as alluvium often extends right up to the cliffs. The same sort of breccia covers much of the uncompahgrite, and occurs in small hollows on the surface of the Kinyamungu Carbonatite, as well as plastering the faces of many carbonatite cliffs. The height of the outcrops varies between near lake level (3,730 ft. above sea level) in the north, to over 5,000 ft. above sea level round the southern margin of Rangwa.

The appearance of the breccia is variable, but there is always a matrix of pale carbonate, either noncrystalline or with small, cloudy crystals (plates 195 and 196), which resembles that of the cemented gravel, except that it is better consolidated. The fragments are angular, unsorted, unbedded and so closely packed that they touch one another. A botyroidal, concretionary coating of matrix sometimes covers them, especially at exposures near to the Kinyamungu Carbonatite. A similar coating may cover the bottom few feet of the cliffs of pyroclastics.

The fragments which are of all sizes up to about 50 cm across are derived locally. Those in the breccia at the bases of the pyroclastic cliffs are of unweathered tuff and agglomerate, and where the pyroclastics above are cut by numerous carbonatite conesheets,

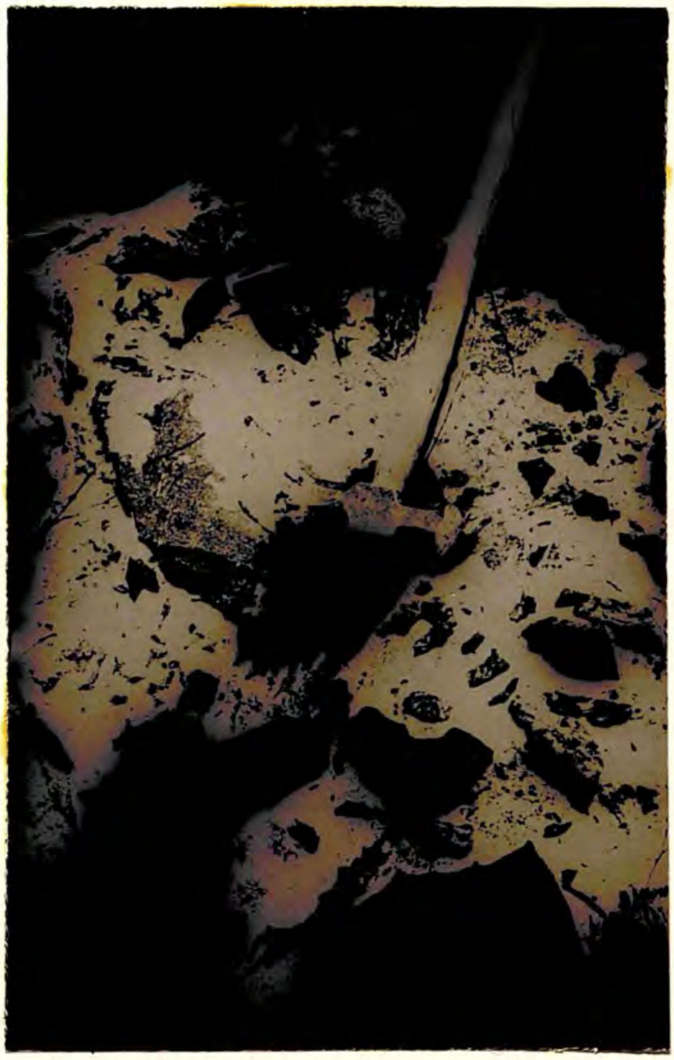


Plate 195. Cemented breccia at the base of the pyroclastic cliffs on Manganga.

Plate 196. Cemented breccia covering the biotite uncompahgrite on Kumugina.

as to the north west of Kinyathengo, a few fragments of carbonatite are present. All the fragments in the breccia that covers the uncompahgrite are of uncompahgrite, and those in the breccia associated with the Kinyamungu Carbonatite are of carbonatite.

The breccia composed of fragments of pyroclastics extends right up to the cliffs, and tongues of matrix penetrate pyroclastics that are in situ. The outcrops are several yards wide, and at their outer edges they disappear beneath the talus slopes. Further outcrops occasionally occur lower down where the talus is gulleyed. The position of the breccia below cliffs, and the local derivation of the fragments imply that the breccia is an early talus slope, which has been cemented, partly eroded away and covered by later talus.

Where breccia covers the uncompahgrite, it is possible to trace progressive brecciation from an exposure of in situ uncompahgrite, through a zone in which small veins of pale matrix penetrate the uncompahgrite along joint planes, upwards to a true breccia, in which fragments that have been broken up can often be fitted together. The whole transition takes place over several feet. The area occupied by this breccia is irregular, and is not dictated by any changes in the nature of the underlying rocks; but since the present land surface is smooth, regardless of whether it has a coating of breccia, the breccia that survives must occupy small depressions on an old surface of unbrecciated uncompahgrite, and possibly the breccia once covered the whole area of the uncompahgrite, and the breccia that protruded has since been planed off. Unlike the fragments in the talus breccia, the uncompahgrite ones have suffered considerable alteration. Often they have been broken down to their constituent minerals, of which the magnetite and biotite survive and the melilite is altered to a yellow clay-like substance. Because of the fact that the fragments are more or less in situ, the gentleness of the slope on which the breccia occurs and the sometimes intense chemical weathering suffered by the uncompahgrite fragments, it is thought that the breccia was formed by both mechanical and chemical weathering on an old land surface. As with the talus breccia, the fragments were cemented by carbonate-rich solutions.

The breccia that is found with the Kinyamungu Carbonatite contains more rounded fragments, usually with limonitic rims. However, it is broadly comparable with the breccia that covers the uncompahgrite, since it often fills hollows and joints within the carbonatite. It is presumably formed from fragments that have been broken off, rounded and cemented by solution and recrystallization of carbonate. The coating of secondary breccia on some of the carbonatite cliffs is probably what survives above the alluvium from old talus slopes.

There is no direct evidence that the three categories of secondary breccia belong to the same episode in the history of Rangwa, but the fact that the breccias all have the same sort of pale matrix of very fine carbonate suggests that they all belong to the same climatic regime. That some of the breccia formed from the uncompahgrite without transportation and was not washed away, even though it was not well-compacted, means that the climate in which it was formed was dry. It is tempting to suggest that the cemented gravel and the breccia were formed at the same time, but evidence from field relations only shows that both came into being after considerable erosion at the volcanic centre and before the deposition of alluvium. The story pieced together from such scattered and unconnected deposits is necessarily incomplete, and it would be remarkable if all the sediments deposited during the erosion of Rangwa had surviving representatives.

C. TUFA.

One small deposit of poorly consolidated calcareous tufa occurs on Rangwa. A few boulders of it were found in the thickly wooded slopes to the south of Nyakirangacha, and its relationship to the underlying breccia is uncertain.

The rock is composed of very fine laminae up to 1 mm across, and its colour varies between light and dark grey. The laminae are concentrically arranged, and are not the result of normal sedimentary deposition. It is thought that the tufa was deposited by hot springs, and, since it survives, it must be of recent origin. Hot springs occur at many igneous centres long after other types of activity have ceased; in the Rufunsa Valley, there are hot salt springs at the present day to the south west of the carbonatite centres with which they are probably connected, though the last volcanic activity occurred in the Cretaceous, (Bailey 1960). So the occurrence of tufa on Rangwa is not unexpected.

D. ALLUVIUM, UNCEMENTED GRAVEL, TALUS AND SOIL.

Alluvium, interspersed with irregular beds of unsorted gravel, is found on the floor of Nyakirangacha, and on all sides of Rangwa except to the south. Talus slopes occur most of the way round Rangwa, again except in the south, between the alluvium and the bounding cliffs of pyroclastics; smaller talus slopes exist below some of the cliffs around Nyakirangacha. Soil, which is defined here as any fine-grained, unconsolidated, untransported weathering product, covers most of the exposures of pyroclastics on the higher parts of Rangwa. All these deposits are interrelated and grade into one another.

The alluvium is cut by steep-sided gulleys, which are up to 50 ft. deep in Nyakirangacha, and sometimes over 100 ft. deep to the south east and south west of Rangwa (plates 197 and 198). No exposures of cemented gravel, basement, plutonics or pyroclastics were found in them, which implies that the alluvium attains great thicknesses. Its surface is smooth, and slopes towards the lake both east and west of Rangwa with an angle of about two degrees,

Plate 197. The main gulley in Nyakirangacha.

Plate 198. Small gulley on Kumugina, south east of Rangwa. Ekiagaria and Kitunda are in the middle distance. The Sindo Pass and part of the Gwassi Hills are in the background.

and with a slightly higher angle in Nyakirangacha. The angle of slope increases a little as the surface of the alluvium approaches the ring of basement hills, but the break in slope is sharp round Rangwa itself, at the transition between the alluvium and talus (plates 2, 3, 4 and 5). North of Rangwa, the smooth surface ends abruptly at an indented terrace, which stands 25 - 30 ft. above the present lake level, and drops to present day beach deposits. However, no terrace exists along the shore north of Sindo. The beach and mud deposits extend into the lake for varying distances, up to another sharp drop of 20 - 30 ft.

Most of the material in the alluvium is red and very fine-grained, although it does include boulders of all the rocks found on the area, both singly and in bands. The surface is covered with loose boulders, probably because the fine-grained material round them has been washed away. There are occasional variations in the composition and appearance of the alluvium; near the uncompahgrite, patches of magnetite soil occur, but this seldom extends more than 3 inches below the surface, and normally occupies minor run-off channels. The fact that there is so much of it on the tracks near the uncompahgrite gives a misleading impression of its importance, as water runs along the tracks during storms, and the lighter red material is washed away, thus concentrating the fragmental magnetite. The amount of niobium in the alluvium increases markedly towards the carbonatite on Kinyamungu and Engima, a feature which will be described in Chapter Xl.

Besides the major alluvial plains around Rangwa, there are smaller alluvial fans, which are below the outflows of some of the valleys that run to the edge of Rangwa; the biggest fan occurs south of Sindo below Manganga. These are recent features, and their surfaces dip more steeply than the older alluvium; they are hardly gulleyed, and are accumulating intermittently today.

The talus slopes round Rangwa are between 200 and 700 ft. high. Their height is least near the lake, and greatest at the eastern side of Rangwa (plates 2, 3, 4 and 5). Throughout, the angle of slope is remarkably consistent, and seldom varies much from 30°. It differs from that of the surface of the alkaline plutonics, whose dip away from Rangwa is far less steep and less regular. To the west of Rangwa, where the outer edge of the pyroclastics is more indented, some of the talus slopes are poorly developed, and are sometimes not so steep. This suggests that the present day differences of relief on Rangwa are a feature of long standing, and the talus slopes to the west are possibly smaller because less material was available from above to feed them. The irregularity of the line of cliffs to the west indicates that the talus slopes below them were built partly from boulders of pyroclastic material that was broken up as the cliff line retreated.

The relief of the surface below the talus must be very variable. At many places, the underlying rocks reach the surface through the talus; no talus covers much of the ijolite and uncompahgrite in the south and south east, outcrops of alkaline plutonics pierce the talus at several other localities, and cemented breccia frequently occurs at the top of the talus slopes and sometimes lower down on them. However, at the outlet to Nyandigida, where the level of the valey is so low that talus is nonexistent, no alkaline plutonics or cemented breccia were found, and only a few fenite boulders, whose place of origin is doubtful, occur on the alluvial plains nearby.

Although some of the cliffs which rise around Nyakirangacha are higher than those at the outer edge of the pyroclastics, talus slopes below them are poorly developed. This may well be because the lower parts of them are covered by alluvium, but it is more probable that, since so much carbonate is present, chemical weathering has been more important than mechanical, and few boulders fell to form talus.

The boulders in the talus are angular, and seldom more than a metre across. Sometimes there is a packing of red earth between them, which was probably washed in later, as it is most evident below the small valleys which cut Rangwa. Presumably the most prevalent boulder size dictated the angle of rest, and hence the angle of slope of the talus. Very large boulders of tuff and agglomerate, the biggest of which is 8 metres across, rest on the alluvium, and some of these, specially the boulders of Bedded Tuff to the north east of Rangwa, had a momentum which carried them at least a hundred yards beyond the base of the talus.

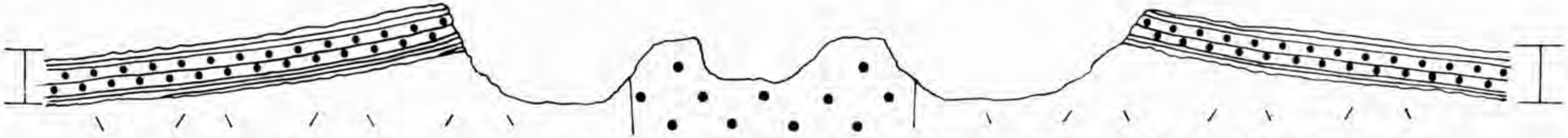
The soil on Rangwa is widespread and thick, and towards the higher and flatter parts of the mountain it envelopes most of the solid rock. It is formed from the disintegration of the pyroclastics, and on the Upper Agglomerate, some of the soil still retains textures from the original rock. The endproduct is similar to the red material in the alluvium, and the process of soil formation which is active today must have been responsible for providing the red earth which was washed down as alluvium. Today however, very little soil is washed from Rangwa, as most of the rainfall sinks into the porous pyroclastics. So it is assumed that when the alluvium was deposited the rainfall was greater.

2. THE EROSION HISTORY OF RANGWA.

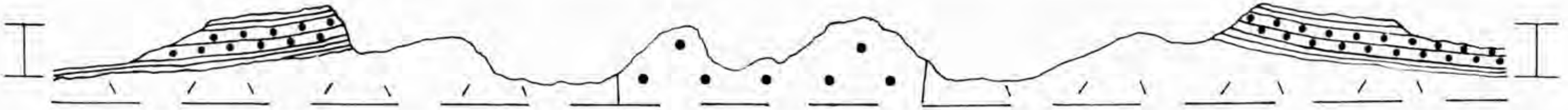
Some of the main events in the erosion history of Rangwa can be deduced from the descriptions of the late deposits.

Prior to the deposition of the secondary breccia and cemented gravel, erosion proceeded to considerably below the present level of alluvium round Rangwa (Figures 32 and 33, illustrating the erosion history of Rangwa); this is evident from the lack of exposure at the bottoms of the deep gulleys in the alluvium. So after the final igneous activity on Rangwa, erosion removed the probable nephelinite agglomerate and lava capping within the area of subsidence, as well

a. AFTER THE FINAL CRATER HAD BEEN BREACHED TO THE NORTH AND AFTER THE FORMATION OF THE MFWANGANO AND KANIAMWA FAULTS.

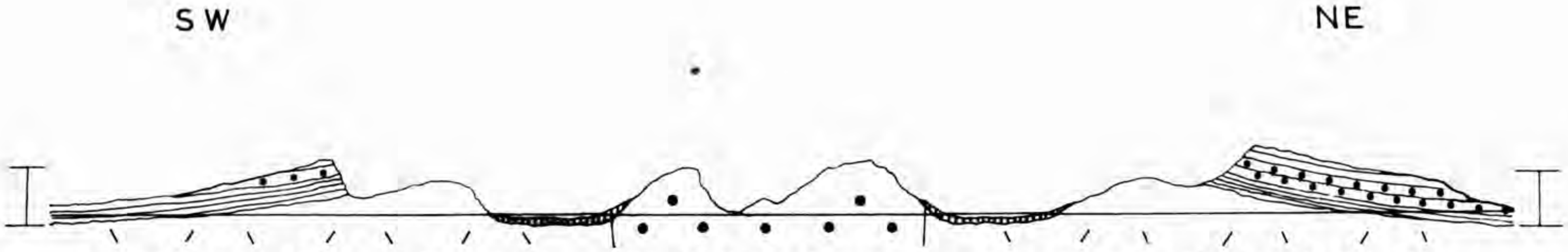


b. DOWNWARD EROSION OF THE VENT AND THE SHATTERED BASEMENT ROUND RANGWA AND RETREAT OF THE VOLCANIC SCARPS.



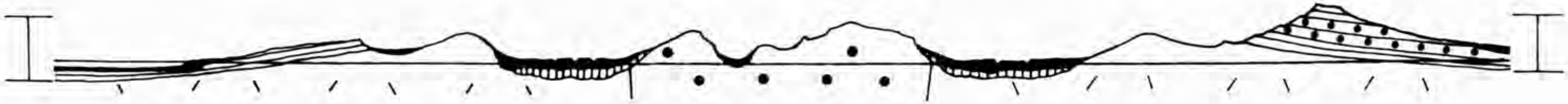
c. CONTINUED EROSION TO A BASE LEVEL WELL BELOW THE PRESENT LAKE LEVEL. THE VOLCANIC SCARPS RETREAT FASTER THAN THE LESS SHATTERED BASEMENT. RADIAL DRAINAGE OFF THE VOLCANICS.

FIGURE 32. SECTIONS ACROSS RANGWA AND THE INNER VOLCANICS ILLUSTRATING THEIR EROSION HISTORY (A).



d. RAISING OF BASE LEVEL AND DEPOSITION OF CALCAREOUS SEDIMENTS IN THE EROSION CALDERA.

e. FURTHER RAISING OF BASE LEVEL AND DEPOSITION OF A BLANKET OF ALLUVIUM.



f. GRADUAL LOWERING OF THE BASE LEVEL CAUSING GULLIES TO BE CUT IN THE ALLUVIUM.

FIGURE 33. SECTIONS ACROSS RANGWA AND THE INNER VOLCANICS ILLUSTRATING THEIR EROSION HISTORY (B).

as much of the lava, agglomerate and shattered basement in the surrounding country. The process by which this is presumed to have happened will be explained in Part III, since it was mainly controlled by the pattern of faulting and erosion elsewhere on the volcano. Before the deposition of the secondary breccia and cemented gravel, the shape of Rangwa was much the same as it is today, except that the relief was more exaggerated; Rangwa itself must have been several hundred feet higher, since some of the material that forms the alluvium was eroded from Rangwa at a later stage, and the arena of Nyakirangacha and most of the large erosion "caldera" must have been in existence, only without their thick blanket of alluvium. At this early stage, erosion proceeded to a base level that was at least a hundred feet below the present level of Lake Victoria, and most of the erosion products were washed right out of the area. This is essential, as the constituents of the cemented gravel, secondary breccia, alluvium and talus have been washed or have fallen into the area after the original erosion products were removed. So, before any sedimentation, Rangwa existed, and had far higher bounding cliffs than it has today.

The form of the land-surface at the bases of the cliffs is not at all clear. In the south and south east the ijolite and uncompahgrite were at much the same erosion level as they are today, since they are covered by secondary breccia which underlies the alluvium laterally and is thought to have formed on an old land surface. Elsewhere the expanse of alluvium and talus is so large that the sort of surface which lies beneath is not known. Erosion to the low base level must have taken place in a wet period during which there were large rivers; otherwise the material could not have been transported so far.

A remarkable feature of the erosion of Rangwa and its surroundings is that the pyroclastic cliffs have survived in their present position for so long without backward erosion except in the west, whereas the nephelinite lava and agglomerate have retreated several miles. A possible reason for this is that erosion proceeded preferentially round the edge of the central area which had subsided, until it reached the base of the nephelinite lavas and agglomerate immediately outside the boundary of the subsided block. Then downward erosion proceeded in the basement which had been weakened and shattered by updoming, brecciation and faulting; also the newly formed scarp of volcanics was eroded backwards, both because the outward dipping pre-volcanic surface was soft and easy to wear away, and because the thicker layers of agglomerate were undercut; this process is continued today on the larger cliffs on Usengere. Once such a trend of erosion had been set, Rangwa itself was not affected so much, because the rocks there are so porous that runoff was comparatively small, and because there was no line of weakness like the base of the volcanics which the erosion could follow easily. Where the alkaline plutonics to the south and south east of Rangwa reach a high level, erosion was impeded also, and, when all the really shattered basement was removed, the volcanic scarp began to suffer erosion more quickly than the underlying basement. This accounts for the present day pattern of basement hills within the volcanic scarp.

As soon as a breach had been made from the central part of Rangwa to the north west, the direction to which most of the erosion products of the central part of the volcano were carried, the material within the central arena was eroded preferentially, until the top of the Kinyamungu Carbonatite was reached, and the irregular form of this proved resistant while material round it was washed away. The course followed by the erosion of the rest of Rangwa was set by the inward dipping planes of bedding, banding and carbonatite conesheet intrusion, so that the main drainage outside Nyakirangacha is concentric, and the largest valleys, Omwoyo and Nyandigida, are curved.

After the carving out of the large amphitheatre round Rangwa and the smaller one within Rangwa, the downward erosion on Rangwa and the backward erosion of the volcanic scarps continued, to provide the components of the cemented gravel and the secondary breccia. However, the base level was raised considerably, and, although evidence is scant, it is thought that much of the area that had been hollowed out by previous erosion was covered by a lake, in which calcareous material and erosion products were deposited. The present day surface of the alkaline plutonics to the south east roughly corresponds to the old land surface, and the early talus slopes round Rangwa were cemented by calcareous material.

There then followed a period of even higher lake level and wet climate. The height to which the lake rose cannot be assessed from direct evidence as there are no obvious erosion benches at a high level round Rangwa, but it is thought to have been at least 200 ft. above the present day lake level, the height to which the alluvial plains around Rangwa rise. During this period, all the red alluvium and unsorted gravel was swept down and deposited, after the surface pyroclastics on Rangwa had first been converted to soil. In wetter conditions soil formation must have proceeded quickly on Rangwa, because of the porosity of the rocks there, and because the soil was removed as it was formed, unlike today.

The final series of events was a spasmodic fall in the level of the lake, which caused the steepsided gulleys that cut the alluvium (plates 197 and 198). That the fall was spasmodic can be demonstrated well at other localities round Lake Victoria by the occurrence of a succession of erosion levels, and on Rangwa there is evidence that the lake level remained stationary at two heights. The higher one is at 60 - 100 ft. above the present level, and can be shown to exist from the depths of some of the longer gulleys along their courses. Both in Nyakirangacha and in the area to the west of Rangwa, the gulleys attain a great depth above the 100 ft. level;

towards it, they gradually die out, until they are only 5 - 10 ft. deep. Since the alluvium they cut is unconsolidated, there are no corresponding erosion benches, but it is thought that it is a level at which the gulleys once poured material into the lake. Below it, the gulleys deepen until 20 - 30 ft. above the present level of the lake which is marked by both an erosion bench along the lake to the north of Rangwa, and by the fact that all the gulleys peter out again.

It is felt that if the gradients of some of the gulleys were measured accurately it would be confirmed that the profiles show that they have been graded to at least two base levels, and further erosion is beginning to form new gulleys which start at today's lake level.

XI

ECONOMIC GEOLOGY

The economic potential of Rangwa has not been investigated fully, but it is possible to enlarge on McCall's brief survey of the area's resources (1958). The area of outcrop of the carbonatites is small, and many of the radioactive and rare earth minerals that are associated with some other carbonatite centres were not found. However, the central carbonatites contain pyrochlore, nearly all the rocks contain apatite and the intrusive body to the southeast is titanium-rich. The distribution pattern and possible economic importance of niobium, phosphorus and titanium are considered here.

1. NIOBIUM.

Except for the streaks that are rich in iron ore in the Kinyamungu Carbonatite, the pyrochlore content of the carbonatites and breccias on Rangwa is very low, and but for perovskite, which is rare in the carbonatites, no other niobium-bearing minerals were found. Nor is there any pyrochlore in the alkaline plutonics or pyroclastics. None of the carbonatites support areas of deep weathering where there could have been pyrochlore enrichment. The main possibility of finding Nb_2O_5 in economic quantities is in the alluvium, where niobium-rich material could have been washed out of the carbonatites and concentrated. To assess the prospects, samples were collected from the main drainage on and around Rangwa; these were analysed for Nb_2O_5 content by the United Nations Mineral Resources Survey in Western Kenya. Dr. Jaffé, the project manager, has kindly supplied the result. Before evaluating the results, it must be stated that, although collected from the present-day drainage pattern, the samples are from alluvium which was washed down when the base level was far higher, and before that pattern was established. The values in parts per million are plotted on Figure 34, and these observations and deductions are made from them:-

1. Values are highest (up to 4,000 ppm) near Kinyamungu and Engima, the largest outcrops of Kinyamungu Carbonatite; this indicates that they are the main sources of Nb_2O_5, and verifies the petrographic evidence.

2. Values from the drainage off the Ekiojango Carbonatite are substantially lower, generally about 1,000 ppm, again what was expected from the petrography.

3. North of the Kiako Carbonatite, values rise to about 600 ppm or nearly twice the background; it is likely that they were affected by material washed from the Kiako Carbonatite, although no pyrochlore was found there, as the values fall again to the east and west. Since the values from Ikoyombe, by contrast, are consistently low, it is thought unlikely that large areas of carbonatite remain undiscovered in the thickly wooded hills to the southeast of Rangwa.

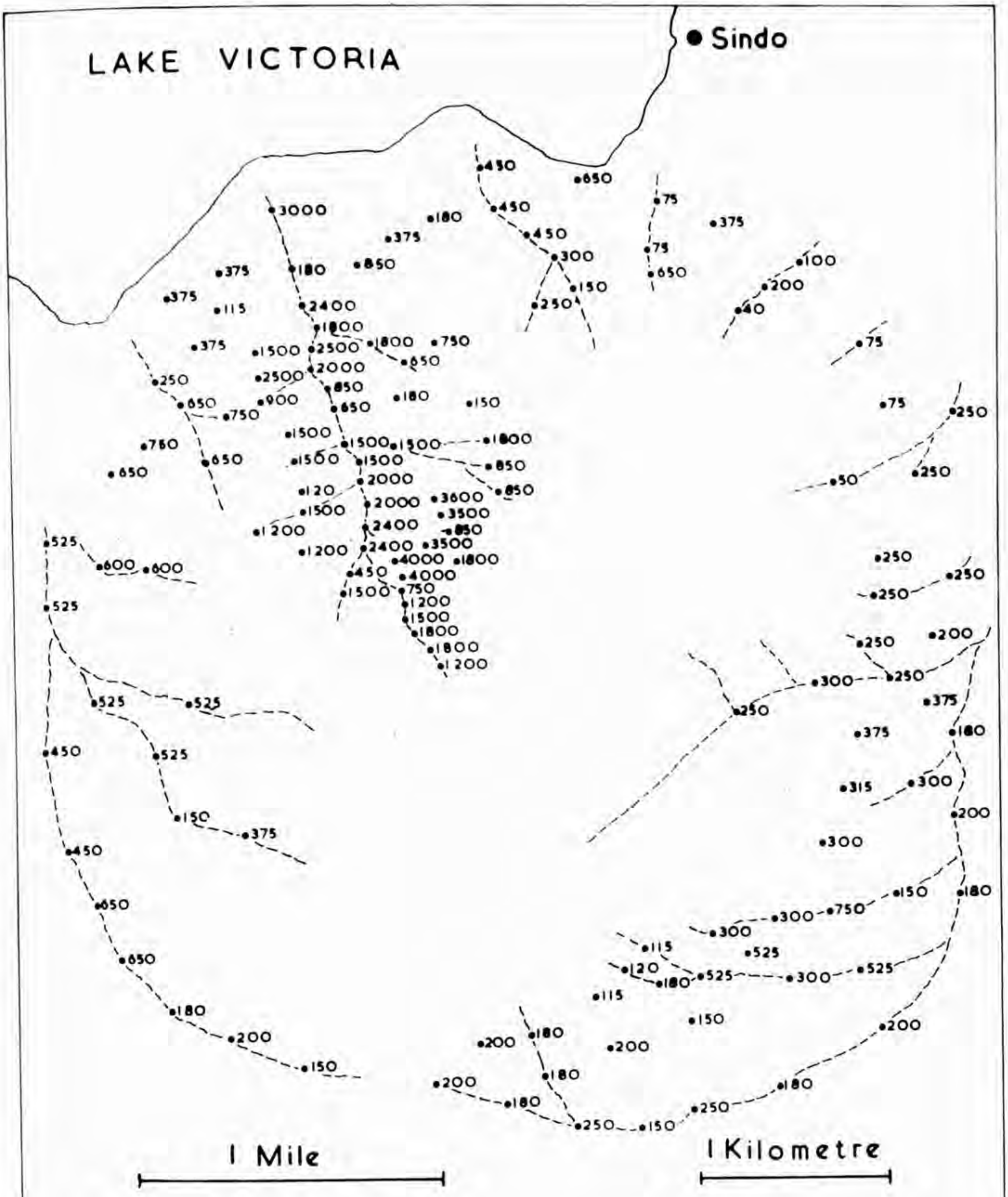


FIGURE 34. MAP SHOWING THE POSITIONS FROM WHICH DRAINAGE SAMPLES WERE COLLECTED ON RANGWA AND THEIR Nb_2O_5 CONTENT IN PARTS PER MILLION

4. Slight enrichment, up to about 500 ppm, occurs on parts of the ijolite-uncompahgrite complex, and is probably cuased by niobium in the perovskite.

5. Otherwise, values conform to a background of 50 - 250 ppm in the east and 400 - 500 ppm in the west. The difference may be due to the carbonatite on Mwisasu and the larger number of small carbonatite dykes and conesheets in the west.

6. A high value (3,000 ppm) is given by the only sample which could represent recent drainage of the carbonatites in Nyakirangacha, collected from the flats by the lake shore near Rowo.

If the alluvium is, on average, 150 ft. deep in Nyakirangacha, and the Nb_2O_5 content does not decrease with depth, the area round Kinyamungu and Engima, where values of 2,000 ppm or more were recorded, represents an ore body of 12,000,000 tons of .2% Nb_2O_5. The United Nations Mineral Resources Survey are at present (April - June 1967) carrying out a pitting programme in Nyakirangacha. But, in advance of their results, it would seem unduly optimistic to expect the Nb_2O_5 values to remain constant at depth. Since the Kinyamungu Carbonatite is probably the top of a larger body of carbonatite, the lower parts of the alluvium would be expected to contain smaller amounts of Nb_2O_5, as less of the carbonatite would have been exposed when they were deposited, and the alluvium accumulated too fast for much Nb_2O_5 to have been concentrated.

Even at the above optimistic assessment, the ore body is uneconomic at current prices of niobium, and the deposit is very much smaller and lower grade than some others in Africa which are not being mined at present. For example, at Panda Hill, there are 125,000,000 tons of .3% Nb_2O_5 ore and 4,500,000 tons of .79% ore, all in sovite (van der Veen 1963), and at Mrima residual soils could yield 49,000,000 tons of .7% Nb_2O_5 ore and 4,500,000 tons of 1.25% Nb_2O_5 ore (Coetzee and Edwards 1959), and lower grade deposits have no economic importance except when they are very large and occur with other viable mineral deposits, as at Sukulu, where Nb_2O_5 could be extracted as a bi-product after phosphate.

Unless the price of niobium is increased considerably, it seems that the best hope of finding workable deposits of Nb_2O_5 is to follow McCall's advice (1958), and drill a deep hole in the middle of Nyakirangacha, in the expectation of striking pyrochlore-rich carbonatite.

2. PHOSPHATE.

Phosphate is the one mineral found on and around Rangwa which could, if found in economic quantities, be used in East Africa. Apatite occurs in minor quantities, up to 5%, in the alkaline plutonics and Ekiojango Carbonatite. Because of difficulties of separation, these occurrences are not considered to be of economic importance.

It is not known to what extent apatite is concentrated in the soil, as ssmples of alluvium have not been analysed for phosphate.

However, the bedded alluvium round Rangwa is not an ideal environment for the differential accumulation of apatite. The alluvium was washed down off Rangwa, and since apatite has a specific gravity of 3.1, only slightly more than that of calcite and less than any of the mafic constituents of the alluvium, there would be little opportunity for secondary enrichment, as the apatite would tend to be washed out at the same rate as the carbonate.

3. TITANIUM.

Although the uncompahgrite to the southeast of Rangwa may contain up to 10% of titania, these are unlikely to be of economic importance, as (Deans 1967) titanium is one of the elements "which are readily available from other types of mineral deposit, and likely to be utilised only if special incentives arise". It is hard to see what special incentives could arise here, as the deposit is too small and too far from lines of communication to be mined on its own, and no mineral of economic importance exists from which it could be extracted as a bi-product.

PART III

THE EVOLUTION OF THE KISINGIRI VOLCANO

XII

THE SEDIMENTATION PATTERN ON THE KISINGIRI VOLCANO

In this chapter, an attempt is made to correlate some of the rock types on Rangwa with those on the rest of the volcano. To this end, the main rock types found on the periphery are described briefly, and some evidence is given both for their mode of origin and source. Tentative grounds for correlation are then presented.

1. DESCRIPTION OF THE ROCKS ON THE PERIPHERY OF THE VOLCANO.

The rocks are considered under the following headings:-

1. Prevolcanic and early volcanic sediments.
2. Conglomerates.
3. Fine-grained ash (both laid in water and in a dry environment).
4. Lava.
5. Nephelinite agglomerate.
6. Intravolcanic sedimentary deposits (erosion products).

These divisions are not historical, but are based on similarity of rock type.

A. PREVOLCANIC AND EARLY VOLCANIC SEDIMENTS.

The main area in which sediments survive exposed, and where sedimentation probably started prior to volcanic activity is to the south of the volcano near Karungu (Figure 2). Most of the sediments

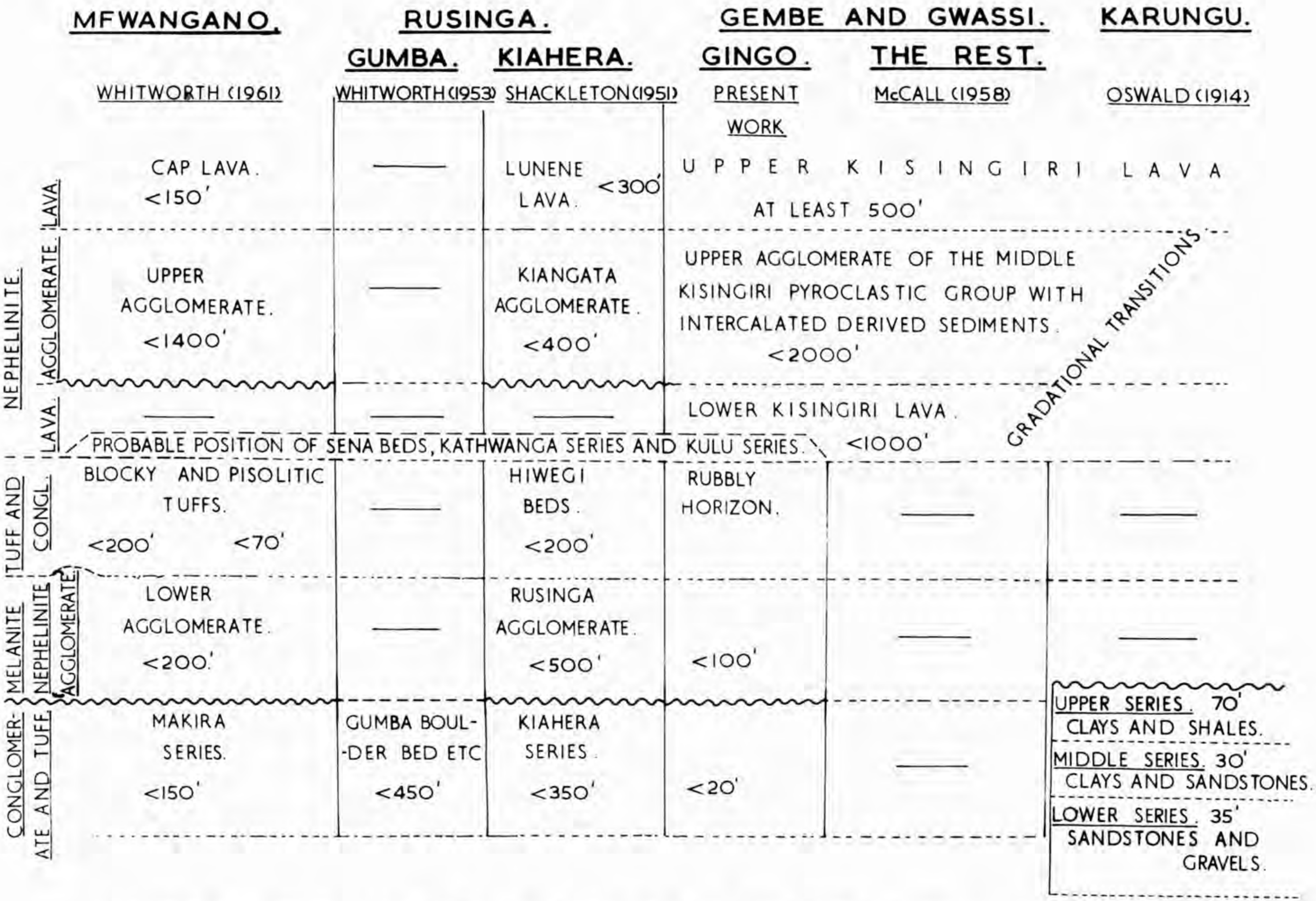


FIGURE 35. THE MAIN ROCK GROUPS ON THE PERIPHERY OF THE VOLCANO AND SUGGESTED CORRELATIONS BETWEEN THEM.

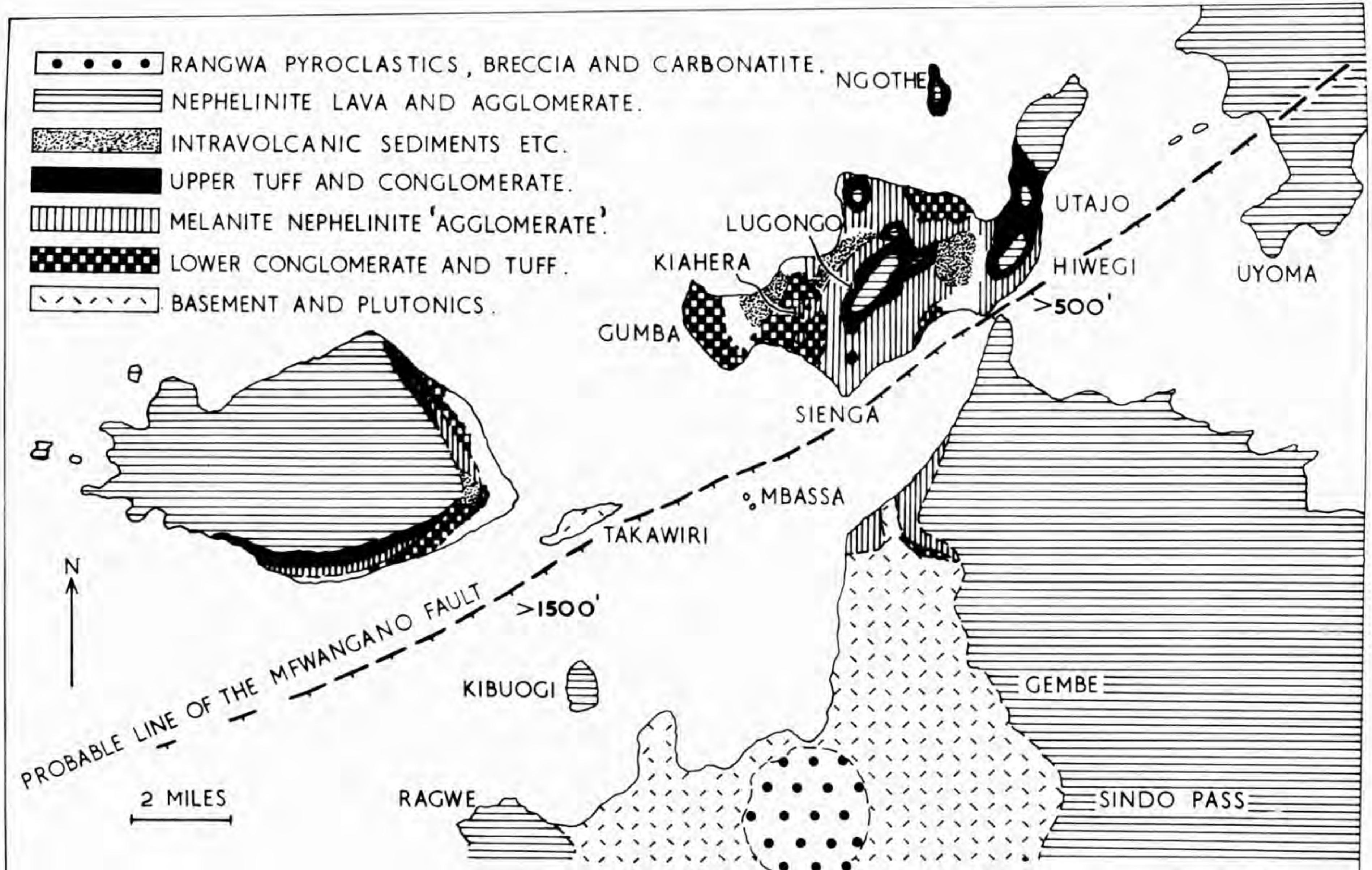


FIGURE 36. SIMPLIFIED GEOLOGICAL MAP OF THE NORTHERN PART OF THE VOLCANO (AFTER McCALL, SHACKLETON AND WHITWORTH).

occur east of Karungu, where they form a discontinuous band between the basement and the main volcanic pile of nephelinite agglomerate and lava. The total length of the band of outcrops is about six miles, and the sediments attain a maximum thickness of over 150 ft. at Nira where they form broken cliffs.

The sediments were described fully by Oswald (1913), who divided them into three groups:-

3. About 70 ft. of shales and grey and brown clays.
2. About 30 ft. of red and grey clays with white sandstones near the base.
1. About 55 ft. of buff sandstones and torrential gravels with clay and marl at the base.

Below the sediments there is a quartz-ironstone breccia, grading down into the Nyanzian basement, and the top of the sediments has been eroded into small valleys and capped by nephelinite lava. The sediments appear to thin southwards. Many of them are fluviatile, and Oswald suggested that the gradual change in sediment type was caused by the downgrading of a large river. Most of the detrital material in the sediments can be matched with nearby basement, and only the top group of beds contains occasional crystals of biotite and green pyroxene, both unweathered, which are probably of Tertiary igneous origin. The fossil assemblage so far collected from near Karungu is broadly similar to those from Rusinga, Mfwangano and the sites round the base of Tinderet (Oswald 1913 and Kent 1944).

No sediments similar to those at Karungu have been found elsewhere. On Rusinga (Shackleton 1951) and Mfwangano (Whitworth 1961), there are discontinuous and poorly exposed lenses of deposits near the base of the succession which contain little or no material of igneous origin. On Rusinga, thin bands of rubbly limestone (unit 2 and parts of unit 4 of Shackleton's Kiahera Series) outcrop to the north and west of Kiahera Hill. In the cliffs at the southeast of Mfwangano, a thin band of limestone occurs within Whitworth's Makira Series (unit 6). Whitworth suggested that the limestone on Mfwangano is like the calcrete formed under the surface in semi-arid conditions today.

B. CONGLOMERATE.

The conglomerates occur mainly on Rusinga and Mfwangano (Figure 36). Shackleton (1948) has mapped three separate bands of conglomerate on Kiahera Hill (Units 3, 5 and 8 of the Kiahera Series), and Whitworth (1953) has found three on Gumba, three miles to the west. The maximum thickness of any of these bands is 150 ft. On Mfwangano, Whitworth (1961) has described two far thinner bands of conglomerate within the Makira Series. A persistent conglomerate is found on Rusinga, at the top of Shackleton's Hiwegi Series, and beneath the nephelinite agglomerate (plate 201). It is well exposed on Waregi Hill in the east, on Kiangata, round Lugongo, and on top of Sienga Hill and Kiahera Hill. Whitworth does not record a similar conglomerate on Mfwangano, although the lower parts of the nephelinite agglomerate there are sometimes packed with boulders of basement and alkaline plutonic rocks.

The matrix of the conglomerate is seldom seen, and where it is, it is highly weathered and consists of grey or brown tuffaceous material. It is very sparing in amount, being subordinate to the close-packed, unsorted, rounded or subangular fragments of a great variety of rock types (plates 199 and 200). The lower conglomerates contain fragments which are up to 10 ft. across and predominantly granitic, whereas in the upper one, the fragments are smaller, and the most usual types are ijolite and melanite nephelinite. Granite boulders were found both unaltered and in every stage of alteration; some specimens show cross-cutting veins of aegirine and sodic amphibole and other features associated with fenitisation (RFR 20 and RFR 21) far better than any in situ exposure on the mainland. Small numbers of fragments of carbonatite are found universally, and since they contain aegirine as well as magnetite they show greater affinities with the early Kiako Carbonatite than to any exposed on Rangwa today; most of the carbonate has recrystallized into a fine-grained mosaic, but some large clear crystals survive. Fragments of ijolite, turjaite (McCall 1958) and nephelinite occur too. Two varieties of almost monomineralic rocks are found as fragments in the conglomerate, as well as in some of the tuffs. RFR 37 consists of over 90 percent of subhedral crystals of hornblende up to 5 mm long, which are pleochroic:- Z = olive, Y = pale olive and X = pale yellow-green. The rock also contains streaks of ore and irregular inclusions of diopside within the hornblende, which have probably been partly absorbed. RFR 20 consists of over 80 percent of elongated crystals of dark green aegirine, which may be one centimetre long, and occasional needles of slightly pleochroic blue to blue-green amphibole (X:c less than 35^{o}, negative, 2 V small) which is possibly similar to the arfvedsonite of the fenite round Rangwa; the amphibole occurs either as separate crystals or within the aegirine, and both tend to radiate. Apatite and carbonate have crystallized interstitially. Neither of these rocks has been found in situ around Rangwa.

During the present work, a careful search was made for similar beds on the mainland, especially close to the inner boundary of the volcanics, but none of comparable extent to the occurrences on Rusinga and Mfwangano were found. The base of the volcanics is nowhere well-exposed, but sometimes (especially south west of Gembe, and near Ragwe, RFP 92), a breccia with a brown carbonate matrix and fragments of both altered and unaltered granite occur, which could well be relics of the subvolcanic land surface. Near the top of the long east-west gulley south of Gingo, the granite basement which floors most of it is succeeded by a breccia that is packed with subangular granite boulders (plate 202 and figure 37). The base is irregular, and most of the fragments there are probably more or less in situ, but higher up exotic fragments of carbonatite are mixed with

Plate 199. Fragments from conglomerate to the south of Kiahera Hill, Rusinga. Most of them are granitic. Melanite nephelinite agglomerate overlies the conglomerate unconformably.

Plate 200. Granitic fragments and tuffaceous matrix from conglomerate, south of Kiahera Hill, Rusinga.

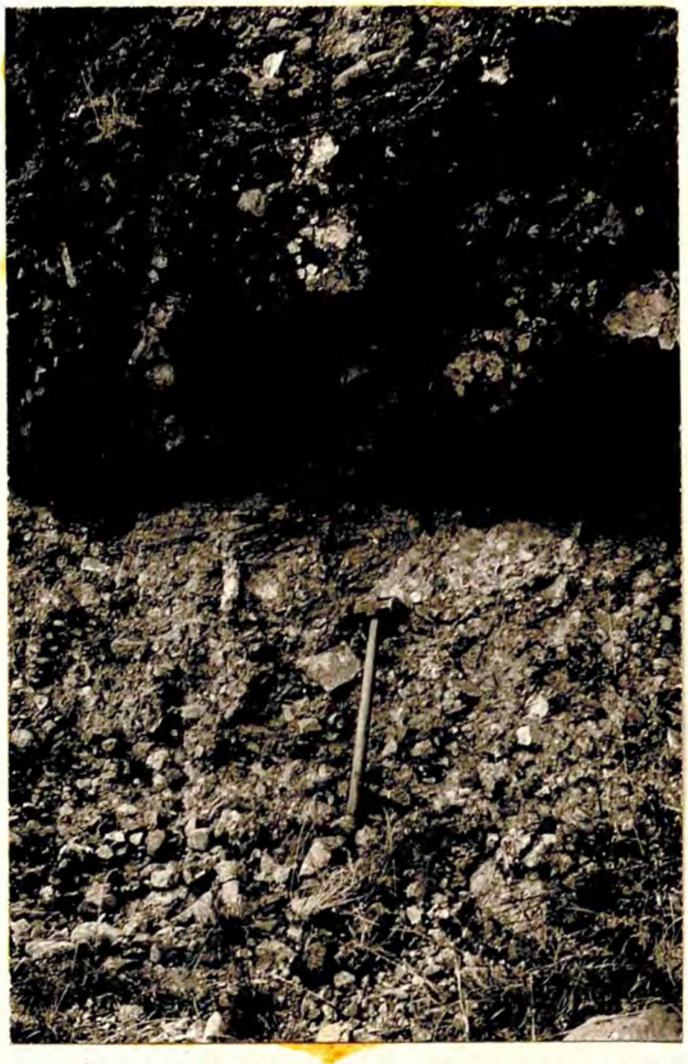


Plate 201. Contact between conglomerate and Nephelinite agglomerate on Kiangata Hill, Rusinga.

Plate 202. Conglomerate in the gulley south east of Gingo. The fragments are mainly granitic.

the granite. The matrix, which is very weathered, is composed of carbonate and noncrystalline ore (RFP 39). From the gulley, a band of conglomerate, never more than 20 ft. thick, can be followed along the southern face of Nyamarandi. The total length of the band is about half a mile, and it is overlain by melanite nephelinite, which transgresses across the conglomerate at each end. A thin band of conglomerate of uncertain origin, which consists of small fragments of granite and felspar rock in a matrix of very fine-grained felspar and aegirine, occurs 100 ft. above the base of the nephelinite on Nyambunana; it bears some similarity to the agglomerate on Rangwa where it is packed with basement fragments.

Shackleton (1951) suggested that the blocks in the conglomerate were ejected explosively. Whitworth (1953), after stating that "the entire content of the Gumba boulder bed probably represents volcanic ejectamenta", gives two objections to an explosive origin, namely that the rounding of the fragments is hard to explain, and that there is no impact disturbance beneath the fragments, and says that "a possible alternative is to regard the boulder bed as an alluvial fan deposit formed through the agency of mudflow". The fact that, in contrast to the truly explosive nephelinite agglomerate, the conglomerates are only found to one side of Rangwa appears to rule out an explosive origin for the blocks, unless the centre of explosion was far removed from Rangwa, a supposition not supported by the outcrop pattern of the conglomerates, which are at their thickest on Kiahera and Gumba, and they thin to the north: Shackleton's Brown Breccia thins from over 150 ft. at the south of Kiahera Hill to 10 ft. at the north. Also they thin and disappear to the north west on Mfwangano. To the northeast, on Uyoma, the conglomerate is missing, and tuff occurs between the basement and nephelinite volcanics (McCall 1958, from bore-hole evidence). Besides, some of the material in the conglomerate, notably the turjaite, only occurs in situ near Rangwa. If the conglomerate was emplaced as flows, the mechanism by which the material flowed is not clear. Presumably (cf. Whitworth 1953) by the time the flows reached Rusinga and Mfwangano, they were mud flows, since they often grade vertically and laterally into muddy and tuffaceous material. The rounding must be due to the fragments rubbing against each other, and it is probable that many of the granitic fragments were scoured off the basement over which the flows moved.

The mudflows of the Bugishu Series to the west of Mount Elgon (Davies 1952) are analogous to the conglomerates found on Rusinga and Mfwangano both in their form and in their position relative to the other volcanics. A series of mudflows that is up to 600 ft. occurs between the basement and the nephelinite agglomerate, and is packed with angular-subangular boulders of granite which are often as much as 20 ft. across. These deposits are not unlike those "ladus", which are described as "avalanches of lava fragments mixed with sand and dust, originating from active domes or lava flows" by van Bemmelen, who cites the huge avalanches from the volcano of Merapi in Indonesia in 1930 as a recent example of this type of deposit (1949 pp 191 - 193).

C. FINE-GRAINED ASH.

Ash deposits of various sorts are the most frequently occurring rock types beneath the nephelinite agglomerate on Rusinga and Mfwangano. Beds of tuff occur within the Kiahera Series on Rusinga and the Makira Series on Mfwangano, within the melanite nephelinite agglomerate, and composing the major part of the Hiwegi Beds on Rusinga, and the pisolitic tuffs and blocky tuffs on Mfwangano. It is evident that tuff is exposed which has been formed in several different ways. Some ash has fallen into a dry environment, some has fallen into water, and some has been redeposited by water.

The ash may be consolidated or friable, and is normally fine-grained and composed of carbonate, with varying amounts of zeolitic material. Sometimes it contains unaltered exotic crystal and mineral fragments. The largest and most conspicuous mineral and rock fragments in the tuff are of biotite and hornblende, which are found mainly in the tuff immediately below and interbedded with the melanite nephelinite agglomerate. Euhedral magnetites are found in some of the tuffs associated with the conglomerates, especially on Mfwangano, and these may have been washed out from magnetite-rich carbonatite. Euhedral melanite, probably derived from the melanite nephelinite, occurs in some of the tuffs of Shackleton's Hiwegi Beds on Rusinga, and among Whitworth's Pisolitic and Blocky Tuffs on Mfwangano, all of which are younger than the melanite nephelinite (Figure 35). Much of the tuff contains very small unorientated plates of pale brown mica. Pyroxenes and pseudomorphed nephelines are seldom found in tuffs, except when they are interbedded with the nephelinite lavas and agglomerates.

The most important inclusions in the tuff for the present purpose are accretionary lapilli; These were noted by Whitworth (1953 and 1961) in the fissile tuff near the top of his succession on Gumba, and in the Pisolitic Tuff at the northeast of Mfwangano, directly below the main nephelinite agglomerate there. During the current work, numerous occurrences were found in the Pisolitic Tuff on Mfwangano and in the Hiwegi Beds on Rusinga, especially near the top of Kiahera Hill, on Waregi Hill and round Kiangata Hill. In these the length of the minor axis is on average 59 percent of the major axis or diameter of the circular section, and the diameters of those measured varies between 4 and 9 mm (specimens RFR 31 and 32). These measurements do not vary much from those of the accretionary lapilli in the Banded Tuff on Rangwa itself, in which the average short axis is 62 percent of the diameter, and the length of the diameter is normally about 7.5 mm (pp 105 - 106). Although occurring in less consolidated tuffs, the appearance of the lapilli is similar to those on Rangwa; they are composed of the same material as the matrix of the tuff, but have a finer-grained, more resistant skin. The matrix contains small unorientated flakes of mica. It is likely that, as on Rangwa, these were deposited in a dry environment, and they are a good indication that the tuff in which they occur is a primary one. The lapilli-bearing tuff may be finely bedded (plate 203), but unlike some of the tuff elsewhere in the succession, it was never found to be cross-bedded.

No extensive deposits of proved primary tuff were found below or within the nephelinite and nephelinite agglomerate succession on the mainland, so that the main tuff only occurs in an arc to the north and northwest of Rangwa. As it has been shown that the conglomerate with which much of the tuff is associated originated in the vicinity of Rangwa, it is reasonable to assume that most of the tuff came from there too. Because of the irregular erosion surfaces that have often been cut into the tuff, and the fact that separate beds of tuff tend to merge as the intercalated deposits wedge out, the tuffs do not necessarily thin away from Rangwa over short distances, but it can be seen, especially in the Pisolitic Tuff on Mfwangano (Whitworth 1961), that the grainsize becomes larger and the included fragments more frequent towards the south. As it is unlikely that similar thicknesses of tuff have been eroded away on every other side of Rangwa, it is suggested that the distribution pattern of the tuff was controlled by the wind, which implies that the prevailing wind direction was from the southeast.

Plate 203. Tuff containing accretionary lapilli near the top of Kiahera Hill, Rusinga.

Plate 204. Melanite nephelinite by the lake at Gingo. It contains large fragments of ijolite and basement.

D. LAVA.

Most of the lava from the Kisingiri Volcano is nephelinitic, containing varying proportions of pyroxene and nepheline (generally highly zeolitised) as phenocrysts, with, sometimes, melilite, both as phenocrysts and in the groundmass. McCall (1958) has given brief petrographic description of varieties of the lava. The lava frequently contains fragments of nephelinite of like composition.

All the thin sections of melanite nephelinite (described as an agglomerate by Shackleton, Whitworth and McCall) that were examined show a lava groundmass which is very rich in large and scarcely altered euhedral-subhedral nephelines (plate 205). The lava contains rounded fragments of ijolite (plate 206), which may be several feet across and often have indeterminate edges across which the nephelines are broken up and the pyroxenes are converted to aegirine. The nepheline of the ijolite fragments is anhedral. The melanite, when it occurs in the lava, is euhedral and generally zoned with small inclusions of sphene, but in the ijolite it is anhedral and grows within and along the edges of pyroxene, and replaces perovskite (RFP 34); larger euhedral sphene is sometimes present in ijolite fragments (RFP 109). The melanite nephelinite also contains fragments of pyroxenite (without magnetite or biotite), and nepheline syenite (RFP 109), which consists of equal quantities of nepheline and twinned laths of orthoclase. Often, especially on the mainland, the rock contains hardly any fragments, and two

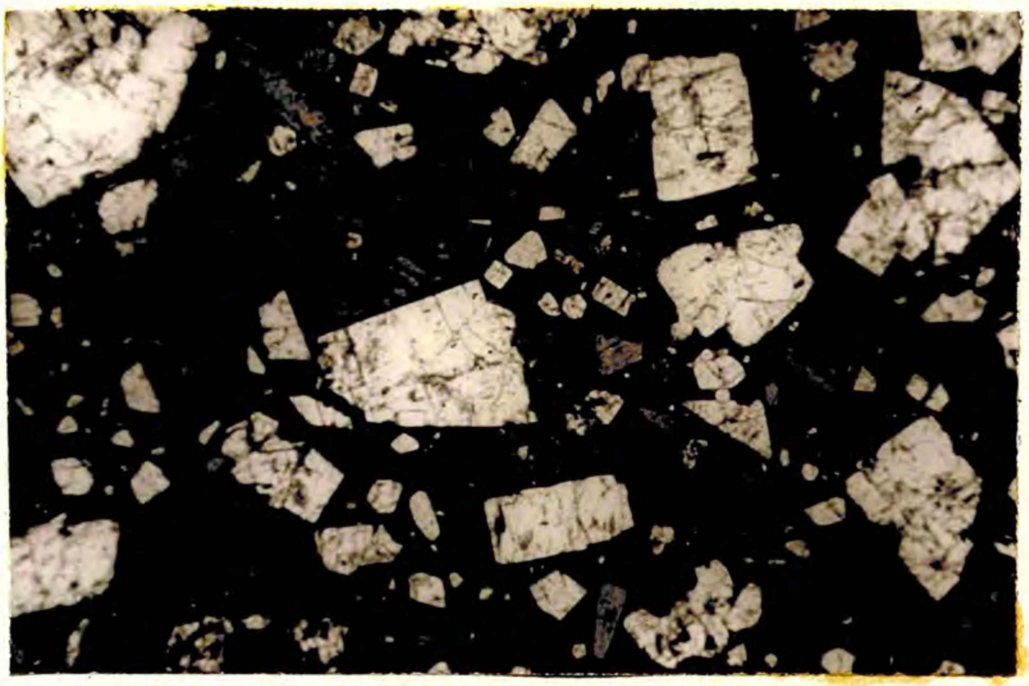


Plate 205. Typical texture of melanite nephelinite, with pyroxenes and euhedral unaltered nephelines. The melanite crystals, which are euhedral and black do not show clearly. (RFR26). x25.

Plate 206. Negative of a thin section of melanite nephelinite showing the edges of an ijolite and a melteigite fragment and the lava between. Black is nepheline, and grey pyroxene. The lava carries both euhedral nephelines, and anhedral fragmental ones. (RFP34). x8.

specimens of felspar-bearing lava were collected from within the melanite nephelinite on Rusinga and Mfwangano (RFR 3 and RFM 29); RFR 3 contains large laths of twinned orthoclase and the felspar in RFM 29 is probably anorthoclase which shows very fine polysynthetic twinning. Apart from ijolite and melanite nephelinite similar to the groundmass, other types of fragments include granite and carbonatite, probably both picked up from the underlying deposits. So, except for what has been redeposited secondarily, the melanite nephelinite is considered to be a xenolithic lava.

The main outcrops of melanite nephelinite are on Rusinga (Shackleton's Rusinga Agglomerate) and Mfwangano (Whitworth's Lower Agglomerate). On Rusinga, they are up to 500 ft. thick, and highly transgressive on the underlying conglomerates and tuffs of the Kiahera Series; the contact is irregular, and some of the underlying beds are cut out on Kiahera Hill and most of them on Lugongo and Sienga at the centre of Rusinga. On Mfwangano, it is also transgressive, and up to 200 ft. of it are exposed; towards the southeast of Mfwangano, melanite nephelinite is missing, probably because of a later unconformity (Whitworth 1961). On the mainland, melanite nephelinite is exposed between Sindo and Mbita on Kibibura and Nyamarandi (Figure 37); its greatest thickness is about 100 ft., and its transgressive base rests either on basement or on conglomerate.

Nephelinite lava is found on Rusinga, Ngothe, Mfwangano and

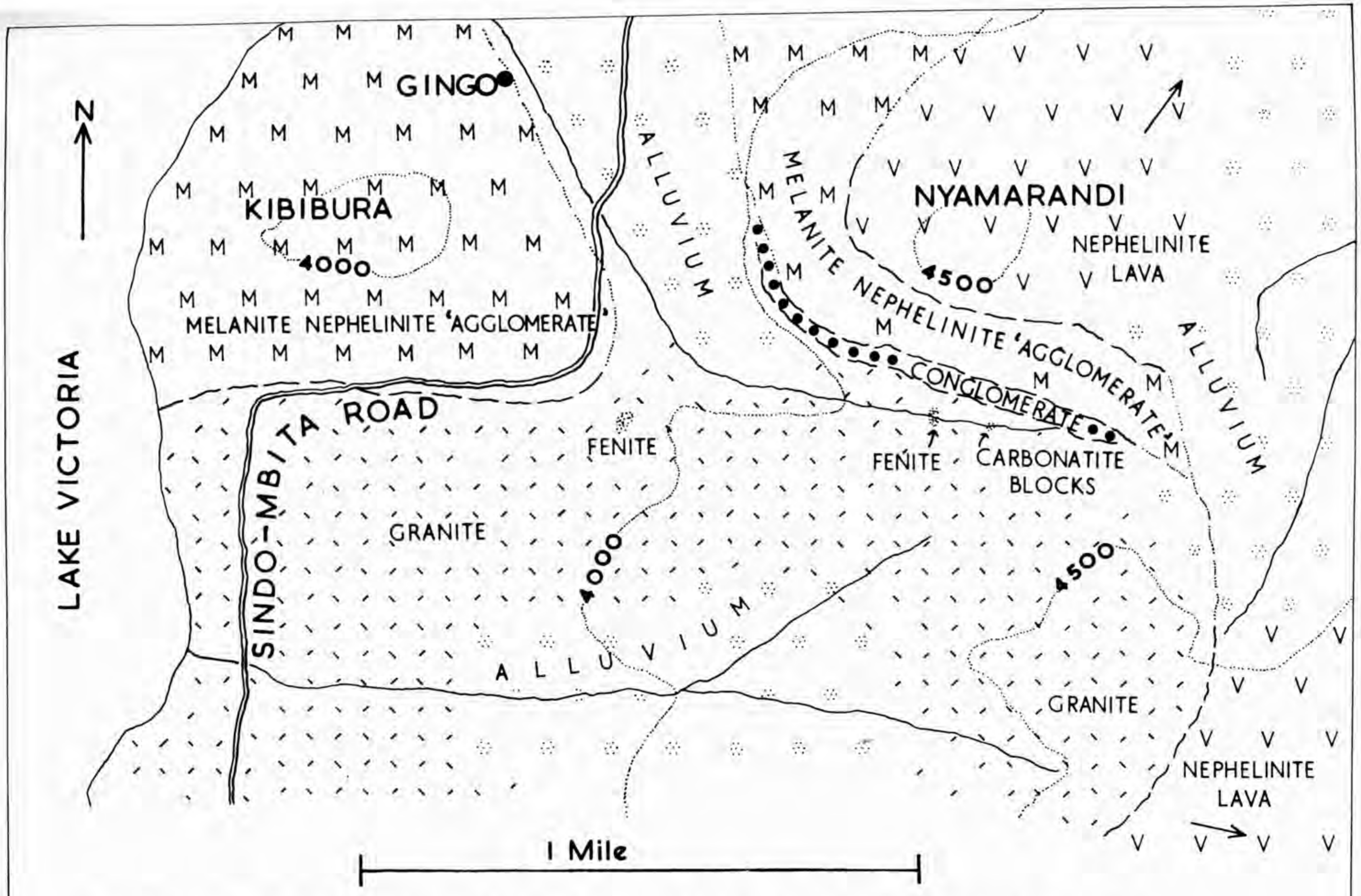


FIGURE 37. GEOLOGICAL SKETCH MAP OF THE GINGO AREA.

Uyoma, as well as in the partial ring of volcanics round Rangwa. On the islands, it occurs towards the top of the succession (Shackleton's Lunene Lava and Whitworth's Cap Lava), and the greatest thickness of lava surviving on Rusinga (Shackleton 1951) is 300 ft. On the mainland, lava occurs throughout the volcanic succession, and individual flows which may extend for many miles can be picked out on the aerial photographs, but on the ground they are not so easily recognized. On the inward-facing erosion scarps of Gembe and the Gwassi Hills, lava often outcrops between the basement and the main bulk of nephelinite agglomerates; there may be 1,000 ft. of lava as on Nyadenda, or it may be insignificant as on the northern slopes of Usengere. Near the base, there occurs a flow with nepheline phenocrysts (unusual elsewhere on the volcano). Since the melanite nephelinite on Nyamarandi is overlain by nephelinite lava, which is at roughly the same level as the lowest lavas on Gembe, where the melanite nephelinite is missing (Figure 37), most of the nephelinite lavas on the mainland must be later than the melanite nephelinite. Many lava flows are intercalated within the succeeding nephelinite agglomerate, and become more frequent towards the top of the succession. These bear the same relation to the nephelinite agglomerate as they do on the islands; they extend very widely and are found on Kaniamwa, near Karungu and on Uyoma. McCall divides the lavas into the Lower and Upper Kisingiri Lavas, depending on whether they occur above or below the nephelinite agglomerate, but this twofold subdivision seems to be unduly simple, since the succession on the mainland appears to consist essentially of lavas, interrupted in the middle by intercalations of agglomerate.

The melanite nephelinite only occurs in the north and north west, whereas the nephelinite lavas are not so extensive in the north as elsewhere. The fact that the lavas radiate intermittently from Rangwa and thin outwards suggests that they mostly originated from this area. The low angle of dip and wide extent of the lavas (up to 30 miles away from Rangwa) led McCall to conclude that they all originated from nephelinite dykes towards the periphery of the dome. However, the fact that there are so few nephelinite dykes exposed in the erosion hollow round Rangwa implies that most of the lavas originated from a central source.

E. NEPHELINITE AGGLOMERATE.

More than half of the present mass of the Kisingiri Volcano consists of explosively erupted nephelinite agglomerate. The proportion is smaller than at Napak and Elgon (King 1948 and Davies 1952), where the volcanoes are composed of over 95 percent nephelinite agglomerate. At least 1,000 ft. of agglomerate survive on Mfwangano, and 400 ft. on Rusinga. On the mainland, nearly 2,000 ft. are exposed on the erosion scarp of Usengere, rather less elsewhere. Where the agglomerate is not intercalated with lava flows, it forms large and overhanging cliffs, notably on Usengere and

Mfwangano. On the islands, it can be shown that there is an unconformity at the base of the agglomerate, as to the southeast of Mfwangano (Whitworth 1961), many of the underlying deposits are missing.

The agglomerate occurs in layers varying from many feet to a few inches thick. The matrix consists of an altered mosaic of carbonate and zeolites, with large vesicles of radiating natrolite. The fragments are generally rounded and unsorted, and vary from crystal size to several feet across. The crystal fragments are mostly subhedral pyroxenes, and bands packed with these were found on Ragwe, Gembe and Kaniamwa; these may be of use as marker horizons during detailed mapping of the volcanics. The rock fragments are mainly of nephelinite with large pyroxene phenocrysts. A few smaller ones are of ijolite and pyroxenite, sometimes very rich in perovskite and magnetite (RFP 21), and basement and carbonatite fragments occur sporadically.

The texture and wide distribution of the agglomerate around Rangwa indicates that, apart from what has been redeposited secondarily, it has been formed by explosive eruption. Since the fragments are large, prevailing wind direction would not have influenced the spread of the agglomerate so much as that of the ash deposits.

F. INTRA-VOLCANIC SEDIMENTARY DEPOSITS.

There are many unconformities within the volcanic succession; major unconformities occur at the bases of the melanite nephelinite and of the nephelinite agglomerate. Associated with these intermissions in volcanic activity sedimentary deposits derived mainly from the erosion of volcanic material occur. Particularly among the tuffs, it is often hard to tell what has been derived and what is primary. These rocks occur towards the edge of the volcano, and they consist of lacustrine, fluviatile and soil deposits, as well as resorted, faulted and slumped pyroclastic material.

On Ikoro Hill, south of Usengere, and at several localities along the Kaniamwa Escarpment, deposits of banded, clay-like material occur (McCall 1958); all these contain pyroxenes and small fragments of lava, and they are sandwiched between nephelinite flows. They were probably deposited in peripheral lakes. On Rusinga, the Kulu Series, to the east of Lugongo, and the Kathwanga Series, to the northwest of Kiahera, which are tentatively correlated by Shackleton, are marls, shales and boulder beds, which rest unconformably on much of the succession beneath the nephelinite agglomerate. Whitworth (1961) has discovered similar deposits, the Sena Beds, at the southeast of Mfwangano, which are overlain by the nephelinite agglomerate, and he interpretes both these and the Kulu Series as lacustrine. Thick and irregularly distributed soils are found on Gumba:- the Gumba Red Earths (Whitworth 1953), on

Kiahera Hill, red pisolitic earths and grits (Shackleton 1951) and possibly on Mfwangano, red clays (Whitworth 1961). Finally, in the Kathwanga area, northwest of Kiahera Hill, a fault occurs with a downthrow to the west of about 150 ft. (Shackleton 1951), to the west of which the beds of the main succession are broken up and slumped. These beds are overlain by undisturbed deposits of the Kathwanga Point Series and Kathwanga Series, proof that the disturbances were penecontemporaneous with the underlying deposits.

2. THE BASIS FOR CORRELATION.

Some tentative correlations are here proposed, which provide the basis for the history of the Kisingiri Volcano (Chapter XIII).

A. CORRELATIONS WITHIN THE VOLCANICS AND SEDIMENTS.

The deposits on Rusinga and Mfwangano have been correlated by Whitworth (1961), and McCall (1958) has related these to the volcanics on the mainland (Figure 35). The discovery of previously unrecorded melanite nephelinite on the mainland near Gingo during the present survey is relevant to these conclusions. It is reasonably certain that melanite nephelinite only occurs at one stratigraphic level, since on the islands and at Gingo its base is strongly unconformable, and derived crystals of melanite only occur in deposits above it. Beneath it, up to 350 ft. of conglomerates and tuffs are exposed on Rusinga, and rather less on Mfwangano. On the mainland, the melanite nephelinite never overlies more than 20 ft. of conglomerate, and sometimes it rests directly on basement.

On the islands, the melanite nephelinite is succeeded by up to 200 ft. of tuffs and conglomerates, as well as some derived secondary deposits, but on the mainland, the place of these is taken by a thin rubbly horizon, which is seen on the southern slopes of Nyamarandi. The upper tuffs and conglomerates on the islands are succeeded unconformably by nephelinite agglomerate, within which nephelinite lava flows gradually become more frequent. On the mainland however, the nephelinite agglomerate is underlain by variable thicknesses of lavas, many of which have been shown to postdate the melanite nephelinite. Thus, in the time between the emplacement of the melanite nephelinite and the nephelinite agglomerate, tuffs and conglomerates were deposited to the north and northwest, while lavas were erupted over other sectors of the volcano.

B. CORRELATIONS BETWEEN RANGWA AND THE REST OF THE VOLCANO.

Since the lowest conglomerates exposed on Rusinga and Mfwangano contain fragments of identifiable alkaline plutonics, and most of the nephelinite lavas and agglomerates postdate these conglomerates, the emplacement of the alkaline plutonics around Rangwa must precede the extrusion of most of the nephelinite lavas and agglomerate as well as the conglomerates to the north (Figure 38).

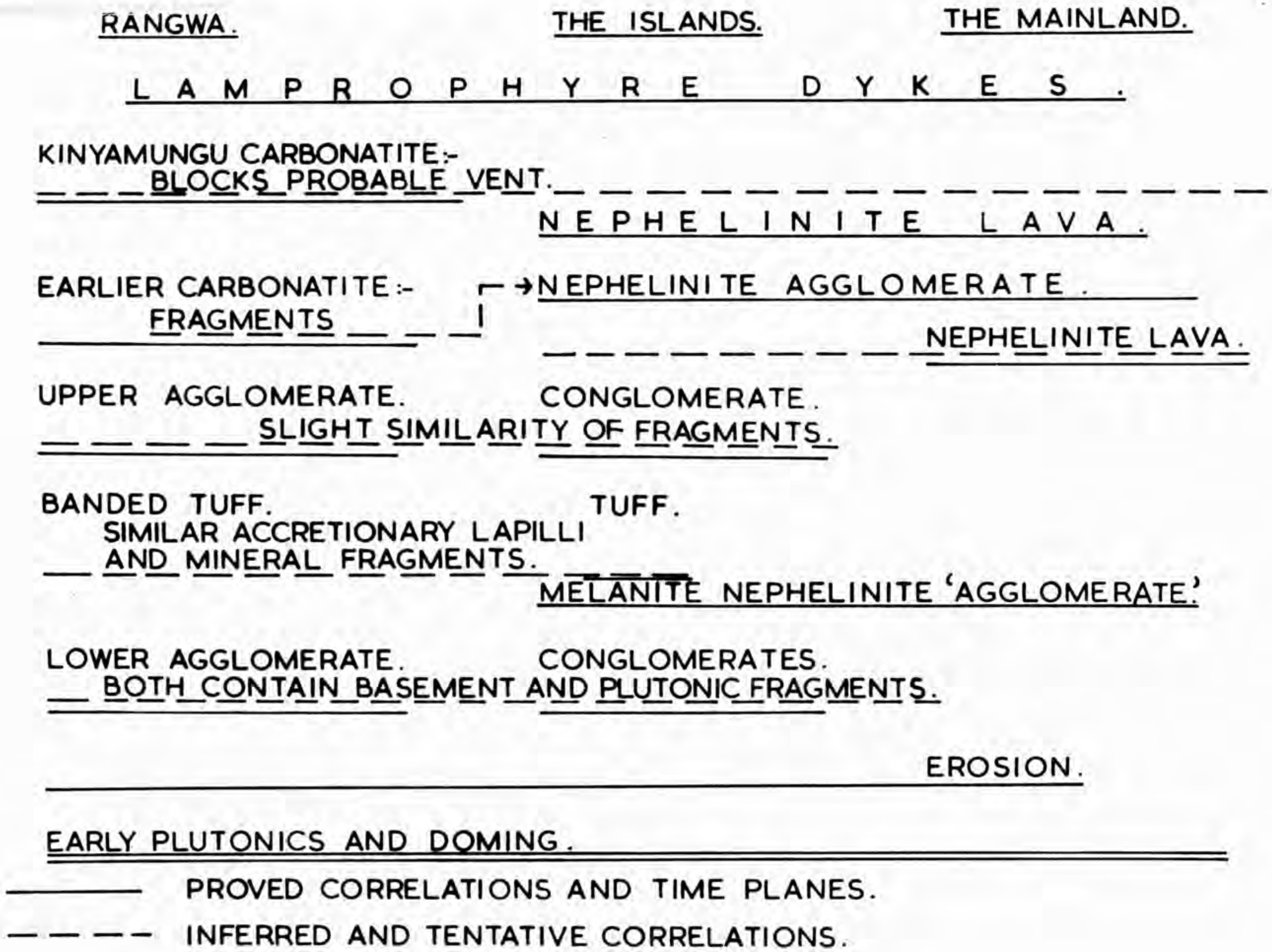


FIGURE 38. GROUNDS FOR CORRELATION ON THE KISINGIRI VOLCANO.

As McCall (1958, p 76) observed, the volcanics on Gwassi and Gembe rest on an irregular and highly eroded basement surface (Figure 39). The inward projection of this surface must have cut some of the plutonics, as on Kiako. A period of erosion is thus represented during which the lower conglomerates and tuffs were deposited on Rusinga and Mfwangano (Figure 38).

From this evidence of included fragments, the pyroclastics, breccias and carbonatites on Rangwa were also formed after the early alkaline plutonics. The pyroclastics contain unaltered fragments of basement and plutonics, but the fragments of volcanics are highly altered; if the pyroclastic vents had been drilled after the building of the main volcanic pile of nephelinite lavas and agglomerates, it is unlikely that the vent rocks would not contain at least some fragments of fresh nephelinite. The texture, composition and probable mode of formation of the pyroclastics on Rangwa (pp120 - 124) rule out any correlation between them and the nephelinite lava and agglomerate of the volcano. Therefore, the pyroclastics must have been formed during the same period as the tuffs and conglomerates to the north and northwest, while erosion continued over other parts of the domed basement.

Some similarities exist between the pyroclastics on Rangwa and the conglomerates and tuffs on the islands:-

1. Accretionary lapilli are found extensively at one stratigraphic level on the islands namely in the tuffs that occur

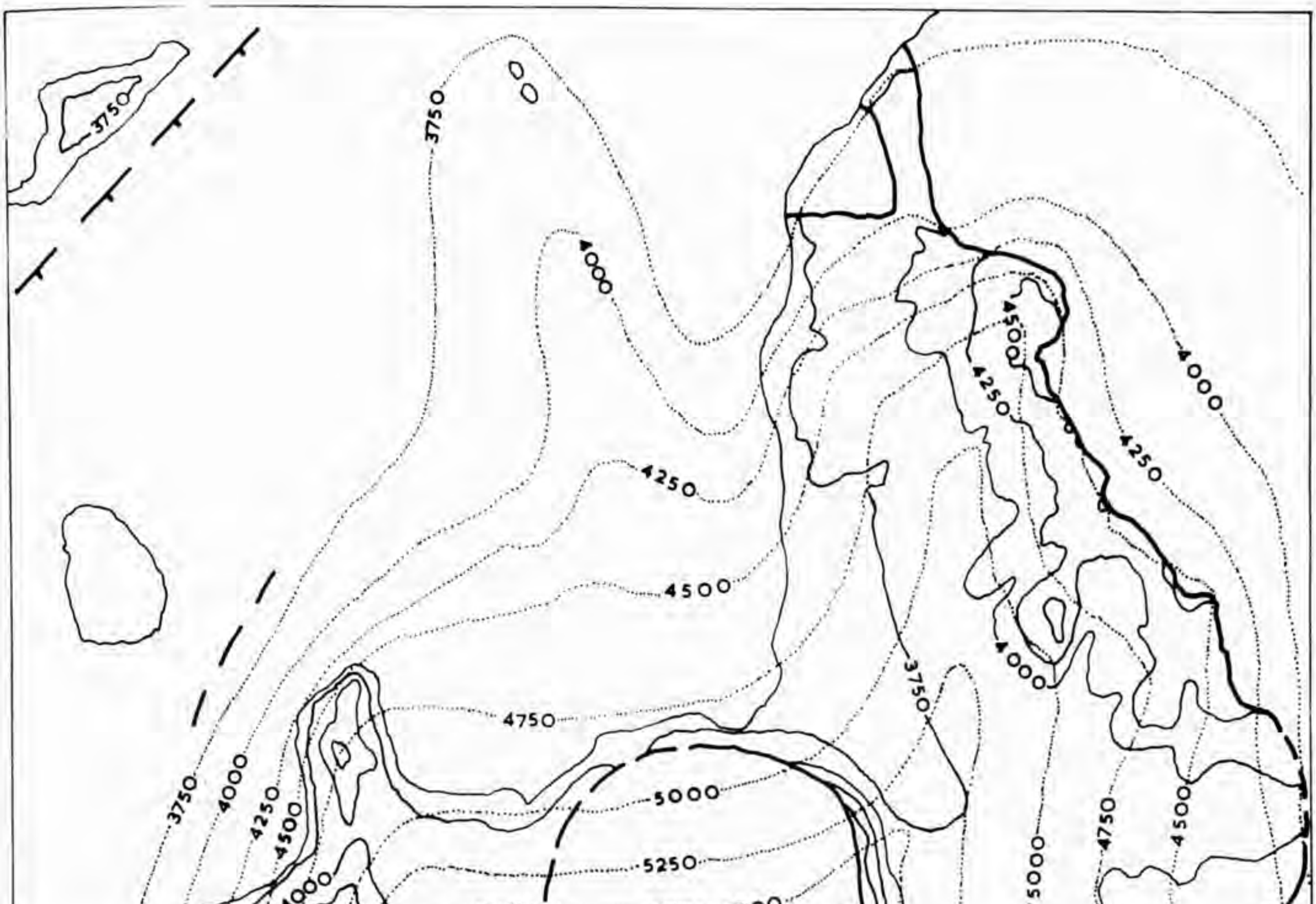


FIGURE 39. CONJECTURAL CONTOURING ON THE PREVOLCANIC DOME.

between the melanite nephelinite and the nephelinite agglomerate; they also occur in smaller amounts lower in the succession. Similar lapilli are found in the Banded Tuff of Rangwa, and the same mineral assemblage occurs in the tuffs on Rangwa and on the islands.

2. The basement and plutonic fragments of the Lower and Upper Agglomerates on Rangwa are similar to those of the conglomerates on Rusinga and Mfwangano.

3. Excluding the melanite nephelinite and the secondary deposits, the successions on Rusinga and Mfwangano consist of:- a predominantly conglomeratic series, and a tuffaceous series, followed by a further thin conglomerate. On Rangwa, the succession consists of the Lower Agglomerate, Tuff Group and Upper Agglomerate.

Based on these three points and on the fact that the pyroclastics on Rangwa and the tuffs and conglomerates to the north were formed during the same period of time, a tentative correlation is made between the two successions.

The fact that some of the nephelinite agglomerates of the Kisingiri Volcano, notably on Mfwangano (Whitworth 1961), contain fragments of carbonatite indicates that phases of carbonatite activity occurred on Rangwa during the period of nephelinite eruptions. The Kinyamungu Carbonatite on Rangwa must postdate these eruptions, as it plugs the area of the vent from which the nephelinites were erupted.

XIII

THE PROPOSED HISTORY OF THE KISINGIRI VOLCANO

1. THE SUBVOLCANIC SURFACE.

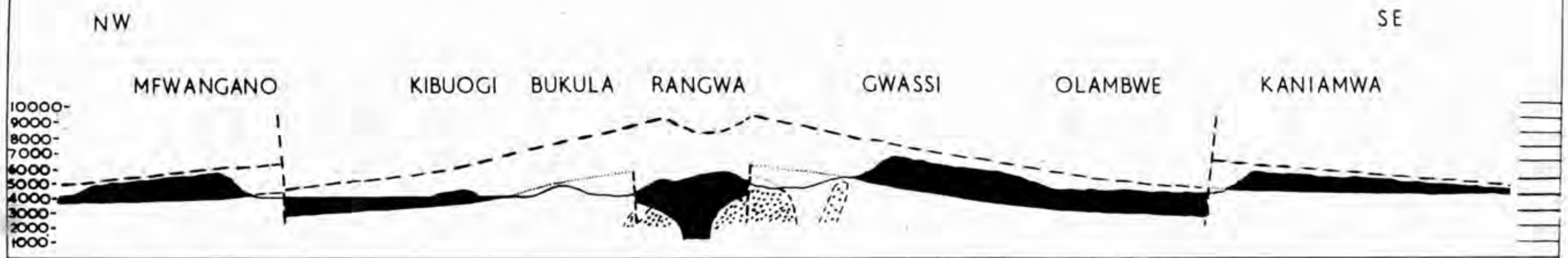
The land surface of the Kavirondo area prior to any volcanic activity, or the doming and faulting associated with it, survives at the contact round the outer limit of the volcanics of the Kisingiri Volcano, to the south and east of Rangwa. The base of the volcanics (McCall 1958 - Map) is irregular, but its height rises gradually from Nira, east of Karungu, where it is near lake level (3,730 ft.), towards the east and northeast, until, about eight miles south of Homa Bay, it crosses the 4,500 ft. contour, and then falls away again towards the lake, near Homa Bay. Between the lines of the Kaniamwa and Mfwangano Faults, the basement surface has been affected both by doming and faulting. To the north, the subvolcanic surface on Uyoma is a monocline (Shackleton 1951), whereas to the north of Rusinga and Mfwangano, it is below lake level.

So the surface declines gently towards the east-north-east, from about 4,500 ft. to 3,500 ft. or less, over a distance of forty miles; the gradient is about 25 ft. per mile.

2. DOMING AND THE EARLY PLUTONIC CENTRE.

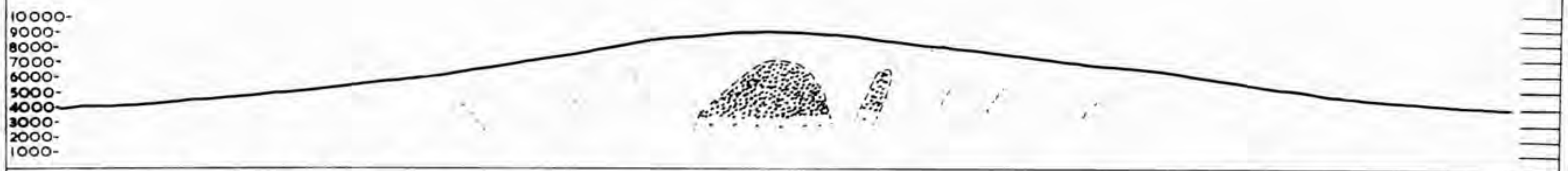
The surface around Rangwa was domed, and much of the basement within the domed area was probably brecciated and altered as a result of intrusions of ijolite, uncompahgrite and carbonatite (pp 67 - 68). The original form of the dome has been obscured by erosion prior to the emplacement of the main volcanics, and by movements on the Kaniamwa and Mfwangano Faults after volcanic activity, but it is possible to assign minimum dimensions to it. Figure 39 shows that the dome is more or less concentric with Rangwa, except that there is a marked bulge beyond the Sagurume Ijolite. Three miles out from Rangwa, the innermost point at which contouring is at all reliable, the dome rises to a height of 3,000 - 4,000 ft. above the undomed surface. The only place where the basement outcrops within the volcanics, but outside the main rift faults is on Takawiri Island, where it rises to about 3,800 ft. above sea level, or 300 - 500 ft. above the surface prior to doming. The surface of the island is near the basement volcanic contact, and, as it is about eight miles from the centre of Rangwa, it can be seen that the approximate slope of the dome is 500 - 750 ft. per mile (or an angle of slope of 6° - 9°). Observations from elsewhere on the dome confirm that the average slope was of this order or rather less towards the outside. The dome must have had a diameter of about twenty miles, and involves a maximum elevation of the prevolcanic surface by at least 5,000 ft. (Figure 40).

Since the doming was probably contemporaneous with some of the early alkaline intrusions, radiometric dates on the intrusives are relevant to the age of the doming (see appendix A).



a. PRESENT DAY.

b. BEFORE MOVEMENT ON THE MFWANGANO AND KANIAMWA FAULTS.



c. BEFORE EROSION OF THE PREVOLCANIC DOME.

2 MILES

THE VERTICAL SCALE IS TWICE THE HORIZONTAL.

FIGURE 40. INFERRED SECTIONS ACROSS THE KISINGIRI VOLCANO DURING ITS DEVELOPMENT.

3. PREVOLCANIC EROSION OF THE DOME.

At several places on the inward-facing erosion scarp, especially on Kiako, early alkaline plutonics are exposed near the basement/volcanic contact. At Kiako where the basement has been eroded down to the plutonics, there are two pronounced notches in the contours on the surface of the dome as it survives today. These may represent prevolcanic valleys carved in the dome, and the same probably occurs elsewhere, where exposure is not so good.

Apart from Mbassa, the ring of basement hills has been removed entirely south of the Mfwangano Fault in the sector between Bukula and Sagurume, and it is suggested that the greatest amount of prevolcanic erosion occurred in that sector (Diagram A in the folder).

During this period of erosion, sedimentation near Karungu probably began, and it is possible that erosion of the dome contributed some of the detritus they contain. The highest beds there include biotite and pyroxene which are similar to those in the igneous rocks at Rangwa, but it is not known whether they are from an early eruption or merely detrital minerals washed down after erosion had reached the alkaline plutonics (McCall 1958 p 28).

It is impossible to judge the original extent of this area of sedimentation, since it is likely that large tracts of it have been removed by subsequent erosion. The probability is that erosion of the dome led to peripheral sedimentation in all sectors.

4. THE EARLY CONGLOMERATES AND TUFFS.

After the early erosion of the dome, what may have been the first extrusive episode at Kisingiri occurred. A gas-drilled vent was pushed through to the surface slightly to the north of the central alkaline intrusion (pp 120 - 124). The fluidised column which filled the vent contained fragments of basement and plutonic rocks which it had dislodged on the way up, as well as liquid and half-consolidated igneous material which were agitated in a turbulent matrix of hot gas and lava droplets. At least three times this column overflowed the crater, and material from the vent is thought to have flowed out to the north as nuées ardentes, causing avalanches and mudflows, which tore up large fragments from the shattered basement over which they flowed and rounded them by abrasion. The flows extended eight - fifteen miles to the north and northwest. Between these out-pourings, parts of the fluidised column solidified, and ash was erupted from the volcanic centre, most of which was blown to the north and northwest by the prevailing winds. During the longer lulls in volcanic activity, some of what had been erupted was eroded and redeposited. Finally, the central crater was filled with flows of agglomerate, which solidified dipping at a low angle towards the vent.

During this time, the environment at the periphery of the dome alternated between shallow lakes and arid terrain (Whitworth 1953), whereas the slopes of the dome may well have supported rain forests, in which the early primates, of which there is fossil evidence on Rusinga and Mfwangano, lived (Bishop 1963). These two types of environment persisted, as the volcano grew.

The relative heights of the source (the Lower Agglomerate on Rangwa) and the deposits on the periphery (the conglomerates on Rusinga and Mfwangano), only differ by a few hundred feet today, but allowing for the displacements along the Mfwangano Fault and the ring fault around Rangwa, the original height of the source may be estimated to have been 3,000 - 5,000 ft. above the areas of deposition; such a gradient would be adequate to explain the landslides and mudflows.

5. THE MELANITE NEPHELINITE.

After further erosion, which removed many of the earlier deposits from central Rusinga, the melanite agglomerate flowed out in the same direction as the conglomerate mudflows, picking up and incorporating fragments from them. The vent from which the melanite nephelinite flowed was certainly in the vicinity of Rangwa, but there is no evidence that it was on Rangwa itself; it might well have been a new vent in Kaksingiri Bay. The melanite nephelinite is, however, packed with ijolite fragments, which must be from an earlier intrusion at the site of the vent.

6. THE SUCCESSION BETWEEN THE MELANITE NEPHELINITE AND THE MAIN NEPHELINITES.

After the emplacement of the melanite nephelinite, ash was erupted again from the central vent of Rangwa in far larger amounts than before. It was blown mainly to the north and northwest, and fell both into water and on dry land. Much of it was blown through clouds of vapour, so that accretionary lapilli formed, and these survive in the tuff that fell in a dry environment. The crater on Rangwa was filled with several thousand feet of ash, some of which, in the northern part, fell into a crater lake. On the periphery to the north, a sufficient gradient existed for much of the tuff to be eroded and redeposited.

When activity at the central vent had temporarily died down, a new vent was formed by gas-drilling through the northern part of Rangwa; this is thought to have overflowed only once to produce the thin horizon of conglomerate beneath the nephelinite agglomerate on Rusinga. The vent rocks survive as the Upper Agglomerate on Rangwa, and, apart from some new basement and plutonic material, most of the fragments are of previously formed pyroclastics. However, on Rusinga, the conglomerate contains fragments from the underlying melanite nephelinite agglomerate, and basement and plutonic fragments which were presumably washed into the path of the flow.

Except for, perhaps, small areas which had been covered by earlier lava flows, the rest of the dome had been suffering erosion since its formation, and it is possible that sedimentation at Karungu and elsewhere lasted until this stage. Before the eruption of the main nephelinites, the volcano consisted of a partly eroded dome, rising 4,000 - 5,000 ft. above the surrounding land surface, with several centrally placed vents enclosed in a large tuff-filled crater. Large gashes were cut in the northern slopes of the dome, and up to 600 ft. of mixed deposits were spread out to the north and northwest. Other detrital sediments occurred round the periphery of the dome, especially to the south (Diagram B in the folder).

7. THE EVOLUTION OF THE MAIN NEPHELINITE VOLCANO.

After the formation of the early gas-drilled vents, the main nephelinite volcano was built. Most of the volcanic material flowed or was ejected from a centrally placed vent on Rangwa, though some of the lavas could have flowed from outlying nephelinite dykes (cf. McCall 1958).

After extensive eruptions of nephelinite, the whole of the central part of the volcano, including the crater formed round the early gas-drilled vent, subsided as much as 2,000 ft., forming a large caldera, which must have been filled by subsequent nephelinite lavas and agglomerates. Periodically, the vent was plugged at a lower level by carbonatite, and carbonatite conesheets and dykes riddled the subsided block. Fragments of carbonatite as well as other plutonics and basement from the vent walls were blasted out from time to time with the agglomerate until the vent was finally plugged by carbonatite.

Outside the vent, an uneven distribution pattern was caused by the fact that the intercalated lavas flowed in some directions more than others. To the north no lavas preceded the first nephelinite agglomerates, whereas to the west of Rangwa up to 1,000 ft. of lava occurred first. Presumably this irregularity was dictated by the erosion pattern on the dome and subsequent volcanic cone. On Usengere, nearly 4,000 ft. of nephelinites survive, so that the volcano must have risen at least 9,000 ft. above the basement surface (Figure 40 and diagram C in the folder). There is no way of telling how much nephelinite has been eroded off the top of the succession. Both the lavas and agglomerates spread a long way from their vent, and some survive today twenty five miles away from Rangwa to the north, east and south.

The individual flows are so poorly exposed that it is rarely possible to measure their dips reliably in the field, though dips of up to 15° have been seen on the inward-facing erosion scarps. However, lava often caps the outward-dipping ridges of volcanics, and, on the aerial photographs, it is sometimes possible to trace individual flows for several miles, specially when they overlie agglomerate. In this way, dips of 4° - 6° were measured seven - ten miles from the centre, northwest of the Olambwe Valley, and on Gembe, four - eight miles from the centre, the dips are 6° - 10°. On

Kaniamwa and Mfwangano, ten - fifteen miles out, the dip is probably about $1\frac{1}{2}^{\circ}$ - 2°. South of Magunga, where the Kaniamwa Fault dies out, there are more or less flat lying lavas on north-south ridges; probably movement on the fault has altered these dips, a factor which may have had an effect on all the dips of the volcanics between the Mfwangano and Kaniamwa Faults. The dips measured are not much different from the inferred slope of the prevolcanic dome.

No large outward-facing cliffs of volcanics of the sort that exist on Elgon occur on Kisingiri; so the agglomerate must thin and die out beneath lava flows, and the higher flows represent the maximum surviving spread of the volcanics. This is well illustrated in the southeast; over a thousand feet of volcanics are exposed on the Kaniamwa Escarpment, but these die out seven miles to the southeast, although the top flow at Kaniamwa can be traced throughout that distance.

8. EARLY POST-VOLCANIC EROSION AND THE MFWANGANO AND KANIAMWA FAULTS.

Probably considerable erosion occurred during the building of the nephelinite volcano. Certainly much of the volcano had been eroded away before the main movement on the Mfwangano and Kaniamwa Faults. It is suggested that, at an early stage, a large radial valley developed, flowing out to the north between Rusinga and Mfwangano, and eroding headwards to the centre of the volcano.

Erosion down this valley must have removed most of the volcanics along its course before any movement on the Mfwangano Fault. Had this not happened, it is hard to explain why such a large section of the scarp of the Mfwangano Fault does not exist today (Figure 36), when the Kaniamwa fault line scarp survives largely uneroded; the first breach in the final crater wall must have been in the north, and, had this happened after the faulting, the stream flowing from it would have been blocked by the fault scarp, so that it would have turned through 120°, and flowed southwest between Takawiri and Kibuogi. It is unlikely that the master stream on the volcano would have done this (Diagram D in the folder).

The Mfwangano and Kaniamwa Faults are almost parallel, and run west-south-west east-north-east about twenty miles apart, one on each side of Rangwa. Their maximum throw towards each other is directly opposite Rangwa. The Mfwangano Fault runs south of Takawiri and Mfwangano, and north of Kibuogi, through the Mbita Channel, and across the Uyoma Peninsula. Between Kibuogi and Mfwangano, the throw, as deduced from the heights of the main nephelinites on the two islands, is at least 1,500 ft. Across the Mbita Channel, the nephelinites have been displaced by over 500 ft. and on Uyoma the fault scarp is only 200 ft. high. Indirect evidence that the Kaniamwa Escarpment is a fault line scarp is that if it were not basement rocks would occur at heights of over 4,000 ft. in the Olambwe

Valley; so far, no correlations have been made between the nephelinites on either side of the fault. The maximum height of the escarpment is 1,800 ft., at the part closest to Rangwa, and the maximum throw on the fault is probably more than this, as the volcanics within the Olambwe Valley are covered by thick alluvium. In both directions the scarp loses height, westwards towards the lake near Karungu and eastwards near Homa Bay. No other large faults have been recognized in the area.

McCall (1958 p 81) notes the difference between the simplicity of these faults and the complexities of the faulting in the Gregory Rift, and because the maximum throws occur opposite Rangwa he infers that the faults "are genetically connected with the eruptions of the extensive Upper Kisingiri plateau lavas". The "rift" here may thus be described as a "volcano-tectonic depression" (Williams 1941).

9. LATE EROSION.

Subsequent erosion was related to the base levels referred to Chapter X (pp 211 - 216). First, valleys were cut to a lavel over a hundred feet below the present lake level. An erosion caldera was hollowed out around Rangwa, since access had been gained to it by a stream from the north, erosion along the radial drainage pattern of the periphery of the volcano was accentuated, and erosion proceeded on the Kaniamwa fault scarp and on what was left of the Mfwangano fault scarp. Apart from the presence of thick alluvium round Rangwa, this lower base level is represented by the very thick secondary deposits in the Olambwe Valley and the apparently drowned topography on Rusinga (Kent 1936 pp 26 - 27). So vast quantities of volcanic detritus were removed from the area altogether; their destination is a matter for conjecture.

The base level was then raised considerably, and, for the first time, the volcano was almost surrounded by an ancestral Lake Victoria. Numerous raised beach levels, testifying to periods of stability of lake level have been recognized in the Kavirondo area. The highest is Kent's level of 320 ft. above the present lake level (1942), below which Kent and Saggerson (1952) have recorded at least six levels. These levels both support and supplement the evidence from around Rangwa (pp211 - 216) of a big rise in lake level, followed by a spasmodic fall. When the lake was at its highest level, many of the valleys eroded during the earlier period were filled with alluvium, and today, as the lake level drops, these are being reeroded (Diagram E in the folder).

As elsewhere round Lake Victoria, the raised beaches are Pleistocene Recent in age, but no correlations with the western shores of the lake have as yet been made.

PART IV.

CONCLUSIONS.

XIV

SUMMARY AND CONCLUSIONS

1. SUMMARY.

A. RANGWA AND ITS IMMEDIATE SURROUNDINGS.

The rocks on and around Rangwa form ring-shaped areas of outcrop, and the outer rings are generally older than the inner ones.

The ijolite and biotite uncompahgrite intrusion is a composite one, and it is thought to have been caused by the multiple injection of material of ijolitic composition into a body of melteigite and pyroxenite.

The doming of the basement was probably caused by the intrusion of the central plutonics.

Brecciation of the country rock occurred during doming.

The outer ring of alkaline plutonics tends to follow zones of brecciation.

In general, ijolites and nepheline syenites caused fenitisation, and carbonatites caused felspathisation. Felspathisation is often superimposed on fenitisation.

The pyroclastics on Rangwa are mainly extrusive.

The pyroclastics can be split into two groups of agglomerate, both formed predominantly by fluidisation, separated by a tuff group, which was deposited partly subaerially and partly in water.

Most of the carbonation and felspathisation in the pyroclastics was caused by volatiles and ions of calcium, potassium and sodium trapped in the rock as it cooled.

Subsidence of the vent rocks and their immediate surroundings occurred after the deposition of the pyroclastics.

The carbonatites are split into three groups, the small conesheets and dykes, coarse brecciated carbonatite, rich in mica and apatite, and fine-grained magnetite-rich carbonatite (emplaced mainly in that order), all of which are related to a centrally placed vent.

The small conesheets and dykes are found throughout the pyroclastics.

The coarse micaceous carbonatite forms a partial ring round the central arena of Nyakirangacha, and is associated with a felspathic breccia.

The magnetite-rich carbonatite was the final plug to the vent, and is exposed on the floor of Nyakirangacha.

Nearly all the carbonatite is predominantly calcitic, but some of it may have originated as dolomite or ankerite.

Some alkaline dykes, mainly phonolite and lamprophyre, were intruded into the complex at a late stage.

Erosion has been controlled mostly by many changes in the base level. Present day activity represents a partial reerosion towards an earlier base level.

Hydrothermal activity continued until quite recently.

B. RANGWA AND THE KISINGIRI VOLCANO.

Nearly all the volcanics originated directly or indirectly at a series of vents at or near the position of Rangwa.

The conglomerates in the lower part of the succession on Rusinga and Mfwangano are thought to be mudflows, initiated by the overflow of material from a vent, and some of them are correlated tentatively with the pyroclastics on Rangwa.

The distribution of the tuffs to the north and northwest of Rangwa is dictated by the prevailing wind direction.

Most of the melanite nephelinites were emplaced by flow rather than explosion.

Frequent lulls in volcanic activity caused unconformities and the deposition of intravolcanic sediments.

Most of the nephelinite lavas and agglomerate on the mainland were emplaced after considerable erosion of the domed basement, and after the eruption of the melanite nephelinite; so the central ijolite can be correlated with few if any of the lavas or agglomerates.

The nephelinite lavas and agglomerates are thought to have originated at a vent on the site of Nyakirangacha, and the phases of carbonatite intrusion there may be related to events in the sequence of eruption of the lava and agglomerate.

The Kaniamwa and Mfwangano Faults, which caused the central part of the volcano to subside, postdate most of the volcanic activity.

Erosion proceeded most quickly to the north, where the nephelinites are underlain by poorly consolidated deposits.

A large basin was hollowed out round Rangwa, as the volcanic scarps retreated, and a radial pattern of drainage was established on the periphery of the volcano.

2. COMPARISONS.

These features found in the area of Rangwa are compared with relevant occurrences elsewhere:-

1. The association of carbonatite with alkaline silicates.
2. The occurrence of alkaline plutonics with volcanics.
3. Fluidisation and brecciation at the vent.
4. The occurrence of pyroclastics round the vent.
5. The emplacement of carbonatite in the vent.

A. THE ASSOCIATION OF CARBONATITE WITH ALKALINE SILICATES.

All the phases of carbonatite on Rangwa are later than the main alkaline plutonic intrusions, a relationship which is widespread in alkaline complexes where carbonatite is present. Although at the present erosion level on Rangwa carbonatite is seldom seen to intrude alkaline plutonics, the age relations are similar to those at many other East African centres, where carbonatite intrudes an envelope of alkaline silicates. For example, on Napak (King 1949) the carbonatite of Lokupoi was emplaced at the centre of a mass of ijolite, and at Tororo (Davies 1956) carbonatite has intruded and brecciated nepheline syenite and ijolite.

Around Rangwa, fenitisation is normally associated with alkaline silicates, and felspathisation with carbonatites. Where the two processes occur together, felspathisation is imposed on fenitisation, a phenomenon which can be seen best at some predominantly carbonatite centres (as at Tororo, King and Sutherland 1967). On Chilwa Island (Garson and Campbell Smith 1958), breccias of fenite are felspathised.

B. THE OCCURRENCE OF ALKALINE PLUTONICS WITH VOLCANICS.

The erosion level is such that a central intrusion of alkaline plutonics and the remnants of a large nephelinite volcano both survive. Napak, where both volcanics and plutonics are exposed, is a large central type volcano which has almost similar rock assemblages. However, some features occur on the Kisingiri Volcano which are not evident or cannot be proved at Napak; large amounts of biotite uncompahgrite occur at the plutonic centre on Rangwa. The central plutonics exposed on Rangwa precede most of the nephelinites of the volcano, whereas the surviving alkaline plutonics at Napak probably postdate the nephelinite eruptions. A large subsided mass of layered pyroclastics, which are later than the alkaline plutonics, surround the central carbonatites on Rangwa.

Davies (1952) inferred that a carbonatite centre exists beneath Elgon, and Dawson (1962), because of the wide range of alkaline plutonic and carbonatite fragments included in the nephelinite agglomerate, showed that earlier alkaline centres existed beneath Oldoinyo Lengai. The fact that nephelinite agglomerates so often contain fragments of alkaline plutonics could imply that their vents have sometimes been drilled through alkaline plutonic centres: this is in fact the case at Napak also. So it is not anomalous that the central plutonic complex which survives at Rangwa was formed before the main nephelinite eruptions there.

At the carbonatite centre at Mbeya in Tanzania (Fawley and James 1955) and at Chilwa in Malawi (Garson and Campbell Smith 1958), it has been supposed that large volcanic superstructures once existed. The occurrence of carbonatites at Rangwa at the centre of a nephelinite volcano must give indirect support to these suppositions.

C. FLUIDISATION AND BRECCIATION AT THE VENT.

Most of the agglomerates on Rangwa show the characteristics of rocks formed by fluidisation (pp 120- 124), and the central carbonatites are intimately associated with breccia formed partly from fragments of the pyroclastics. These features are found widely both at carbonatite centres and in other volcanic environments.

The rocks of the three carbonatite volcanoes of the Rufunsa Valley in Zambia (Bailey 1960) have some affinities with the pyroclastics and carbonatites on Rangwa. The agglomerate on Chasweta consists mainly of rounded fragments in a calcareous matrix, and Bailey considers that these were formed during the continuous phase of fluidisation; the larger of the vents at Chasweta has been plugged by a concentrically banded carbonatite, which has caused brecciation and felspathisation.

Reynolds (1954) described the process of fluidisation, and cites a wide range of geological examples in which it could have operated, some of which are volcanic or subvolcanic, for example the uprushing gas phase on Vesuvius and the Swabian tuff pipes. The vent agglomerate of the Peripheral Zone of the caldera of the Ardh Bheinn area in Arran (King 1955), with its great variety of rounded fragments in an inhomogeneous, sometimes banded matrix has a similar texture to some of the agglomerates on Rangwa.

D. THE OCCURRENCE OF PYROCLASTICS ROUND THE VENT.

The inward dips of the banding and bedding of the agglomerates and tuffs on Rangwa have been interpreted as being partly depositional, and partly due to the subsidence of the volcanic centre, and the carbonation and felspathisation of the agglomerates are thought to have been caused by carbonate and alkalis trapped in the rock as it cooled. Two examples show that rocks of superficial similarity may be formed in very different ways or have different relations to their surroundings.

Verwoerd (1966 p 153) described the Goudini Volcano in South Africa as "a basin-shaped accumulation of partly carbonatised lava and tuff". More than two thirds of the area is covered by fine-grained sediments with inward dips of 30° - 80°. The body is oval with a longer diameter of nearly four miles. Verwoerd maintains that the tuffs were formed by the subaqueous redeposition of volcanic material in a continually subsiding basin, and that, since some bands are more carbonate-rich than others, the alteration was caused by "selective carbonatisation".

Richey (1938) described the vents of tuff and agglomerate drilled through the Tertiary Plateau Basalts at Ben Hiant on Ardnamurchan. He supposed that the original craters were formed by gigantic explosions, and that rhythmic deposition of agglomerate and tuff followed, as a result of periodic blasting out of the vent material succeeded by gas phases. Near the vent-walls, the agglomerates contain many fragments of basalt, which Richey interpretes as scree from the walls. So, although the mode of formation of some of the agglomerates and tuffs may not have been unlike that of the pyroclastics on Rangwa, their outer boundary is not faulted.

E. THE EMPLACEMENT OF CARBONATITE IN THE VENT.

The emplacement of the Kinyamungu Carbonatite on Rangwa was the final major igneous event on Rangwa, and it probably plugged the main vent of the Kisingiri Volcano. Carbonatite plays a similar part at many other alkaline volcanic centres. At Kerimasi, the vent is plugged by banded magnetite-rich carbonatite (James 1956). At other more eroded complexes, the central position and late occurrence of carbonatite imply that the vents of alkaline volcanoes are normally plugged by carbonatite. The trend towards carbonate enrichment in the lavas of Oldoinyo Lengai (Dawson 1962) is probably an extrusive manifestation of this phenomenon.

3. GENERAL OBSERVATIONS.

The order of formation of the main groups of rocks on Rangwa is:-

1. Alkaline plutonics.
2. Carbonated pyroclastics.
3. Late carbonatites and carbonated and felspathised breccias.

It has been suggested that most of the nephelinites of the Kisingiri Volcano were extruded after the Rangwa pyroclastics, and before the final carbonatite on Rangwa.

The early alkaline plutonics form a related group, of which the earliest formed members are probably pyroxenite and melteigite and which include carbonatite. Vents were drilled through the early plutonics by rising streams of gas which was rich in carbon dioxide and contained calcium, sodium and potassium. The material carried by these streams was emplaced either as flows of agglomerate or as ash falls. It is thought that the nephelinite lavas and agglomerates were erupted from the centre of the vent area, and the vent was plugged by a series of carbonatites, which were emplaced either by explosive action or as liquids.

The rocks formed on Rangwa and the Kisingiri Volcano form two series:-

1. Alkaline silicates, both intrusive and extrusive, and fenites.

2. Carbonatites, rocks of carbonatitic affinities and felspathic fenites.

In a cycle of activity, the second group nearly always succeeds the first.

Appendix A.

The following radiometric dates have been given for rocks from Rangwa:-

(a) By Dr. Miller of Cambridge:-

Biotite from biotite uncompahgrite of the central plutonic complex:-

19.0 ± 0.3 million years
19.0 ± 0.3 " "
19.2 ± 0.3 " "
19.3 ± 0.3 " "

Phlogopite from the Ekiojango Carbonatite:-

42 ± 5 million years.

(b) By Dr. Snelling of Oxford:-

Pyroxene from Sagurume Ijolite:- 38 million years.
Biotite from turjaite of the central complex:- 17.5 " "
Orthoclase-aegirine rock from Kiako:- 24 million years.

Dr. Miller and Dr. Snelling are thanked for making these results available.

Appendix B.

The following four analyses of minerals from the alkaline plutonic rocks on Rangwa were received after the present study was completed:-

	Pyroxene from RFA 2.	Pyroxene from RFA 6.	Melilite from RFA 3.	Biotite from RFA 3.
SiO_2	50.54	51.60	42.89	38.48
TiO_2	1.65	0.55	0.11	2.95
Al_2O_3	2.44	1.09	5.87	14.22
Fe_2O_3	2.24	2.88	1.00	1.09
FeO	2.42	4.83	2.35	6.73
MnO	0.07	0.27	0.13	0.16
MgO	15.54	14.20	8.28	21.56
CaO	24.78	23.63	33.75	0.98
Na_2O	0.38	0.93	3.56	0.32
K_2O	0.05	0.10	0.38	10.36
H_2O+	-	-	1.05	0.64
F_2	-	-	-	0.27
P_2O_5	0.07	0.01	0.47	0.07
Total	100.18	100.09	99.84	97.83

Analyst:- H. Lloyd.

RFA 2 and RFA 3 are biotite uncompahgrite.

RFA 6 is coarse-grained ijolite.

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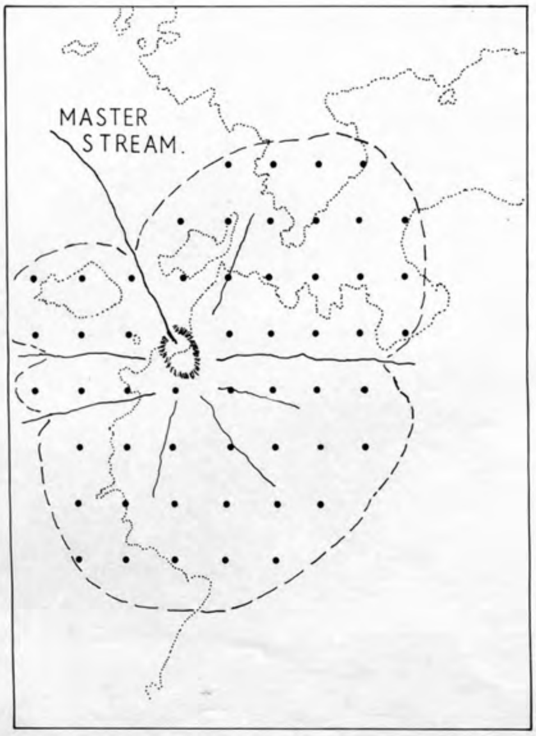
A. AFTER SOME EROSION OF THE BASEMENT DOME.

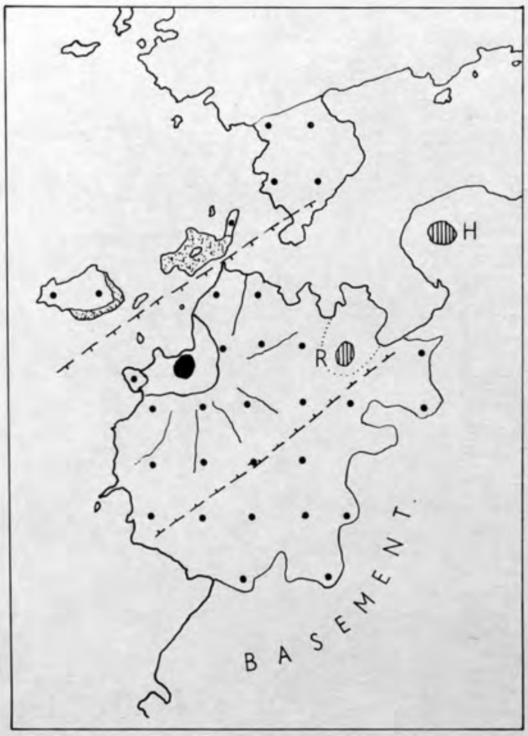
B. BEFORE THE EMPLACEMENT OF THE MAIN NEPHELINITES.

C. AFTER THE EMPLACEMENT OF THE MAIN NEPHELINITES.

MAPS ILLUSTRATING STAGES IN THE PROPOSED HISTORY OF THE KISINGIRI VOLCANO.

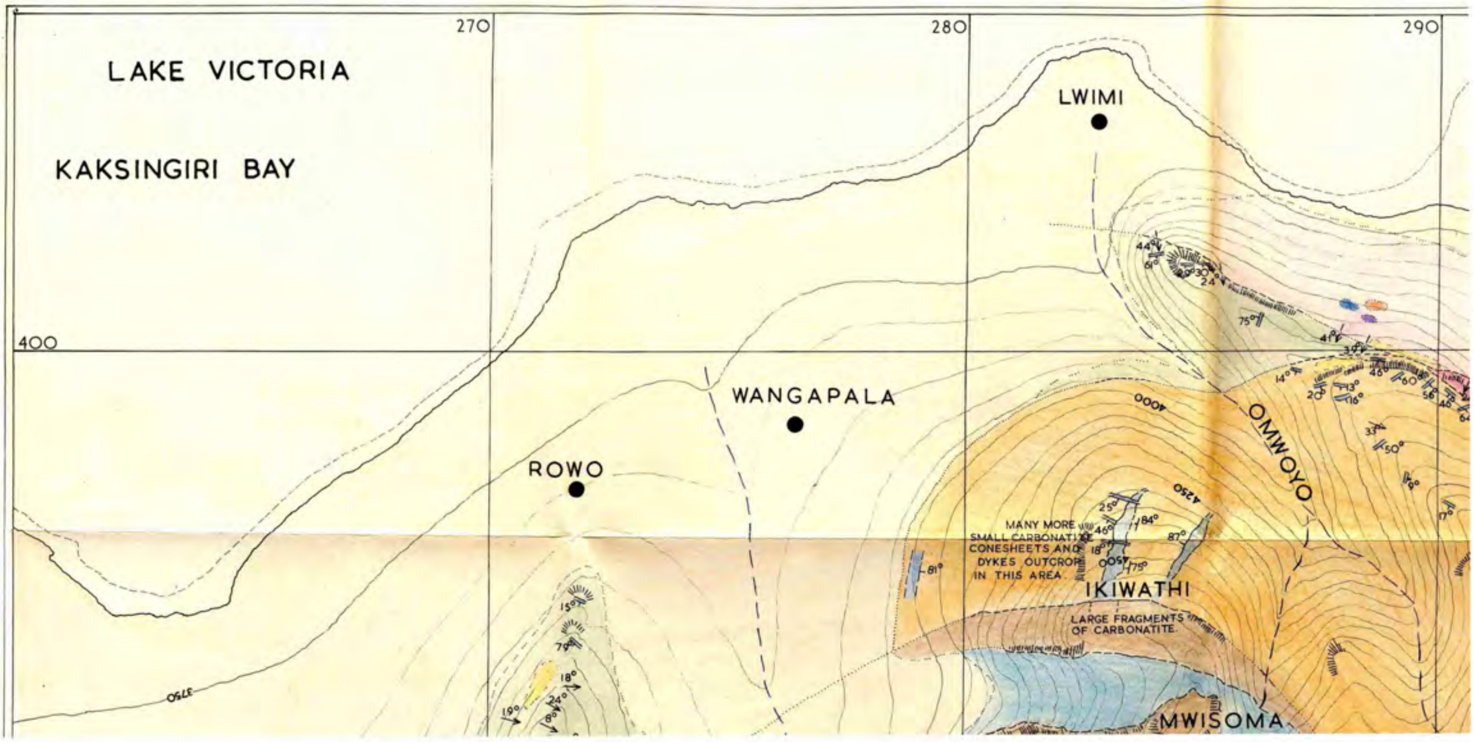


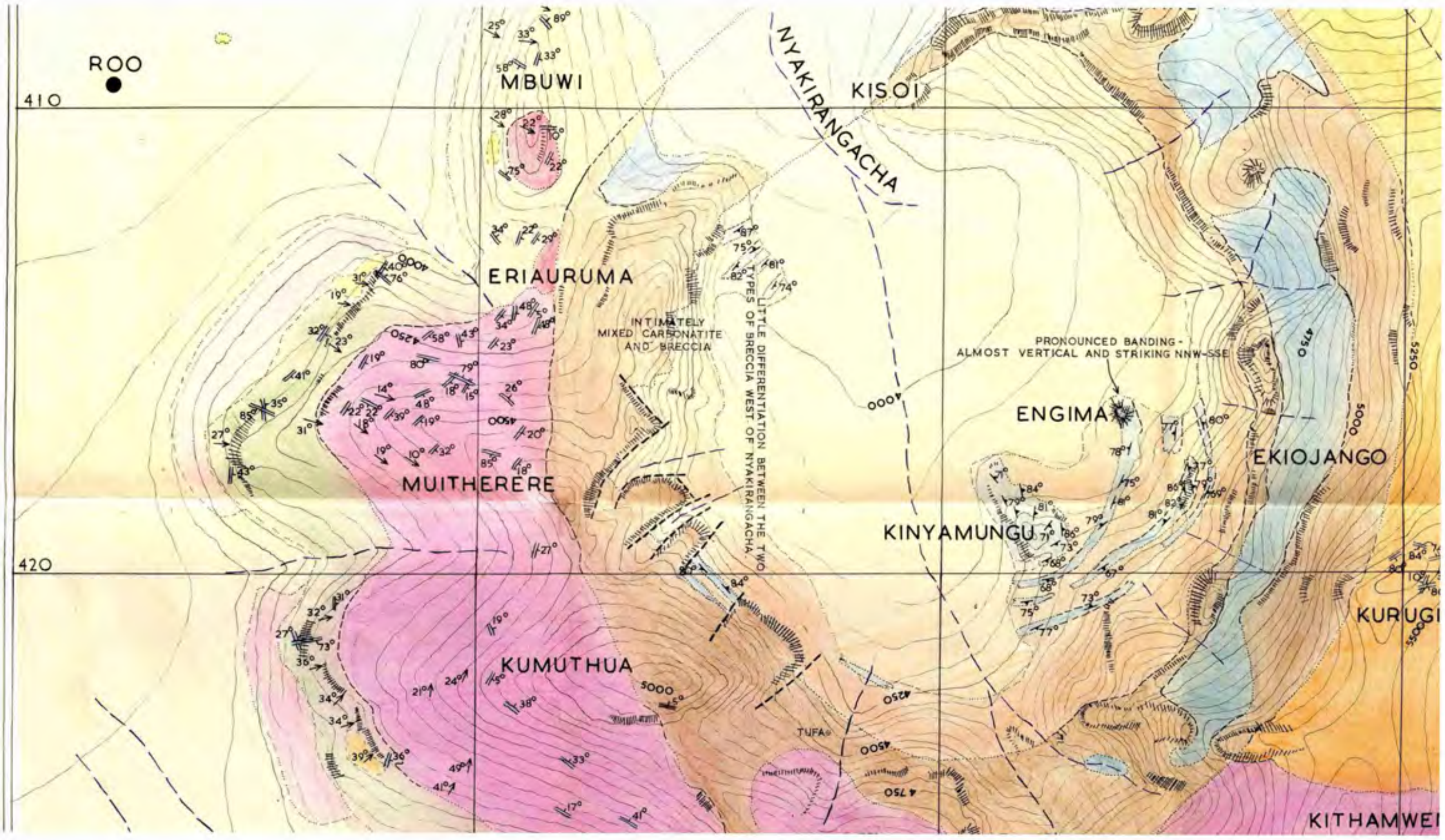
D. AFTER EARLY EROSION.

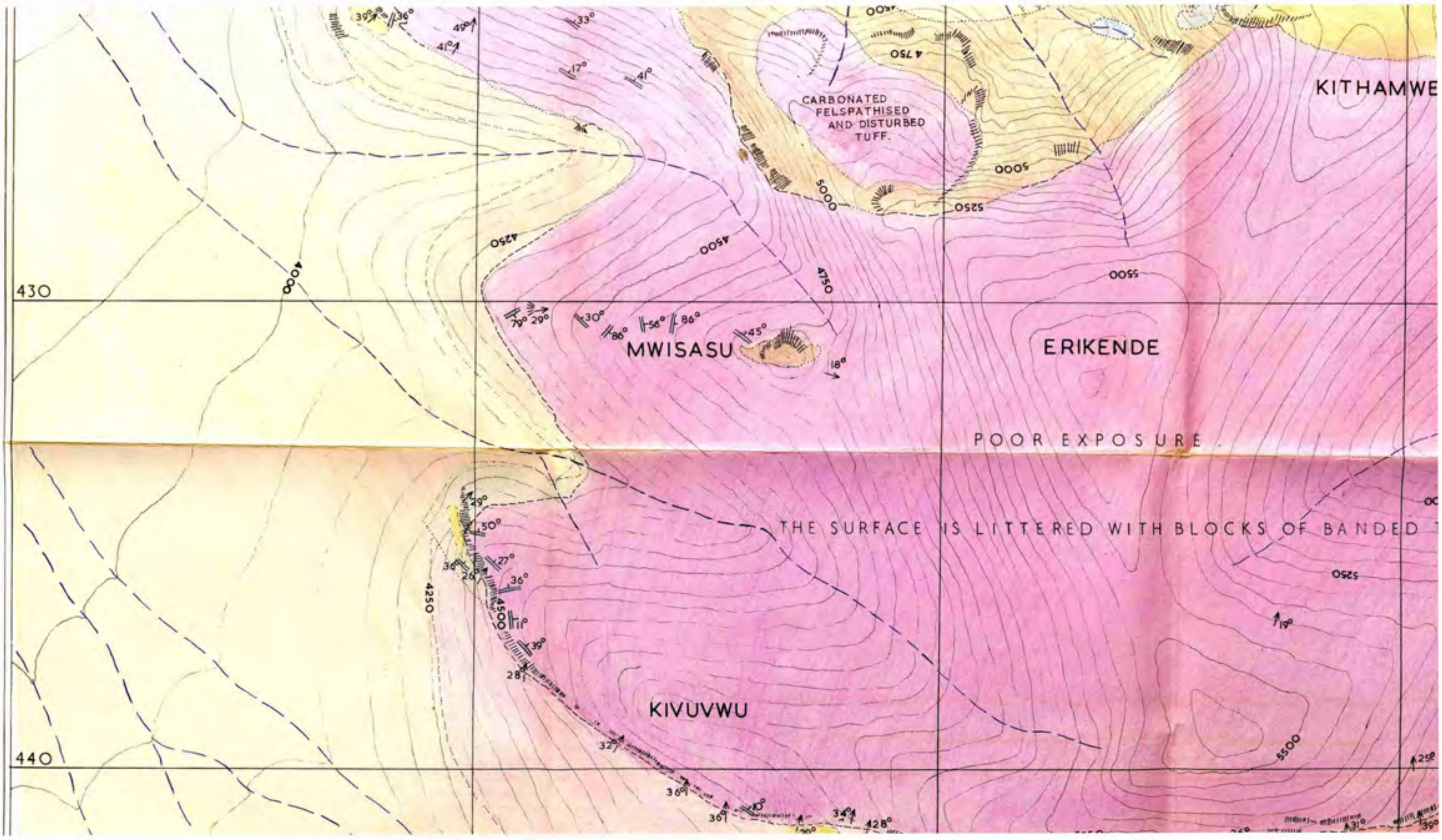


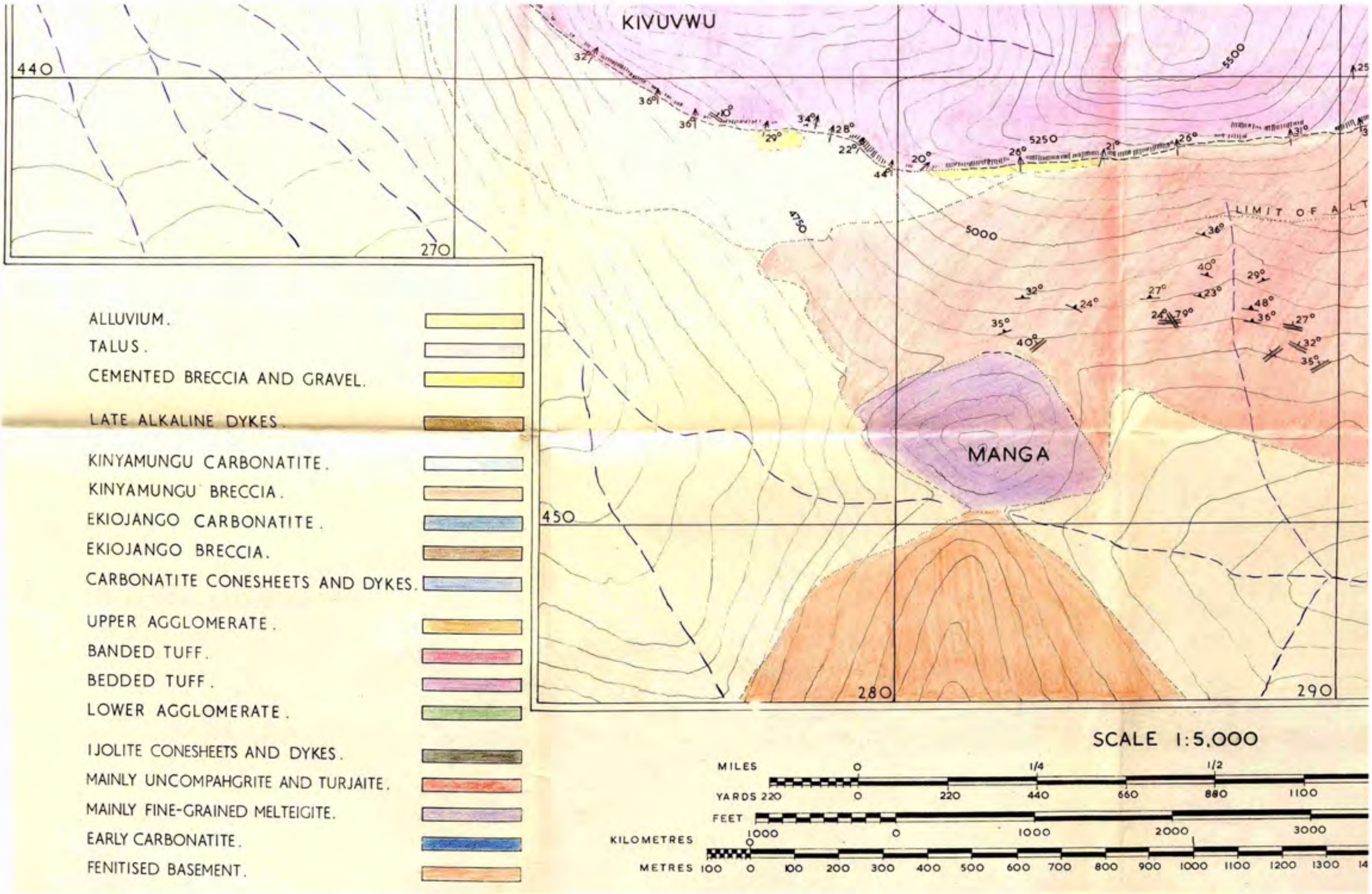
E. AT THE PRESENT.

A GEOLOGICAL MAP OF RANGWA.




ROO
410
420
MBUWI
NYAKIRANGACHA
KISOI
ERIAURUMA
INTIMATELY MIXED CARBONATITE AND BRECCIA
LITTLE DIFFERENTIATION BETWEEN THE TWO TYPES OF BRECCIA WEST OF NYAKIRANGACHA
PRONOUNCED BANDING - ALMOST VERTICAL AND STRIKING NNW-SSE
ENGIMA
EKIOJANGO
MUITHERERE
KINYAMUNGU
KURUGI
KUMUTHUA
TUFA
KITHAMWE
4000
4250
4500
4750
5000
5250


KITHAMWE
CARBONATED FELSPATHISED AND DISTURBED TUFF.
4750
5000
5250
4250
4500
4000
430
5500
MWISASU
ERIKENDE
POOR EXPOSURE
THE SURFACE IS LITTERED WITH BLOCKS OF BANDED
4250
4500
5250
KIVUVWU
440
5500


KIVUVWU
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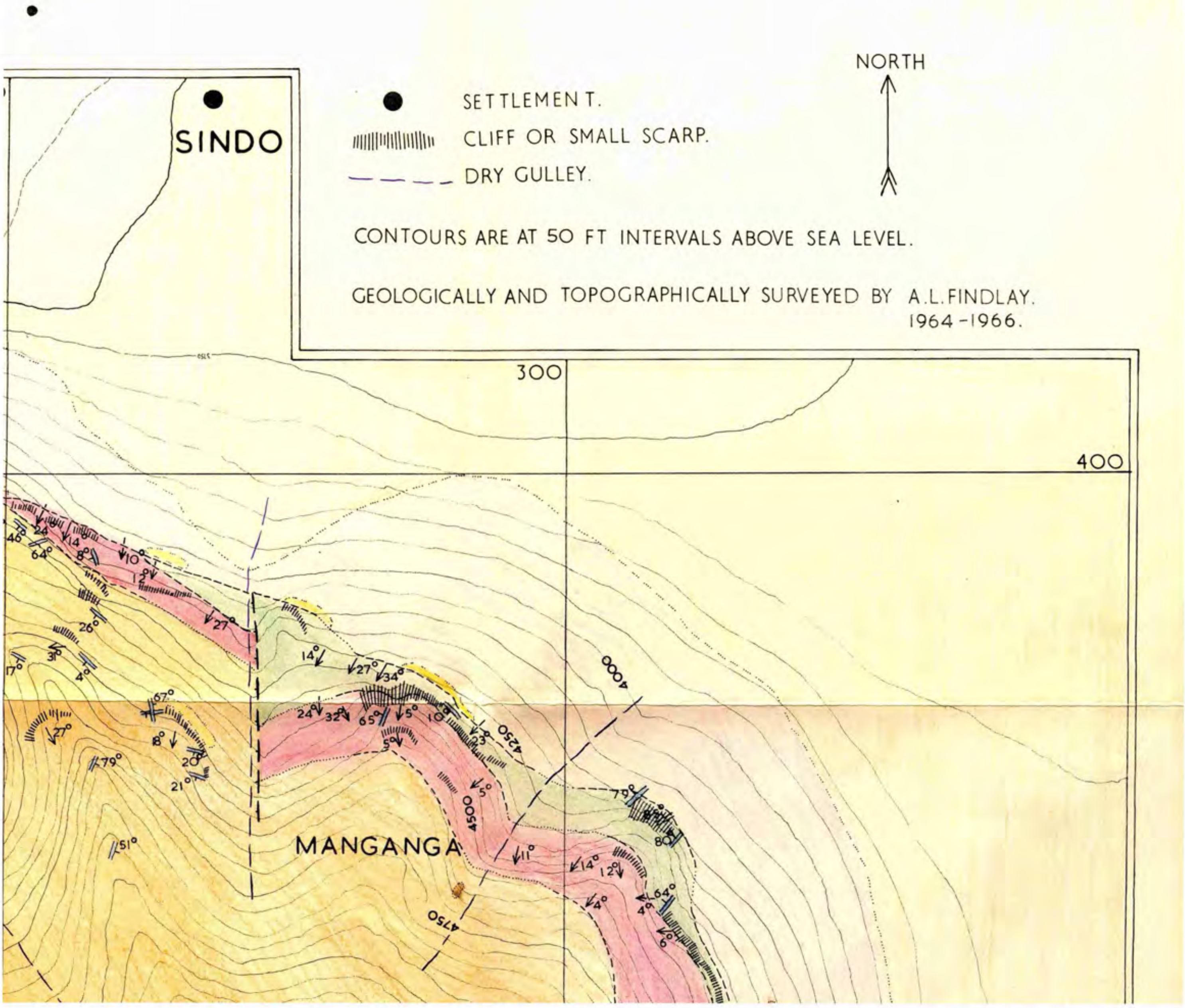
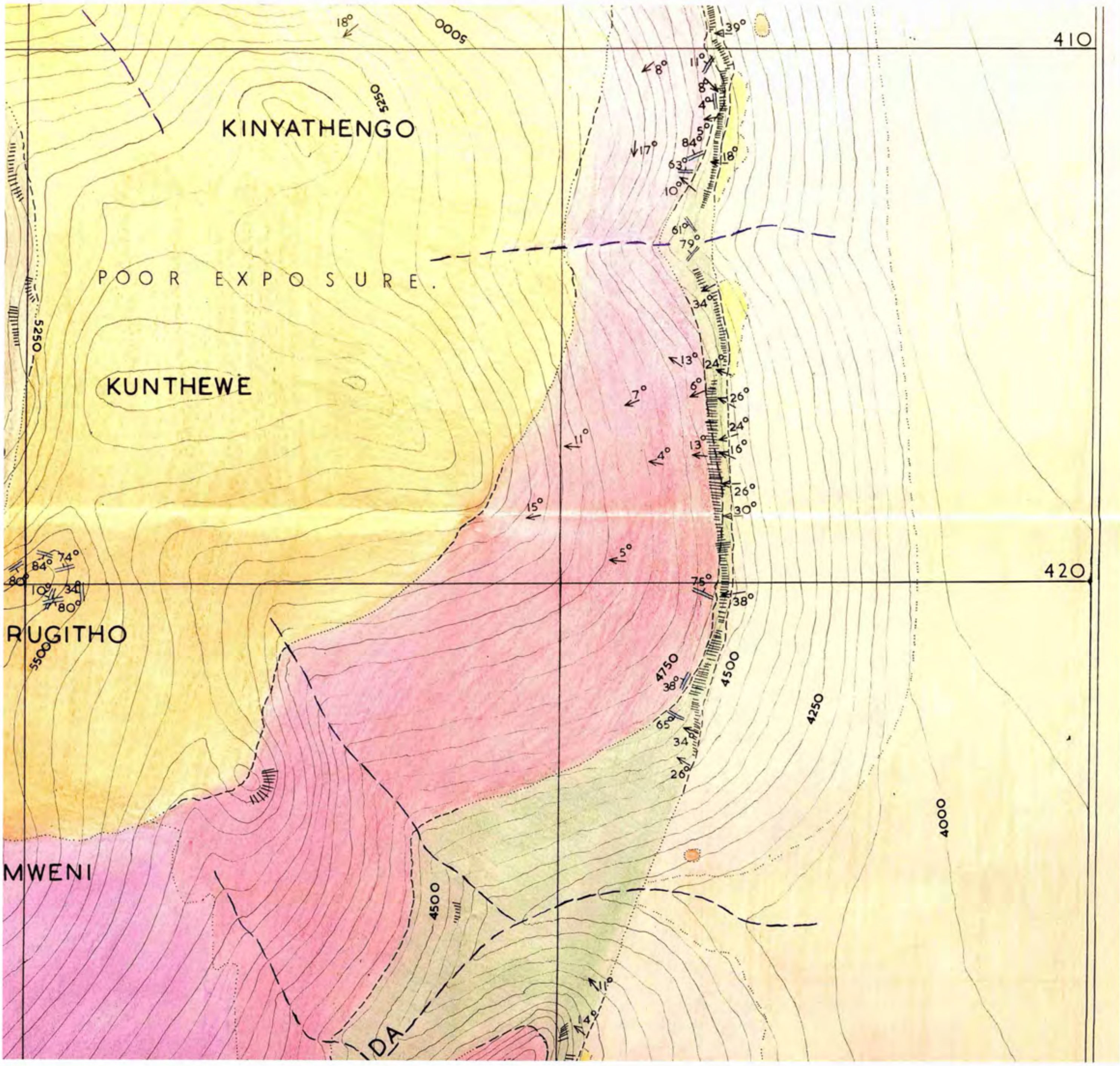
LIMIT OF ALT
440
450
270
280
290
ALLUVIUM.
TALUS.
CEMENTED BRECCIA AND GRAVEL.
LATE ALKALINE DYKES.
KINYAMUNGU CARBONATITE.
KINYAMUNGU BRECCIA.
EKIOJANGO CARBONATITE.
EKIOJANGO BRECCIA.
CARBONATITE CONESHEETS AND DYKES.
UPPER AGGLOMERATE.
BANDED TUFF.
BEDDED TUFF.
LOWER AGGLOMERATE.
IJOLITE CONESHEETS AND DYKES.
MAINLY UNCOMPAHGRITE AND TURJAITE.
MAINLY FINE-GRAINED MELTEIGITE.
EARLY CARBONATITE.
FENITISED BASEMENT.
SCALE 1:5,000
MILES 0 1/4 1/2
YARDS 220 0 220 440 660 880 1100
FEET 1000 0 1000 2000 3000
KILOMETRES 0
METRES 100 0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 14


NORTH
● SETTLEMENT.
CLIFF OR SMALL SCARP.
DRY GULLEY.
CONTOURS ARE AT 50 FT INTERVALS ABOVE SEA LEVEL.
GEOLOGICALLY AND TOPOGRAPHICALLY SURVEYED BY A.L.FINDLAY.
1964-1966.
SINDO
MANGANGA
300
400
4000
4250
4500
4750



KINYATHENGO
POOR EXPOSURE.
KUNTHEWE
RUGITHO
MWENI
DA
410
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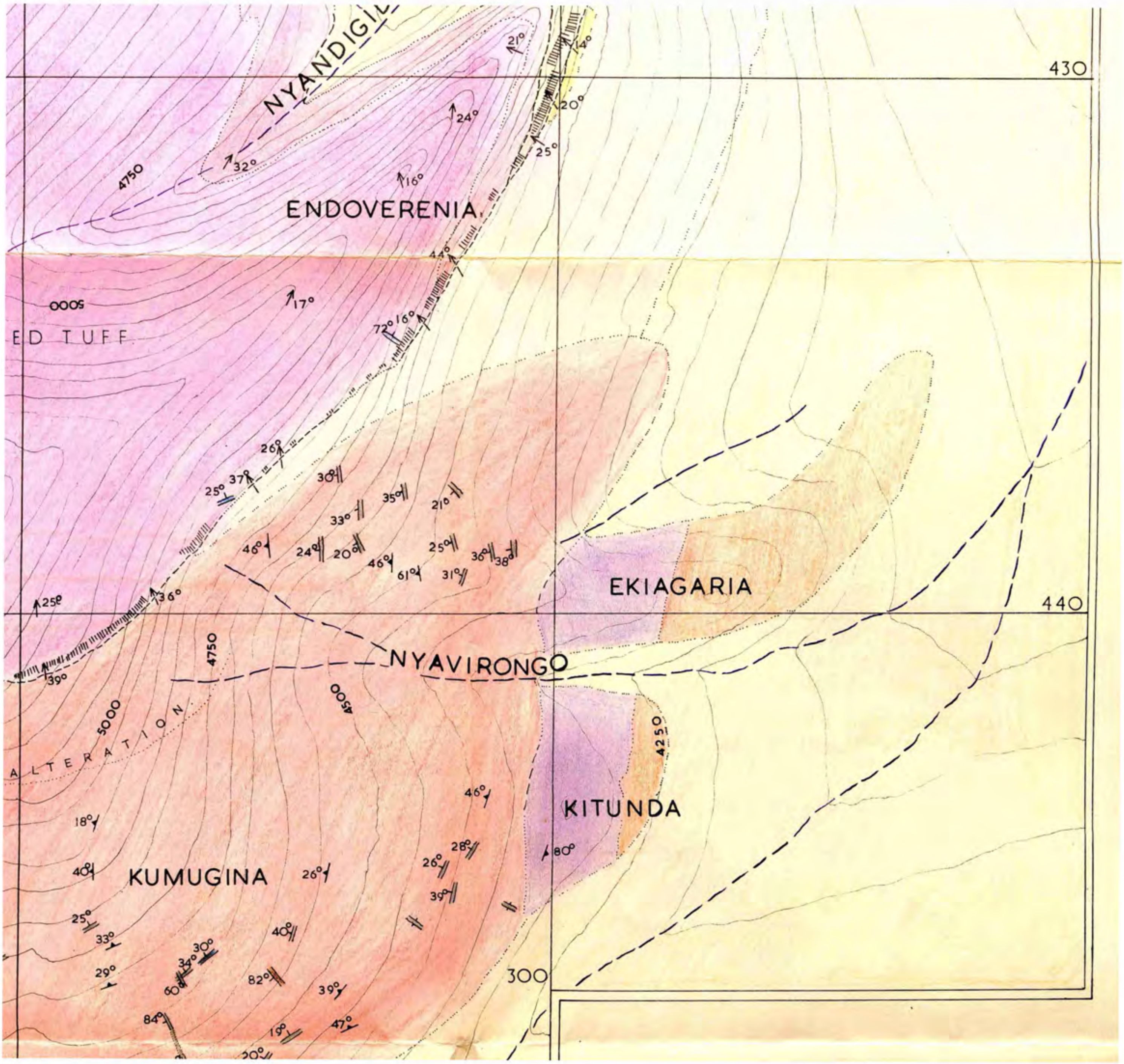
4000


NYANDIGI
ENDOVERENIA
ED TUFF
EKIAGARIA
NYAVIRONGO
KITUNDA
KUMUGINA
ALTERATION
430
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4750
5000
4500
4250
32°
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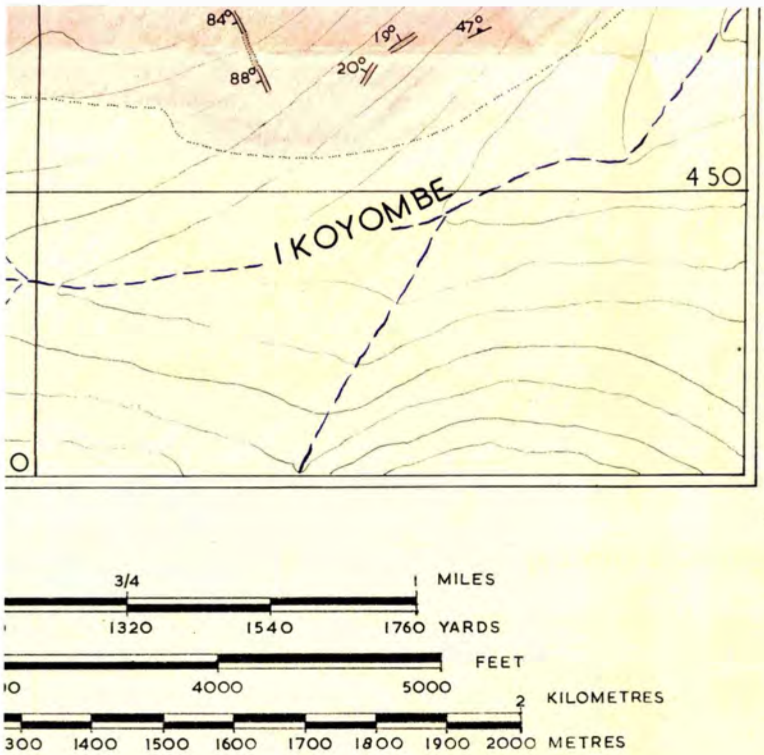

——	OBSERVED BOUNDARY.
- - - -	INFERRED OR GRADATIONAL BOUNDARY.
··········	APPROXIMATE BOUNDARY.
·· ··· ··· ··	BOUNDARY OF SECONDARY DEPOSITS.
▬ ▬ ▬	FAULT.
12° ↗	BANDING AND BEDDING IN THE PYROCLASTICS.
45°	BANDING IN THE ALKALINE PLUTONICS AND KINYAMUNGU CARBONATITE.
34°	SMALL CONESHEET OR DYKE. THE WIDTHS OF THESE ARE NORMALLY EXAGGERATED. ONE SYMBOL SOMETIMES REPRESENTS A SWARM OF CONESHEETS OR DYKES.