RING COMPLEXES IN THE YOUNGER GRANITE PROVINCE OF NORTHERN NIGERIA

CONTENTS

SUMMARY

This memoir presents a summary of recent studies on the Nigerian Younger Granite complexes. Sufficient information is now available to indicate that the province includes some of the finest examples of granitic ring-complexes in the world.

The cycle of igneous activity was initiated by a volcanic phase during which large volumes of rhyolitic lavas were extruded. These lavas were succeeded by series of granitic intrusions whose emplacement and form have been mainly controlled by ring-fracturing and major block subsidence. As a result of the extensive down-faulting accompanying the granite emplacement, some of the rhyolites have been preserved at the present erosion level. Basic and intermediate rocks occur in some of the complexes.

The memoir is divided into two main sections. The first includes a general discussion of the essential structural, petrographic and geochemical characteristics of the province. The second section is devoted to the description of individual complexes which have been selected to illustrate the varieties of structure and rock type which are encountered.

I. Introduction

The separate identity of the Younger Granites, as distinct from the Older Granites in the Basement Complex, was first recognized by J. D. Falconer during the Mineral Survey of Northern Nigeria between 1903 and 1911. After the establishment of the Geological Survey in 1919, most of the Younger Granite complexes were identified and their boundaries defined. The initial survey recorded the presence of riebeckite-granite, the discordance between the Younger Granites and the structures in the Basement Complex, the absence of contact metamorphism and the importance of the suite in tin mineralization.

One of the Younger Granite complexes, the Kudaru Hills, was shown by A. D. N. Bain (1934) to have a ring structure. In 1946, R. R. E. Jacobson found the Liruei complex to possess a similar form and recognized the importance of ring-structures in the Younger Granite province (University of London thesis, unpublished). During the resurvey of the Plateau tinfields between 1945 and 1948, R. A. Mackay, R. Greenwood and J. E. Rockingham (1949) described the Neil's Valley ring-structure and the great granite-porphyry ring-dykes surrounding the Rop and Sha complexes. Greenwood (1951) drew attention to the close structural and petrological similarity between the Younger Granites and the White Mountain magma series of New Hampshire.

In 1950, some of the riebeckite-granites, which were known to contain radioactive minerals such as pyrochlore, were studied by R. A. Mackay and K. E. Beer of the Atomic Energy Division of the Geological Survey of Great Britain (Mackay & Beer 1952 ; Beer 1952). The present phase of detailed investigation was begun in 1951 by W. N. MacLeod (1956) and R. Black and since then many of the important complexes in the province have been mapped.

II. General Features of the Younger Granites

(a) Distribution of the Younger Granites

The Younger Granites are a group of granitic massifs which are discordantly intrusive into the Pre-Cambrian Basement Complex in Northern Nigeria. They are high-level, magmatic granites with sharply defined, cross-cutting contacts against the older rocks. The Younger Granites cannot be related to any cycle of orogeny. The precise age of the granites is unknown and cannot be determined stratigraphically. Radioactive age determinations have given divergent results but the most reliable of these indicate a late Pre-Cambrian or early Palaeozoic age.

There are about forty Younger Granite complexes in Nigeria. Until a complete survey of the province has been made the exact number cannot be defined, as many of the larger massifs are due to the fortuitous contiguity and overlapping of separate cycles of intrusion. Examples of the coalescence of complexes are provided by the Tongolo–Rishi–Saiya–Shokobo and the Amo–Buji–Rukuba groups.

The Younger Granites occur entirely in the Northern Region of Nigeria, between latitudes 8° and 12° N. and longitudes 8° and 10°E. They lie within a northerly-trending rectangle about 250 miles long and 100 miles wide. The massifs show great variations in size. The largest is the Ningi–Kah–Burra complex, which covers an area of 350 square miles. The Jos–Bukuru and Sha–Kaleri complexes each exceed 200 square miles. The majority of the others are much smaller, ranging between 25 and 100 square miles, and many small isolated intrusions exist, some of which are only one or two miles in diameter. The distribution, areas and principal rock types of the complexes are shown in Pl. VII and Table I.

The Younger Granites are also widely distributed in French West Africa. The riebeckite-granites of Zinder in French West Africa have long been recorded, and more recent work by the French geologists has revealed a widespread occurrence in the Aïr, Ahaggar, Tibesti and Adrar des Iforas regions of the central Sahara. Younger Granites also occur in the French and British Cameroons and in the Sudan. Over 100 separate Younger Granite complexes have been recognized in North and West Africa, scattered over a total area of about a million square miles. These granites, accordingly, comprise one of the largest petrographic provinces in the world.

The Younger Granites show a greatly superior resistance to erosion in comparison to most rocks of the Basement Complex and form high, dissected plateaus with steep escarpments which are striking topographic features in the level and monotonous terrain of Northern Nigeria. The Older Granites of the Basement Complex weather to isolated groups of inselbergen and rarely form continuous ranges or plateaus. In the central area of the province, where the complexes are close together, there is the continuous upland region of the Jos Plateau. The intervening Basement rocks have here been protected from erosion by the proximity of the resistant Younger Granites.

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TABLE I.—AREAL EXTENT OF THE PRINCIPAL ROCK TYPES IN THE YOUNGER GRANITE PROVINCE (in square miles)

COMPLEX	Biotite-granite	Riebeckite-granite	Amphibole-fayalite-granite	Rhyolite	Basic and intermediate rocks	Totals
Jos–Bukuru .	233	4	48	3	—	288
Sha–Kaleri . .	142	—	72	16	4	234
Afu . . .	185	—	—	—	—	185
Kila–Wurji . .	—	29	—	—	102	131
Fagam–Gadama .	4	114	1	9	—	128
Saiya–Shokobo .	17	4	—	92	2	115
Ningi . . .	22	2	13	70	2	109
Kwandonkaya .	71	—	3	—	—	74
Vom . . .	59	8	4	—	—	71
Rop . . .	37	8	25	—	—	70
Liruei . .	13	4	11	25	1	54
Rukuba . .	49	—	1	—	—	50
Banke . .	18	—	2	29	—	49
Amo . . .	35	5	2	—	—	42
Kudaru . .	1	25	8	—	—	34
Tongolo . .	15	9	7	1	—	32
Jere–Sanga . .	24	5	—	—	3	32
Buji . . .	10	2	3	11	—	26
Kerku . .	—	5	—	—	7	12
Zaranda . .	—	3	—	—	7	10
Forum . .	5	—	—	—	—	5
Kofayi . .	2	—	—	—	2	4
Sharwai . .	1	—	—	—	—	1
Sutumi . .	—	—	1	—	—	1
Totals . .	943	227	201	256	130	1757
All other complexes*	492	97	—	225	6	820
Grand totals .	1435	324	201	481	136	2577
Areal percentages	56	12	8	19	5	

*Approximate only, no detailed maps available.

(b) Structural Features

The Younger Granite complexes have all resulted from high-level magmatic activity, and the structural features revealed in individual complexes show a close correlation with the depth to which they have been eroded. In several of the complexes, where the structural relationships of the component phases are clearly revealed, it is apparent that a difference of as little as 1000 feet in erosion level would profoundly modify the surface plan of the complex. Fortunately, with a large number of well-exposed massifs available for study, information which is concealed in some is revealed in others and an overall picture of the form and tectonic structure of the suite has been obtained. For convenience a three-fold structural subdivision can be made, although it must be remembered that the divisions are transitional and variations are due to essentially the same tectonic processes operating at different levels and to different degrees.

(i) *Volcanic Structures*

The emplacement of the Younger Granites has been preceded by the extrusion of great quantities of rhyolitic lavas, which are still preserved in many of the complexes, as a result of subsequent subsidence along ring-faults. The close association between the extrusion of acid lavas and the high-level emplacement of granites is one of the most important features of the province.

The rhyolites fall into two distinct groups which represent different modes of eruption. The earlier rhyolites are typical products of vent extrusion from simple central volcanoes or from groups of vents aligned along ring-fractures. In many cases it is clear that the ring-fractures extended to the surface and that they formed lines of weakness up which the magma rose to cause vent activity. The later rhyolites, which are of greater areal extent, are believed to have been extruded as a result of surface cauldron subsidence, the lava welling up the ring-fault around the margin of the subsiding block. In addition to the major surface cauldrons, the late rhyolites also occur as high-level intrusions in the form of dykes, irregular sheets, diatremes and shallow subsurface cauldrons within the earlier volcanic accumulations.

The essential difference between the two groups of lavas is reflected both in their structural distribution and their petrography. The vent rhyolites and the associated pyroclastic rocks are typical of spasmodic vent activity. Individual lava flows, which commonly show autobrecciation, are interbedded with tuffs, breccias and coarse agglomerates. In the rugged and dissected terrain usually associated with the lavas it is sometimes possible to establish a definite succession of lavas and interbedded pyroclastic rocks. In some complexes, where the individual vents are exposed, the heterogeneity of the early lavas is strikingly revealed.

In contrast to the great diversity of the early rhyolites, the late rhyolites, which have been extruded as a result of surface cauldron subsidence, display a remarkable homogeneity, both in individual occurrences and over the entire province. In thickness and areal extent they are the more important of the two groups of lavas and form some of the most striking topographic features of the region. The late rhyolites are most abundant in the complexes north of the Jos Plateau, such as the Saiya–Shokobo Hills, where they form extensive dissected plateaus rising up to 2000 feet above the surrounding plains. In these plateaus there is usually little variation in texture or composition either laterally or vertically. Pyroclastic rocks are absent and individual lava flows cannot be distinguished. The late rhyolites are usually porphyritic with a microcrystalline groundmass, and their texture suggests rapid chilling and crystallization under conditions which permitted the ready escape of volatile constituents. It is considered that surface cauldron subsidence along major ring-faults provides the most satisfactory explanation of the mode of origin of these great plateaus of homogeneous lava.

In all the complexes so far studied, the two types of rhyolites appear in varying proportion. In some, such as Liruei and Buji, it is apparent that normal vent eruptions have provided most of the extruded materials. In others, such as Banke and Saiya–Shokobo, vent activity has been comparatively unimportant and surface cauldron subsidence has intervened before the formation of any great thickness of vent-extruded materials. The differences between the patterns of volcanic activity are more fully illustrated in the detailed descriptions of individual complexes (see also Fig. 8).

The rhyolites in the Younger Granite province are almost always confined within the granitic ring-complexes and they cannot be used as a means of determining the extent of subsidence, as has been done in the case of the Scottish and Norwegian ring-complexes. In all the complexes where rhyolites are present, down-faulting has taken place during the emplacement of the later ring-dykes and granite plutons, and in most cases it is impossible to reconstruct the detailed tectonic features of the volcanic cycle. In the Buji complex the pattern of the original vents can be seen, but in most of the other complexes the vents are either concealed beneath lava accumulations or they have been obliterated by the later granite intrusions. In many cases it is also probable that the original attitude of the lavas has been considerably disturbed during the granitic cycle by segmentation, differential subsidence and tilting of the sinking block.

(ii) *Cone-sheets and Ring-dykes*

Cone-sheets have been recognized in several of the complexes and are best exemplified in the Kudaru, Amo, Buji and Tongolo massifs. In contrast to the Scottish examples, all the cone-sheets in Nigeria are made of highly acid rocks and no basic and intermediate types have been recorded. They precede the intrusion of the granites, by which they are frequently truncated, and are themselves intrusive into the rhyolites. The Younger Granite cone-sheets are usually fine-grained quartz-porphyries and felsites, some of which show a glassy texture with strong flow-banding.

At Amo and Kudaru the sheets attain a thickness of 200 feet and all gradations in size are found, down to narrow veins a few inches in width. Deviations from the ideal pattern of dip and distribution are common, as can be expected when intrusion has occurred in a zone which has already been intensely fractured during the early volcanic cycle. Many of the granites are associated with extensive and irregular swarms of felsite dykes which were probably emplaced during a period of upward magmatic pressure which prevailed prior to the emplacement of the granites. It is possible that these dykes are tectonically related to the cone-sheets.

The ring-dykes are the most striking structural feature of the Younger Granite province, and the ring-fracturing accompanying their emplacement has exerted a major control on the structure, form and distribution of the numerous complexes. The ring-dykes are both circular and polygonal, the latter form predominating among the narrower dykes in the Basement Complex and the former in the broad ring-dykes within the massifs. In some polygonal ring-dykes there is clear evidence that the form has

TABLE II.—DIMENSIONS OF SOME TYPICAL RING-DYKES IN THE YOUNGER GRANITE PROVINCE

Rock type	Complex	Diameter(s) (miles)	Length (miles)	Extension of arc (degrees)
Mongu granite-porphyry	Rop	16×10	35	340
Mbar granite-porphyry	Sha–Kaleri	15	22	185
Pitti biotite-granite	Sha–Kaleri	$13\frac{1}{2}$	$19\frac{1}{2}$	190
Richa granite-porphyry	Sha–Kaleri	$11\frac{1}{2}$	$17\frac{1}{2}$	165
Neil's Valley granite-porphyry	Jos–Bukuru	$11\frac{1}{2}\times5$	27	350
Granite-porphyry	Liruei	9×7	20	295
Quartz-fayalite-porphyry	Kudaru	$11\times7\frac{1}{2}$	$22\frac{1}{2}$	285
Riebeckite-granite	Amo	7	12	180
Hotum arfvedsonite-granite	Sha–Kaleri	$5\frac{1}{2}$	10	195

been controlled by structural trends in the Basement rocks. The dykes exhibit great variations in width even in the one intrusion. Many of the massifs have been compounded by concentric and overlapping ring-dykes and earlier intrusions are frequently cut out and partly obliterated by later ones. Table II gives the dimensions of some typical ring-dykes in the province.

It is clear that many of the narrow ring-dykes are permissive intrusions along steeply dipping fracture planes which were opened during block subsidence and thus allowed a free upward movement of the magma. In others, intrusion by piecemeal or minor block stoping has occurred along a wide fracture zone which itself is arcuate or polygonal in form.

Elliptical and crescentic-shaped intrusions are common throughout the province. Such bodies may have resulted from the subsidence of blocks bounded by two or more ring-fractures of different radii or they may have been emplaced by piecemeal stoping in zones of more intensive fracturing within a broad arc of disturbance. As in New Hampshire, few of the ring-dykes appear as complete circles, although the original extent of many has been partly obscured by later intrusions. Practically all the rock types in the suite appear as ring-dykes, but this intrusive form is most favoured by the amphibole-fayalite-granites and granite-porphyries. In the description of individual complexes, which follows later, many examples of ring-dykes are described.

(iii) *The Granite Intrusions*

In areal extent, these intrusions occupy the greater part of the province, particularly in the Jos Plateau area, where there are eight large granitic massifs in close proximity which together cover an area exceeding 1000 square miles. The granites commonly display a circular or elliptical outline and there is often a concentric arrangement of the successive phases of intrusion. Sometimes a pronounced eccentric pattern of successive granites is in evidence which reflects a shift in the centre of magmatic activity. It is certain that ring-faulting and cauldron subsidence have initiated the process of granite emplacement, and the ideal, simple forms which this mechanism of emplacement tends to produce have been modified and distorted both by minor stoping and the superposition of later cauldron structures. Intrusive patterns of great intricacy are produced by the continued operation of cauldron subsidence, as will be demonstrated in later sections of this memoir. In some complexes, such as Amo, a close approach is

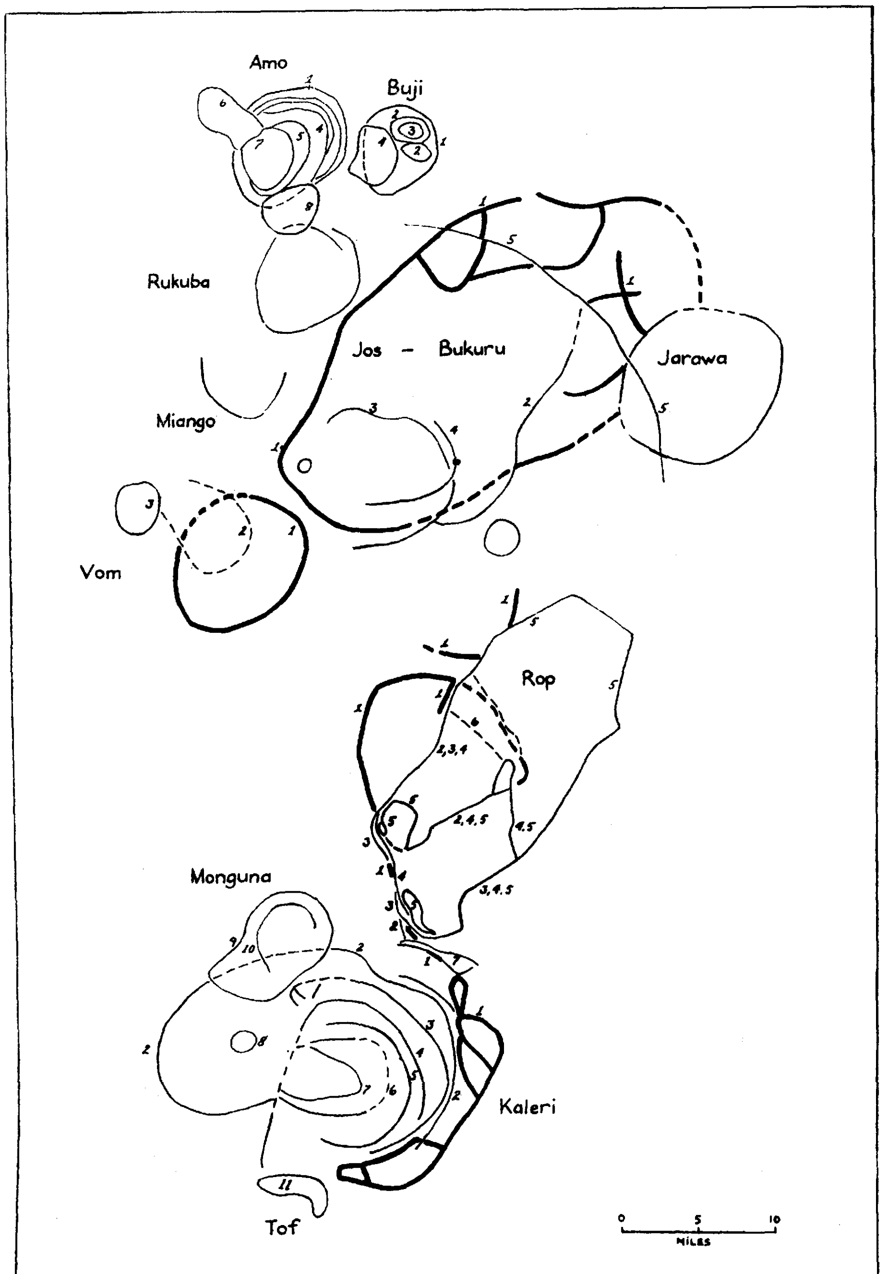

Fig. 1.—Tectonic plan of the Jos Plateau showing the distribution of the major ring-fractures that have controlled the emplacement of the Younger Granites. The numbers refer to the age sequence of fractures in individual complexes and, except for the earliest set of fractures shown as thick lines, no correlation is implied for the entire Plateau region.

seen to the ideal pattern of concentric intrusion controlled by successive cauldron subsidences. In others, such as Jos–Bukuru and Kwandonkaya, the pattern of granite intrusion is too intricate and irregular to permit a ready interpretation of the structure.

Figure 1 illustrates the major ring-fractures of the Jos Plateau. It can be seen that they fall into three main groups and are, as a whole, larger and more concentrated than elsewhere in the province. The earliest fractures, shown by heavy lines, have frequently determined the general outline of the individual complexes. The northern group embraces the large Jos–Bukuru, Vom and Jarawa complexes and is surrounded by the satellite ring-structures of Miango, Rukuba and Amo–Buji. The central and southern groups of fractures have controlled the granite emplacement of the Rop and Sha–Kaleri complexes respectively.

The depth of erosion exerts a profound influence on the surface form of the granite intrusions. Many which appear as circular bosses at the present level would doubtless appear as ring-dykes at greater depth. In some of the massifs, the granites display a nearly horizontal sheeted structure due to the exposure of the upper, flat-lying sections of the ring-intrusions. The Rop complex, which is described later in detail, provides a fine example of this type of structure. In both the horizontal and vertical types of structures, screens of the earlier rocks are common and provide valuable guides in interpretation.

(c) The Principal Rock Types

(i) *Rhyolites*

As already explained, the rhyolites fall into two distinct groups. The earlier rhyolites and associated pyroclastic rocks are the products of individual vent eruptions, the vents frequently being aligned along ring-faults. It is believed that the later rhyolites are the products of surface and shallow subsurface cauldron subsidence and they may be either intrusive or extrusive in nature. The two types are often found together in the one complex.

The early vent rhyolites display great diversity in texture and composition. Porphyritic, spherulitic and glassy varieties are represented and individual flows can often be distinguished in the field. Autobrecciation is a common feature. The associated pyroclastic rocks range from crystal and vitric tuffs, only recognizable on microscopic examination (Pl. IV, figs. 3–5), to coarse volcanic breccias and agglomerates. In contrast, the late cauldron rhyolites display a remarkable uniformity of texture and composition both laterally and vertically. No pyroclastic rocks are found in the lava accumulations and individual flows cannot be distinguished. The late rhyolites often appear as dykes, diatremes and irregular sheet intrusions in the early lavas and adjacent Basement rocks. They also include spectacular intrusion breccias in which the volume of included xenolithic material equals or even exceeds that of the late rhyolite matrix. In the Buji complex there are many fine examples of early vent agglomerates closely net-veined by the late intrusive rhyolite.

Table III, showing the chemical analyses and normative compositions of the rhyolites, reveals that they are practically identical with the granites and have about the same range of alkalinity. The comendite from Liruei is chemically indistinguishable from the riebeckite-granites.

Petrography.—In the hand-specimen, the rhyolites display great diversity in colour and texture. The colour ranges from various shades of grey and brown to green in the alkaline varieties. In thin section they usually contain scattered phenocrysts of alkali-felspar and small corroded crystals of quartz in a cryptocrystalline to microcrystalline groundmass. Most of the rhyolites show evidence of extensive devitrification of the originally glassy base. Irregular microcrystalline zones, composed of minute rounded grains of quartz and felspar, show ill-defined and gradational boundaries with isotropic and cryptocrystalline zones. In view of the age of the lavas it is unlikely that any true glass remains. Crystallites and perlitic cracks are sometimes to be seen. The mafic minerals appear only as spongy, dyscrystalline aggregates and as finely dispersed wisps in the groundmass. Aegirine and soda-amphiboles can be identified in some of the peralkaline rhyolites from Liruei and Buji and these rocks have a characteristic green colour.

TABLE III.—CHEMICAL ANALYSES AND NORMS OF THE RHYOLITES

	1	2	3	4
SiO_2	74·04	74·66	77·47	75·9
Al_2O_3	10·95	11·50	11·46	12·2
Fe_2O_3	2·08	1·70	0·67	1·4
FeO	1·72	1·94	1·01	0·40
MgO	0·02	0·03	0·11	0·20
CaO	0·35	0·17	0·64	0·33
Na_2O	4·46	3·16	3·28	3·9
K_2O	4·76	5·30	4·61	5·4
H_2O+	0·65	0·52	0·30	0·01
H_2O-	0·20	0·18	0·10	—
CO_2	tr.	0·03	n.d.	n.d.
TiO_2	0·17	0·17	0·13	0·15
ZrO_2	0·27	0·30	n.d.	n.d.
P_2O_5	0·05	0·06	0·02	0·01
Cl	tr.	tr.	tr.	n.d.
F	0·11	0·11	0·04	0·22
S	0·02	0·07	tr.	n.d.
MnO	0·02	0·02	0·02	0·03
	99·87	99·92	99·86	100·15
Less O	0·06	0·08	0·01	0·09
Total	99·81	99·84	99·85	100·06
Sp. gr.	2·68	2·69	2·61	2·62
Q	30·51	35·40	38·81	32·32
or	28·13	31·36	27·35	31·91
ab	29·71	26·20	27·72	32·48
an	—	—	2·89	—
ns	0·28	—	—	—
ac	6·01	—	—	0·41
di	0·82	—	—	0·04
hy	2·44	1·78	1·35	0·48
mg	—	2·46	1·00	0·83
hm	—	—	—	0·67
il	0·32	0·32	0·24	0·29
pr	—	0·13	—	—
Z	0·40	0·44	—	—
fr	0·23	0·23	0·08	0·45

1. Comendite, Liruei. Analyst, Geochem. Lab. X.572
2. Rhyolite, D. Ginshi, Liruei. Analyst, Geochem. Lab. X.584.
3. Late rhyolite, Daffo, Kaleri. Analyst, Mrs. M. H. Kerr, Res. Inst. African Geol., Univ. Leeds. L.620.
4. Early vent rhyolite, Buji. Analyst, P. J. Curtis, Imp. Coll. Sci. & Tech. L.891.

Spherulitic and axiolitic textures are commonly displayed (Pl. IV, figs. 1, 2). At Buji, individual spherulites up to 5 cm. in diameter have been seen and such rocks develop a distinctive nodular appearance on weathering. Often the spherulites have a core of pyrite or iron oxide and their enclosure within polygonal cells has been noted in some localities. Near the contacts with the granites the rhyolites are often recrystallized for a distance of a few feet. The original flow structure is preserved, but there is a general coarsening of the microcrystalline groundmass and small flakes of mica or amphibole are often developed. Some of the darker rhyolites contain an abundance of iron oxides which impart a reddish colour to the rock on weathering. Certain horizons of the tuffs at Buji, Neil's Valley and Liruei are strongly impregnated with haematite.

The phenocrysts in the early rhyolites vary considerably in size and number. They include corroded crystals of bipyramidal quartz, orthoclase and sodic plagioclase. No sanidine has been detected. The euhedral felspar phenocrysts are often oriented parallel with the flow structure of the groundmass. In the early vent rhyolites the proportion of phenocrysts rarely exceeds 20 per cent and is generally much less.

The late rhyolites are invariably porphyritic and usually the proportion of phenocrysts is of the order of 50 per cent and sometimes greater (Pl. IV, fig. 6). The quartz phenocrysts range between 1 and 2 mm. in diameter and they are often deeply embayed and veined by the microcrystalline quartzo-felspathic groundmass. The orthoclase phenocrysts are of comparable size and more abundant than the quartz. They are euhedral or ovoidal and often show extensive zones of cloudy alteration both around the margins and within the cores. This alteration is found in the freshest of specimens and is attributed to deuteric alteration rather than to weathering. Occasional phenocrysts of sodic plagioclase are also present. The felspar phenocrysts often show a high degree of aggregation and the clusters are usually drawn out in the direction of the flow banding. The aggregates are frequently surrounded by cryptocrystalline zones free of phenocrysts and in some exposures the weathered surface of the rock has a strongly banded appearance due to the alternation of porphyritic and cryptocrystalline zones. The latter zones often weather to a lighter colour, which greatly accentuates the banded appearance.

Spherulites and perlitic cracks have been observed in some of the late rhyolites. The groundmass is usually uniformly microcrystalline or cryptocrystalline but traces of its original fluidal nature are generally preserved. Owing to the high proportion of phenocrysts, the flow-lines in the matrix often follow extremely contorted patterns.

The mafic minerals are rarely sufficiently well crystallized to be accurately determined. There are diffuse and wispy shreds of blue-green amphibole and occasional small grains of fayalite and hedenbergite have been noted. Finely dispersed iron oxides are abundant. Variants of the normal type of late rhyolite are found which resemble the early vent rhyolites and the quartz-pyroxene-fayalite-porphyries.

(ii) *Biotite-granites*

Biotite-granite is the most abundant and widespread facies in the Younger Granite province, and it forms some of the largest individual intrusions (see Table I). It occasionally occurs as ring-dykes but is more commonly found as large circular and crescentic plutons and as small stocks. Some of the important intrusions of biotite-granite exceed 50 square miles in area. The most extensive areas of biotite-granite occur on the Jos Plateau, where the Jos–Bukuru and Sha–Kaleri complexes together include about 400 square miles of this facies.

As a group, the biotite-granites show a comparatively small range of chemical composition (see Table IV). They are either peraluminous or metaluminous, consistently low in lime and magnesia and rich in fluorine. Any single intrusive phase shows a general consistency of texture and mineralogical composition over the greater part of its extent, although a great variety of textures is encountered among the separate granite intrusions in any one complex.

The nature of the contacts between successive phases of biotite-granite varies considerably. Often the granite shows a progressive decrease in grain-size towards its outer contact and porphyritic and microgranitic zones appear, sometimes as gradations from the main body or as separate minor, irregular intrusions. Within a few feet of the contact, pegmatitic knots and miarolitic cavities appear, and there is often a pronounced development of the melanic minerals in segregations and bands parallel to the contact. Sometimes the contact is so sharp that the normal texture of both granites can be seen in a single hand-specimen. It is probable that the variations in the nature of the border facies of the granites can be attributed to differential concentrations of hyperfusible constituents in different zones of the consolidating granites. In some cases the contact zones between the phases of the granites are confused by the incorporation and partial mechanical disintegration of xenoliths of the host granite.

Petrography (Pl. V, figs. 11, 12; Pl. VI, fig. 13).—The biotite-granites contain between 25 and 35 per cent of free quartz, the crystals of which are often clustered or arranged in arcuate trains between

TABLE IV.—CHEMICAL ANALYSES AND NORMS OF THE BIOTITE-GRANITES

	1	2	3	4	5	6	7
SiO_2	73·19	76·50	75·77	76·52	76·70	76·19	76·15
Al_2O_3	13·03	12·03	12·61	11·93	12·06	13·51	12·48
Fe_2O_3	0·50	0·77	0·31	0·83	0·61	0·43	0·50
FeO	2·22	0·98	1·07	0·50	0·60	0·61	0·73
MgO	0·22	0·01	tr.	0·19	0·13	0·08	0·19
CaO	1·25	0·22	0·72	0·57	0·42	0·10	0·51
Na_2O	3·70	4·17	4·08	3·64	4·35	4·23	4·06
K_2O	5·05	4·80	4·65	5·10	4·43	4·61	4·43
H_2O+	0·22	0·20	0·16	0·52	0·56	0·13	0·33
H_2O-	0·00	0·12	0·14	0·23	0·23	0·15	0·20
CO_2	n.d.	n.d.	n.d.	n.d.	n.d.	0·01	0·02
TiO_2	0·32	0·09	0·07	0·09	0·05	0·04	0·06
ZrO_2	n.d.	n.d.	n.d.	n.d.	n.d.	0·04	0·04
P_2O_5	0·12	0·04	0·03	0·01	n.d.	tr.	tr.
Cl	0·03	tr.	tr.	0·04	0·01	0·02	0·01
F	0·05	0·04	0·11	0·25	0·30	0·22	0·35
S	0·03	0·03	tr.	n.d.	n.d.	0·02	0·02
MnO	0·05	0·02	0·02	0·02	0·01	0·01	0·01
Li_2O	n.d.	n.d.	n.d.	n.d.	n.d.	tr.	0·08
$(Nb, Ta)_2O_5$	n.d.	n.d.	n.d.	n.d.	n.d.	0·02	0·01
	99·98	100·02	99·74	100·44	100·46	100·42	100·18
Less O	0·04	0·03	0·04	0·11	0·13	0·09	0·15
Total	99·94	99·99	99·70	100·33	100·33	100·33	100·03
Sp. gr.	2·65	2·60	2·63	2·61	2·60	2·61	2·61
Q	28·45	33·59	32·36	35·54	34·01	33·52	34·91
or	29·86	27·86	27·52	30·02	26·19	27·24	26·19
ab	31·28	35·21	34·32	30·18	36·78	34·74	35·37
an	4·03	0·17	2·39	1·05	—	—	—
C	—	—	—	0·19	0·09	1·55	1·00
di	1·57	0·60	0·60	—	—	—	—
hy	2·86	0·71	1·25	0·55	0·91	0·98	1·40
mg	0·60	1·11	0·46	1·23	0·61	0·60	0·72
il	0·60	0·15	0·15	0·16	—	—	—
hl	0·06	—	—	0·06	—	—	—
fr	0·01	0·08	0·23	0·52	0·59	0·14	0·71
excess F	—	—	—	—	0·15	0·15	—
Z	—	—	—	—	—	0·05	—

1. Teria biotite-granite, Amo. Analyst, Mrs. M. H. Kerr, Res. Inst. African Geol., Univ. Leeds. L.955.
2. Rough Range biotite-granite, Amo. Analyst, Mrs. M. H. Kerr. L.1822.
3. Gana biotite-granite, Rop. Analyst, Mrs. M. H. Kerr. B.850.
4. Bargesh biotite-granite, Kaleri. Analyst, P. J. Moore, Min. Res. Div., Colonial Geol. Surv. L.796.
5. Bukka Bakwai albite-biotite-granite, Rop. Analyst, P. J. Moore. B.364.
6. Rayfield-Gona albite-biotite-granite, Jos. Analyst, G. Jefford, Geol. Surv. Nigeria. L.168.
7. Biotite-granite, Liruei. Analyst, Min. Res. Div., Colonial Geol. Surv. X.568.

the larger felspars. Orthoclase- and microcline-microperthites are the common potash-felspars, the former being the more common. The proportion and mode of occurrence of the plagioclase show great variation. Exsolution perthites are present in most of the granites and the plagioclase is generally a sodic variety with a range of composition between $Ab_{85}An_{15}$ and $Ab_{95}An_5$. Late deuteric albitization is a common feature and the granites can be broadly subdivided on the basis of the extent of this process. In the normal biotite-granites, exsolution perthites are predominant, but in the albite-biotite-granites the perthitic textures have been masked or completely obliterated by later generations of albite, and the proportion of modal albite is sometimes in excess of the potash-felspar. In some of the albite-biotite-granites there is evidence of at least two generations of late albite.

The biotite shows great variation in colour and refractive index in the different phases of the granites. A chemical analysis of the biotite from Liruei shows that it is a lepidomelane rich in iron, potash and fluorine (see Table V). The magnesia content is very low, and the presence of lithia is noteworthy. An analysis of the green mica from the tin-bearing greisens of the Liruei lode shows that it is also rich in iron, potash, lithia and fluorine. The optical properties of these micas are given in Table VI.

TABLE V.—CHEMICAL ANALYSES AND ATOMIC PROPORTIONS OF THE MICAS

	1	2		1a	2a
SiO_2	37·38	42·24	Si	6·03	6·22
Al_2O_3	11·89	19·62	Al^{iv}	1·97	1·78
Fe_2O_3	4·38	2·02	Al^{vi}	0·29	1·62
FeO	28·65	18·64	Fe^{iii}	0·53	0·22
MgO	0·22	0·08	Fe^{ii}	3·86	2·29
CaO	0·16	0·11	Mg	0·05	0·02
Na_2O	0·39	0·14	Ti	0·22	0·02
K_2O	8·78	8·84	Li	0·50	1·12
H_2O+	1·84	2·35	Mn	0·06	0·04
H_2O-	0·67	0·48	Ca	0·01	0·01
CO_2	0·08	0·05	Na	0·12	0·04
TiO_2	1·84	0·18	K	1·81	1·66
Cl	0·09	0·02			
F	4·36	5·02	(OH)	1·98	2·30
S	0·03	0·02	F	2·22	2·33
MnO	0·41	0·30	Cl	0·02	—
Li_2O	0·77	1·90			
	101·94	102·01			
Less O	1·86	2·11			
Total	100·08	99·90			

1. Biotite (lepidomelane), from biotite-granite, Liruei. Analyst, Min. Res. Div., Colonial Geol. Surv. X.568.
2. Green mica (ferrophengite), from greisen zone, Lireui lode. Analyst, Min. Res. Div., Colonial Geol. Surv. X.700.

TABLE VI.—OPTICAL PROPERTIES OF THE MICAS

	1	2	3	4	5
Ng	1·654	1·602	1·683	1·606	n.d.
Nm.	n.d.	1·601	1·682	1·602	1·583 to 1·623
Np	1·600 (calculated)	1·563 (calculated)	1·621 (calculated)	n.d.	n.d.
Ng—Np	0·054	0·039	0·062	n.d.	n.d.
2V	$-6°\pm2°$	0° to $-3°\pm1°$	0° to $-3°\pm1°$	n.d.	$-20°$ to $-30°\pm\frac{1}{2}°$
Ext. $Z\wedge a$.	n.d.	0°	+4°	n.d.	n.d.
X	pale straw-yellow	pale green to colourless	light red-brown	n.d.	colourless to pale brown
Y	dark brown	pale greyish-green to brownish green	brown	light olive-green to yellow	colourless to pale yellow, brown, or green
Z	opaque	light olive-green to light brownish green	dark greenish red-brown	dark olive-green	colourless to pale yellow, brown, or green
	X<Y<Z	X<Y=Z	X<Y<Z	Y<Z	X<Y=Z

1. Biotite (lepidomelane), from biotite-granite, Liruei. X.568.
2. Biotite, from albite-biotite-granite, Rayfield. L.168A.
3. Biotite (lepidomelane), from riebeckite-biotite-granite, Amo. L.1816.
4. Green mica (ferrophengite), from tin-bearing greisen zone of the Liruei lode. X.700.
5. Green mica (ferrophengite), from the greisen zone of the Liruei lode. X.751.

Optical properties determined by A. W. Günthert, Geological Sürvey of Nigeria.

The biotite-granites contain a variety of interesting accessory minerals, some of which are of considerable economic importance. Columbite is found as an accessory mineral in most of them. Its distribution has been closely studied and it has been shown that the highest concentrations occur in the more highly albitized facies, such as the Rayfield–Gona granite (MacLeod 1956). Thorite, monazite and xenotime are other accessory minerals which have been extracted as by-products of alluvial tin mining in Nigeria. Fluorite is present in most of the biotite-granites and sometimes attains a proportion of 2 or 3 per cent of the rock. Zircon, ilmenite and magnetite are the remaining common accessories.

Tin mineralization in the Younger Granite province is almost entirely associated with the biotite-granites. Over three-quarters of the total Nigerian tin production is derived from alluvial concentrations shed from the biotite-granites of the Jos–Bukuru and Rop complexes on the Jos Plateau. Detailed mapping of the granites has revealed that the mineralized greisens are concentrated near the roofs of the granites and the richest alluvial concentrations are found in the vicinity of granite intrusions which have undergone only shallow erosion. Topaz, beryl, wolfram and sulphide minerals are commonly found in the greisens and quartz veins, but the absence of tourmaline is a notable feature of the province. It has been found that the richest concentrations of tin are developed in the albite-biotite-granites.

(iii) *Riebeckite-granites*

The Nigerian Younger Granite province embraces the most extensive known occurrence of riebeckite-granite in the world. The Younger Granites of the Sahara have not yet been studied in detail, but preliminary indications suggest that the riebeckite-granites there may be even more extensive than in Nigeria. Riebeckite-granite appears in practically all the Nigerian complexes but, with few exceptions, it is greatly subordinate in areal extent to the biotite-granites. In general, the proportion of riebeckite-granite to biotite-granite is higher in the northern complexes than in those of the Jos Plateau area. The order of intrusion of the two granites is inconstant and either may appear first in any intrusive cycle. The riebeckite-granites occasionally occur as ring-dykes but are more often found as elliptical plutons and as smaller sheet-like intrusions.

The riebeckite-granites fall into the peralkaline group of Shand's classification, in contrast to the biotite-granites, which are either peraluminous or metaluminous. In the normal type of riebeckite-granite the soda content is of the same order as that of biotite-granites, but there is a comparative deficiency of alumina (see Table VII) and the excess soda combines with iron and silica to form riebeckite and aegirine. As can be seen from Table VII, acmite appears in the norm of all riebeckite-granites. The albite-riebeckite-granites, which contain over 6 per cent of soda, are characterized by a high proportion of deuteric albite which replaces all the earlier-crystallized minerals. Only six intrusions of albite-riebeckite-granite have been located in Nigeria and all are of restricted areal extent. In general, the iron content of the riebeckite-granites is higher than that of the biotite-granites but there is a similar paucity of lime and magnesia (see Figs. 3, 4 and 5).

Petrography (Pl. IV, figs. 14, 15, 17).—Many of the riebeckite-granites contain aegirine intergrown with the soda-amphibole, but biotite is generally absent except for occasional crystals in the pegmatitic contact facies. There are, however, four intrusions of riebeckite-biotite-granite on the Jos Plateau in the Amo, Rop, Sanga and Kigom hills. The general textural relationships between aegirine, riebeckite and biotite are as shown in Fig. 2, nos. 5, 6, 7.

Petrographic descriptions of the Nigerian riebeckite-granites are to be found in previous literature (Falconer 1921; Bain 1934; Greenwood 1951; Beer 1952). The riebeckite-granites contain about the same proportion of free quartz as the biotite-granites but the crystals do not show the same high degree of aggregation. Individual intrusions of riebeckite-granite generally show a much greater textural variation than those of biotite-granite, and it is often difficult to distinguish separate intrusions in the field. The

TABLE VII.—CHEMICAL ANALYSES AND NORMS OF THE RIEBECKITE-GRANITES

	1	2	3	4	5	6	7
SiO_2	76·25	75·26	71·38	71·13	76·84	75·26	76·65
Al_2O_3	10·86	10·48	12·34	13·39	11·24	11·88	11·66
Fe_2O_3	1·23	2·42	1·96	1·63	1·06	0·91	0·80
FeO	0·76	1·32	0·91	1·12	1·27	0·90	1·14
MgO	0·18	0·35	0·16	0·38	0·11	0·19	0·10
CaO	0·37	0·57	0·17	0·75	0·54	0·70	0·34
Na_2O	4·68	4·04	7·17	6·00	4·29	4·45	4·53
K_2O	4·65	4·66	4·17	4·40	4·28	4·53	4·44
H_2O+	0·50	0·48	0·30	0·45	0·08	0·52	0·10
H_2O-	—	0·08	0·12	0·15	0·04	0·29	0·18
CO_2	n.d.	0·01	n.d.	n.d.	n.d.	n.d.	n.d.
TiO_2	0·11	0·26	0·07	0·04	0·07	0·08	0·16
ZrO_2	0·10	0·18	0·37	n.d.	n.d.	n.d.	n.d.
P_2O_5	0·01	0·08	0·01	0·02	0·01	0·01	0·01
Cl	0·03	0·06	—	0·03	0·07	0·06	0·06
F	0·29	0·09	1·08	1·69	0·04	0·52	0·12
S.	—	—	0·05	n.d.	tr.	n.d.	tr.
MnO	0·03	0·10	0·05	0·04	0·02	0·01	0·02
$(Nb, Ta)_2O_5$	n.d.	n.d.	0·22	n.d.	n.d.	n.d.	n.d.
	100·05	100·44	100·53	101·22	99·96	100·31	100·31
Less O.	0·10	0·04	0·48	0·72	0·03	0·23	0·05
Total	99·95	100·40	100·05	100·50	99·93	100·08	100·26
Sp. gr.	2·61	2·64	2·67	2·63	2·64	2·61	2·62
Q	34·54	33·56	22·10	19·81	35·25	32·18	33·42
or	27·47	27·80	24·63	26·03	25·30	26·80	26·24
ab	29·92	27·61	40·19	44·22	33·90	35·74	35·16
ns	1·32	—	3·25	0·27	—	—	—
ac	3·51	5·78	5·68	4·71	1·06	0·83	1·85
di	—	—	—	—	2·08	—	0·71
hy	1·82	1·62	2·06	2·99	0·94	1·48	1·59
mg	—	0·60	—	—	1·02	0·90	0·23
il	—	0·50	—	—	0·15	0·15	0·30
hl	—	—	—	—	0·12	0·10	0·11
fr	0·51	0·19	0·23	1·04	0·08	1·93	0·25
Excess F	0·04	—	0·97	1·18	—	0·05	—
Z	—	—	0·55	—	—	—	—

1. Riebeckite-aegirine-granite, Kudaru. Analyst, R. O. Roberts, Min. Res. Div., Colonial Geol. Surv. B.285.
2. Riebeckite-aegirine-granite, Liruei. Analyst, Miss E. Waine, Min. Res. Div., Colonial Geol. Surv. X.575.
3. Kaffo albite-riebeckite-granite, Liruei. Analyst, R. O. Roberts. X.674.
4. Durowa albite-riebeckite-granite, Rop. Analyst, Miss E. Waine. B.525
5. Riebeckite-biotite-granite, Amo. Analyst, Mrs. M. H. Kerr, Res. Inst. African Geol., Univ. Leeds. L.1816.
6. Butra riebeckite-biotite-granite, Rop. Analyst, P. J. Moore, Min. Res. Div., Colonial Geol. Surv. B.587.
7. Ruku riebeckite granite-porphyry, Rop. Analyst, Mrs. M. H. Kerr. B.611.

riebeckite-granites are rich in hyperfusibles, and there is usually a spectacular development of marginal pegmatites with riebeckite crystals up to 10 cm. in length.

Microcline-microperthite is the common felspar and, as in the case of the biotite-granites, both exsolution and replacement perthites are abundant. In the riebeckite-granites there is a greater tendency for the late replacement albite to appear in the form of small broadly twinned laths at the interfaces between adjacent euhedra of microcline-perthite. The granites can be broadly subdivided on the basis of the proportion of albite (see modal analyses, Table VIII).

Aegirine is usually intergrown with the riebeckite and locally becomes the more abundant of the two. There is no regular pattern in these intergrowths and only rarely can the order of crystallization be established. From the frequency with which both the soda-amphibole and soda-pyroxene assume interstitial and spongy forms, it is inferred that they are of late crystallization. The aegirine appears both in the cores and around the borders of the riebeckite and it would appear that fluctuating chemical conditions in the magma may have effected partial transformation of one mineral into the other. The optical properties and chemical analyses of the riebeckite and aegirine are listed in Tables IX and X. It can be seen that both approach closely to the theoretical composition.

Two unusual accessory minerals occur in the riebeckite-granites. These are astrophyllite, which locally assumes the proportion of a major constituent near the margins of the intrusions, and pyrochlore, which

TABLE VIII.—MODAL ANALYSES OF SOME TYPICAL YOUNGER GRANITES

	1	2	3	4	5	6	7	8	9	10	11	12
Quartz	35·6	37·0	31·4	30·0	35·5	33·2	24·4	23·4	28·0	16·5	19·19	0·2
Orthoclase and microcline-perthite	55·9	54·8	22·0	52·9	33·8	30·3	54·5	63·0	41·5	54·6	72·56	52·6
Albite-oligoclase	4·9	6·3	35·2	8·3	24·6	32·1	15·2	3·8	16·0	15·5	—	22·5
Biotite	3·2	1·4	—	—	—	4·2	1·7	—	2·7	1·3	—	—
Hornblende	—	—	—	—	—	—	—	—	4·3	11·7	1·58	10·6
Riebeckite and aegirine	—	—	3·9	8·7	4·3	—	4·2	—	—	—	—	—
Arfvedsonite	—	—	—	—	—	—	—	8·6	—	—	—	—
Augite	—	—	—	—	—	—	—	—	—	tr.	—	9·4
Hedenbergite	—	—	—	—	—	—	—	—	—	—	5·35	—
Fayalite	—	—	—	—	—	—	—	0·7	—	tr.	0·97	—
Iron oxides	tr.	0·2	—	—	—	—	—	0·3	tr.	0·3	0·04	3·0
Apatite	—	—	—	—	—	—	—	—	—	tr.	—	1·7
Zircon	—	tr.	—	tr.	—	—	—	—	—	—	tr.	—
Fluorite	0·2	0·3	—	0·1	—	0·2	tr.	0·2	tr.	—	—	—
Allanite	—	—	—	—	—	—	—	tr.	0·2	—	0·10	—
Pyrochlore	—	—	0·3	—	0·4	—	—	—	—	—	—	—
Cryolite	—	—	3·3	—	1·4	—	—	—	—	—	—	—
Topaz	—	—	3·9	—	—	—	—	—	—	—	—	—
Astrophyllite	—	—	—	—	—	—	tr.	—	—	—	—	—

1. Bargesh biotite-granite. L.796.
2. Liruei biotite-granite. X.568.
3. Amo albite-riebeckite-granite. L.994.
4. Liruei riebeckite-aegirine-granite. X.575.
5. Kaffo albite-riebeckite-granite. (Beer 1952)
6. Amo albite-biotite-granite. L.946.
7. Amo riebeckite-biotite-granite. L.1816.
8. Hotum arfvedsonite-granite. L.680.
9. Monguna hornblende-biotite-granite. L.1657.
10. Mbul hornblende-biotite-granite (melanic). L.1652.
11. Kudaru quartz-pyroxene-fayalite-porphyry. KD.46. (Bain 1934)
12. Kila-Wurji porphyritic syenite. (Beer 1952)

Analyses 1, 3, 6–10 are from an unpublished thesis by W. N. MacLeod in the University of London.

TABLE IX.—CHEMICAL ANALYSES AND ATOMIC PROPORTIONS OF THE RIEBECKITE AND AEGIRINE

	1	2	3	4	5
SiO_2	51·01	49·05	48·83	46·98	51·92
Al_2O_3	0·80	2·91	2·31	1·29	1·85
Fe_2O_3	16·41	13·98	10·90	11·93	31·44
FeO	17·62	19·04	21·77	23·38	0·75
MgO	0·22	0·33	0·06	0·13	—
CaO	0·19	1·36	1·32	1·91	—
Na_2O	7·98	9·19	8·75	8·90	12·86
K_2O	1·80	1·27	1·22	2·74	0·19
H_2O+	0·91	0·38	1·47	1·10	0·17
H_2O-	—	0·42	0·28	—	—
TiO_2	0·96	0·71	1·12	1·49	0·77
ZrO_2	n.d.	n.d.	0·31	n.d.	n.d.
P_2O_5	n.d.	n.d.	tr.	n.d.	n.d.
F	1·70	n.d.	2·30	n.d.	n.d.
S	n.d.	n.d.	0·03	n.d.	n.d.
MnO	0·48	0·06	0·27	0·24	—
Li_2O	0·56	n.d.	n.d.	n.d.	n.d.
	100·64	98·70	100·94	100·09	99·95
Less O	0·71	—	0·97	—	—
Total	99·93	98·70	99·97	100·09	99·95
Sp. gr.	—	3·40	3·43	—	—

	1a	2a	3a	5a
Si	7·92	7·96	6·64	7·91
Al^{iv}	—	—	0·37	—
Al^{vi}	0·15	0·56	—	0·33
Fe^{iii}	1·91	1·71	1·06	3·60
Ti	0·11	0·09	0·11	0·09
Fe^{ii}	2·28	2·58	2·47	0·09
Mg	0·05	0·08	0·01	—
Mn	0·06	0·01	0·03	—
Li	0·34	—	—	—
Na	2·55	2·50	2·31	3·80
K	0·36	0·26	0·21	0·03
Ca	0·03	0·23	0·19	—
OH	0·94	0·41	1·33	0·17
F	0·84	—	0·99	—

1. Riebeckite, from riebeckite-aegirine-granite, Kigom. Analyst, F. A. Gonyer (Greenwood 1951).
2. Riebeckite, from pegmatitic contact facies of the albite-riebeckite-granite, Liruei. Analyst, B. C. King (Jacobson, thesis, Univ. London).
3. Riebeckite, from riebeckite-granite, Kudaru. Analyst, Miss H. Bennett, Imp. Inst. (Bain 1934).
4. Riebeckite, Mill Mtn., New Hampshire. Analyst, F. A. Gonyer (Greenwood 1951).
5. Aegirine, from riebeckite-aegirine-granite, Kigom. Analyst, F. A. Gonyer (Greenwood 1951).

TABLE X.—OPTICAL PROPERTIES OF THE AMPHIBOLE AND PYROXENE FROM THE RIEBECKITE-AEGIRINE-GRANITES

	1	2	3	4	5	6
Ng	1·703	1·700	1·694	1·826	1·838	1·836
Nm	1·697	n.d.	1·690	1·802	n.d.	1·816
Np	1·697 (?)	1·693	1·687	1·769	1·769	1·776
Ng—Np	0·006	0·007	0·007	0·057	0·069	0·060
2V	large	n.d.	n.d.	n.d.	n.d.	—60°
Ext.	$X \wedge c = 9°$	$X \wedge c = -2°$	$X \wedge c = -8{\cdot}5°$	$X \wedge c = 2{\cdot}3°$	$X \wedge c = 5{\cdot}4°$	$X \wedge c = 2°$
X	dark blue	dark blue	dark blue	light green	light green	—
Y	blue-grey	n.d.	light blue	light greenish yellow	n.d.	weakly pleochroic
Z	yellow-green	light blue-grey	light green-yellow	faint green	faint green	—
	$X>Y>Z$	$X>Z$	$X>Y>Z$	$X \geqq Y>Z$	$X>Z$	—
Disp.	n.d.	n.d.	$r>v$	n.d.	n.d.	—

1. Riebeckite, from riebeckite-aegirine-granite, Kigom. (Greenwood 1951).
2. Riebeckite, from riebeckite-aegirine-granite, Liruei. X.575.
3. Riebeckite, from albite-riebeckite-granite, Liruei. X.674.
4. Aegirine, from riebeckite-aegirine-granite, Liruei. X.575.
5. Aegirine, from albite-riebeckite-granite, Liruei. X.1356.
6. Artificial acmite.

Optical properties of Nos. 2, 3, 4 and 5 determined by A. W. Günthert, Geol. Surv. Nigeria.

is most abundant in the soda-rich facies. The albite-riebeckite-granites in the Liruei, Rop and Amo complexes contain between 0·3 and 1·0 per cent of pyrochlore. These granites are the richest in niobium in the entire province, being rivalled in this regard only by restricted zones of high columbite concentration in some of the albite-biotite-granites. The pyrochlore can be clearly discerned as small, honey-coloured grains in the hand-specimen. Microscopic examination discloses that it is often intergrown in a complex fashion with both riebeckite and albite. Even in the one intrusion, the pyrochlore content undergoes abrupt and apparently random variations. No columbite has been recorded in the riebeckite-granites. The other common accessory minerals include cryolite, thomsenolite, fluorite, thorite and ilmenite. In the Kaffo albite-riebeckite-granite there is over 4 per cent of cryolite which could possibly be separated as a by-product if these granites are ever commercially exploited for their niobium content. The Kaffo pyrochlore is relatively rich in uranium whereas that of Rop and Amo shows only a low degree of radioactivity (Mackay & Beer 1952). The texture, composition and unusual assortment of accessory constituents strongly suggest that the albite-riebeckite-granites have a close affinity to pegmatites.

(iv) *Amphibole-fayalite-granites*

The amphibole-granites include granites, granite-porphyries and quartz-pyroxene-fayalite-porphyries. They are almost as abundant as the riebeckite-granites and form the majority of the ring-dykes in the province, although, in common with the other two groups, they also appear as large plutons and stocks. The larger intrusions are usually granitic in texture with coarse- and medium-grained varieties predominating. In the narrower ring-dykes this facies usually appears as a granite-porphyry. The quartz-pyroxene-fayalite-porphyries generally occur in the form of small plugs, but they are occasionally found as ring-dykes.

The amphibole-granites show a greater range of chemical composition than the biotite- and riebeckite-granites and include both metaluminous and peralkaline varieties. As can be seen in Table XI, the amphibole-granites are slightly less siliceous and are generally higher in iron, lime and titania than the other types of granite. It is possible that these rocks closely approach in composition the parent magma from which the biotite- and riebeckite-granites have been differentiated. In the Younger Granite complexes in the northern part of the province, the granite-porphyries are usually the first rocks to appear in the granitic cycle, and their intrusion is believed to correspond to the extension of deep ring-faults into the underlying magma chamber compared with the comparatively poorly developed ring-fractures associated with the early volcanism.

In the Jos Plateau region this tectonic correlation is not applicable as the amphibole-granites appear at all stages of the intrusive cycles and show a greater diversity of intrusive form. In the Jos–Bukuru and Rop complexes there are three separate phases of amphibole-granite intrusion, and in the Sha–Kaleri complex the amphibole-granites form the majority of granitic intrusions, although they occupy a smaller total area than the biotite-granites.

TABLE XI.—CHEMICAL ANALYSES AND NORMS OF THE AMPHIBOLE-GRANITES

	1	2	3	4	5	6	7
SiO_2	71·68	71·25	71·51	73·16	72·72	68·65	74·36
Al_2O_3	12·04	12·22	12·91	12·07	13·18	13·50	12·40
Fe_2O_3	2·28	1·81	1·14	1·86	1·01	0·93	1·10
FeO	1·89	2·79	2·87	1·99	1·50	3·97	1·83
MgO	0·29	0·27	0·15	tr.	0·31	0·55	0·09
CaO	0·79	1·15	1·16	0·50	0·17	2·14	0·84
Na_2O	4·36	4·34	4·17	4·57	3·90	4·18	3·71
K_2O	5·12	5·08	5·12	4·79	5·55	4·85	4·94
H_2O+	0.61	0·38	0·26	0·20	0·40	0·57	0·18
H_2O-	0.16	0·21	0·16	0·20	0·19	0·09	0·12
CO_2	0·09	0·05	n.d.	n.d.	n.d.	n.d.	n.d.
TiO_2	0·30	0·34	0·30	0·27	0·27	0·54	0·17
ZrO_2	0·11	0·15	n.d.	n.d.	n.d.	n.d.	n.d.
P_2O_5	0·07	0.04	0·04	0·02	0·05	0·17	0·03
Cl	0·02	0·01	0·02	tr.	0·04	0·03	0·06
F	0·12	0·07	0·09	0·06	0·22	0·22	0·13
S	n.d.	0·09	nil	tr.	n.d.	n.d.	tr.
MnO	0·13	0·12	0·09	0·07	0·04	0·10	0·06
	100·06	100·37	99·99	99·76	100·55	100·49	100·02
Less O	0·05	0·08	0·04	0·02	0·10	0·10	0·06
Total	100·01	100·29	99·95	99·74	100·45	100·39	99·96
Sp. gr.	2·61	2·68	2·65	2·61	2·63	2·67	2·63
Q	25·79	24·03	24·24	27·39	26·20	18·87	31·58
or	30·30	30·02	30·30	28·36	33·08	28·64	29·19
ab	33·27	34·48	35·27	35·27	33·01	35·42	31·33
an	—	—	1·33	—	1·76	3·58	2·64
ac	3·00	1·94	—	2·96	—	—	—
di	2·11	4·47	3·30	1·84	2·01	7·85	0·51
hy	1·56	1·79	3·11	1·66	1·24	2·97	2·01
mg	1·81	1·64	1·64	1·21	1·41	1·34	1·60
il	0·58	0·65	0·58	0·52	0·56	1·03	0·30
pr	—	0·17	—	—	—	—	—
ap	—	—	—	—	—	0·41	—
cc	0·20	—	—	—	—	—	—
hl	—	—	—	—	0·06	—	0·11
fr	0·25	0·15	0·18	0·12	0·45	0·45	0·26

1. Arfvedsonite granite-porphyry, Liruei. Analyst, Miss E. Waine, Min. Res. Div., Colonial Geol. Surv. X.592.
2. Quartz-fayalite-hedenbergite-porphyry, D. Shetu, Liruei. Analyst, R. O. Roberts, Min. Res. Div., Colonial Geol. Surv. X.511.
3. Yelwa hornblende-fayalite-granite, Rop. Analyst, Mrs. M. H. Kerr, Res. Inst. African Geol., Univ. Leeds. B.851.
4. Hotum arfvedsonite-granite, Kaleri. Analyst, Mrs. M. H. Kerr. L.680.
5. Monguna hornblende-biotite-granite, Monguna. Analyst, Miss E. Waine. L.1657.
6. Mbul hornblende-fayalite-granite, Kaleri. Analyst, P. J. Moore, Min. Res. Div., Colonial Geol. Surv. L.1623.
7. Early hornblende-biotite-granite, Jos. Analyst, Mrs. M. H. Kerr. L.350.

Petrography (Pl. V, figs. 7–10).—The occurrence of fayalite-bearing rocks in Nigeria was first recorded by Bain (1934) in the quartz-pyroxene-fayalite-porphyries at Kudaru. Fayalite and pyroxene are also found occasionally in the granite-porphyries and amphibole-granites, but in these relatively coarse-grained facies they have generally been converted into later members of the reaction series, such as soda-iron amphiboles and biotite.

The proportion of free quartz in this group is generally slightly lower than that of the biotite- and riebeckite-granites, ranging between 20 and 30 per cent. A feature of the quartz is the frequent appearance of the high-temperature bipyramidal form which is universal in the granite-porphyries and also appears in many of the granites. Transitions between granitic and porphyritic textures are commonly encountered in the one intrusion. These transitions are probably due to variation in the rate of chilling and differential concentration of the hyperfusible constituents in different parts of the mass. The narrow ring-dykes, such as Kudaru and Dagga Allah, are composed of granite-porphyry throughout, but some of the more complex bodies, such as Mbar and Mongu, show gradations to granite in the wider parts of the intrusions. In some cases, such as Shen, Mbul and Neil's Valley, it is apparent that there has been a close succession of separate amphibole-granite and granite-porphyry intrusions within the one major fracture zone.

In the granite-porphyries the bipyramidal quartz phenocrysts are usually rounded and embayed by the microcrystalline groundmass. Orthoclase-microperthite is the dominant felspar in the group. It usually assumes a corroded, ovoidal form and is occasionally rimmed by albite-oligoclase. The great variety of exsolution and replacement perthite textures found in the biotite- and riebeckite-granites is rarely encountered in these rocks, and the plagioclase generally occurs in discrete crystals.

TABLE XII.—OPTICAL PROPERTIES OF PYROXENE AND AMPHIBOLES FROM THE AMPHIBOLE-FAYALITE-GRANITES

	1	2	3	4	5
Ng . . .	1·759	1·699	1·701	n.d.	n.d.
Nm . . .	1·742	1·695	1·700	n.d.	n.d.
Np . . .	1·729	1·692	1·689	n.d.	n.d.
Ng–Np . .	0·030	0·007	0·012	0·026	0·024
2V . . .	$63° \pm 1°$	80° to 87°	n.d.	−55°	−34° to −44°
Ext. . .	$Z \wedge c = 46°$	$X \wedge c = 3°$	$Z \wedge c = 5°$	$Z \wedge c = 15°$	$Z \wedge c = 29°$
X . . .	bluish to olive-green	dark blue	dark bluish green	pale greenish yellow	light green-yellow
Y . . .	light bluish green	light olive-brown	light brownish yellow	green	yellow-green
Z . . .	yellow-green	dark blue-grey	dark blue-grey	olive-green to dark green	dark bluish green
	$X > Z > Y$	$X \geqq Z > Y$	$X > Z > Y$	$X < Y \leqq Z$	$X > Y \sim Z$
Disp. . .	strong $r > v$	strong $r < v$	strong $r < v$	n.d.	n.d.

1. Hedenbergite, from quartz-fayalite-hedenbergite-porphyry, Liruei. X.511.
2. Arfvedsonite, from arfvedsonite-fayalite-hedenbergite granite-porphyry, Liruei. X.592.
3. Arfvedsonite, from quartz-amphibole vein in granite-porphyry, Liruei. X.1357.
4. Hornblende, from Mbul granite, Kaleri. L.770.
5. Hornblende, from hornblende-biotite-granite, Monguna. L.1671.

Optical properties determined by A. W. Günthert, Geological Survey of Nigeria.

The varied assemblages of the femic minerals are the most distinctive petrographic feature of this group. Reaction relationships are almost invariably displayed, and the early crystallized fayalite and hedenbergite are often mantled by rims of amphibole and biotite. Common textural relationships between the ferromagnesian constituents are illustrated in Fig. 2, nos. 1–4, 8–13. The amphiboles are known to include arfvedsonite, soda-hornblendes and iron-rich hornblendes. Great variations in optical properties are encountered, and until chemical analyses are available precise determination is impossible (see Table XII). Blue-green arfvedsonite and soda-hornblendes are usually present in the more alkaline facies and green-brown hornblende appears in the metaluminous varieties.

Biotite is usually intergrown with the hornblende and, in many examples, it is clearly a reaction product. The close approach of the hedenbergite and fayalite to the pure mineral species in composition reflects the consistently low magnesia content of the Younger Granite magma. The relative proportion of pyroxene to fayalite varies in different occurrences, but in most they are apparently cogenetic.

The quartz-pyroxene-fayalite-porphyries are finer in grain than the granite-porphyries and there is a preponderance of fayalite and hedenbergite among the femic minerals. Structural studies of the complexes

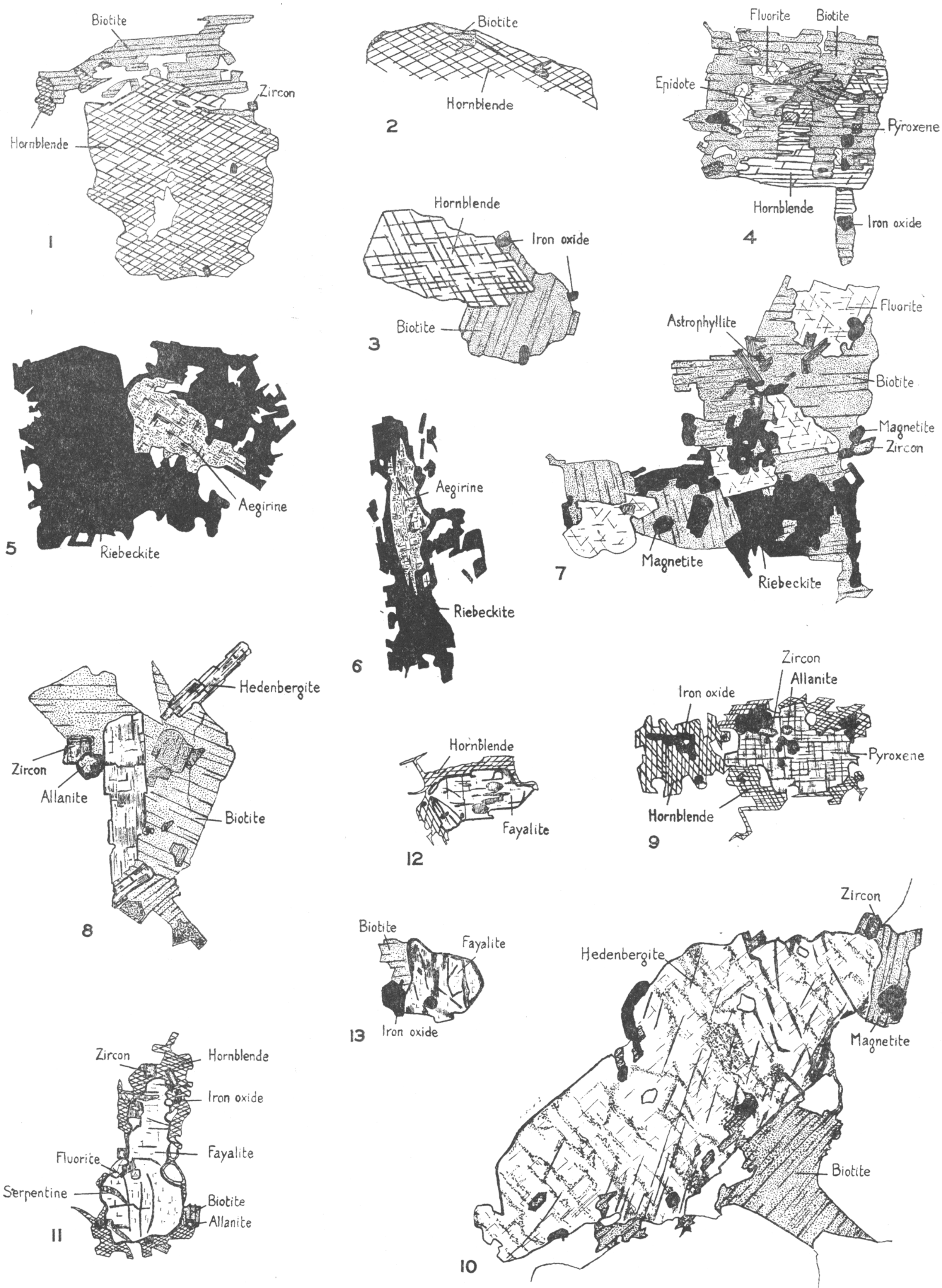

FIG. 2.—Reaction relationships among the mafic minerals in the Younger Granites.

1, 2, 3.—Hornblende–biotite association in the amphibole-granites. The biotite is of later crystallization than the hornblende. It forms ragged, irregular plates at the boundaries of the subhedral hornblende, and it also develops along the cleavage planes. B.851, × 30; B.851, × 40; and B.577, × 100.

have revealed that these rocks have been emplaced at an extremely high level, and they have apparently crystallized under conditions which have permitted rapid chilling. At Liruei and Buji they have been emplaced as plugs near the base of the early volcanic accumulations. The microcrystalline textures and absence of pegmatites and miaroles suggest that the volatile constituents readily escaped during consolidation.

There is a distinctive assortment of accessory minerals in the amphibole-granites. Allanite, showing typical deep-red to brown pleochroism, is common as small crystals in the mafic aggregates. The amphibole-granites have a higher proportion of titanium than the other granites, and this is shown by the abundance of ilmenite. Titanite is also occasionally found in some facies. The iron oxides, which are commonly intergrown with biotite and hornblende, sometimes attain the proportions of a major constituent. The amphibole-granites contain a distinctive coarse, colourless zircon which is also usually associated with the femic aggregates. Apatite is common in some of the more melanic facies of the group. Niobium, tantalum and rare earths are included in fergusonite, an yttrium tantalo-niobate, but columbite and pyrochlore have not been recorded. There is very little tin mineralization in the amphibole-granites, and then only in facies which approach closely to biotite-granite in composition.

(v) *Basic and Intermediate Rocks*

Basic and intermediate rocks occupy less than 5 per cent of the total area of the Younger Granite province and, with one exception, they form comparatively small intrusions which commonly precede the granites. They can be subdivided into two main groups. Firstly, there are the larger elliptical or circular intrusions which appear early in the intrusive cycles in about a dozen of the complexes. This group shows a considerable range in basicity, from olivine-gabbro to quartz-syenite. The largest occurrence is in the Kila–Wurji complex in the north-eastern corner of the province. The rocks are mainly of intermediate composition, but they have not yet been studied in detail. Under conditions of tropical weathering the more basic members of the group weather to level, boulder-strewn plains, and the contacts with the surrounding rocks are generally too poorly exposed to determine the attitude or form of the intrusions in depth. The largest body of gabbro in the Jos Plateau area occurs in the Sha–Kaleri complex, which is described later. In the same complex, microgabbro appears during the major cycle of granitic ring-intrusion and forms part of one of the ring-dykes.

The syenites and monzonites are more resistant to erosion and appear as prominent hills, as in the Jere–Sanga and Zaranda complexes. In the Jere–Sanga hills the syenite forms a large polygonal ring-dyke which has been partly obliterated by later granite intrusions.

The second group of basic rocks mainly appear in the form of doleritic and gabbroic dykes which both precede the granites and recur throughout the cycles of granite intrusion. In the Liruei and Buji complexes,

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4.—A complex aggregate of hornblende, biotite, epidote, hedenbergite, fluorite and iron oxides in the Yelwa hornblende-fayalite granite-porphyry from the Rop complex. Fluorite is generally most abundant in the mafic aggregates. Only cores of the pyroxene remain. B.851, × 25.

5, 6.—Intergrowths of riebeckite and aegirine in the Durowa albite-riebeckite-granite from the Rop complex. In both examples, the riebeckite crystallized as a mantle around the pyroxene core. Y.8, × 20; Y.6, × 15.

7.—A complex aggregate of reddish-brown biotite, riebeckite, fluorite, astrophyllite, magnetite and zircon in the Ruku riebeckite-biotite granite-porphyry from the Rop complex. The riebeckite is considered to have crystallized before the biotite. B.630, × 30.

8.—An intergrowth of hedenbergite and biotite in the Yelwa amphibole granite-porphyry from the Rop complex. Zircon and allanite are commonly found in the mafic aggregates. B.580, × 50.

9.—Hornblende mantling hedenbergite in the Kuru amphibole-granite from the Jos–Bukuru complex. In this rock the pyroxene is rarely seen without a reaction rim of amphibole. Coarse iron oxides are almost invariably associated with the pyroxene-amphibole aggregates. L.250A, × 30.

10.—A large crystal of hedenbergite with marginal flakes of biotite and inclusions of zircon and magnetite in the Yelwa amphibole granite-porphyry from the Rop complex. B.455, × 40.

11, 12, 13.—Fayalite crystals in the Kuru amphibole granite-porphyry Most of the fayalite crystals are surrounded by reaction rims of hornblende and biotite. Zircon, allanite and magnetite are concentrated in the mafic aggregates. L.250A, × 30; L.250A, × 20; and L.252, × 40.

dykes and concordant intrusions of dolerite post-date the rhyolites and in many other areas late dolerites are found intrusive into the granites. At the northern end of the Jos Plateau there is an extensive swarm of dolerite and gabbro dykes trending NE.–SW. which precede the Younger Granites. Their petrological affinities suggest that they are related to the Younger Granites, and they are provisionally correlated with the dolerites and gabbros which recur at intervals during the cycles of granite intrusion.

Petrography.—Syenites, both with and without quartz, are the most abundant rock types within this group, and in many cases they are transitional both in chemical and mineralogical composition from the amphibole-fayalite-granites. The syenites contain more lime and magnesia than the granites, and the plagioclase is accordingly more calcic and augite appears instead of hedenbergite (see Table XIII). Fayalite has not been recorded but it may have been present in some of the altered cores found in the amphiboles. Hornblende is the most common mafic constituent and frequently forms mantling rims around augite cores. The proportion of biotite shows great variation in different occurrences and it is often entirely absent. Some of the amphiboles show the characteristic bluish-green pleochroism of the soda-amphiboles in the granites.

Perthitic textures are poorly developed in the syenites. The orthoclase and plagioclase usually occur in discrete crystals, the plagioclase showing a range in composition between Ab_{80} and Ab_{60} with pronounced gradational and oscillatory zoning to more sodic exteriors. The high proportion of plagioclase to orthoclase in some facies indicates that they belong to the monzonitic and dioritic families. Quartz is usually interstitial and appears as vermicular intergrowths with the potash-felspar. Apatite, magnetite, ilmenite, fluorite and allanite are the common accessory minerals.

Gabbro is of restricted occurrence in the Younger Granite province and is always found to precede the intermediate rocks in order of intrusion. The intrusions are generally of limited areal extent and no information is yet available of the mode of emplacement.

The Mama gabbro, which may be regarded as typical of the group, is composed of almost equal proportions of andesine-labradorite and melanes which include hornblende, augite, biotite and olivine in that order of abundance. The rock has a striking ophitic texture. The plagioclase is often strongly zoned with a core of $Ab_{55}An_{45}$ and an exterior of $Ab_{75}An_{25}$.

The hornblende is usually cored with purple titaniferous augite and, rarely, olivine, and the margins are frequently intergrown with felted, reddish-brown biotite. In some zones the hornblende is almost completely converted to fibrous chlorite. A feature of this gabbro is the exceptionally high content of titania, which in one facies approaches 6 per cent (see Table XIII). Ilmenite is a major constituent of the rock and is clearly discernible in the hand-specimen, and needles of apatite are abundant. The Kofayi gabbro, which is described later, is slightly more basic than the Mama occurrence and richer in olivine.

(d) Summary of the Chemical Characteristics of the Younger Granite Province

The essential chemical characteristics of the Younger Granite magma may be summarized as follows :—

(1) The lime and magnesia content is consistently low in all facies of the granites and rhyolites. The low lime content is reflected in the nature of the plagioclase, which rarely contains more than 15 per cent of the anorthite molecule. The low magnesia content is shown by the nature of the femic minerals : hedenbergite, fayalite, soda-iron amphiboles and iron-rich micas. The granites have a low magnesia/iron ratio and the Niggli values for mg are usually between 0·10 and 0·20.

(2) Despite the general alkaline nature of the province, the soda and potash values are not particularly high for granites. It is only the albite-riebeckite-granites that have a notably high soda content. In terms of molecular proportions there is generally a slight excess of soda over potash. The Niggli values for k mainly lie between 0·40 and 0·45. The peralkaline character of the riebeckite-granites and some of the amphibole-granites is due to the deficiency of alumina relative to the alkalis. The alumina

TABLE XIII.—CHEMICAL ANALYSES AND NORMS OF THE BASIC AND INTERMEDIATE ROCKS

	1	2	3	4	5	6	7
SiO_2	63·54	62·00	59·50	61·80	47·36	43·76	52·20
Al_2O_3	15·30	14·08	13·60	13·20	19·69	17·07	14·64
Fe_2O_3	1·34	4·06	2·30	2·10	1·17	1·75	3·14
FeO	4·44	4·37	6·70	6·60	6·05	10·18	7·44
MgO	0·72	0·38	1·50	1·30	6·14	5·81	2·45
CaO	2·34	2·18	4·30	3·70	13·28	10·94	8·12
Na_2O	5·12	5·36	4·20	4·00	2·58	2·66	2·76
K_2O	5·12	4·70	3·80	3·70	0·38	0·56	2·72
H_2O+	0·62	0·81	0·80	1·20	1·24	0·88	1·75
H_2O-	0·26	0·57	—	—	0·24	0·20	0·28
CO_2	0·15	0·28	n.d.	n.d.	0·05	0·11	1·80
TiO_2	0·52	0·66	1·70	1·40	1·60	5·97	1·78
P_2O_5	0·24	0·23	0·57	0·48	0·21	0·15	0·75
Cl	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
F	n.d.	n.d.	0·18	0·17	n.d.	n.d.	n.d.
S	0·04	0·03	n.d.	n.d.	0·07	0·03	0·09
MnO	n.d.	n.d.	0·06	0·19	n.d.	n.d.	n.d.
	99·75	99·71	99·21	99·84	100·06	100·07	99·92
Less O	—	—	0·08	0·08	—	—	0·04
Total	99·75	99·71	99·13	99·76	100·06	100·07	99·88
Q	7·70	9·03	9·56	14·31	—	—	7·97
or	30·13	27·80	22·24	21·68	2·22	3·34	16·23
ab	43·18	45·16	35·63	34·06	22·01	22·64	23·37
an	3·72	0·44	6·95	6·45	40·87	32·94	24·07
C	—	—	—	—	—	—	0·68
di	4·64	6·35	8·61	6·00	19·10	15·99	—
hy	5·61	1·13	7·33	8·24	—	—	14·03
ol	—	—	—	—	9·80	10·25	—
mg	1·95	4·40	3·25	3·02	1·62	2·55	4·50
il	0·99	1·31	3·19	2·74	3·04	11·35	3·44
pr	—	—	—	—	0·12	—	0·18
cc	0·34	0·66	—	—	0·10	—	4·10
ap	0·53	0·43	1·34	1·27	0·50	0·34	1·78
fr	—	—	0·18	0·16	—	—	—

1. Syenite, Zaranda. Analyst, Imperial Institute. NT.1793.
2. Syenite-porphyry, Zuku. Analyst, Imperial Institute. NT.1072.
3. Daffo quartz-syenite, Kaleri. Analyst, P. J. Curtis, Imp. Coll. Sci. & Tech. L.1652.
4. Mbul quartz-syenite, Kaleri. Analyst, P. J. Curtis. L.1621.
5. Mungar gabbro, Tof. Analyst, Imperial Institute. NT.1923.
6. Jinni Valley gabbro, Tof. Analyst, Imperial Institute. NT.1924.
7. Buji quartz-dolerite. Analyst, Imperial Institute. NT.128.

contents of the granites show a wide range, between 10·5 and 13·5 per cent. The ratio of the molecular proportions of alkalis to alumina varies between 0·80 and 1·30. In the peraluminous biotite-granites this ratio averages about 0·90, whereas in the riebeckite-granites, with an excess of alkalis, the ratio is usually within the range 1·05 to 1·15. Corundum appears in the norm of some of the strongly peraluminous granites, and sodium metasilicate appears in the norm of some of the peralkaline granites.

(3) The suite is characterized by a high content of fluorine. Fluorite is a common accessory mineral in most of the granites and in some facies it amounts to 3 per cent of the rock. In the riebeckite-granites other alkaline fluorides, such as cryolite and thomsenolite, appear. Topaz is abundant in the tin-bearing greisens and it is occasionally found as an accessory mineral in the granites. The amphiboles and micas are exceptionally rich in fluorine. The combination of low lime and high fluorine results in the unusual appearance of excess fluorine in the norms of many of the granites.

(4) Cassiterite is abundant in the Younger Granite province. It is usually found in greisens associated with the biotite-granites, but it is also present as a fine-grained accessory constituent in some of the granites.

(5) The high content of niobium is a unique feature of the Younger Granite province. Some of the granites contain more than 0·25 per cent of $(Nb, Ta)_2O_5$. Tantalum is much less abundant than niobium, and the niobium-rich end-members, such as columbite, pyrochlore and fergusonite, are invariably found. The columbite shows a range in the niobium/tantalum ratio of between 25 : 1 and 5 : 1. This is an important point of contrast with the Older Granite pegmatites of central Nigeria, in which the complete range of the columbite–tantalite series is encountered in different occurrences. In the Younger Granites there is a definite geochemical correlation between soda and niobium. Niobium minerals are most abundant in granites which have undergone extensive deuteric albitization. Jacobson & Webb (1946) have shown that there is a similar relationship between soda and niobium–tantalum in the Older Granite pegmatites.

(6) Yttrium and the rare earth elements are abundant in the Younger Granites. In addition to the pyrochlore and fergusonite, many of the granites contain accessory monazite, xenotime and allanite. Euxenite has also been recorded.

(7) There is a moderate content of uranium and thorium in the granites. Thorite, and its metamict form orangite, are almost invariably present in the biotite- and riebeckite-granites, and high concentrations are sometimes found in the albite-biotite-granites. Both the pyrochlore from the riebeckite-granites and the fergusonite from the amphibole-granites are uraniferous. The Kaffo pyrochlore contains up to 3·5 per cent of urania and 4·3 per cent thoria (Beer 1952), while the fergusonite from Jarawa contains 3·5 per cent thoria and 1·7 per cent urania. Many of the zircons in the granites are highly radioactive.

(8) There is a deficiency of boron in the Younger Granite magma and it is of particular interest to note that tourmaline has never been recorded in the Younger Granites or in the associated tin veins. The abundance of tin and the absence of tourmaline is a unique feature of the province.

(9) Lithium is abundant in the green mica from the greisens and it is also present in the biotites and riebeckite and other amphiboles.

(10) Spectrographic estimations of rubidium indicate that the proportion of this element is higher than is usual for granites.

(11) Hafnium has been determined in some of the zircons and it has been found that in some varieties the ratio of hafnium to zirconium is exceptionally high and of the order of 1 to 10.

The variation diagrams, Figs. 3, 4 and 5, serve to illustrate the essential chemical relations between different rock types of the province. Figure 3 shows the close balance between alumina and alkalis which prevails in the acid and intermediate members of the suite and the significant diminution of lime, iron and magnesia on passing from the syenites to the granites. The syenites appear to be directly transitional in composition from the amphibole-fayalite-granites. Figure 4 illustrates the variation between the acid members of the suite and provides an indication that the parent magma of the granites may be represented by the amphibole–fayalite group. The diagram suggests that differentiation has trended towards an alumina-rich fraction represented by the biotite-granites and an alumina-deficient fraction represented by the riebeckite-granites, but the process of differentiation is not understood.

As differentiation proceeded the residual magma became richer in silica; this is confirmed by the chemical analyses, which show that the biotite- and riebeckite-granites are generally more siliceous than the amphibole-fayalite-granites. This can also be seen from the Niggli parameters as plotted in Fig. 5. Riebeckite-biotite-granites are rare in the province, and their composition is close to the critical ratio between alumina and alkali which controls the formation of riebeckite. The rarity of this facies, in contrast to the abundance of transitional types between the riebeckitic and fayalitic granites and the biotitic and fayalitic granites, lends support to the hypothesis of divergent differentiation in the generation of the riebeckite- and biotite-granites.

The presence of fayalite as a normal constituent of acid igneous rocks is now widely recognized. Whatever the mechanism of differentiation may have been, it is certain that the low magnesia content

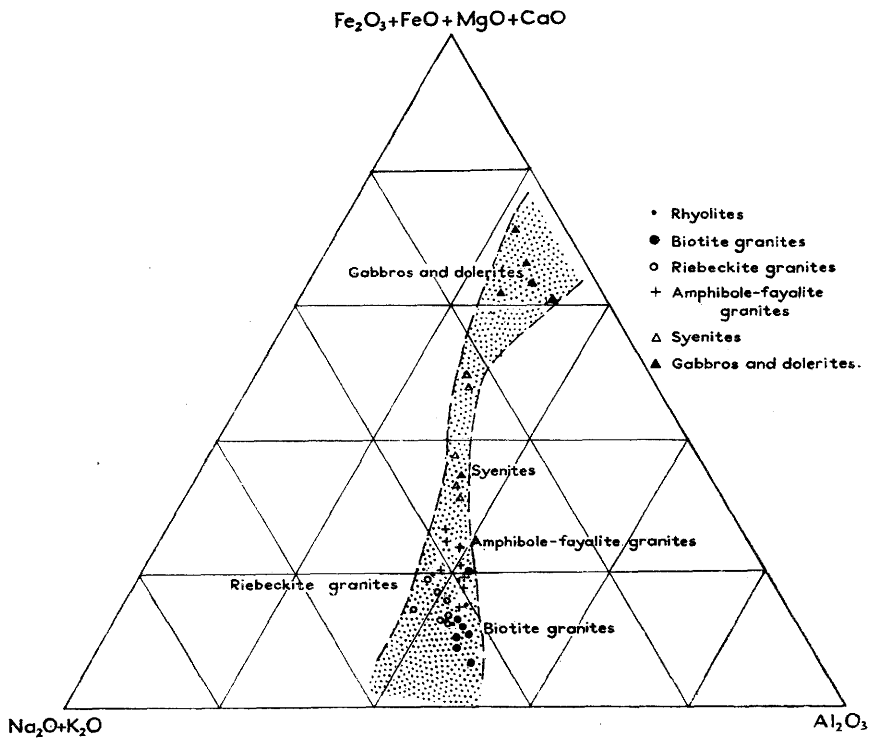


FIG. 3.—Variation diagram illustrating the chemical relations between the principal rock types in the Younger Granite suite.

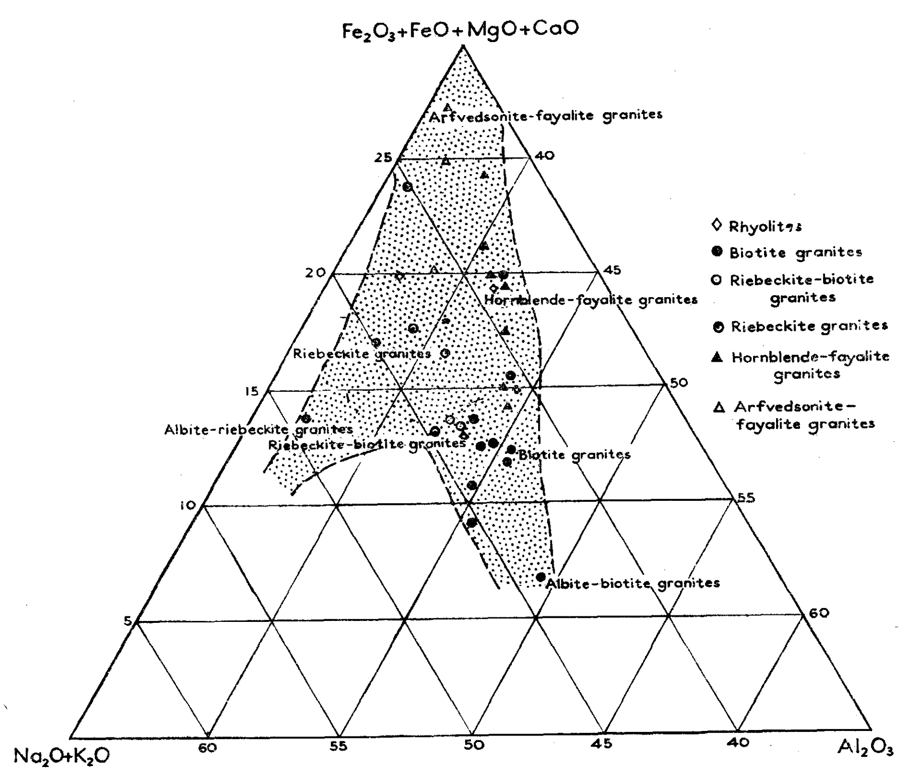


FIG. 4.—Variation diagram illustrating the chemical relations between the acid members of the Younger Granites.

of the Younger Granite magma was an important factor controlling the crystallization of the fayalite and hedenbergite. Bowen & Schairer (1935, 1938) have shown that fayalite and silica can exist in equilibrium at high temperatures. In the Nigerian quartz-fayalite-hedenbergite-porphyries it is clear that the fayalite was one of the first minerals to crystallize, and its association with bipyramidal quartz indicates that it was formed at a high temperature. In the coarse-grained granite-porphyries and amphibole-fayalite-granites, which have cooled more slowly, the fayalite has generally been converted into amphibole and biotite.

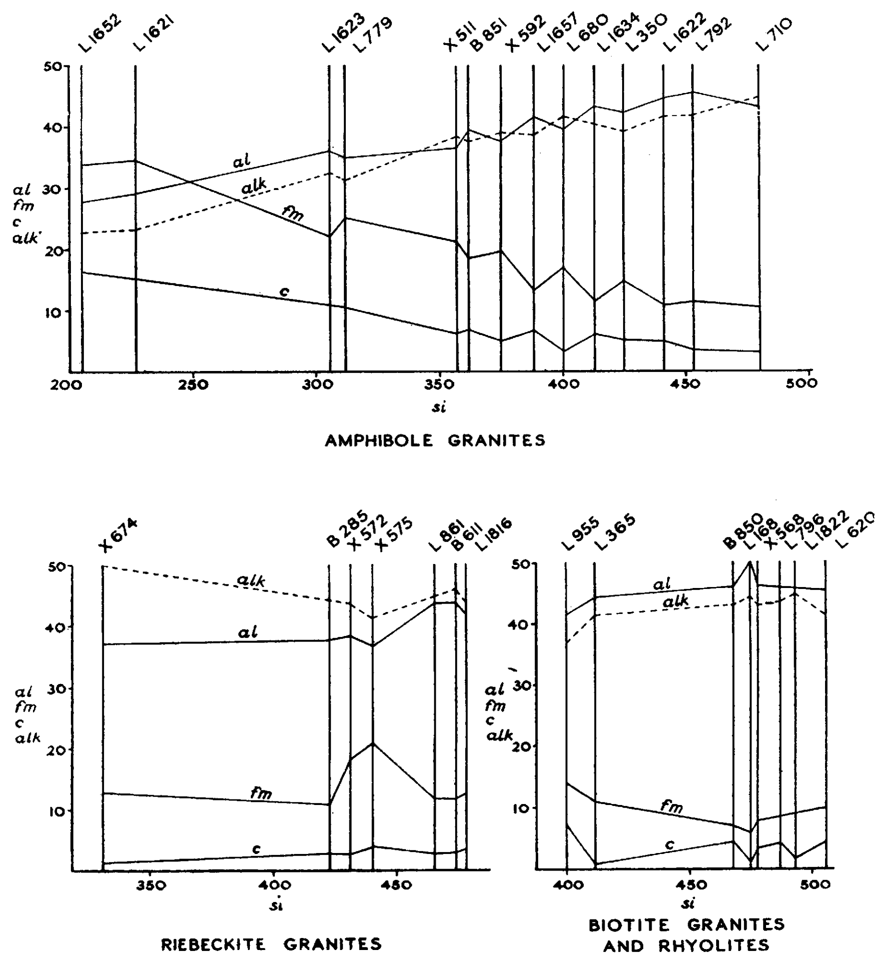


Fig. 5.—Diagram illustrating the variations in the Niggli values for the principal rock types.

Probably the most significant chemical feature of the province is the fact that slight differences in the proportion of soda, potash and alumina can produce such striking changes in the mineralogical composition of the suite.

III. Description of Individual Complexes

(a) The Liruei Complex[1] (Fig. 6)

(i) *Location, Topography and Previous Work*

The Liruei complex occupies an area of about 50 square miles in the extreme southern corner of Kano Province, about midway between Jos and Kano. It is oval in outline with the longer and shorter axes measu ring nine and seven miles. The complex appears as a prominent massif rising 1500 feet above the

[1] Part of a thesis for the degree of Ph.D. submitted to the University of London by R. R. E. Jacobson, 1947.

level plains. In the centre of the massif there is a wide amphitheatre occupied by the granites, which is surrounded by a broad tract of hilly country composed of rhyolite. D. Shetu and D. Ginshi[2], the highest peaks, rise over 4000 feet above sea-level. The drainage pattern is radial and some of the rivers have cut deep gorges in the steep outer escarpment.

Russ (in Raeburn, Bain & Russ 1927) gave a brief description of the general geology of the complex. He distinguished between the granites and the rhyolites and gave a short account of the tin mineralization.

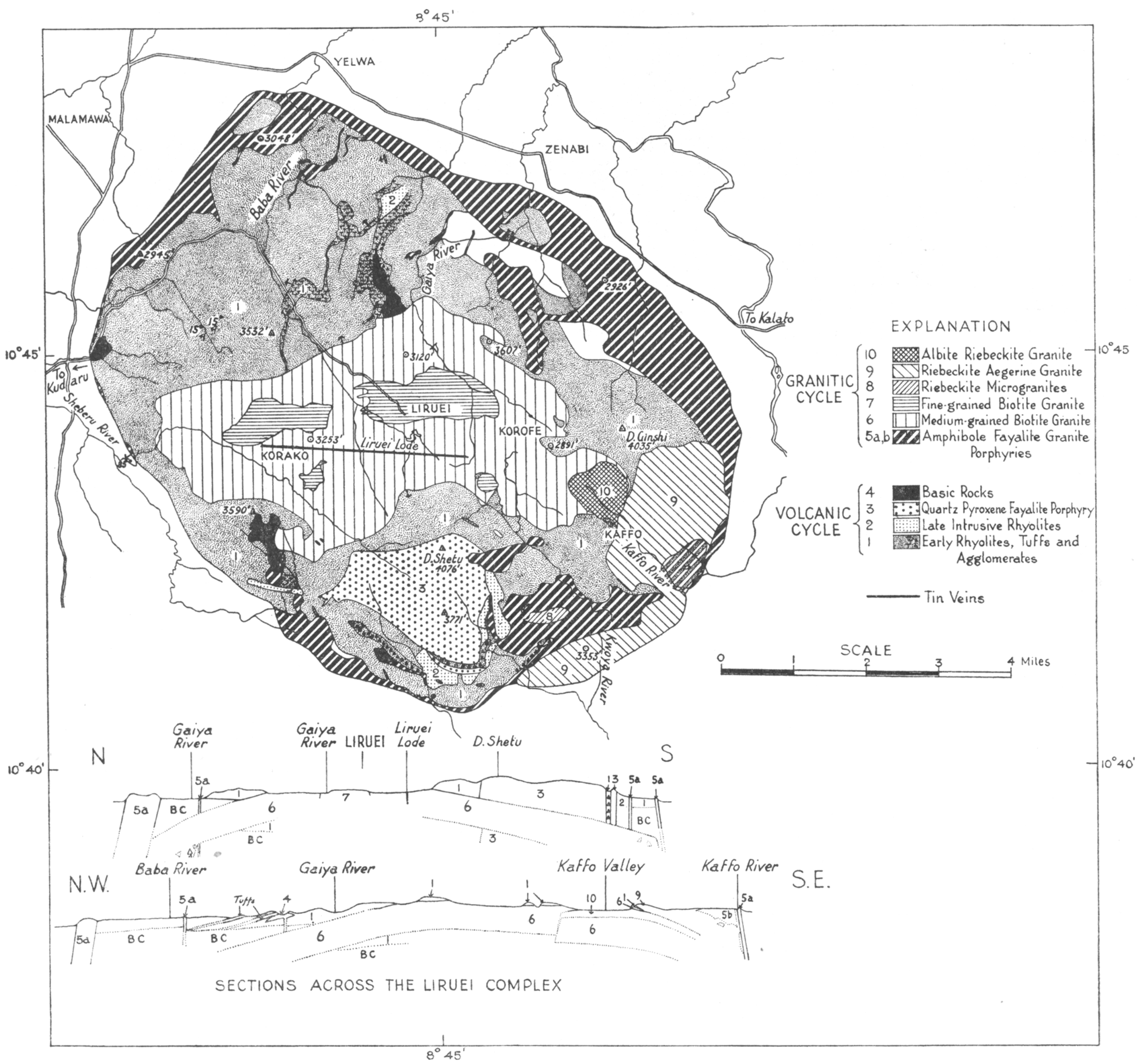


FIG. 6.—GEOLOGICAL MAP OF THE LIRUEI YOUNGER GRANITE COMPLEX.

(ii) *General Structure of the Complex*

The Liruei complex is a comparatively simple type of ring-structure in which two major cycles of magmatic activity can be distinguished. The early volcanic cycle is believed to have been initiated by ring-fracturing and block subsidence which led to the formation of a large caldera in which a great volume of lavas and pyroclastic material accumulated. In addition to the peripheral vents aligned along the ring-

[2] D., abbreviation for ' Dutsen ', the Hausa for ' Hill of '.

fracture, there may have been one or more central type vents in the floor of the caldera. The complete absence of lavas outside the ring-structure suggests that the ring-fault was operative at an early stage and that the volcanism was mainly confined within the limits of the caldera. The volcanic cycle was succeeded by a phase of deep-level cauldron subsidence during which the peripheral ring-dyke and central granites were emplaced.

As in other complexes, two stages of volcanic activity can be distinguished. In the first, a considerable volume of lava and pyroclastic material was erupted from vents in the floor of the caldera. In the second stage, the rhyolites were entirely intrusive and appear as dykes and intrusion breccias in the early lavas. The late rhyolites are believed to have been emplaced during a further period of fracturing and subsidence of the caldera block. Both types of rhyolite are intruded by a steeply dipping plug of quartz-pyroxene-fayalite-porphyry, which was probably emplaced as a result of further high-level cauldron subsidence.

The granitic cycle is represented by the outer ring-dyke of arfvedsonite granite-porphyry which has been followed by several phases of biotite-granite and riebeckite-granite. Only the upper sections of the granite intrusions are exposed and little information can be obtained of their attitude and form in depth (see sections accompanying Fig. 6). The cycles of volcanic and granitic activity are summarized as follows :—

GRANITIC CYCLE .	(10) Minor acid dyke rocks (9) Albite-riebeckite-granite (8) Riebeckite-aegirine-granites (7) Riebeckite-microgranites (6) Biotite-granites (5) Arfvedsonite-fayalite granite-porphyry ring-dyke
VOLCANIC CYCLE .	(4) Basic dykes and semi-conformable basic intrusions (3) Quartz-pyroxene-fayalite-porphyries (2) Late intrusive rhyolites and intrusion breccias (1) Early rhyolites, tuffs and agglomerates

(iii) *The Volcanic Cycle*

Early rhyolites, tuffs and agglomerates.—The peripheral distribution of several large arcuate vents filled with agglomerate and explosion breccia on the southern side of the complex suggests that the early volcanism was more intense in the vicinity of the ring-fault. It is also possible that one or more large cones may have been formed near the centre of the caldera, and the existence of a large central cone is suggested by the fact that the lavas and interbedded pyroclastic rocks in the north-western part of the complex maintain a general westerly dip over a wide area. It is not known, however, if this is the original attitude of the lavas or whether the dip has resulted from subsequent differential subsidence and tilting of the floor of the caldera.

The rhyolites have the same range of alkalinity as the granites (see Tables III, IV and VII). In the peraluminous varieties, phenocrysts of orthoclase and corroded crystals of quartz are generally present, but they vary considerably in size and number. There is little doubt that the microcrystalline groundmass originally contained a high proportion of glass and that the textures now found are largely due to devitrification. Flow-banding is a common feature and spherulites are present in some varieties. The alkaline facies are usually strongly banded, and spherulitic and axiolitic structures are common (see Pl. IV, figs. 1, 2). The presence of green aegirine and blue-green soda-amphibole impart a greenish colour to these rocks. Autobrecciation is a common feature of all the extrusive rhyolites, and it is sometimes difficult to distinguish between the autobrecciated flows and the true pyroclastic material.

Tuffs and agglomerates are well developed in the north-western part of the complex, where two thick beds with a combined maximum thickness of about 200 feet can be traced for a distance of several miles. The rhyolites and interbedded pyroclastic rocks dip to the west at 10 to 15 degrees. Coarse agglomerates with boulders of rhyolite up to a foot and more in diameter occur at the base of the lower bed. They are succeeded by tuffs and breccias composed largely of subangular fragments of rhyolite with occasional xenoliths of Older Granite, gneiss and basic rocks. Towards the top of the series, the fine-grained tuffs in the upper bed show distinct graded bedding. The tuffaceous matrix is composed of microscopic fragments of various kinds of rhyolite and angular pieces of quartz and felspar. The proportion of crystal components varies greatly and in places the pyroclastic rocks grade into crystal tuffs. Extensive exposures of the tuffs and breccias have been noted in other localities in the complex, especially to the south of Liruei.

The vent agglomerates are particularly well exposed in the two great arcuate peripheral vents on the south side of the complex. The vent to the west of the Shere River forms a prominent ridge extending for a distance of over a mile and it averages about 500 feet in width. The agglomerates are composed of rounded boulders of rhyolite set in a fine-grained tuffaceous matrix. The rhyolite fragments range from a few inches in diameter to huge boulders weighing many tons, and the rounding of the boulders is undoubtedly due to mutual attrition during explosive activity in the vent. The arcuate vent parallel to the south-eastern escarpment of the Shetu massif is filled with coarse agglomerate, and towards its northern end it is net-veined by late intrusive rhyolite. On the northern side of the complex, small exposures of vent agglomerate can be seen on the bank of the Baba River to the south of Yelwa and on the west bank of the Gaiya River to the south of Zenabi. In the Baba River occurrence, the agglomerate is traversed by irregular, branching dykes of late rhyolite, and a small dyke of volcanic breccia is also to be seen cutting the coarse agglomerate.

The explosion breccias, which are obviously associated with vent activity, are found in several localities. In the Kaffo Valley, an irregular plug filled with breccia can be seen in the rhyolites to the north-west of Kaffo, and to the west of the plug a narrow dyke of breccia can be traced for several hundred yards. The breccia is composed largely of rounded boulders of porphyritic Older Granite and fragments of rhyolite in a matrix of finely pulverized rock. Irregular tongues of breccia can be seen penetrating into the surrounding rhyolites, and it is not uncommon to find boulders of Older Granite almost as wide as the fissures into which the breccias have been injected. Such features suggest that these explosion breccias have been intruded under extremely high pressure. Another extensive outcrop of explosion breccia is found along the inner contact of the granite-porphyry ring-dyke on the south-eastern margin of the complex. It occupies a narrow zone along the contact between the granite-porphyry and a screen of the Basement Complex. Like the Kaffo occurrence, it is composed largely of rounded boulders of Older Granite set in a fine matrix of pulverized rock. A small pipe filled with explosion breccia can also be seen in the rhyolites to the north-west of Liruei town.

Late rhyolites and intrusion breccias.—At a late stage in the cycle of volcanic activity the early extrusive lavas were invaded by a swarm of dykes and irregular bodies of intrusive rhyolite. These late intrusive rhyolites are often crowded with xenoliths of the earlier rhyolites, and they are probably transitional into a spectacular type of intrusion breccia in which the inclusions form up to 50 per cent and more of the rock. The xenoliths and the flow-structure in the glassy groundmass frequently show an alignment parallel to the walls of the intrusion. The late rhyolites contain numerous phenocrysts of bipyramidal quartz and alkali-felspar, and the abundance of angular microscopic fragments of quartz and felspar suggests that much fine xenolithic material was incorporated during intrusion. The late intrusive rhyolites were probably injected under high pressure into zones of intense brecciation formed by explosive gas activity in the vicinity of vents. Many of the phenocrysts in the late rhyolites show signs of fracturing and this process may be responsible, to some extent, for the abundance of angular fragments in the groundmass. The fluidity of the late rhyolite magma is indicated by its intimate penetration into the surrounding rocks. Similarly, the intrusion breccias, containing almost equal amounts of late rhyolite and xenolithic inclusions, also appear to have been highly mobile. It is suggested that the fluidity was probably due to the high gas content of the magma and the sudden release of pressure during intrusion into intensely brecciated zones.

Quartz-pyroxene-fayalite-porphyries.—Towards the end of the volcanic cycle a boss of quartz-fayalite-hedenbergite-porphyry was intruded into the rhyolites, probably by high-level cauldron subsidence. The porphyries, which occupy an area of about three square miles, form the rugged hills around D. Shetu, the highest point in the complex. The contacts with the rhyolites are steeply inclined, and on the south-eastern flank of the massif there are several arcuate intrusions which may represent transitional phases between the quartz-fayalite-porphyries and the late intrusive rhyolites.

The porphyry contains numerous phenocrysts of bipyramidal quartz and pale-green glassy orthoclase with small crystals of fayalite and hedenbergite (see Pl. V, fig. 8) set in a microcrystalline groundmass composed of quartz, alkali-felspar and spongy, blue-green soda-amphibole. The fayalite is sometimes mantled by a reaction rim of the late amphibole. Allanite, zircon and iron ore are constant accessory constituents. The quartz-fayalite-porphyries sometimes contain rounded xenoliths of rhyolite and Older Granite, but these are never as abundant as in the late rhyolites and intrusion breccias.

Basic dykes and semi-conformable basic intrusions.—Numerous small basic dykes are found in the rhyolites. Most of them are fine-grained rocks of basaltic composition with a few large phenocrysts of plagioclase. Occasional small dykes of dolerite with an ophitic texture have also been recorded.

In addition to the small basaltic dykes, there are four larger basic intrusions. One of these underlies the tuffs to the north of Liruei town. Its texture varies from a coarse porphyritic basalt to a fine-grained greenstone, which suggests that it may be a complex body composed of several separate intrusions. The body appears to be sill-like or laccolithic in form, with the roof of the intrusion roughly conformable with the bedding of the tuffs and agglomerates. The fine-grained shaly tuffs overlying the intrusion are heavily impregnated with secondary iron oxides. The green colour of the basalts is due to extensive saussuritization of the felspar and uralitization of the pyroxene. The alteration is probably deuteric in origin. The basic intrusion to the south of the Sheberu River is intrusive into the overlying rhyolites, but it predates both the granite-porphyries and biotite-granite.

The basic rocks, which form only 2 per cent of the area of the Liruei complex, were probably intruded at the beginning of the granitic cycle, the magma rising up deep-seated fissures which were temporarily opened when major block subsidence commenced.

(iv) *The Granitic Cycle*

Arfvedsonite-fayalite granite-porphyry ring-dyke.—One of the most striking features of the Liruei complex is the great ring-dyke of granite-porphyry which extends, with a few small breaks, for a distance of about 20 miles around the northern, eastern and southern perimeter of the complex. The dyke varies from about 100 feet to over a mile in width. The granite-porphyry is a coarse-grained rock crowded with tabular phenocrysts of orthoclase up to 1 cm. in length, rounded bipyramidal grains of quartz and ragged prisms of blue-green amphibole set in a fine-grained matrix composed of the same minerals. The chief mafic constituent is arfvedsonite, but scanty pyroxene and occasional grains of fayalite are also present. Allanite, ilmenite and zircon are constant accessory constituents. In chemical composition the rock is closely related to the quartz-pyroxene-fayalite-porphyries (see Table XI). Xenoliths of basic composition are widely distributed in the granite-porphyries. These are always well-rounded and partially granitized by reaction with the host rock. It is possible that these xenoliths represent an early intrusion of basic magma into the ring-fault which was subsequently brecciated and incorporated in the main ring-dyke.

Of special interest are the tongues, dykes and irregular bodies of granite-porphyry which penetrate into the heart of the complex. They were apparently intruded into subradial and concentric fractures which developed during the segmentation of the caldera block. Both the rhyolites and underlying Older Granites forming the floor of the caldera were extensively fractured, and the irregular shape of the granite-porphyry dykes is probably due both to differential subsidence of adjacent segments and to minor stoping.

A screen of Older Granite can be seen along the inner contact of the ring-dyke on the southern margin of the complex, and farther east there is a narrow screen of porphyritic Older Granite which grades laterally into explosion breccias. On the northern side of the complex, two large blocks of Basement rocks are exposed along the inner contact of the ring-dyke. They probably represent part of the floor of the caldera on which the lavas were extruded. The small isolated blocks of Older Granite found to the east of D. Shetu and to the south of Kaffo probably represent small screens of Basement which have been isolated by subsidiary block faulting.

It will be noted that several large bodies of rhyolite are enclosed within the ring-dyke near Zenabi and Yelwa. They have been isolated by subsidiary fractures from the main ring-fault, and the structure strongly suggests that block stoping has played an important part in the emplacement of the ring-dyke, especially in the wider parts.

The ring-fault is generally obscured by scree, but a good exposure can be seen on the banks of the Sheberu River. The granite-porphyry dips outwards at an angle exceeding 80 degrees, and the gneisses have been sheared and mylonitized for a distance of several feet from the ring-fault. To the west of the Shere River there is a small exposure of the ring-fault with a narrow, irregular band of flinty crush-rock between the granite-porphyry and the Basement.

The granite-porphyry to the north of the Kaffo River is a separate intrusion. It is composed of phenocrysts of orthoclase, quartz and small prisms of arfvedsonite set in a fine-grained, drusy and micropegmatitic groundmass.

Biotite-granites.—The biotite-granites occupy an area of about 13 square miles in the centre of the complex. Several facies can be distinguished but they are all similar in texture. The smaller bodies are intrusive into the main granite and have chilled micrograniitic margins. The granites are intrusive into the rhyolites, basic rocks and granite-porphyries. Towards the contact with the rhyolites they become finer in grain and numerous knots and streaks of drusy pegmatite make their appearance. Small dykes and tongues of granite penetrate into the rhyolites for a short distance. The contacts are sharply defined and the rhyolites are generally recrystallized for a short distance from the contact.

The biotite-granite is a medium-grained equigranular rock composed of quartz, orthoclase-microperthite, albite and biotite. The texture of the simple exsolution perthite has been extensively modified by irregular, patchy, replacement perthites, and late deuteric albite ($Ab_{90}An_{10}$) often appears as narrow rims and as well-twinned crystals around the borders of the perthite. The dark-brown biotite is found in clusters and is frequently partly replaced by fluorite. Zircon, thorite and columbite are the main accessory minerals. A chemical analysis and mode of the granite are given in Tables IV and VIII, and the chemical composition and optical properties of the mica are quoted in Tables V and VI.

The granite–rhyolite contact slopes outwards towards the margins of the complex. The dip is usually less than 40 degrees and in places the contact is almost horizontal. The granite is considered to have been emplaced by cauldron subsidence, the roof being localized by a gently domed cross-fracture extending almost across the full width of the structure. In the Kaffo Valley, the sheeted structure of the granites can be clearly demonstrated. On the north-eastern side of the valley the biotite-granite wedges out into a thin sheet about 50 feet thick dipping at a low angle to the north and east. The albite-riebeckite-granite, which underlies the biotite-granite, probably represents a relatively thin sheet extending eastwards towards the peripheral ring-dyke (see sections accompanying Fig. 6).

Numerous small dykes and sheets of microgranite are to be found in the biotite-granites and greisenization along joint-planes is widespread. Most of the tin veins are relatively small, but the Liruei lode, which extends for a length of nearly three miles, is an outstanding exception. Both cassiterite and wolfram are found in the lode, and the gangue minerals include galena, sphalerite and a little chalcopyrite. The rich alluvial tin deposits around Liruei have been derived from the lodes and greisens in the biotite-granite. The tin veins occasionally extend for a short distance into the rhyolites overlying the granite and they have also been noted in the quartz-pyroxene-fayalite-porphyries. The biotite-granite is also rich in primary columbite, and values up to 1·6 lbs. per ton have been recorded. It is of historical interest to note that tin mining has been carried on at Liruei for at least 150 years and, prior to 1860, it was the main site of the native tin-smelting industry.

The abundance of minor intrusions of microgranite and the well-developed greisens are indications of proximity to the original roof of the intrusions. These features have often been noted in granite intrusions of comparable depth of erosion in other parts of the province.

Riebeckite-microgranites.—Several small intrusions of riebeckite-microgranite have been recorded. The largest is about half a mile long and is orientated parallel with the south-eastern margin of the complex.

Riebeckite-aegirine-granites.—The riebeckite-aegirine-granites, which occupy an area of about four square miles, are confined to the eastern end of the complex. Part of the feeder ring-dyke can be seen along the south-eastern border of the complex. The riebeckite-granite is intrusive into the rhyolites, and towards the contact the granite becomes finer in grain-size with drusy cavities and pegmatitic knots. Riebeckite crystals up to six inches in length can be seen in the pegmatites, and astrophyllite is common in the contact facies. The contact with the rhyolites is quite sharp, and the lavas are invariably recrystallized for a short distance and carry spongy porphyroblasts of riebeckite. South of Kaffo, the riebeckite-granite is crowded with large blocks of rhyolite, suggesting that some piecemeal stoping occurred during emplacement.

The analysed specimen is moderately coarse-grained and is composed of quartz, orthoclase-microperthite, albite, riebeckite and aegirine. Well-twinned albite (about $Ab_{95}An_5$) is rather more abundant than in the biotite-granites. The aegirine and riebeckite are present in about equal proportions and the two minerals are often intergrown. In this particular granite the aegirine probably crystallized before the riebeckite and some of the intergrowths are the result of selective replacement of the pyroxene by the soda-amphibole. The interstitial nature of both the aegirine and riebeckite indicates that they were among the last minerals to crystallize (see Pl. VI, fig. 14). A chemical analysis and the mode of the granite are given in Tables VII and VIII, and the optical properties of the riebeckite and aegirine are given in Table X.

Albite-riebeckite-granite.—The albite-riebeckite-granite is a small intrusion occupying the floor of the Kaffo Valley. The contacts with the surrounding rhyolites and biotite-granite dip outwards at angles of less than 20 degrees, and it is probable that this intrusion is a gently domed sheet which has been emplaced by cauldron subsidence between the biotite-granite and the riebeckite-aegirine-granite. The albite-riebeckite-granite is intrusive into the biotite-granite, and it has a distinctive chilled margin containing irregular streaks of pegmatite aligned parallel to the contact. The joint-planes in the biotite-granite are frequently coated with riebeckite and small pegmatitic knots are locally abundant.

The albite-riebeckite-granite is a relatively fine-grained rock containing phenocrysts of quartz, orthoclase and riebeckite set in a fine-grained, white matrix composed largely of well-twinned albite laths (see Pl. VI, fig. 15). Pyrochlore, cryolite and topaz are the principal accessory constituents. The albite replaces the earlier-formed quartz and potash-felspar, and forms complex intergrowths around the borders of the riebeckite prisms. The riebeckite, which is frequently intergrown with emerald-green aegirine, forms acicular and prismatic crystals often showing flow alignment. A spongy variety is found in the south-eastern corner of the intrusion. The pyrochlore is visible in the hand-specimen as small honey-coloured grains, and Mackay & Beer (1952) have estimated that the average $(Nb,Ta)_2O_5$ content of the rock is about 0·26 per cent. The pyrochlore contains up to 3·5 per cent of U_3O_8 and 4·3 per cent of ThO_2. The cryolite content of the rock is exceptionally high, with a maximum of about 4 per cent. The unusual composition of this granite suggests that it has strong pegmatitic affinities (see Tables VII and VIII). The optical properties of the riebeckite and aegirine from the granite are given in Table X. Beer (1952) has given a detailed petrographic description of the albite-riebeckite-granites.

(v) *Summary*

The essential features of the Liruei complex may be summarized as follows :—

1. The early lavas and pyroclastic rocks, which were extruded prior to the granite intrusions, are well preserved.

2. The pattern of volcanic activity was controlled by a ring-fault which probably extended to the surface, and block subsidence appears to have been operative at an early stage during the volcanism, as the lavas and pyroclastic material are mainly confined to the caldera.

3. Following further fracturing and subsidence of the caldera block, the late intrusive rhyolites, intrusion breccias and quartz-fayalite-porphyries were emplaced near the base of the early volcanic pile. They represent the transition from volcanic to hypabyssal activity.

4. The segmentation and differential subsidence of the caldera block during the emplacement of the granite-porphyry ring-dyke led to the formation of subradial and concentric intrusions of granite-porphyry in the heart of the complex.

5. There was a continuation of cauldron subsidence at greater depth during the emplacement of the central granites.

(b) The Buji Complex[1] (Fig. 7)

(i) *Location, Topography and Previous Work*

The Buji complex occupies an area of about 30 square miles and lies about 10 miles north of Jos. The complex is well exposed and readily accessible, as it is traversed by the Jos–Zaria trunk road. The north-eastern sector is dominated by the high, dissected Buji Plateau, of which D. Buji (4111 feet) forms the highest point. On the eastern margin of this plateau there is an abrupt descent of 700 feet to the Delimi plains and the deep dissection of this part of the complex has aided the interpretation of the geological structure. The southern area is of more subdued topography, with low rocky hills around the margin of a level internal basin which is underlain by the Basement Complex and largely covered by alluvium. The granite area to the west is broken, difficult country with low, rock-strewn ridges and hills separated by gullies choked with granite boulders.

Falconer (1921) made a brief study of the area during the original survey of the Plateau tinfields and distinguished between the rhyolitic and granitic components of the complex. The first detailed study was made by W. N. MacLeod in 1955, when accurate topographical maps and aerial photographs became available.

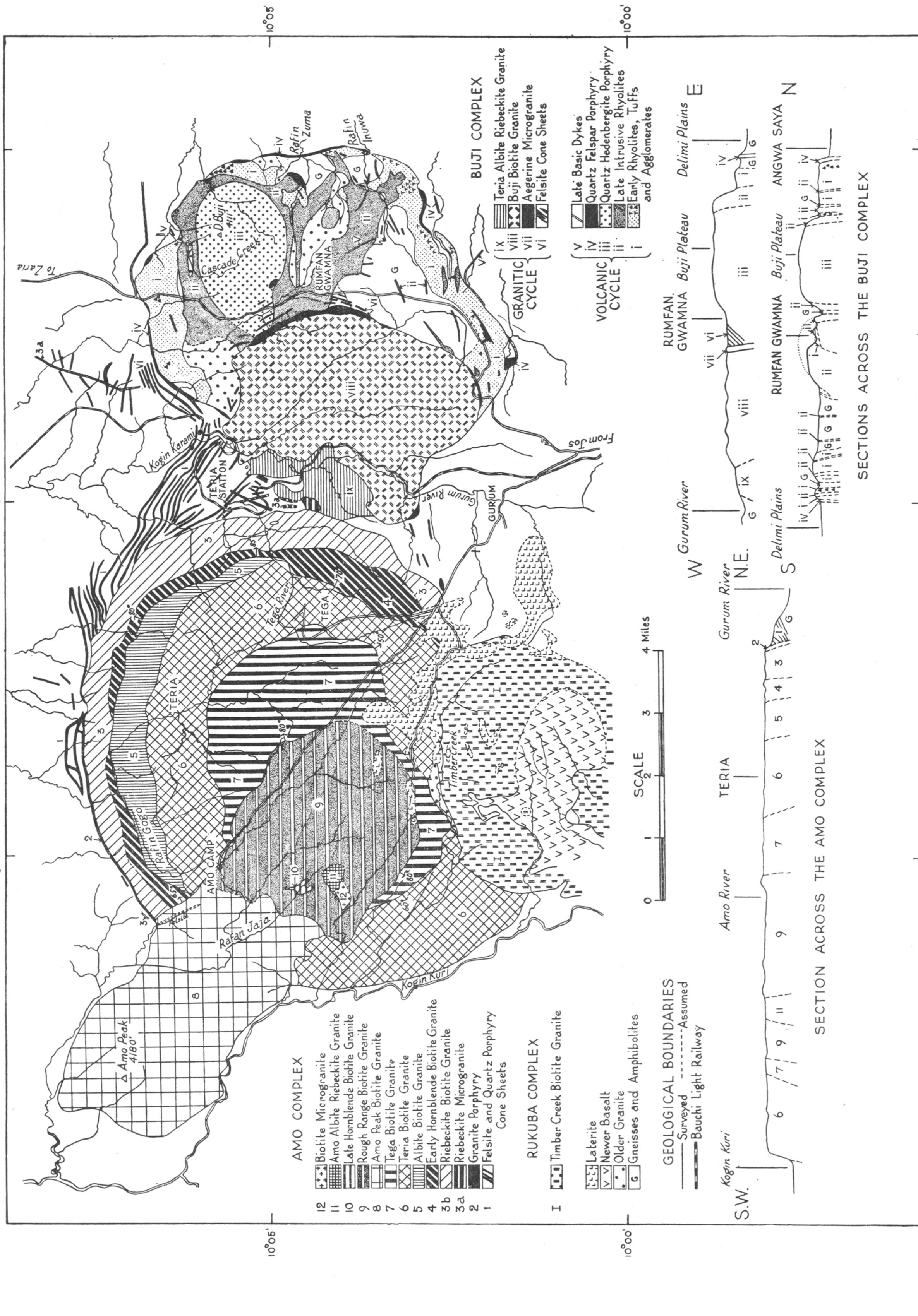
(ii) *General Structure of the Complex*

The Buji massif includes two superimposed ring-complexes which are arranged in an eccentric pattern and are sufficiently separated to reveal the structure of both. The earlier, eastern ring-complex is composed almost entirely of volcanic and high-level hypabyssal rocks, while in the western structure granitic rocks predominate.

In the volcanic ring-complex, erosion has removed the overlying accumulations of lavas and pyroclastic rocks and revealed the subsurface vent pattern. In this respect the Buji structure differs from that of Liruei, where the surface lavas are still preserved and only restricted exposures of the vents can be seen.

Two stages of volcanic activity can be distinguished, the patterns of which have been controlled by essentially the same tectonic processes that govern the emplacement of the granites and ring-dykes at a

[1] Part of a thesis for the degree of Ph.D. submitted to the University of London by W. N. MacLeod, 1957.



GEOLOGICAL MAP OF THE AMO AND BUJI YOUNGER GRANITE COMPLEXES

FIG. 7.—GEOLOGICAL MAP OF THE AMO AND BUJI YOUNGER GRANITE COMPLEXES.

deeper level. In the earlier stage, a series of vents was developed along the line of a ring-fault which had possibly been operative concurrently with the volcanism and had produced a large caldera about six miles in diameter. From the size and number of the vents, it may reasonably be inferred that a considerable volume of lava was erupted and originally overlay the entire structure.

The later volcanic stage is marked by intensive fracturing and differential subsidence of the circular block bounded by the early peripheral vents. The late rhyolites are entirely intrusive and are believed to have been emplaced mainly by high-level cauldron subsidence near the base of the early volcanic pile. An elliptical plug of quartz-hedenbergite-porphyry has been intruded into the late rhyolites and a narrow and discontinuous ring-dyke of quartz-felspar-porphyry has been emplaced around the northern and eastern boundary of the complex. It is considered possible that the intrusion of this ring-dyke accompanied a final block subsidence of the entire volcanic structure.

The granitic ring-structure occupies the western half of the complex and is of comparatively simple pattern. The granite emplacement was preceded by a swarm of cone-sheets which cuts the Basement and the rhyolites on the eastern and northern sides of the granite. A ring-dyke has followed the cone-sheets and this has been partly obliterated by the later biotite-granite. An intrusion of albite-riebeckite-granite on the western side of the complex completes the magmatic cycle. The cycle of magmatic activity in the Buji complex is summarized in the following table :—

Granitic cycle	(9) Teria albite-riebeckite-granite (8) Buji biotite-granite (7) Aegirine-microgranite ring-dyke (6) Felsite cone-sheets
Volcanic cycle	(5) Late basic dykes (4) Quartz-felspar-porphyry ring-dyke (3) Quartz-hedenbergite-porphyry (2) Late intrusive rhyolites (1) Early rhyolites, tuffs and agglomerates.

As can be seen from this table, a complete succession from volcanic rocks through hypabyssal intrusions to high-level plutonic activity is presented in the Buji complex.

(iii) *The Volcanic Ring-complex*

Early rhyolites, tuffs and agglomerates.—The Buji volcanic cycle commenced with the development of a group of vents along the line of a ring-fault which marks the outer boundary of the complex. The vents themselves, of which about a dozen have been distinguished, are arcuate or elliptical in plan and show a circumferential alignment parallel to the ring-fault. It is possible that the ring-fault was operative concurrently with the vent activity and produced a large caldera within which the greater part of the early volcanic products were confined.

At the present erosion level only the vent structure remains. All the overlying, subaerial accumulations of volcanic materials have been removed from the outer zones of the complex and only restricted occurrences of the extruded materials are preserved in the central area of the complex as a result of later differential subsidence of blocks within the caldera. No estimation can be made of the original thickness or areal extent of the early lava flows, but from the size and distribution of the vents they would appear to have been considerable and probably comparable with the lava flows in the Liruei complex.

The individual vents can often be differentiated by the distinctive association of rock types in each. Some are entirely filled with lava and others display all degrees of intermingling of lava and coarse and fine fragmental materials. Over a dozen separate vents have been recognized but the number is probably greater, due to the overlapping and filling of adjacent vents with identical materials.

The peripheral vents show steeply dipping contacts with the Basement gneisses and the flow-banding of the rhyolites is always steeply inclined and often vertical. In some of the elongated vents at the southern end of the complex a zonal arrangement of lava and fragmental material has been observed with the trends of the zones showing the same arcuate alignment as the vent itself. In nearly all the vents a constant age relationship is observed between the lavas and the fragmental materials. Where the two appear in the same vent, the agglomerates, breccias and tuffs always include fragments of the surrounding or adjacent undisturbed lavas. This relationship suggests that the earliest phase of volcanism was the extrusion of lava and, following its partial or complete consolidation in the vents, a phase of vigorous gas explosion ensued which disrupted the lavas and produced an abundance of fine fragmental material. Under the high pressures, the fragmental material, mobilized by gas, intruded and net-veined the surrounding rocks, which had probably been weakened during the explosive stage. In some of the vents there are indications that the fragmental material has been incorporated in later upwellings of lava.

In the central area of the complex there are several small exposures of the early rhyolites, which are lying horizontally, in contrast to the steeply dipping lavas of the vents. These low-dipping lavas occur only within the later cauldron subsidence structures of the late rhyolites and are believed to be remnants of the original subaerial lava flows. The occurrence of these horizontal rhyolites provides reasonable evidence of the later differential subsidence which accompanied the emplacement of the late rhyolites.

The vents at the southern end of the complex are filled almost entirely with rhyolite ; porphyritic, spherulitic and glassy non-porphyritic varieties are represented. The rhyolites immediately adjacent to the biotite-granite have been recrystallized for a distance of several feet from the contact. Pyroclastic rocks predominate in the vents around the eastern and south-eastern perimeter. These range from fine tuffs to coarse agglomerates composed entirely of large blocks of rhyolite in a fine fragmental groundmass. In the northern vents, a distinctive and widespread pink porphyritic rhyolite is the most common rock type. Here the agglomerates show the most spectacular development and include almost equal amounts of Basement granite and rhyolites.

Late intrusive rhyolites.—In contrast to the great variety of textures encountered in the early volcanic group, the late rhyolites are remarkably uniform. They form the high hills and plateaus in the northern half of the complex. The relationship between the early and late rhyolites is clearly displayed in the southern area of the complex, where the latter occur as steeply dipping dykes and diatremes cutting the early lavas and tuffs in the vents and the surrounding Basement gneiss. Within the vents the dykes are most abundant in the agglomerates and tuffs, and in several places they occur at the junction of vent agglomerate and unbrecciated rhyolite.

The late rhyolite dykes rarely have sharp walls, and the margins are often crowded with xenoliths of rhyolite. The agglomerates in the vents are sometimes intricately net-veined by the late rhyolite. The late rhyolites always carry inclusions which reflect the nature of the zone traversed by the dyke. The rhyolite and Basement fragments frequently show a strong alignment parallel to the direction of the dyke.

In the north-central area, the late intrusive rhyolites appear in two major ring-structures with minor branching irregularities. In the centre of the southern ring-structure, a small mass of late rhyolite forms a flat hill-capping overlying early rhyolite and Basement. This may represent a remnant of the roof of the cauldron. In all other areas, so far as exposures permit of observation, the late rhyolites are steeply dipping and show a correspondingly steep flow-banding. The high proportion of angular fragments in the late rhyolites suggests a forceful mode of intrusion, and it is believed that the emplacement was accompanied by intensive fracturing and differential subsidence of the caldera block. The late rhyolite has forced its way into these fracture zones under considerable pressure and incorporated a great number of inclusions.

The uniform fine-grained texture of the late rhyolites suggests that they were intruded under conditions permitting rapid chilling and the ready escape of the volatiles. These conditions would be fulfilled by the intrusion of magma into the basal zone of an intensely fractured lava and tuff accumulation. No evidence can be obtained of the original thickness of the early lavas, but it is difficult to conceive how rocks of such fine-grained and glassy textures as the late rhyolites could have been emplaced under any but the most shallow conditions.

In thin section, the intrusive rhyolites show bipyramidal quartz, tabular orthoclase phenocrysts and poorly crystallized mafic minerals in a glassy groundmass which itself includes angular fragments of quartz and felspar that show a pronounced flow-lineation around the phenocrysts (see Pl. IV, fig. 6). The mafic minerals include blue-green hornblende and hedenbergite. At Buji, the proportions of phenocrysts and groundmass are about equal. It is believed that the angular, microscopic inclusions in the groundmass were incorporated together with the megascopic fragments during the upward surge of the magma into the fracture zones.

Quartz-hedenbergite-porphyry (Pl. V, fig. 9).—The high, dissected Buji plateau at the northern end of the complex is mainly composed of quartz-hedenbergite-porphyry, which forms an elliptical, plug-like body completely surrounded by late rhyolite. The rock closely resembles the late rhyolite in general appearance, but it has a uniformly microcrystalline groundmass free of flow-structure, and coarser and more widely scattered phenocrysts of quartz and orthoclase. The principal mafic mineral is green hedenbergite, and occasional grains of fayalite are present. The porphyry carries a small proportion of Basement and rhyolite inclusions. The contacts with the late rhyolite are of hairline sharpness and show a steep outward dip. The porphyry is believed to have been emplaced by further cauldron subsidence following the emplacement of the late rhyolites.

Quartz-felspar-porphyry ring-dyke.—The intrusion of a narrow ring-dyke of quartz-felspar-porphyry around the margin of the complex marks the close of the Buji volcanic cycle. The volcanic cycles in the Buji and Liruei complexes are similar, but in the latter the basal zones of the volcanic structure have been largely obliterated by block subsidence and extensive granite intrusion directly beneath the volcanic pile. At Buji, however, a westward shift of the focus of magmatic activity occurred near the close of the volcanic cycles and the later granites were emplaced eccentrically. It is considered that the narrow and discontinuous nature of the ring-dyke reflects a condition of near exhaustion of the volcanic magma chamber. As at Liruei, the marginal ring-dyke porphyry has filled minor fractures in the central subsided block.

The texture of the ring-dyke porphyry shows a marked variation with the width of the intrusion. In the wider parts it resembles a typical granite-porphyry save that the proportion of mafic minerals is much lower than normal. In the northern and eastern exposures of the ring-dyke the rock contains coarse, bipyramidal quartz phenocrysts up to 3 mm. in diameter and large ovoidal crystals of pink orthoclase ranging between 4 and 6 mm. The groundmass is of granophyric texture and includes finely dispersed wisps of hornblende and green biotite.

Late basic dykes.—Both the early and late rhyolites in the Buji complex are cut by minor basic intrusions. The majority of these are thin dolerite dykes, one of which follows the ring-fracture for a distance of over a mile around the southern perimeter of the complex. East of Rumfan Gwamna, there is a large dyke of coarse gabbro over a mile in length and about 100 feet wide. The relationship of these dykes to the Buji magmatic cycles is not understood.

(iv) *The Granitic Cycle*

Felsite cone-sheets.—The intrusion of a dense swarm of cone-sheets into the western and northern sections of the volcanic complex represents the first phase of the granitic cycle. The cone-sheets are felsites and quartz-porphyries and show a general inward dip towards the granite of between 25 and 45 degrees.

Some of them are only a few inches in thickness and are glassy and strongly flow-banded ; others exceed 200 feet in thickness and are porphyritic in texture with a microcrystalline groundmass. Many of the sheets are composite intrusions with alternating and intermingled glassy and porphyritic members. Others branch and anastomose and surround elliptical eyes of the earlier rocks. Minor dykes and veins, some only a few inches in width, cut directly across the main trend of the cone-sheets.

The cone-sheets are well developed west of the Zaria road near Rumfan Gwamna and also at the extreme northern end of the complex. In the field they appear as low, boulder-strewn ridges, and in areas of high concentration individual sheets cannot be distinguished, although aerial photographs clearly reveal the pattern of distribution.

In the cone-sheet swarm at the northern end of the complex, the volume of sheets at least equals that of the enclosing Basement gneiss and there is a distinct step in the Plateau escarpment in this area occasioned by the superior resistance of the felsites and quartz-porphyries.

The most common rock type amongst the cone-sheets is a grey quartz-porphyry with small rounded phenocrysts of quartz and clustered pink and white phenocrysts of orthoclase-perthite. The felspars are usually aggregated. The groundmass is usually granophyric but all stages of transition are observed, from a spherulitic graphic texture to a random microcrystalline association of quartz and felspar. Greenish-brown biotite is the only mafic constituent and fluorite is the most abundant accessory.

Aegirine-microgranite ring-dyke.—A narrow ring-dyke of aegirine-microgranite has truncated the cone-sheets, but its original extent cannot be determined as it has been partly obliterated by the later Buji biotite-granite. Remnants of the ring-dyke can be seen only on the eastern and southern sides of the granite. The dyke is widest west of Rumfan Gwamna, where it forms a prominent ridge nearly 100 feet high.

Aegirine, in clusters of small blocky crystals, is the main mafic mineral, and the matrix consists of fine-grained quartz and albite in micropegmatitic intergrowth. There are occasional phenocrysts of lamellar orthoclase-perthite. The rock has a distinctive drusy appearance in the hand-specimen.

Buji biotite-granite.—This granite forms a nearly circular boss about five miles in diameter. It is a typical medium-grained biotite-granite with no unusual petrographic features. The contacts with the earlier rocks are sharp and steeply dipping and it would appear that the granite has been emplaced by a simple block subsidence.

Teria albite-riebeckite-granite.—This is the largest intrusion of this type of granite in the Younger Granite province and covers an area of about one and a half square miles. It is intrusive into the western side of the Buji biotite-granite, where the contact is well exposed and can be closely followed in the valley of the Gurum River. The contact zone is so confused by sheets and veins of pegmatite and microgranite that no reliable determinations of the attitude of the contact can be made.

The north-western sector of the intrusion is deeply embayed and shows an impressive development of pegmatites in which individual crystals of riebeckite up to 10 cm. in length have been recorded. The granite has a fine- to medium-grained porphyritic texture and the essential constituents are clear, rounded quartz, subhedral microcline-perthite, albite and riebeckite-aegirine intergrowths. In some zones, where the proportion of replacement albite is greater, the porphyritic appearance of the rock is greatly enhanced, due to the almost complete replacement of the coarser potash-felspar by fine-grained laths of albite. The degree of albitic replacement shows great variation in different parts of the intrusion. The riebeckite and aegirine are usually intergrown but no constant relationship is observed in the mode of intergrowth. Both minerals appear as the cores of the composite crystals and each appears as fine needles along the cleavage planes of the other. Both minerals, however, seem to be of later crystallization than the quartz and felspar.

Fluorite is the main accessory constituent of the rock and is sufficiently abundant to merit classification as a major constituent. The rock has a low content of accessory pyrochlore. It is yellow-brown and isotropic and intergrown with the albite. Zircon, monazite and iron oxides are the remaining accessories.

Basement Complex.—The Older Granite in the central area of the complex is a gneissose, medium-grained variety with a variable proportion of melanes. It is faulted into contact with the gneisses around

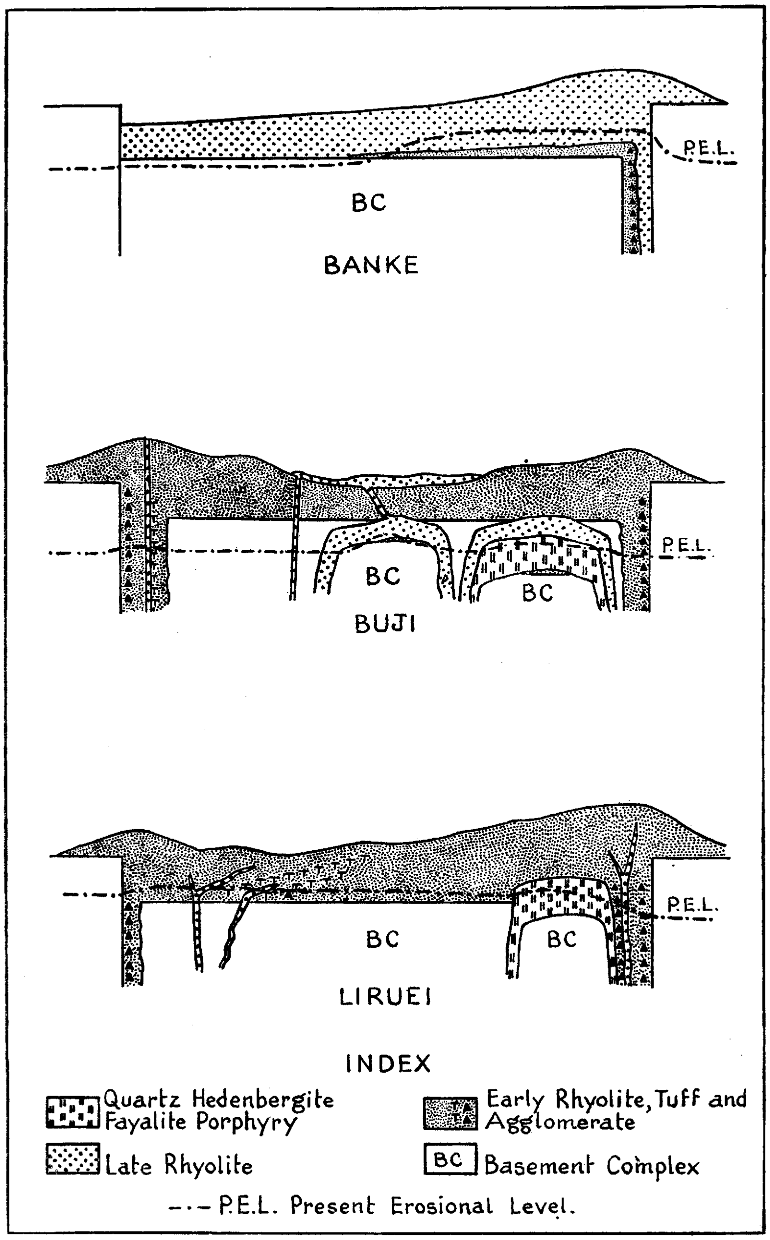


FIG. 8.—Diagrammatic comparison of the volcanic structures of the Banke, Buji and Liruei complexes.

the outer ring-fault in the northern section of the structure. The Basement rocks within the southern half of the complex and surrounding the perimeter are gneisses and amphibolites which have undergone extensive pegmatitization and silicification. South of the complex the gneisses are traversed by numerous large dykes of quartz up to 20 feet in width, some of which can be traced for nearly a mile. The pegmatites and quartz dykes in the Basement produce a characteristic gritty and micaceous soil which has proved a useful indicator in mapping some of the poorly exposed areas of the complex.

(v) *Summary*

The main features of the Buji complex may be summarized as follows :—

1. The same processes controlled the structural pattern of the complex at the volcanic, hypabyssal and plutonic levels of magmatic activity.

2. The pattern of the early volcanic activity was controlled by ring-fracturing and the early vents are situated along the line of a major ring-fault which probably extended to the surface.

3. The late rhyolites were intruded after further ring-fracturing and differential subsidence of the central caldera block. The structure of the Buji complex is transitional between that of Liruei, where the volcanic accumulation has been almost entirely extruded from vents, and the Banke structure, where large quantities of late rhyolite have been extruded by surface cauldron subsidence rather than from individual vents.

4. The quartz-pyroxene-fayalite-porphyries represent a hypabyssal intrusion intermediate between the early volcanism and the later granite emplacement. This relationship has also been noted in other complexes.

5. There has been a pronounced westward shift in the focus of magmatic activity between the volcanic and granitic cycles.

(c) The Amo Complex[1] (Fig. 7)

(i) *Location, Topography and Previous Work*

The Amo complex lies immediately west of Buji, the two massifs being contiguous for a short distance in the Gurum Valley. The northern and western margins of the Amo massif form the Plateau escarpment for a distance of about 20 miles. The escarpment is about 800 feet high and makes a striking topographical feature. Except for a prolongation in the north-western corner, the complex has an almost circular outline and covers an area of about 45 square miles. It is extremely well exposed, particularly near the northern and western margins, where the outward-flowing rivers have cut deep gorges in the Plateau escarpment. In the south, extensive laterite cappings mask some of the geological structure.

A brief reconnaissance survey was made by Falconer (1921). He recorded the presence of riebeckite-granite along the northern and eastern borders of the massif and noted that biotite-granite occurred in the vicinity of Amo Peak, the highest point in the complex. Accurate topographical maps and aerial photographs have only recently been made available. The detailed geology of the complex was first studied by W. N. MacLeod in 1955.

(ii) *Structure of the Complex*

The Amo complex shows the closest approach to the ideal form of a ring-structure of any of the Younger Granites in Nigeria. As at Buji, the cycle of granite emplacement was preceded by the intrusion of cone-sheets which are identical in texture and mineralogy with those of Buji. The Amo cone-sheets show an alignment about a centre which lies considerably to the west of the Buji centre, but the age relationship of the two swarms is uncertain and it is possible that both sets of cone-sheets may be partly contemporaneous.

The Amo cone-sheets are well developed at the north-eastern corner of the massif, where they occur in such abundance as to form a distinct step in the escarpment, over which the Gurum River descends in a series of waterfalls. The largest sheets are up to 200 feet thick and all gradations are seen down to narrow veins less than a foot wide. Most of the cone-sheets have an inward dip towards the granite of between 40 and 60 degrees. Actual exposures of the dips of contacts are rarely seen but the general attitude

[1] Part of a thesis for the degree of Ph.D. submitted to the University of London by W. N. MacLeod, 1957.

of the sheets may be deduced from the dip of the flow-banding and their topographical relationships. The cone-sheets are most abundant in the area immediately north of Teria railway station, where their volume exceeds that of the host Basement gneiss. Many of the cone-sheets branch and anastomose, and in places present a pattern of great intricacy. Their representation on the map is partly diagrammatic.

The Amo massif is compounded of a series of ring-dykes and granite plutons, the distribution of which shows that there was a gradual westward shift of centres during the intrusive cycle. The earlier members, which occur on the eastern side of the complex, have been partly cut out by the later intrusions. The ring-dykes show steeply dipping contacts with the Basement and the earlier granites. Screens of Basement gneiss are preserved between the ring-intrusions in several localities. The structural pattern of the complex presents an almost perfect example of the cauldron subsidence mechanism of granite emplacement. The geometrical perfection of the complex has only been marred by one of the later granites, which has been emplaced eccentrically to the general structure, and by one of the granites of the Rukuba intrusive cycle, which has cut out part of the southern area of the complex.

(iii) *The Rock Types*

The succession of ring-intrusions in the Amo complex is as follows :—

12. Biotite-microgranite
11. Amo albite-riebeckite-granite
10. Late hornblende-biotite-granite
9. Rough Range biotite-granite
8. Amo Peak biotite-granite
7. Tega biotite-granite
6. Teria biotite-granite
5. Albite-biotite-granite
4. Early hornblende-biotite-granite
3. Riebeckite-biotite-granite
2. Granite-porphyry
1. Felsite and quartz-porphyry cone-sheets (see p. 42).

Granite-porphyry.—The granite-porphyry occurs as a narrow ring-dyke along a section of the northern margin of the complex. It rarely exceeds 50 feet in width and is generally poorly exposed, having a cover of boulders fallen from the adjacent riebeckite-granite. Small lenticular screens of gneiss have been noted between the porphyry and the riebeckite-granite. The western extension of the granite-porphyry has been truncated by the Amo Peak intrusion and at the eastern end it is cut off by the riebeckite-biotite-granite. The rock possesses a microcrystalline groundmass, which appears to have been rapidly chilled, with poorly crystallized mafic constituents of which green biotite is the most common. The abundant bipyramidal quartz phenocrysts are embayed and veined by the microcrystalline groundmass.

Riebeckite-biotite-granite.—The riebeckite-biotite-granite forms a great ring-dyke, in places nearly half a mile in width, which extends around the northern and eastern margins of the complex for a distance of 12 miles. It is highly resistant to erosion and appears as an arc of steep rugged hills. The outer contact with the Basement gneiss can be seen in several localitites and shows an outward dip of between 60 and 80 degrees.

This granite shows the unusual association of riebeckite and biotite with the relative proportions of the two minerals varying across the width of the intrusion. The outer margin is almost entirely riebeckitic but the proportion of biotite increases steadily inwards and almost equals the proportion of riebeckite near the inner margin. The outer zones of the intrusion are exceptionally rich in astrophyllite, which in places is almost as abundant as the riebeckite. The felspar is microcline-perthite associated with a high proportion of late replacement albite. No aegirine is found in this rock.

As is common with most riebeckite-granites in Nigeria, considerable textural variations are displayed over the extent of the intrusion. These variations are most pronounced near the outer contact with the

Basement complex. Fine-grained dykes and sills of riebeckite-microgranite are abundant in the contact zone; they seem to be confined to the margin of the granite and do not extend into the Basement. A fine saccharoidal facies which contains large sieve crystals of riebeckite up to 2 cm. in diameter is often noted near the contact. Another variant, best seen on the escarpment on the western side of the Teria basin, contains almost equal proportions of riebeckite and astrophyllite as uniformly dispersed, fine needles in an albitic groundmass. Pegmatites are common in the contact zone both as dykes and knots, and the dykes often extend for a considerable distance into the Basement. Dendrites of riebeckite are commonly found on the close joint-planes of the cone-sheet felsites in the vicinity of the boundary of the riebeckite-granite. Chemical and modal analyses of the rock are quoted in Tables VII and VIII.

Screens of gneiss and trains of xenoliths representing disrupted screens are common along the inner contact with the hornblende-biotite-granite. On the eastern side of the intrusion there are several large elliptical pendants of gneiss with their long axes aligned parallel to the general trend of the ring-dyke. It is possible that the riebeckite-biotite-granite is itself a composite intrusion and that the elongated pendants of gneiss represent screens between successive phases of intrusion. The contact with the Basement is well-exposed in the Tega River. It is of knife-edge sharpness and cuts across the foliation of the gneiss, with an outward dip of about 60 degrees.

Early hornblende-biotite-granite.—This granite occurs as a ring-dyke which has been emplaced concentrically within the riebeckite-biotite-granite and is of similar arcuate extent.

The hornblende-biotite-granite is the coarsest in the complex and one of the most easily recognized in the field. The large euhedral crystals of lamellar orthoclase-perthite attain a length of 1·5 cm. and the quartz clusters and mafic aggregates often exceed 0·5 cm. in diameter. The mafic aggregates are composed of large sieve crystals of bluish-green hornblende intergrown with reddish-brown biotite and iron oxides. Fluorite, allanite and coarse prismatic zircon are commonly associated with the mafic aggregates. A small amount of fergusonite has been detected in the alluvial concentrates derived from this granite.

Towards its outer margin, the granite assumes a porphyritic texture which is similar to the texture of the inner, biotite-rich margin of the riebeckite-biotite-granite and the contact between the two rocks is difficult to distinguish in the field. The westward extension of the ring-dyke has been cut out by the later granite intrusions.

Albite-biotite-granite.—This granite forms a ring-dyke eight miles in length which extends from north of Amo Camp around the northern section of the massif to the vicinity of Tega. It is well exposed and its contacts with the earlier and later intrusions can be clearly defined. Along its outer margin it is intrusive into the hornblende-biotite-granite and the attitude of the contact is either vertical or of steep outward dip. On the inner margin it is, in turn, intruded by the coarse-grained Teria biotite-granite. This contact also dips steeply, and screens of Basement gneiss are common, indicating that the Teria granite has closely followed the inner margin of the albite-biotite-granite at this level.

The Amo albite-biotite-granite displays the typical petrographic features of this group. The granite is of medium grain-size with clustered anhedral quartz and highly albitized microcline-perthite. Biotite occurs in coarse flakes and is of rather lighter colour than is normal in the biotite-granites. Columbite, zircon and ilmenite are the main accessory minerals.

The potash-felspar has been extensively replaced by late deuteric albite. The albite content of the perthites ranges between 70 and 90 per cent and only residual eyes of microcline remain in the albitic matrix. The albite within the perthites rarely shows twinning, but along the interfaces between adjacent perthites it is usual to find veins composed of small crystals of broadly twinned albite. These veins also traverse the feebly twinned albite of the perthites and are clearly of later generation (Pl. V, fig. 12).

The albite-biotite-granite is of some economic importance as it contains moderate amounts of columbite and there is a certain amount of tin mineralization. Small alluvial deposits of both minerals have been worked along the gorge of the Rafin Gogo in recent years.

Later biotite-granites.—The albite-biotite-granite has been followed by four distinct phases of biotite-granite. Three of these, the Teria, Tega and Rough Range granites, are arranged concentrically in the centre of the complex. The fourth biotite-granite, the Amo Peak granite, has been emplaced eccentrically and forms an elliptical prolongation at the north-western corner of the massif.

The *Teria biotite-granite* is the most extensive of the later granites. It is almost circular in form and extends for a considerable distance along the western margin of the complex. It is a coarse-grained equigranular rock which becomes finer-grained and porphyritic near its outer margin. Lenticular screens of Basement gneiss occur between the Teria granite and the albite-biotite-granite, and there is a large screen separating it from the hornblende-biotite-granite at Tega. South of Tega, the Teria granite makes direct contact with the hornblende-biotite-granite. This contact dips to the south at about 70 degrees.

The *Tega porphyritic biotite-granite* is entirely enclosed by the Teria granite and the dip of the contact varies between 60 degrees outwards and vertical. This granite is invariably porphyritic, with large phenocrysts of orthoclase and oligoclase in a groundmass which is unusually rich in free plagioclase. A little muscovite appears in the groundmass in association with the biotite. Greisenization is a common feature in the Timber Creek area, and topaz and beryl are found in the marginal pegmatites. Most of the alluvial tin deposits in the Amo hills have been shed from the Tega granite.

The *Amo Peak granite* forms an elliptical intrusion in the north-western corner of the complex. It is intruded by the Rough Range granite, to which it bears a strong textural resemblance although it is generally coarser in grain and has a more open joint pattern. In the vicinity of Amo Peak, the granite becomes variable in texture and porphyritic and microgranitic varieties are common. Amo Peak (4181 feet) is a dominating inselberg rising about 500 feet above the general level of the massif and flanked by enormous exfoliation surfaces, some of which exceed 200 feet in height. Near Amo Camp, the Amo Peak granite truncates the earlier ring-dykes and dips to the north at 70 degrees.

The *Rough Range biotite-granite* occupies a central position in the massif and derives its name from the high and rugged hills in the area. It is a fine to medium-grained biotite-granite rich in biotite and basic inclusions. Porphyritic varieties appear on the eastern margin, and some of them may be separate intrusions. It is a typical biotite-granite which includes orthoclase-perthite showing both exsolution and replacement textures (see Pl. V, fig. 11).

Late hornblende-biotite-granite.—This is a small intrusion in the centre of the Rough Range granite which is mineralogically similar to the early hornblende-biotite-granite. The mafic aggregates consist of bluish-green hornblende and biotite with a little fayalite. Irregular apophyses of hornblende-biotite-granite penetrate into the surrounding biotite-granite.

Albite-riebeckite-granite.—This intrusion represents the final stage in the Amo cycle. It is entirely surrounded by the Rough Range granite and appears to be a steeply dipping plug of circular plan. The albite-riebeckite-granite is practically identical with the Kaffo granite in the Liruei complex. The dominant felspar is albite and the rock contains pyrochlore, cryolite and abundant topaz as accessory constituents. The riebeckite is acicular in habit, the needles often being aligned in swirl and eddy patterns. A small amount of aegirine appears in intergrowths with the riebeckite. This pyrochlore-bearing granite is of potential economic importance as a source of niobium; the Nb_2O_5 content averages about 0·25 per cent.

Late microgranites and felsites.—There is a small intrusion of biotite-microgranite adjacent to the albite-riebeckite-granite in the centre of the complex, and on the western side of the massif many felsite dykes, with a general northerly trend, cut the Rough Range and Amo Peak granites.

(iv) *Summary*

During the Amo cycle there was a general westerly shift of the focus of magmatic activity and the complex provides a fine example of how earlier ring-intrusions can be partly obliterated by later ones.

The emplacement of the granites can be explained by successive block subsidence and it would appear that the upper horizontal sections of the fractures occurred at practically the same level in each stage of block faulting. If each ring-dyke followed the lower and inner margin of the preceding intrusion, a total subsidence of the order of five miles would be necessary to accommodate the structure. If the successive ring-fractures occurred at or near the same level, the entire group of ring-dykes and plutons could be accommodated by a total subsidence of the order of 10,000 feet. This latter figure is more in accordance with the established extent of subsidence in some of the Scottish and New Hampshire ring-structures.

It is clear that each ring-intrusion must have consolidated completely before the next phase of intrusion began. This is shown by the sharp, chilled contacts and the consistency of their attitudes. There is little evidence that piecemeal stoping has occurred during the emplacement of the early ring-dykes. The contact zones are free of xenoliths of the earlier granites and only carry pendants and xenoliths of Basement gneiss which are almost certainly derived from disrupted screens between the successive ring-fractures. Some of the later central plutons have plentiful xenoliths of Basement and earlier granites and it is possible that some minor stoping has occurred during their emplacement.

It is noteworthy that the successive ring-fractures in the Amo complex follow smooth curves. This is in contrast to the Rosses granitic ring-complex in Donegal, where the ring-fractures have assumed a polygonal form due to the influence of joints in the host granite (Pitcher 1953).

(d) The Rop Complex (Pl. VIII)

(i) *Location, Topography and Previous Work*

The Rop complex is situated in the central region of the Jos Plateau and covers a roughly triangular area of about 240 square miles, of which only 71 square miles are occupied by Younger Granite. The structure is bounded by arcuate and polygonal dykes which enclose extensive areas of Basement rocks and a prominent central massif of Younger Granite.

The resistant Younger Granites form most of the hills within the complex, some of which rise to over 5000 feet above sea-level. Good exposures are found east of Gana, where a continuous hill-mass rises about 1000 feet above the plains, and in the rough hills west of Dress. The Tenti–Mbar apophysis, which links the Rop and Sha–Kaleri complexes, appears as a line of low hills extending south from Tenti. Elsewhere the granite forms isolated inselbergs piercing a thick mantle of drift and basalt flows. The drainage pattern is radial and is entirely controlled by the distribution of the Younger Granite.

The general outline of the complex was first mapped by Falconer (1921). During the resurvey of the Plateau tinfields, Greenwood (1951) interpreted the apophyses as ring-dykes and maintained that major stoping has been the operative factor in the emplacement of the granites. The occurrence of riebeckite-granite at Durowa, Monguna and Butra was recorded. The first detailed study of the complex was made by R. Black between 1953 and 1955.

(ii) *General Structure of the Complex*

As in the case of the other complexes which have been described, both a volcanic and plutonic cycle can be distinguished in the Rop complex. Rhyolite, explosion breccias and quartz-porphyries are found in the volcanic group, but are of limited extent in comparison with the effusive rocks of the Buji and Liruei complexes. The cycle of granite intrusion was initiated by granite-porphyry and this was followed by a succession of biotite- and riebeckite-granites which display a progressive increase in alkalinity. Late granite-porphyries occur at the conclusion of the granitic cycle.

The structural pattern of the complex has been determined by the discordant superposition of two major fracture systems. The earlier Sho system on the western side of the complex has been truncated and its eastern extension obliterated by the later system of Mongu fractures. These two important zones of fracturing have served as the loci of most of the succeeding intrusions. The shape of the two fractures shows a dependence on the nature of the country rocks which they traverse. The Sho fracture is arcuate, owing to the relative isotropy of the Older Granite on that side of the complex. In contrast, the Mongu fracture pattern, which traverses the heterogeneous and strongly foliated gneisses, is polygonal. The intrusion of the granites has followed the foundering and segmentation of individual blocks within the extensive zone of superimposed fractures and it is believed that most of the intrusions are permissive.

The high topographical relief in the Rop complex makes it possible to see certain elements of the structure in three dimensions. The preservation of screens of earlier phases along both the horizontal roof fractures and the vertical ring-faults often provides a clear demonstration of the mechanism of intrusion. In some instances it has been possible to estimate the extent of subsidence of the blocks.

The volume of magma is thought to be small in comparison to that of the adjoining Jos–Bukuru and Sha–Kaleri complexes. It is apparent that deeper erosion would leave only a network of feeder dykes cutting the Basement. This is in complete antithesis to the interpretation of Falconer (1921), who ascribed the irregularity in the shape of the massif to the incomplete removal of the cover of older rocks.

The sequence of intrusions in the Rop complex closely parallels that of the Jos–Bukuru complex, which indicates that the underlying magma chambers were connected in depth and that the two cycles of intrusion were contemporaneous. A correlation between the phases of the two complexes is suggested in the following table :—

Rop	Jos–Bukuru
GRANITIC CYCLE	
(15) Late dolerites	
(14) Mongor granite-porphyry	
(13) Kaskara biotite-granite	Late biotite-granites
(12) Yelwa granite-porphyry	Shen granite-porphyry
(11) Ruku riebeckite-biotite granite-porphyry	
(10) Durowa albite-riebeckite-granite	
(9) Butra riebeckite-granite	
(8) Kassa albite-biotite-granite	
(7) Bukka Bakwai biotite-granite and associated microgranites	Rayfield–Gona biotite-granite
(6) Gana biotite-granite and microgranites	N'gell biotite-granite
(5) Kwop biotite-granite	Jos biotite-granite
(4) Early granite-porphyry	Neil's Valley granite-porphyry.
VOLCANIC CYCLE	
(3) Quartz-porphyries and quartz-felspar-porphyries	
(2) Rhyolites and explosion breccias	Rhyolites and tuffs, Neil's Valley
(1) Basic dykes	

(iii) *The Rock Types*

Basic dykes.—Several dykes of hornblende-microgabbro cut the Basement west of Sho. They have a general trend of N.20°E. and one of the larger dykes has been traced for a distance of two and a half miles. They are believed to precede the intrusion of the Younger Granites.

Rhyolites and explosion breccias.—The early volcanic rocks are restricted to a large pendant in the Yelwa granite-porphyry situated about a mile south of Rop Rest House. As at Buji, there is evidence that a phase of lava effusion has been succeeded by a phase of explosive brecciation. The exposure probably represents a high-pressure zone within a vent. The rhyolite net-veins the Older Granite and is in turn cut by a mobilized explosion breccia which contains angular fragments of rhyolite and Basement rocks (Fig. 9). Some of the larger blocks in the breccia attain a diameter of several feet. It is significant that the pendant occurs along a line which is continuous with the Sho ring-fracture. This is in accordance with the volcanic patterns of Liruei and Buji, where vents are found in the proximity of the ring-faults.

Quartz-porphyries and quartz-felspar-porphyries.—The quartz-porphyries are microcrystalline rocks with small corroded phenocrysts of quartz and felspar. Biotite is the dominant femic mineral and appears as dyscrystalline shreds in the groundmass. These porphyries are regarded as equivalent to the late intrusive rhyolites in the Buji complex. In the vicinity of Rop Rest House they are seen to be intrusive into the volcanic breccia ; they also appear on the east bank of the Kassa River, where they are faulted against the early granite-porphyry and the Kwop biotite-granite.

The quartz-felspar-porphyries are distinguished by the presence of large embayed phenocrysts of felspar, some of which exceed 1 cm. in diameter. Two bodies of the porphyry are preserved in Balfour Hill as screens between the Yelwa granite-porphyry and the Basement. The porphyry which lies farther north, at Merit, has invaded an altered basic rock. Quartz-felspar-porphyry has also been seen as pendants in the Yelwa granite-porphyry west of Durowa and as dykes cutting the gneisses west of Balfour Hill.

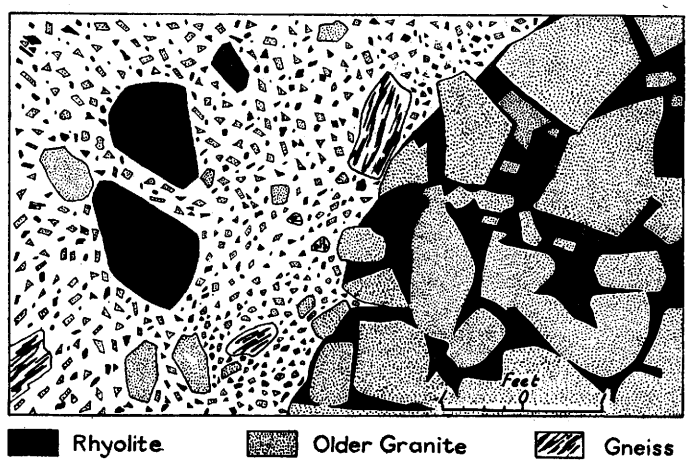


FIG. 9.—Vent explosion breccia, Rop Hills.

Early granite-porphyry.—The early granite-porphyry can be correlated with the major ring-intrusions that initiated the cycles of granite emplacement in other complexes of the Jos Plateau. The distribution of the early fractures is shown in Fig. 1. The early granite-porphyry of the Rop complex which fills the Sho fracture zone can be correlated with the early amphibole-granites and granite-porphyry of the Jos–Bukuru complex and the early Mbar porphyry of the Sha–Kaleri complex.

The Sho ring-dyke is truncated at both its northern and southern extremities by later riebeckite-granite and granite-porphyry which have been emplaced along fracture zones belonging to the later Mongu system. In the area around the hospital, this line of dislocation coincides with a cross-fracture in the original Sho system. In the Tenti–Mbar apophysis, numerous screens and pendants of the early granite-porphyry are present and provide a link with the Mbar granite-porphyry in the Sha–Kaleri complex. The arcuate body at the northern end of the complex has a convex alignment with the Sho arc and may be tectonically related to the Jos–Bukuru massif.

The granite-porphyry displays considerable variation in texture. Around the hospital and in the wider portions of the Sho ring-dyke, the phenocrysts of felspar and quartz attain a size of 1 cm. and 3 mm. respectively, and have irregular and intergrown boundaries with the micrographic groundmass which amounts to about 50 per cent of the rock. East of Monguna, the rock is of granitic texture with large idiomorphic felspars up to 2 cm. in diameter. At Nafam, the porphyry contains ovoid, embayed felspars which sometimes attain a length of 5 cm.

The early granite-porphyry rarely develops a marginal pegmatitic facies and only limited greisenization has been observed. This would suggest intrusion into open fractures which permitted both rapid chilling of the residual liquids and the ready escape of the volatile constituents.

The mineral constituents of the granite-porphyry are bipyramidal quartz, orthoclase-perthite, hornblende and subordinate biotite. The perthite generally shows a lamellar exsolution texture and, in places, a small amount of deuteric replacement by late albite. Allanite, fluorite, zircon and ilmenite are the main accessory minerals. Basic xenoliths are a common feature and are most abundant in the Nafam area. Near Nding, on the northern bank of the Kassa River, a mylonitized screen of basic rock is preserved between the granite-porphyry and the Basement. This would suggest that the fracture had been first sealed by a more mobile and basic forerunner of the granite-porphyry.

Kwop biotite-granite.—This, the earliest granite in the complex, is restricted by later faulting to the north-western corner of the Rop Hills. The normal texture is coarse and equigranular but towards the borders the rock becomes porphyritic. The granite is cut by numerous sheets of microgranite which are probably derived from the later Gana biotite-granite.

Gana biotite-granite and associated microgranites.—The central area of the Rop massif is occupied by the Gana granite and its former wider extent is indicated by the presence of screens beneath the Yelwa porphyry and the occurrence of numerous pendants and xenoliths in the later granites in the area east of Gindi Akwati.

The granite is of medium grain and is readily distinguished in the field by the pink perthitic felspar and discrete grains of white albite. Porphyritic and microgranitic facies occur in the vicinity of Kwop and the contact zones are characterized by miaroles and pegmatitic knots.

Two later bodies of microgranite occur on the flanks of the Gana granite, near Gana and south of Rop dome. These are intruded by the later Bukka Bakwai granite, which has intimately penetrated the microgranite along the joint-planes. The microgranites show all gradations in texture from a uniformly fine-grained microgranite to a medium-grained porphyritic granite. In some areas the xenoliths of the Gana granite display all stages of mechanical disintegration, and it is likely that many of the phenocrysts in the microgranite are xenocrysts or microxenoliths which have been liberated by the break-down of the larger xenoliths. Probably the hybridization occurred at a greater depth and the heterogeneous material has been emplaced as a separate intrusion.

Bukka Bakwai biotite-granite and associated microgranites.—Both the vertical and horizontal components of the Bukka Bakwai granite are seen in the Rop complex. In the hills east of Yelwa adit this granite dips at a low angle beneath a screen of Gana biotite-granite which in turn is overlain by the later Yelwa granite-porphyry. It is also seen as a sheet west of Rop dome, where it dips to the north at an angle of 8 degrees beneath the Gana granite. The bottom surface of the intrusion has not been located in this area, but near Dress, where the Bukka Bakwai granite has been down-faulted during the emplacement of the Yelwa granite-porphyry ring-dyke, the granite is seen to overlie the Basement. Calculations show that the upper subhorizontal section of the Bukka Bakwai granite must be about 1000 feet thick. On the sections accompanying the map of the complex (see Pl. VIII), which are drawn to true vertical scale, it can be seen that the roof section of the intrusion has a remarkably attenuated form.

The vertical component of the granite body is seen in the narrow, steeply dipping dyke which extends from South Rop to Tenti. This dyke is regarded as the feeder to the upper horizontal section of the intrusion. The fracture utilized by it has served as the locus of intrusion for succeeding granites and granite-porphyries.

The Bukka Bakwai granite is of medium grain and has the typical equigranular sugary texture of the albite-biotite-granites. Late replacement albite is the dominant felspar and forms cores within the perthite, which in some crystals is almost completely replaced. A zone of microgranite riddled with drusy cavities and knots of pegmatite is usually developed near the contacts with the earlier rocks. Euhedral crystals of white quartz up to a foot in length have been noted in the marginal facies.

The Bukka Bakwai granite is the richest in columbite of all the granites in the complex, and values ranging between 0·5 and 1·0 lb. per ton have been recorded in the area east of Rop dome. Greisen zones are widely distributed and have been the source of most of the alluvial cassiterite in the Rop area. Around Rop dome greisens are developed along joint-planes in the Gana granite and microgranites which are underlain by the Bukka Bakwai granite. They also occur in the Older Granite that surrounds the dyke between South Rop and Tenti.

Minor intrusions of albite-biotite-microgranite, bluish-grey in colour and mottled with red iron oxides, both precede and follow the main Bukka Bakwai granite.

Kassa albite-biotite-granite.—This granite occurs at the extreme northern end of the complex but only limited exposures are seen, owing to a cover of Newer Basalt. It is a medium-grained equigranular rock rich in albite.

Butra riebeckite-biotite-granite.—This granite was emplaced as a result of further subsidence of the Mongu block. It appears as a narrow dyke east of the hospital, and follows the western margin of the Tenti–Mbar apophysis. A small isolated exposure occurs near Butra on the line of the main Mongu fracture. The granite contains a minor proportion of biotite in addition to the riebeckite, and abundant astrophyllite is developed near Monguna Hausa. Wide pegmatite zones are found at the borders of the intrusion.

Durowa albite-riebeckite-granite.—The albite-riebeckite-granite is poorly exposed in the drift-covered area south-east of Durowa, and contacts with the earlier rocks are not seen. The rock has a compact sugary texture with small prisms of riebeckite in a white matrix of albite, microcline and quartz. Pyrochlore and thomsenolite are important accessory minerals, with the former amounting to about 0·5 per cent of the rock. As can be seen from Table VII, this rock has an exceptionally high content of fluorine. The pyrochlore from this granite differs from that of the Liruei albite-riebeckite-granite in having only a low content of uranium.

Ruku riebeckite-biotite granite-porphyry.—This phase is one of the most widely distributed in the complex and occurs along both the Sho and Mongu fractures. Contacts with the earlier rocks are of knife-edge sharpness and pegmatites are absent. South of Tenti, the porphyry carries abundant xenoliths of riebeckite-granite and Basement.

Yelwa granite-porphyry.—The intrusion of this phase was accompanied by extensive fragmentation of the Basement. The porphyry magma invaded the entire network of Mongu fractures and truncated the southern part of the Nding–Nafam body of the early granite-porphyry. The Yelwa phase forms the great polygonal Mongu dyke, which has a length of 35 miles and varies between 300 and 1400 feet in width.

Around Yelwa adit the granite-porphyry occurs as a subhorizontal sheet above the screens of the Gana biotite-granite and has been intruded by the Kaskara biotite-granite. The porphyry appears as an eroded dome in the Dress area and has an outward dip of 30 degrees on the western flank. Here it is superposed on the flat-lying sheet of Bukka Bakwai granite, and there is a small satellite ring-dyke on the south-western side. Between Tenti and Batura, the porphyry appears in an elongated crescentic outcrop and has apparently been emplaced by piecemeal stoping. It is crowded with xenoliths of Basement and earlier granites and in places the volume of the inclusions is in excess of that of the host rock. On the northern side of Balfour Hill, the porphyry contains small pendants of pelitic metasediments and chiastolite-schist which are akin to certain members of the schist belts in the Basement complex of western Nigeria.

The Yelwa granite-porphyry displays a considerable variation in the proportion of phenocrysts. In the horizontal part of the body, the texture is granitic, owing to the presence of an impermeable roof which prevented the escape of the volatile constituents. The mafic constituents are fayalite and hedenbergite mantled by hornblende and biotite (see Fig. 2, nos. 4, 8, 10). A leucocratic facies is developed in the north-eastern section of the Mongu dyke and a marginal facies of biotite-microgranite is found around Yelwa adit.

Kaskara biotite-granite.—The Kaskara granite has been intruded beneath the Yelwa granite-porphyry in the high hills near Yelwa adit. The preservation of screens of Gana granite along the contact shows that the roof fracture which controlled the emplacement of the Kaskara granite occurred close to the contact between the Yelwa porphyry and the underlying Gana granite. It is believed that some of the microgranite which has been intruded along the Mongu fracture east of Keffi Abo is of the same age. The granite has a fine-grained sugary texture and shows large plates of biotite up to several millimetres in diameter. Greisens, derived from the Kaskara granite, occur within the Yelwa porphyry directly above the contact.

Mongor granite-porphyry.—This granite-porphyry forms a lenticular intrusion which extends from Monguna Hausa to Mbar. It is intrusive into the early granite-porphyry and the Bukka Bakwai biotite-granite. The alignment of the intrusion suggests that it may be structurally related to the adjacent Kaleri ring-complex.

Late dolerite dykes.—Vertical dykes of late dolerite are common in the Tenti–Mbar apophysis but are absent in the central massif of the complex. They rarely exceed 10 feet in width but some can be traced for over a mile. South of Gindi Akwati one of the dykes expands to a plug-like body nearly 500 feet wide.

Mylonitization.—Evidence of faulting and block subsidence is frequently seen at the contacts between the units. In these zones, it is significant that it is the earlier rock that displays cataclastic textures, a circumstance indicating that faulting occurred either prior to or during the intrusion of the later phase. Mylonitization is commonly developed in the vertical dykes, where a succession of intrusions have followed the same fracture zone.

A fine example is seen two miles east of Keffi Abo, where a crush zone with a maximum width of 40 feet is exposed for a distance of several hundred feet along the line of the fault. All degrees of mylonitization are represented and where the frictional temperatures have been sufficiently high the rock has been fused and mobilized and displays intrusive relationships with the surrounding mylonite. Ultramylonite is intrusive along the joint-planes of the early granite-porphyry at the contact with the Yelwa porphyry south of Nafam.

(iv) *Summary*

The essential features of the Rop complex may be summarized as follows :—

1. The pattern of the complex has been determined by extensive superposed fracture systems and these fractures have provided the loci of intrusion for the successive granites and granite-porphyries.

2. Major block subsidence and permissive intrusion are the dominant processes which have controlled the emplacement of the granites. The presence of screens in both the horizontal and vertical fracture zones provides evidence for this mechanism of intrusion.

3. There are indications that the early volcanism was localized by the same fracture systems that controlled the emplacement of the granites.

4. The successive granite intrusions show a trend towards increasing alkalinity.

(e) The Sha–Kaleri Complex[1] (Pl. IX)

(i) *Location, Topography and Previous Work*

The Sha–Kaleri complex, which is the second largest in the province, occupies an area of nearly 250 square miles in the south-western region of the Jos Plateau. The western and southern margins of the complex coincide with the Plateau escarpment for a distance of about 30 miles. In places, the escarp-

[1] Part of a thesis for the degree of Ph.D. submitted to the University of London by W. N. MacLeod, 1957.

ment is 3000 feet high and is one of the most striking topographical features in Northern Nigeria. The central, eastern and northern parts of the massif are continuous with the general Plateau level at an altitude between 4200 and 4900 feet above sea-level. To the south and west, the country becomes progressively more dissected and, along the escarpment, culminates in precipitous cliffs and deep gorges, many of which are extremely difficult of access.

The entire drainage is towards the south and west, the main units being the Daffo, Sha and Andafar rivers, all of which are tributaries of the Farin Ruwa. The highest part of the complex is near Monguna, where the hill summits approach 5000 feet. In the Sha and Monguna districts many of the hills are capped with laterite and show flat summits of concordant level. The Mama country, below the southern escarpment, is only 1500 feet above sea-level and is covered with dense vegetation.

The Sha–Kaleri complex was first studied by Falconer and Raeburn during the initial survey of the Plateau tinfields (Falconer & others 1926). The main outline of the complex was mapped and its identity with the Younger Granite suite was confirmed. Falconer recorded the presence of Basement rocks and rhyolites within the massif and Raeburn described the granite and gabbro of the Mama district in the southern area of the complex. In the resurvey of the Plateau tinfields Greenwood and Rockingham revised the original mapping in the northern and southern areas respectively. In this survey a distinction was drawn between granite and granite-porphyry in some areas and the outer boundaries with the Basement rocks were remapped. The first detailed study of the complex was made by W. N. MacLeod between 1954 and 1956.

(ii) *General Structure of the Complex*

The large size of the Sha–Kaleri complex is due to the superposition of three distinct cycles of Younger Granite intrusion, the mutual age relationships of which can only be approximately defined. The three units are the Kaleri, Monguna and Tof complexes, of which the first-named is the largest and most intricate in structure. Their general characteristics may be summarized as follows :—

The *Kaleri complex* is probably one of the largest ring-complexes in the world. It extends 23 miles in an E.–W. direction and 15 miles in a N.–S. direction, covering an area of nearly 200 square miles. The complex includes 18 separate intrusions arranged in a concentric pattern with the earliest members on the outside. Like the Amo complex, it is composed almost entirely of a series of granite and granite-porphyry ring-dykes. Rhyolites have been preserved by down-faulting in the centre of the complex, and as screens between some of the ring-dykes.

The *Monguna complex* covers an area of about 30 square miles at the northern end of the massif. It is of comparatively simple structure, consisting of only two granites, of which the later has been emplaced inside the earlier.

The *Tof complex* forms the southern prolongation of the massif and is of particular interest because of the association of acid and basic rocks. The earliest member is the large intrusion of gabbro in the Jinni Valley below the Plateau escarpment. This has been intruded and partly surrounded by an arcuate intrusion of granite-porphyry which in places net-veins the gabbro. Intermediate rocks also appear which have resulted from hybridization.

The sequence of intrusion in the Sha–Kaleri complex is summarized in the following table. The three main units have been intruded concurrently and their precise age relationships cannot be determined, although it seems likely that the Kaleri intrusions initiated the cycle of magmatic activity.

MONGUNA COMPLEX	(2) Mofram microgranite (1) Monguna hornblende-biotite-granite
TOF COMPLEX	(4) Late biotite-microgranite (3) Tof plateau porphyry (2) Tof River microgranite (1) Mama gabbro

KALERI COMPLEX	(18) Passa Kai biotite-granite
	(17) The Sha Basin granite-porphyry
	(16) Hotum arfvedsonite-pegmatites
	(15) Hotum arfvedsonite-granite
	(14) Daffo Gorge biotite-granite
	(13) Hotum quartz-felspar-porphyry
	(12) Mbul biotite-microgranite
	(11) Mbul hornblende-fayalite-granite
	(10) Mbul microgabbro
	(9) Daffo hornblende-biotite-granite
	(8) Pitti Basin microgranites
	(7) Bargesh biotite-granite
	(6) Richa granite-porphyry
	(5) Mongor fayalite-granite
	(4) Barrikin William biotite-granite
	(3) Sha–Pitti biotite-granite
	(2) Mbar granite-porphyry
	(1) Rhyolites.

(iii) *The Kaleri Complex*

General features of the complex.—The Kaleri complex provides examples of how minor stoping can considerably modify the form of a ring-complex. At Kaleri, the separate granite intrusions are arranged in a concentric pattern, but the majority show a broad crescentic form in plan and are of limited arcuate extent. Ring-fracturing and block subsidence have certainly been the major tectonic controls in the emplacement of the granites, but the simple ideal patterns of this mechanism have been modified by the development of subsidiary fractures along the trend of the major ring-fractures. In these zones of fracturing both major and minor stoping have occurred during the emplacement of the granites.

In the earliest ring-dyke, the Mbar granite-porphyry, the complex pattern of minor fracturing is clearly demonstrated. Emplacement has been controlled by minor, interlocking polygonal fractures along a wide zone for a distance of 20 miles, resulting in a network of minor dykes in association with the main dyke. There is a close correlation between the direction of the minor dykes and the directional features in the gneissose granite of the Basement Complex.

The later granites in the centre of the complex have smooth, curved boundaries. This is a common feature of ring-intrusions which have been emplaced inside the Younger Granites, in contrast to the polygonal forms which are more common among the narrow ring-dykes cutting the Basement rocks. It appears that the later ring-dykes have been localized by broad zones of ring-fracturing, and that areas of intensive fracturing in these zones have provided favourable loci for crescentic intrusions of limited arcuate extent with broad and blunt terminations. It is also possible that crescentic blocks have been cut off by intersecting ring-fractures of different radii of curvature, and the shapes of such subsided blocks are approximately mirrored in the broad, lenticular intrusions which have taken their place.

Evidence of minor stoping is provided by two of the earlier ring-dykes, the Sha–Pitti biotite-granite and the Richa granite-porphyry, which dip outwards at angles exceeding 80 degrees and in places are over two miles wide. To accommodate such a ring-dyke as a purely permissive intrusion by block subsidence would necessitate a total subsidence of the order of 10 miles, which is far in excess of the amount of subsidence established in comparable structures in other parts of the world. Both these ring-dykes are crowded with xenoliths and pendants of earlier rocks, particularly near their contacts.

Rhyolites.—The rhyolites appear only in the centre and eastern parts of the complex, where they owe their preservation to down-faulting during the emplacement of the ring-dykes. Two distinct types are represented. The earlier lavas, which are typical products of vent extrusion, appear only at the periphery of the main rhyolite mass. They are glassy in texture and strongly flow-banded and autobrecciated. The later rhyolite is more uni form in texture, with crowded quartz and orthoclase phenocrysts in a glassy groundmass. As discussed earlier, such lavas are believed to have been originated by large-scale surface cauldron subsidence rather than by vent extrusion. The rhyolites are poorly exposed, but the general topography suggests that they are at least 400 feet thick and flat-lying. The rhyolites are strongly sheared and mylonitized in the area west of Daffo, between the ring-fractures which have controlled the emplacement of the late Passa Kai and Hotum granites. The rhyolite is traversed by a multitude of minor faults and dislocations and narrow veins of mobilized ultramylonite occur on the fault-planes. In places the rock is completely comminuted to a mass of angular fragments ranging down to microscopic dimensions.

Mbar granite-porphyry.—This intrusion, which initiated the cycle of granite emplacement in the Kaleri complex, occurs as a large ring-dyke which extends for a distance of 22 miles around the eastern and southern margins of the complex. It has filled a ring-fracture which is continuous with the great Sho–Nafam fracture in the Rop complex. As can be seen from Fig. 1, this fracture is one of the main tectonic units of the Jos Plateau. The rock is a coarse-grained hornblende-biotite granite-porphyry showing great variations in the proportion of groundmass. Green hornblende and biotite are the principal mafic minerals and relict crystals of fayalite appear in some of the finer-grained zones of the dyke. An analysis of a similar rock (No. 7) is quoted in Table XI.

Sha–Pitti biotite-granite.—This coarse-grained biotite-granite is probably one of the largest single intrusions in the province. In plan, the intrusion could be described as retort-shaped. It appears as a large circular boss, nine miles in diameter, on the western side of the complex, and as a great ring-dyke extending for 20 miles along the northern and eastern margins. Portions of the northern sections of the intrusion have been cut out by the later Monguna and Mongor granites. The Sha–Pitti granite carries many inclusions of Basement gneiss, particularly in the ring-dyke section. In texture and mineralogy the granite is a typical biotite-granite and the only distinctive feature is an unusually high proportion of free plagioclase which is more basic than usual ($Ab_{82}An_{18}$). To the west, the granite is extensively lateritized. The Barrikin William biotite-granite is intrusive into the western area of the Sha–Pitti granite. It is a porphyritic biotite-granite with which a small amount of tin mineralization is associated.

Mongor granite.—This is a medium-grained hornblende-fayalite-granite which occurs as a lenticular intrusion in the north-eastern corner of the complex. It is identical in texture and mineralogy with the same facies in the Rop complex. It is intrusive into the Sha–Pitti granite and the Mbar granite-porphyry, but its relationship to the later granites of the Kaleri cycle is unknown.

Richa granite-porphyry.—The Richa granite-porphyry forms a ring-dyke that follows the inner margin of the Sha–Pitti granite into which it is intrusive. The contact with the granite is well exposed in the rugged country on the western side of the Mungar Basin, where it can be seen to be dipping outwards at a high angle, exceeding 80 degrees. The ring-dyke is variable in width and encloses many large pendants of Basement gneiss in the Richa and Mungar districts. Like the Sha–Pitti granite, it is probable that a considerable amount of minor stoping occurred during the emplacement of the Richa porphyry.

The northern prolongation of the ring-dyke narrows rapidly and the porphyry here develops a microgranitic texture and is intrusive into the intensely sheared and mylonitized Sha–Pitti biotite-granite. In this area the actual ring-fault is seen and, from the strong shearing of the host granite, it is inferred that this sector remained closed during the block-faulting and the intrusion of the Richa porphyry was prevented. Apparently the Richa fracture zone continued to the west but became more irregular in pattern, as is evidenced by the small, isolated, arcuate intrusions of the Richa porphyry in the northern section of the Pitti Basin. It is possible that there may have been some tilting of the Richa block during subsidence. The Richa porphyry closely resembles the Mbar porphyry in composition but has a finer texture. Biotite is the main mafic mineral, both in the groundmass and as phenocrysts, and is intergrown with minor amounts of hornblende.

The Bargesh biotite-granite.—The Bargesh biotite-granite is one of the major granite intrusions in the Sha–Kaleri complex and has followed the emplacement of the Richa porphyry. The original form of the intrusion has been partly obliterated by the later ring-dykes and granite plutons in the central area of the complex, but it would appear to have been a large elliptical pluton about 10 miles in diameter at the present erosion level.

The contact of the granite and the Basement gneiss is seen in the cliffs below the Farin Ruwa falls and is of hairline sharpness and dips steeply. The contact with the Richa porphyry is well exposed in the hills east of Richa, where it can be followed almost continuously for a distance of about two miles. Here the contact dips outward at a consistently steep angle, exceeding 75 degrees.

The Bargesh granite displays no unusual petrographic features. It is of medium to coarse grain, with clustered anhedral grains of quartz whose margins are intergrown with orthoclase-perthite and albite-oligoclase. Discrete plagioclase is abundant in this rock, although it forms smaller crystals than the mottled orthoclase-perthite. Fluorite is an abundant accessory and is commonly intergrown with the coarse biotite. An analysis of the rock is quoted in Table IV.

Daffo biotite-hornblende-granite.—The Daffo granite occurs in a broad arc which extends from Daffo to the Mungar Basin. It is intrusive into the Richa granite-porphyry, the Bargesh biotite-granite and the rhyolites. In turn it is intruded by the Mbul group of granites and intermediate rocks. The Daffo granite is separated from the Richa porphyry by a screen of rhyolite for a distance of about four miles.

Both the inner and outer contacts with the rhyolites are well exposed and are of vertical dip. A steep dip is also observed on the outer side of the intrusion in the Mungar Basin, where the Daffo granite is in contact with the Bargesh biotite-granite and the Basement complex.

The granite is of fine to medium grain and has a peculiar drusy appearance in the hand-specimen, with a multitude of small cavities. Biotite forms open clusters of small crystals which impart a distinctive appearance to the rock. Hornblende is variable both in proportion and mode of crystallization, and is always greatly subordinate to the biotite and, in places, entirely absent. The granite is exceptionally rich in allanite, which forms large prisms up to 1 mm. in length.

The Mbul group of intrusions.—The Mbul intrusions occur in three separate arcuate outcrops which together form a discontinuous ring-structure within the Bargesh biotite-granite into which they are intrusive. The group appears in a broad arc north-west of Daffo, in a smaller arc north-east of Richa and as a long crescentic body south of Mbul and Bargesh. The ring-intrusion is of a composite nature and includes a succession of rock types which show a progressive increase in acidity from the earlier members to the later. In this regard it is unique in the Younger Granite province. There are abundant examples of the same ring-fracture being utilized as a locus of intrusion for a succession of granite phases, but a basic to acid sequence of intrusions has never been previously observed in the one fracture zone.

In all three exposures there is a similar grouping and sequence of rock types, but the relative areal proportions of the different facies show considerable variation. The sequence of intrusion is as follows :—

(5) Biotite-microgranite
(4) Hornblende-biotite-granite (leucocratic facies)
(3) Hornblende-biotite-granite (melanic facies)
(2) Syenite
(1) Microgabbro

The melanic facies of the hornblende-biotite-granite and the syenite are transitional but the other members of the series are clearly separate intrusions between which definite contacts can be located.

The microgabbro appears in all three exposures but is most abundant in the area north-east of Richa, where it appears as elongated pendants and small xenoliths in the later intermediate and acid intrusions. Some of the basic xenoliths show a measure of hybridization with the enclosing rocks. The xenoliths are embayed and have diffuse outlines and the host rock shows a local increase in the proportion of melanes. It is considered likely that the smaller xenoliths have been carried up from depth by the acid magma and sufficient time has elapsed in this medium to permit some degree of disintegration and reaction of the basic fragments. In contrast, the net-veined zones exhibit no evidence of reaction between the two rocks and the penetrating acid veins are free of the diffuse inclusions which characterize the hybrid zones.

The microgabbro has an ophitic texture with intergrown laths of hornblende and plagioclase of grain-size between 0·5 and 1·5 mm. The plagioclase is an andesine of composition ranging between Ab_{51} and Ab_{57} in the cores and mantled by narrow rims of oligoclase of composition averaging $Ab_{74}An_{26}$. Orthoclase is rare in this rock and appears only as interstitial blebs and discontinuous rims on some of the plagioclases. Many of the dark-green hornblende grains have cores of augite whose boundaries with the surrounding amphibole are diffuse and poorly defined. Reddish-brown biotite amounts to about a quarter of the proportion of the hornblende, with which it is frequently intergrown. Many of the hornblendes are partially altered to chlorite. Serrated needles of iron oxides and elongated prisms of apatite are the main accessory minerals. The later intrusions show a progressive increase in the proportion of the orthoclase at the expense of the plagioclase, which itself becomes increasingly sodic. The character of the melanes remains essentially the same but the overall proportion decreases. Fayalite is abundant in the hornblende-biotite-granites. It is to be noted that no fluorite has been detected in any of the Mbul intrusions, a most unusual feature for amphibole-bearing granites in the province.

Hotum arfvedsonite-granite.—The arfvedsonite-granite forms two lenticular intrusions partly surrounding the rhyolites in the centre of the complex. The granite is blue when fresh, medium-grained and becomes porphyritic near its margins. The granite has steeply dipping contacts in both occurrences. Arfvedsonite is the principal mafic mineral with a small amount of altered fayalite. A conspicuous feature of the rock is the abundance of cognate basic xenoliths which are mainly composed of felted aggregates of arfvedsonite. The inclusions are rounded and embayed and rarely exceed 5 cm. in diameter. Basic inclusions are common in the amphibole-fayalite-granites and granite-porphyries and they are considered to have been derived from earlier basic intrusions into the fracture zones which have been fragmented and incorporated in the later acid magma. The granite displays the unusual appearance of titanite as an accessory mineral.

The Hotum granite commonly develops pegmatites near the margins, and north of Hotum village there is a separate intrusion of pegmatite which follows the northern margin of the main granite for three-quarters of a mile. The Hotum granite has been preceded by the Daffo Gorge biotite-granite, a small lenticular intrusion near the eastern end of the southern body. An analysis of the Hotum granite is quoted in Table XI.

The Passa Kai biotite-granite.—The emplacement of the central boss of Passa Kai biotite-granite marks the close of the Kaleri intrusive cycle. The Passa Kai granite is rich in albite and is variable in texture. It is traversed by many irregular sheets and dykes of microgranite. Greisenization is common and most of the alluvial deposits of tin and columbite in the massif have originated from this granite. It seems likely that only the roof zones of the Passa Kai granite have been exposed. A thin dyke-like prolongation of the granite follows the eastern margin of the Sha–Pitti granite in the Pitti Basin. The contacts with the surrounding rocks are poorly exposed and no reliable estimations of their attitudes can be made.

Basement Complex.—The extensive screens of Basement rocks are an important structural feature of the Kaleri complex. The largest are those between the Mbar porphyry and Sha–Pitti granite in the Mungar and Richa basins, and the broad arcuate area between the Sha–Pitti and Bargesh granites in the headwater region of the Sha River. Because of lower resistance to erosion, the Basement areas form low swampy plains surrounded by the granite hills. Biotite-gneiss is the common rock type, in places highly felspathized and transitional to migmatite. A porphyritic Older Granite adjoins the eastern margin of the complex.

(iv) *The Monguna Complex*

The Monguna complex occupies an area of about 30 square miles at the northern end of the Sha–Kaleri massif, and for a short distance it coincides with the Plateau escarpment. It is comparatively simple in constitution, consisting of only two concentric granites.

The *Monguna hornblende-biotite-granite* is the earliest and most extensive member of the complex. It is elliptical in plan and forms most of the outer margin. The granite is medium-grained and equigranular and rich in equal proportions of green hornblende and biotite. Inwards, the grain-size is reduced and the rock becomes variably porphyritic in texture.

The *Mofram microgranite* occurs as an irregular crescentic intrusion in the north-central area of the complex. Around the northern margin, near the Tenti River, steeply dipping screens of the early Monguna granite have been preserved between the late microgranite and the Basement Complex. The Mofram intrusion is a typical biotite-microgranite with no unusual petrographic features. A small amount of tin mineralization has occurred near the margins of the microgranite in the vicinity of Dambwash and Monguna.

The Monguna granite is intruded by the Richa porphyry and is intrusive into the Sha–Pitti granite at the north end of the Pitti Basin. It is apparent that the Monguna and Kaleri cycles were concurrent.

(v) *The Tof Complex*

The feature of greatest interest in the Tof complex is the association of acid and basic rocks. The earliest member of the suite is the large body of coarse gabbro in the Jinni Valley at the base of the Plateau escarpment. The gabbro occupies an area of four square miles. Unfortunately, the contacts are not exposed; the northern boundary is hidden beneath the enormous screes at the base of the Tof Plateau, while to the south there is a thick soil cover and dense vegetation. A smaller body of the same Pabbro is found on the Tuke Plateau, where it appears to be a roof pendant which has been intricately veined by the Tof Plateau porphyry. Spotted hybrid rocks occur near Tuke Crag.

It seems likely that there were several separate phases of gabbroic intrusion. At Jinni, Ambuga and Tof the gabbro is extremely coarse-grained and composed of almost equal amounts of hornblende and plagioclase. At Tuke and Dafot the rock has an ophitic doleritic texture and a grain-size less than a third of that of the other occurrences. On the extreme eastern flank of the Tuke Plateau there is another medium-grained facies which could be classified as a diorite because of the higher content of plagioclase and the lower colour index.

In the coarse-grained facies the plagioclase forms large rectangular prisms up to 8 mm. in length and is strongly zoned. The cores of the crystals, which range between Ab_{55} and Ab_{61}, grade into an outer rim with a composition of $Ab_{72}An_{28}$. The cores of the plagioclase crystals are often intensely sericitized. Green hornblende and reddish-brown biotite are the main mafic minerals, with the former amounting to more than double the proportion of the mica. Augite cores are often noted in the hornblende crystals, which themselves have undergone extensive chloritization. Ilmenite, pyrite and acicular apatite are the most abundant accessory minerals.

In the finer-grained facies the plagioclase laths range between 1 and 3 mm. and are of composition Ab_{55} to Ab_{45}. Most of the crystals show an outer sodic-rich zone averaging $Ab_{74}An_{26}$. The lath crystals show albite, pericline and Carlsbad twinning and the cores are often intensely sericitized. In some thin sections a small proportion of interstitial quartz is noted. Green hornblende is the principal mafic constituent as elongated prisms and broad laths ranging between 1 and 3 mm. Residual cores of titaniferous augite appear within many of the hornblendes. Reddish-brown biotite occurs usually in intergrowth with the hornblende as felted aggregates of fine crystals. As in the case of the coarse facies, extensive chloritization has affected both the hornblende and biotite.

Iron oxides are the most abundant of the accessory minerals and appear as long serrated needles which interpenetrate all other minerals. Apatite needles are particularly abundant as inclusions within the felspars and often the groups of needles show a parallel or echelon alignment. Small interstitial blebs of secondary calcite occur in association with the mafic aggregates.

There are various hybrid rocks on the Tuke Plateau which are intermediate in composition between the Mama gabbro and the Tof Plateau porphyry. These appear to have resulted from the partial assimilation of the gabbro xenoliths in the granite-porphyry magma. The gabbro occurs both as large pendants and small xenoliths. These inclusions are usually intricately embayed and surrounded by wide zones of hybridized gabbro with strongly segregated melanes and greatly variable proportions of quartz and felspar.

The presence of these hybridized xenoliths is suggestive of piecemeal stoping during the emplacement of the Tof Plateau porphyry. The large blocks and small xenoliths of gabbro appear to have sunk from a higher level into the porphyry magma and sufficient time has elapsed prior to consolidation to permit of reaction and partial assimilation of the gabbro. Both in thin section and in the hand-specimen the gabbro xenoliths can be seen to have undergone various stages of mechanical disintegration, with the liberation of detached individual xenocrysts and microxenoliths.

Near Tof village there is a ring-intrusion of a melanic biotite-microgranite with a low content of free quartz. It surrounds a small zone of Basement and is intrusive into the Bargesh biotite-granite and the Mbar granite-porphyry. This is an unusual rock in the Younger Granite suite, and it has been recorded only in association with basic rocks. It resembles some of the intermediate rocks in the Mbul group of intrusions and may have resulted from hybridization or contamination of acid magma in depth by assimilation of the basic rocks. Alternatively, it may represent a differentiated product of the early gabbro.

The *Tof Plateau porphyry* is extremely variable in texture, grading from a medium-grained granite to a granite-porphyry with the groundmass greatly in excess of the phenocrysts. The proportion of melanes shows an equally great variation. Green hornblende and biotite are the dominant mafic minerals and at Tuke Crag the amphibole amounts to over 10 per cent of the rock. The Tof Plateau porphyry is intrusive into the Bargesh biotite-granite, indicating that the Kaleri cycle was well advanced before the acid members of the Tof cycle appeared. The age of the gabbro in relation to the Kaleri granites is unknown. A small elliptical intrusion of biotite-microgranite in the centre of the Tof Plateau concludes the Tof intrusive cycle.

(vi) *Summary*

The main features of the Sha-Kaleri complex may be summarized as follows :—

1. The coalescence and overlapping in time of three distinct cycles of Younger Granite intrusion.

2. The predominance of crescentic and lenticular intrusions arranged in a concentric pattern over the normal type of elongated and continuous ring-dykes found in other complexes.

3. The great width of the ring-intrusions and the abundance of xenoliths and pendants of earlier rocks indicate that piecemeal stoping has occurred in addition to block subsidence during the emplacement of the granites.

4. The occurrence of rhyolites in the central area of the complex indicates that a phase of volcanism preceded the granite intrusions. The central area has undergone the maximum amount of down-faulting and it is only here that the early rhyolites are preserved.

5. The association of acid and basic rocks and the possibility of contamination of acid magma by basic material is of special interest. The appearance of basic rocks in the Mbul group in the middle of a cycle of acid intrusion is a problem that admits of no ready explanation.

6. The greater number of intrusions in the Sha-Kaleri complex are amphibole-fayalite-granites and in this respect it differs from other Younger Granite complexes of the Jos Plateau. It is noteworthy that there are no riebeckite-granites.

(f) The Jos–Bukuru Complex[1] (Fig. 10)

The Jos–Bukuru complex is the largest single Younger Granite massif in Nigeria and covers an area of 288 square miles in the northern section of the Jos Plateau. Over half the total production of tin and columbite in Nigeria has been derived from alluvial deposits in the vicinity of this granite. The first detailed study of the complex was made by W. N. MacLeod in 1952 during an investigation of the distribution of columbite in the biotite-granites of the Jos Plateau (MacLeod 1956).

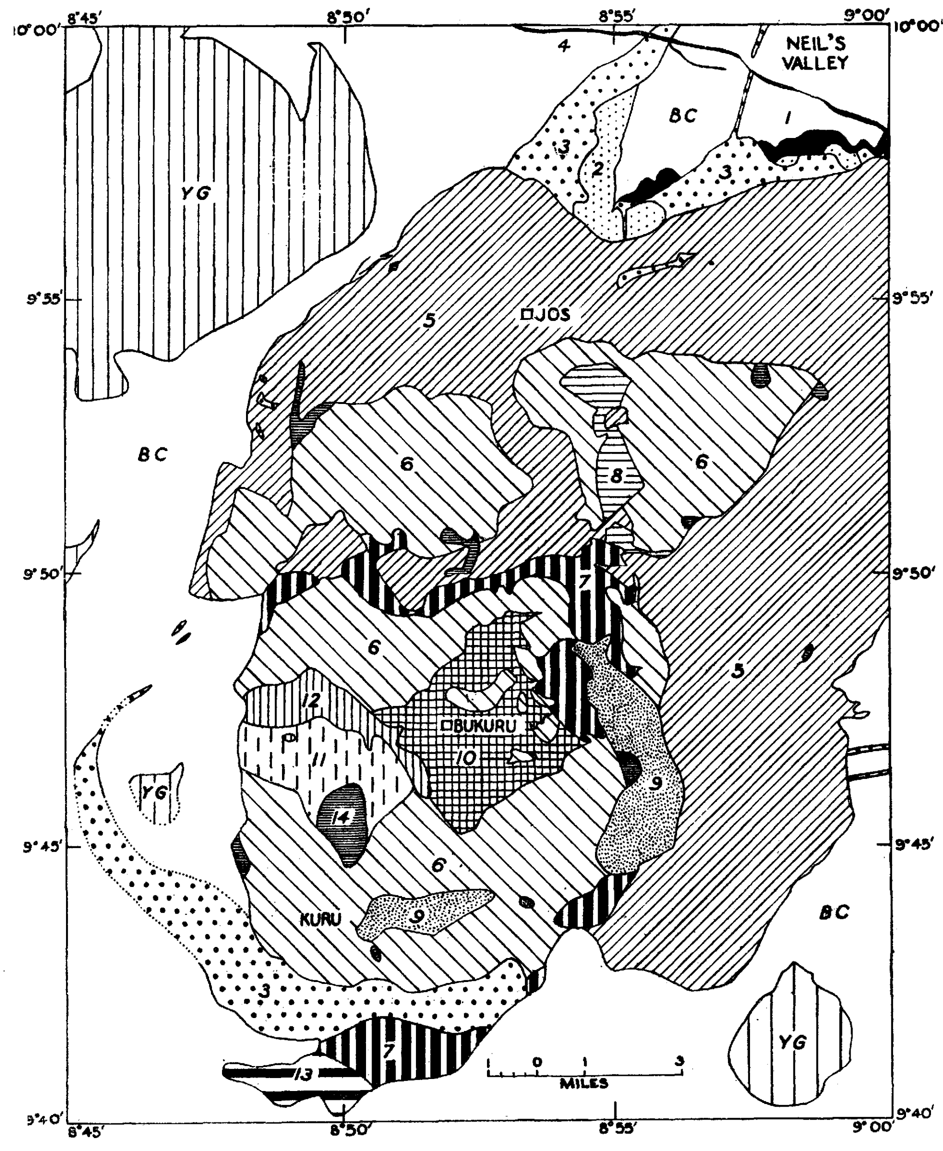


Fig. 10.—Simplified geological map of the Jos–Bukuru complex. (After MacLeod 1956.)

Key

7. Rayfield–Gona biotite-granite
6. N'gell biotite-granite
5. Jos biotite-granite
4. Rafin Jaki granite-porphyry
3. Early granite-porphyry and hornblende-biotite-granite
2. Quartz-fayalite-porphyry
1. Rhyolites

14. Vom road microgranite
13. Kuru biotite-granite
12. Sabon Gida II biotite-granite
11. Sabon Gida I biotite-granite
10. Bukuru biotite-granite
9. Shen hornblende-fayalite-granite
8. Delimi biotite-granite

YG. Younger Granite, undifferentiated
BC. Basement Complex

[1] Part of a thesis for the degree of M.Sc. submitted to the University of Melbourne by W. N. MacLeod, 1953.

The complex displays an extremely intricate pattern of successive granite intrusions but, owing to the low topographical relief and absence of exposures in many critical areas, only an incomplete picture of the structural relations of the component granite phases can be obtained. It is certain that ring-faulting and block subsidence have operated during the initial stages of granite emplacement but the original pattern has been extensively modified by stoping and only vestiges of the original ring-structures can be traced.

The sequence of magmatic activity can be subdivided into a volcanic cycle and three cycles of granite intrusion. The separate intrusive cycles have been directly superimposed, in contrast to those of the Sha–Kaleri complex, which are sufficiently separated to be readily recognizable. For this reason the intrusive pattern of the Jos–Bukuru complex has been rather more difficult to interpret. The sequence of activity is outlined in the following table :—

Late granitic cycle	(15) Sabon Gida II biotite-granite
	(14) Sabon Gida I biotite-granite
	(13) Bukuru biotite-granite
	(12) Shen amphibole-fayalite-granite and granite-porphyry
Shere granite cycle	(11) Albite-riebeckite-granite
	(10) Riebeckite-granite
	(9) Hornblende-fayalite-granite
Early granitic cycle	(8) Kuru biotite-granite
	(7) Delimi biotite-granite
	(6) Rayfield–Gona albite-biotite-granite
	(5) N'gell biotite-granite
	(4) Jos biotite-granite
	(3) Neil's Valley hornblende-biotite-granite and granite-porphyry
Volcanic cycle	(2) Quartz-fayalite-hedenbergite-porphyry—Neil's Valley
	(1) Rhyolites and quartz-porphyries

The age of the Shere cycle in relation to that of the late granitic cycle is indeterminable but both are known to follow the early granitic cycle.

The main outline of the massif has been determined by a major ring-fracture which extends around the southern, western and northern boundaries of the complex and which probably includes the large Jarawa massif to the east. This great fracture is one of the major tectonic features of the Jos Plateau as shown in Fig. 1. Minor ring-fractures have developed along the trend of this major fracture in the same fashion as those in the Mbar fracture system in the Sha–Kaleri complex. Some of these subsidiary structures are preserved at the northern end of the complex and in the Jarawa Valley on the eastern side. The Neil's Valley ring-structure has been described by Mackay (1949). Early extrusive rhyolites and pyroclastic rocks have been preserved on the floor of the valley in the centre of this structure as a result of down-faulting. As at Buji, the early volcanic rocks have been succeeded by a high-level intrusion of quartz-fayalite-hedenbergite-porphyry.

Amphibole-granites and granite-porphyries have been intruded into this major fracture as the earliest members of the Jos–Bukuru granitic cycle. A broad, arcuate intrusion of coarse-grained hornblende-biotite-granite occurs in the south-western corner of the massif and can be traced around the western margin to connect with the northern section of the great Neil's Valley ring-dyke in which the rock alternates between an equigranular granite and a granite-porphyry. The same granite also appears at the northern end of the Jarawa complex and in the Fusa Valley near the south-eastern corner of the complex. It is possible that the entire area now occupied by the granites of the Jos–Bukuru cycle was originally segmented and cut by a network of interlocking dykes of the early granite-porphyry. Only the peripheral zones of this structure have escaped obliteration during the late period of large-scale granite intrusion. This is the largest individual ring-structure in Nigeria, with a maximum diameter approaching 35 miles.

The Neil's Valley ring-structure is traversed diagonally by the great arcuate dyke of the Rafin Jaki granite-porphyry. This dyke has been traced for a distance of 23 miles and extends as far east as the Jarawa massif from a point a few miles north of Jos. The porphyry is of later age than all other rocks in the Neil's Valley ring-complex, and is provisionally correlated with the later arcuate granite-porphyry intrusions within the Jos–Bukuru massif to which it bears a similar alignment.

In appearance the Rafin Jaki porphyry is one of the most remarkable in the province. It carries large ovoidal phenocrysts of felspar up to two and a half inches in diameter associated with rounded quartz and coarse clusters of amphibole and biotite. The perthite cores of the felspar have often been replaced by granophyre and there is usually an outer rim of sodic plagioclase. Inclusions of amphibole are commonly found within the composite felspars.

A feature of the rock is the high proportion of doleritic inclusions, which range in size from a few millimetres to blocks exceeding two feet in diameter. Inclusions of Basement gneiss are rarely seen and it seems likely that the basic material represents an earlier injection into the Rafin Jaki fracture zone which has been disrupted and incorporated by the later granite-porphyry. Mackay (1949) considers that the large felspar phenocrysts are of post-consolidation origin.

The early amphibole-granite and granite-porphyry have been succeeded by the Jos biotite-granite, which is one of the largest single granite intrusions in the entire province. It covers an area of nearly 100 square miles in the north-central part of the complex and its original extent must have been much greater than the present exposures. Other biotite-granites have followed the Jos phase and are termed, in order of intrusion, the N'gell, Rayfield–Gona and Delimi granites. The Rayfield–Gona albite-biotite-granite has proved to be the richest in accessory columbite of all the biotite-granites in the province, and it has been the subject of detailed economic investigation (MacLeod 1956; Williams & others 1956). The columbite values range between 0·5 and 7·0 pounds per ton and great areas of the granite are decomposed to the consistency of clay.

Near Rayfield, about four miles south-east of Jos, there is an intensely albitized zone of the granite which has been mined for primary columbite during the last four years. Here the granite is decomposed to depths exceeding 150 feet. The columbite-rich facies differs from the normal granite in that it contains a higher proportion of late deuteric albite as broadly twinned laths, and the texture is similar to that of the pyrochlore-bearing albite-riebeckite-granites. It is apparent that there is a geochemical relation between niobium and soda in the Younger Granite province. Another zone of highly albitized granite, rich in columbite, has been found in the Afu Hills to the south-west of Jos.

The Rayfield–Gona granite is a ring-intrusion of low outward dip which, for a considerable distance, has followed the junction between the Jos and N'gell granites. Along the northern limb the intrusion dips to the north at angles between 5 and 25 degrees. Lack of exposures prevents the determination of the attitude of the contact on the eastern and southern limbs of the granite. It is considered to be a truncated dome in which only the upper zones of the granite are exposed at the present erosion level.

The late granitic cycle was initiated by two large, lenticular intrusions of amphibole-bearing granites in the central area of the complex. The eastern mass of the late porphyry at Shen is a composite intrusion in which five separate facies of amphibole-granite and granite-porphyry can be recognized. The Shen porphyries have been followed by three later biotite-granites, all of which are rich in albite and extensively greisenized. The Sabon Gida biotite-granites have been the source rock of most of the rich alluvial tin deposits in the lower N'gell Valley. Wolfram is present, in addition to cassiterite, in some of the lodes.

The Shere complex, at the north-eastern corner of the Jos–Bukuru massif has not yet been studied in detail but is known to include quartz-fayalite-porphyry, hornblende-fayalite-granite, riebeckite-granite and albite-riebeckite-granite. The hornblende-fayalite-granite is rich in fergusonite, a niobate of the rare earths, and rich alluvial concentrations of this mineral are found in the Jarawa Valley on the eastern side of the Shere Hills. This granite is highly resistant to erosion and forms most of the high hills in the central region of the massif, some of which rise to nearly 6000 feet above sea-level.

(g) The Banke Complex

This complex occupies the third corner of a triangle formed with the Liruei and Kudaru complexes. The geological mapping has not been completed but sufficient work has been done to reveal the essential structural features. The complex is of a simple general pattern with three main units : rhyolite, granite-porphyry and biotite-granite.

The rhyolite forms an extensive plateau, measuring six miles by four, in the northern half of the complex which, in places, rises nearly 1000 feet above the plains. The Banke rhyolite is practically homogeneous both laterally and vertically and presents a sharp contrast to the rhyolites in the Liruei complex. The rhyolite carries abundant quartz and felspar phenocrysts in a blue-grey glassy groundmass. The mafic minerals are too poorly crystallized for accurate determination. As has been mentioned earlier, these large bodies of homogeneous lava are believed to have resulted from surface cauldron subsidence rather than from vent activity. The heterogeneous vent rhyolites, which appear to form only a minor component of the Banke complex, occur near the base of the southern escarpment of the cauldron rhyolite (see Fig. 8).

The granite-porphyry forms a narrow and discontinuous ring-dyke around the southern half of the complex. It shows the abrupt changes in direction and width characteristic of such narrow dykes when they cut the Basement. Zones of intensive shearing with thin veins of ultra-mylonite have been noted in the Basement near the dyke.

The biotite-granite appears as an irregularly shaped intrusion in the centre of the complex and it probably extends to the north beneath the rhyolite plateau. It is a typical biotite-granite with a small amount of tin mineralization and low columbite values. Intensive greisenization has occurred in the Basement near the contact, and some wolfram has been mined in the past.

(h) The Kudaru Complex (Fig. 11)

The Kudaru complex has been described by Bain (1934) and was the first ring-complex to be recognized in the Younger Granite province (Fig. 11). It bears a general structural similarity to the nearby Liruei complex but differs in the absence of extrusive rhyolites and in the presence of spectacular swarms of cone-sheets. The essential structural components of the complex are summarized as follows :—

(4) Late quartz-porphyries and microgranites	— post-granite cone-sheets and radial dykes
(3) Riebeckite-, biotite- and amphibole-fayalite-granites	— plutons
(2) Quartz-porphyries and intrusive rhyolites	— pre-granite cone-sheets
(1) Quartz-pyroxene-fayalite-porphyry	— ring-dyke

The quartz-pyroxene-fayalite-porphyry forms an impressive ring-dyke which extends almost completely around the complex for a distance of $22\frac{1}{2}$ miles. The complex is oval in outline, the axes measuring $7\frac{1}{2}$ and 11 miles. The ring-dyke is separated from the granitic core of the complex by a wide screen of Basement gneiss and has clear topographical definition. The pre-granite cone-sheets are confined within this screen and show a general inward dip towards the centre of the granite which varies between 30 and 65 degrees. Bain has calculated that the focus of the sheets lies about three miles below the present surface. The cone-sheets are clearly seen as low rocky ridges rising above the level Basement area. Some of the sheets exceed 200 feet in thickness and cannot be distinguished as individuals in areas of dense concentration.

The major granite intrusion is of riebeckite-granite. There is a small marginal intrusion of biotite-granite and a late central intrusion of amphibole-granite. A later swarm of cone-sheets and radial dykes of quartz-porphyry completes the magmatic cycle.

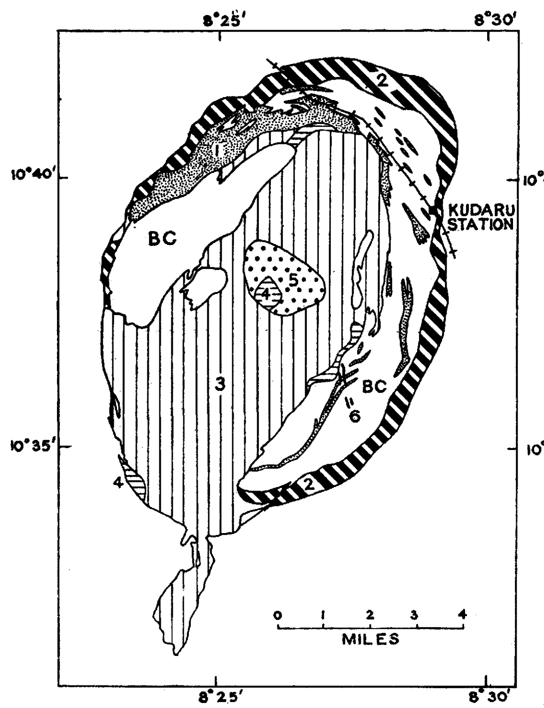


FIG. 11.—Simplified geological map of the Kudaru complex. (After Bain 1934.)

KEY

6. Late radial dykes : quartz-porphyries
5. Hornblende-fayalite-granite
4. Biotite-granite
3. Riebeckite-granite
2. Ring-dyke : quartz-pyroxene-fayalite-porphyry
1. Cone-sheets : quartz-porphyries and felsites

BC. Basement Complex.

(i) The Ningi Complex

The Ningi complex lies at the eastern end of the extensive Burra–Kah–Ningi massif. This massif covers an area of about 350 square miles and probably includes at least three contiguous Younger Granite complexes. Of these, only the Ningi complex has been mapped in detail (Jacobson & Jaques 1944). The structure of the Ningi complex is seen to be similar to that of Liruei (see Pl. VII). A complex granite-porphyry ring-dyke extends almost entirely around the perimeter with minor prolongations into the central block. The form of the ring-dyke suggests a system of concentric and radial fractures which have been filled with the granite-porphyry during block subsidence. The centre of the structure is occupied by rhyolites, and both biotite-granites and subordinate riebeckite-granites are present.

(j) The Tongolo, Dagga Allah and Kwandonkaya Complexes (Fig. 12)

These complexes form a group of contiguous massifs situated to the north of the Jos Plateau. Detailed study of the area is not yet complete but the main structural features have been established.

The *Tongolo complex* covers an area of 32 square miles and includes a wide variety of rock types. There are indications of an early volcanic cycle. Rhyolites occur as pendants enclosed in the granite-porphyry on the north-eastern side of the complex, and in association with vent agglomerates which form a vertical screen separating the granite-porphyry ring-intrusion from the Older Granite. This structure is similar to the pattern of volcanic activity at Liruei and Buji.

Cone-sheets composed of felsite and spherulitic rhyolite cut the Older Granite to the north of the massif. They range between 1 and 10 feet in thickness and dip to the south at about 30 degrees. The

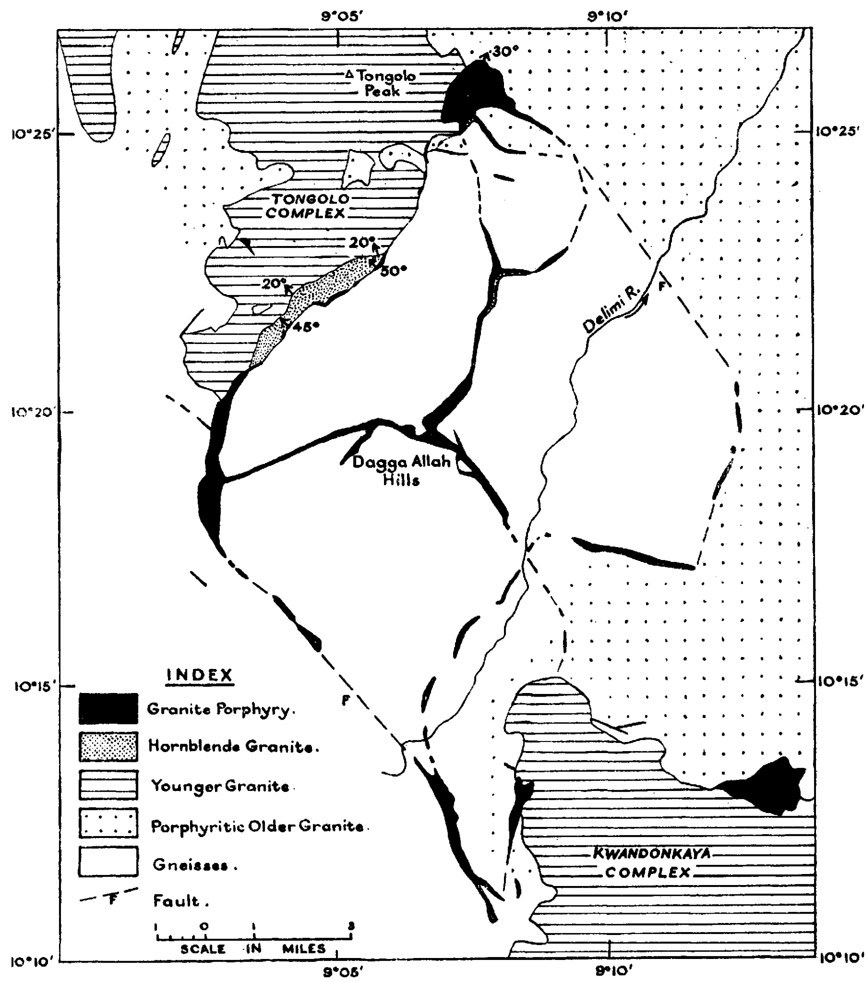


FIG. 12.—Simplified geological map of the Tongolo, Dagga Allah and Kwandonkaya complexes.

granite-porphyry initiates a cycle of granite intrusion which includes six successive phases of biotite-granite, one of which is an albite-rich variety with high columbite values. There is a late intrusion of riebeckite-granite in the centre of the complex which has probably been emplaced by cauldron subsidence. A narrow screen of one of the earlier biotite-granites is preserved along the northern boundary of the riebeckite-granite with the Older Granite.

The *Dagga Allah complex* consists of a spectacular network of polygonal dykes composed of hornblende-granite and granite-porphyry which link the Tongolo and Kwandonkaya complexes (see Fig. 12). The dykes form a series of closed loops with a total diameter of about 11 miles. The hornblende-granite and granite-porphyry are intrusive along the south-eastern margin of the Tongolo massif and dip to the north-west at angles between 25 and 50 degrees. The enclosed blocks of Basement are composed of gneiss which has been down-faulted into contact with the Older Granite outside the structure. This is clearly revealed about two miles south-east of Tongolo Peak, where the faulted boundaries between the Older Granite and the gneisses are defined by narrow dykes of granite-porphyry. It is also of interest to note that the segmented margins of the sinking block have undergone less subsidence than the centre. It is possible that at an earlier stage of erosion the entire area enclosed by the Dagga Allah fracture system was overlain by horizontal or low-dipping sheets of amphibole-granite and granite-porphyry, and the similarity between this structure and that of the Rop complex is noteworthy.

The *Kwandonkaya complex,* which covers an area of 74 square miles, is entirely granitic. The hornblende-granite and granite-porphyry, which form the Dagga Allah structure, are the earliest members of the intrusive cycle in the Kwandonkaya complex. They have been succeeded by four separate phases of biotite-granite. An early swarm of quartz-felspar-porphyry dykes occurs along the north-eastern flank of the complex.

The most interesting tectonic feature is the preservation of part of the horizontal roof-structure at Ziem Peak in the south-east. The peak, which rises 2000 feet above the surrounding plains, is capped by a flat-lying remnant of early amphibole-granite. Beneath the amphibole-granite there is a narrow horizontal screen of a later biotite-granite with another fine-grained biotite-granite below. The main body of coarse biotite-granite appears at the base of the fine-grained biotite-granite several hundred feet below the screen. There is clear evidence that the coarse biotite-granite was down-faulted during the emplacement of the late fine-grained granite. A similar type of structure has been described in the Rop complex, where the horizontal fracture plane has also closely followed the contact between two intrusions.

(k) The Kofayi Complex (Fig. 13)

This complex is situated to the south-east of the Kwandonkaya massif and is of importance because of the relationships displayed between the acid and basic rocks. The complex is oval in plan with a maximum diameter of about three miles.

There are four structural units at Kofayi which are clearly defined topographically. The earliest member of the suite is a gabbro which forms the low-lying, marshy ground in the central and south-eastern parts of the complex. Along its western and north-eastern margins, the gabbro is closely net-veined by acid material and this zone of injection outcrops in the form of low pyramidal hills. The third unit consists of granite and granite-porphyry which form the compact hills at the northern end of the structure. Finally, the central and southern parts of the complex are traversed by low ridges of microgranite which form part of a ring-structure that determines the outline of the complex.

The order of intrusion is from basic to acid. The early gabbro forms the core of the structure and is cut by numerous dolerite dykes which increase in abundance towards the edge of the mass. Owing to poor exposures, the form of the gabbro intrusion is unknown, but the irregular shape and discordance with the later acid ring-structure suggests that it may have had a different tectonic history from that of the granites.

The zone of acid injection on the flanks of the gabbro displays spectacular examples of net-veining. The acid material was injected under considerable pressure. The dolerite dykes have often served as planes of weakness along which injection has occurred, and many examples are seen where the walls of the dykes have been prised apart by the acid material. Transitions are encountered between zones of close net-veining where only the intrusive acid material has been mobile and zones of intrusive brecciation in which the entire mass of composite material has been mobilized. Reaction between the microgranite and the basic host rock is common and all degrees of hybridization and contamination are to be seen.

The hills at the northern end of the complex are composed of granite-porphyry, biotite-granite and microgranite. The biotite-granite is identical with the early biotite-granite in the Kwandonkaya complex.

The granite on the southern flanks of the hill contains abundant basic xenoliths and appears to be gradational into the zone of early acid injection.

The ring-dyke is well developed in the southern half of the area. It is mainly composed of biotite-microgranite, but there are local transitions into a hornblendic facies. At the southern end of the complex the ring-intrusion consists of a number of parallel, vertically dipping branches which form chords to the outer arc. Along the eastern margin the microgranite is crowded with basic xenoliths aligned parallel to the trend of the dyke.

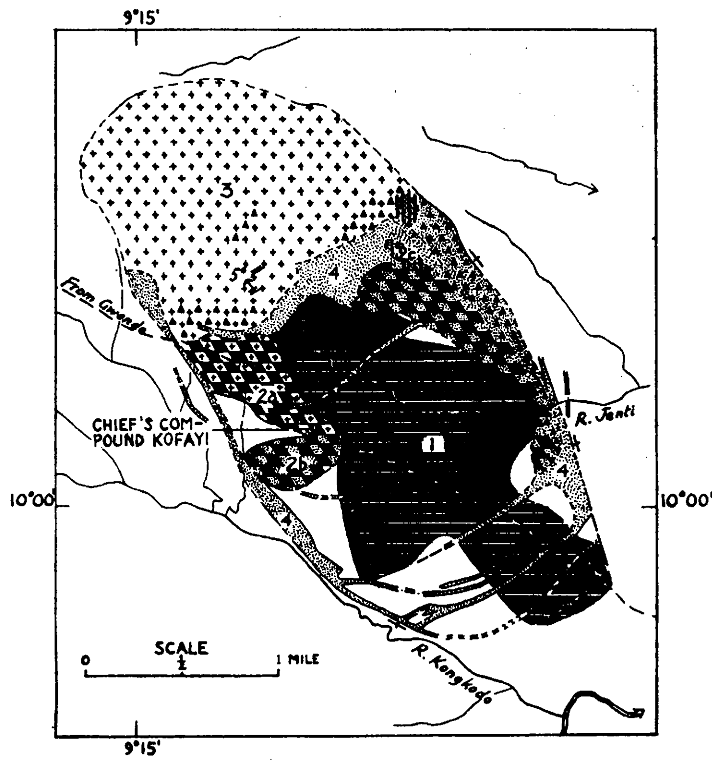


FIG. 13.—Simplified geological map of the Kofayi complex.

KEY

4. Biotite- and hornblende-microgranites
3. Granite-porphyry, biotite-granite and microgranite
2 (c). Zone of acid injection. Diorite and dolerite invaded by fine-grained intermediate and acid material
2 (b). Zone of acid injection. Gabbro and dolerite invaded by fine-grained intermediate and acid material
2 (a). Zone of acid injection. Gabbro and dolerite invaded by biotite-granite
1. Gabbro

(l) The Sutumi and Kunkur Complexes

These small complexes appear as prominent, isolated hills a few miles to the north-east of the Kwandonkaya massif (see Pl. VII). They are among the simplest types of volcanic structure found in the province. They are essentially eroded volcanic plugs which have served as centres of minor granite intrusion.

D. Sutumi covers an area of about one square mile and rises several hundred feet above the Bauchi plains. Intrusive rhyolite and vent agglomerate are preserved along the south-eastern margin of the hill as a vertical screen between the Basement and the succeeding granite-porphyry. The granite-porphyry, which forms the core of the hill, is intruded by biotite-granite on the north-eastern and southern flanks.

D. Kunkur covers less than one-quarter of a square mile in area and is composed of vent agglomerate, vertically dipping rhyolite and granite-porphyry. Numerous intrusions of felsite, some of which may be cone-sheets, cut the Basement between the two hills.

(m) The Miango Granite

This intrusion is situated on the western side of the Jos–Bukuru complex (see Pl. VII) and represents a simple case of the emplacement of granite by block subsidence. The granite is crescentic in plan and encompasses an arc of about 180 degrees. The diameter of the arc is five miles and the area covered by the granite is about five square miles. A granite-porphyry ring-intrusion outcrops along the western limb of the structure as a thin sheet dipping at 40 degrees to the west. This dyke thins out to the north and eventually passes into a zone of mylonitized Older Granite which probably represents the northerly continuation of the ring-fault. The main subsidence which followed permitted the emplacement of the biotite-granite which forms the southern and eastern limbs of the structure. The intrusion is widest at the southern end, and the contact with the Older Granite has an outward dip of 60 degrees. The form of the Miango intrusion suggests that some tilting of the block occurred during subsidence (cf. Oftedahl 1953).

A swarm of microgabbro dykes cuts the Older Granite to the north-west of the Miango structure. The largest of these can be traced for a distance of 10 miles and locally attains a width of 200 feet. The dykes predate the Younger Granite since they are sometimes truncated and silicified by the Miango granite.

(n) The Rukuba Complex

This massif covers an area of about 50 square miles in the north-western region of the Jos Plateau. It represents a simple type of Younger Granite structure with two eccentrically placed plutons of which the later has cut out the northern section of the earlier. Large roof-pendants of an early hornblende-biotite-granite occur in the biotite-granite of the southern pluton. The sequence of granites is as follows :—

(3) The Timber Creek biotite-granite — northern pluton
(2) The Rukuba biotite-granite — southern pluton
(1) Early hornblende-biotite-granite

The Rukuba biotite-granite, which has a diameter of six miles, appears as an almost circular pluton in the southern half of the complex. It is a typical medium-grained biotite-granite which shows little textural variation. The proportion of albite increases towards the eastern boundary and there are numerous minor irregular intrusions of albite-biotite-granite, some of which carry high columbite values.

The Timber Creek albite-biotite-granite is intrusive into the northern part of the Rukuba granite and also transgresses the southern section of the Amo complex. It also is circular in plan and on the western margin is seen to have a sharp, steeply dipping contact with the Basement. Minor alluvial deposits of tin and columbite are found in the vicinity of the granite, and the pegmatites at the northern contact are exceptionally rich in well-crystallized topaz.

(o) The Jere–Sanga Complex

This small complex is situated about 25 miles north of Jos and occupies an area of about 30 square miles. It includes the only known example of a syenite ring-dyke in the province. There are only four units in the complex : (1) Limoro syenite, (2) early biotite-granite, (3) riebeckite-granites, (4) late biotite-granite.

The Limoro syenite forms an elongated polygonal ring-dyke in the north-western area of the complex. The southern extension of the dyke has been obliterated by the later granite intrusions. Near Limoro village, the syenite intrusion swells out to a square plug which forms the prominent hill mass of D. Limoro. The syenite is mainly composed of orthoclase and hornblende with subsidiary andesine. Augite appears in the cores of some of the hornblende crystals. There is a small amount of free quartz and an abundance of fluorite.

The early biotite-granite is a broad crescentic intrusion which extends across the massif in a E.–W. direction. This granite has been intruded by two lenticular bodies of riebeckite-granite which form the two highest hills of the complex, D. Jere and D. Sanga. The D. Sanga intrusion is composed of a riebeckite-biotite-granite with the highest proportion of riebeckite in the core of the body and a predominance of biotite in the outer zones. In the central area there is a small irregular intrusion of late biotite-granite and a narrow arcuate tongue of granite-porphyry.

(p) The Sharwai Granite

The simplest type of Younger Granite intrusion is exemplified by the small Sharwai stock which lies about five miles south-west of the Tof complex in the Mama district below the escarpment of the Jos Plateau. The intrusion is elliptical in plan, with the longer and shorter axes measuring one and a half and half a mile respectively. The pluton cuts directly across the N.–S. trend of the foliation of the surrounding gneisses, but the boundaries are too poorly exposed to reveal the attitude of the contacts. It may represent a cupola of a larger deep-seated granite body.

The Sharwai stock is entirely composed of a white albite-biotite-granite which becomes porphyritic and finer-grained towards the margins. Pegmatites and greisens are common in the boundary zones and have given rise to restricted tin deposits. An unusual feature of the Sharwai granite is the absence of perthitic felspars. Albite (Ab_{94}) and orthoclase occur in almost equal proportions and, except for occasional interfacial intergrowths, are entirely discrete. The albite appears mainly as small euhedral laths which replace both the quartz and felspar. The biotite is the pale-green variety which is typical of the albite-biotite-granites and is almost invariably intergrown with fluorite. Despite the highly albitic nature of the granite, no columbite has been detected in the surrounding alluvial deposits.

IV. Summary and Comparison with Other Regions

There are a great number of complexes in the province which have not yet received detailed study but, from the information gained during the early and more recent reconnaissance surveys, it is apparent that many of these conform closely to the same structural patterns as those described in the foregoing pages.

Although many transitional types exist, it can be said that the complexes fall into two broad groups. Many of the northern massifs display a comparatively simple cycle of magmatic activity. Early volcanism has been succeeded by the intrusion of a single ring-dyke, usually an amphibole-fayalite granite-porphyry, which in turn has been followed by one or two phases of granitic intrusion. The granite cycle often begins with biotite-granite, which is succeeded by riebeckite-granite. Liruei, Ningi, Banke and Kudaru best exemplify this sequence of activity. The granites themselves are usually medium-grained in texture, of limited areal extent, and show little variation from complex to complex. The early volcanic rocks cover great areas and basic rocks are common but of restricted extent. In the complexes which lie north of latitude 10° the rhyolites cover as large an area as the granites.

A different pattern prevails in the complexes which occur in the central and southern regions of the province, including those of the Jos Plateau. These complexes are much larger and predominantly granitic in composition, while more intricate structures are encountered, due to the coalescence and superposition of separate intrusion cycles. The individual granite intrusions within the complexes are considerably larger and more diverse. On the other hand, the occurrences of rhyolites and basic rocks are comparatively restricted. The large size and close proximity of the complexes on the Jos Plateau suggest that this area has been the focal point of Younger Granite magmatic activity.

In a magmatic province of this nature, where such a pronounced repetition of rock types has occurred, it is tempting to endeavour to establish an age correlation between the individual cycles of intrusion. This can be partly done by direct methods on the Jos Plateau, where some of the complexes are continuous. Elsewhere in the province, petrographic affinity is the only available criterion and, in the present state of knowledge, this is of doubtful validity. On this criterion, however, there is some evidence which suggests that the intricate Plateau complexes may be of later age than the simpler complexes in the northern part of the province.

The coarse-grained, distinctive, hornblende-biotite-granite which is encountered in all the Plateau massifs has not been recorded in the extreme northern part of the province. In the Tongolo complex this granite appears at the conclusion of a granitic cycle in which the typical medium-grained biotitic and riebeckitic facies of the northern complexes are the forerunners. The same hornblende-biotite-granite initiates the cycle of intrusion in the Kwandonkaya complex, which lies immediately to the south of Tongolo. This same granite then appears early in the intrusive cycles of all the large granitic massifs of the Jos Plateau. It may well be that this rock type marks the initiation of the later " Plateau stage " of Younger Granite activity. The majority of rock types in the province show such slight differences in chemical composition and such variations in the sequence of intrusion in different complexes that it has not been possible to form any coherent picture of the chemical evolution of the magma.

Greenwood (1951) has drawn attention to the close petrological and structural similarity which exists between the Nigerian Younger Granites and the White Mountain magma series of New Hampshire. More recent mapping of various Younger Granite complexes has emphasized the structural similarity of these two petrographic provinces. There is an almost exact parallel between the form and size of the individual ring-intrusions in Nigeria and New Hampshire. The ring-intrusions range from complete ring-dykes which encompass 360 degrees of arc to broad lenticular intrusions of limited arcuate extent. Most of the Nigerian ring-intrusions extend for less than 200 degrees of arc, a figure which is in close accordance with that of the New Hampshire ring-dykes (see Kingsley 1931 ; Chapman 1935, 1942 ; Chapman & Williams 1935 ; Modell 1936 ; Billings 1943, 1945).

As in New Hampshire, most of the Nigerian ring-dykes are either vertical or dip steeply outwards, and they often provide clear evidence of emplacement by piecemeal stoping. In many examples the control exerted on the form of the ring-intrusions by the development of minor radial, tangential and polygonal fractures within broad annular zones of disturbance is clearly demonstrated. In Nigeria it is apparent that the ring-dykes have been emplaced both by permissive intrusion due to simple cauldron subsidence and by piecemeal stoping into arcuate fracture zones. Often the two mechanisms of ring-emplacement can be observed in different parts of the one intrusion, and for many of the ring-intrusions in the Nigerian province the term " ring-fracture zone " is more appropriate than " ring-fault ".

Petrologically, the Nigerian Younger Granite province differs from the White Mountain magma series in the greater preponderance of highly acid rocks. The majority of the ring-dykes in New Hampshire are of intermediate to sub-acid composition, whereas those of Nigeria are of essentially the same high degree of acidity as the succeeding granite stocks and plutons. In the White Mountain magma series Chapman & Williams (1935) and Billings (1945) have established a correlation between the tectonics of the province and the chemical evolution of the magma. Unfortunately, this cannot be done with precision in Nigeria owing to the general highly acid nature of the rocks and the diversity of their intrusive forms. Important features common to both provinces are the late appearance of biotite-granite as large plutons and the early volcanism which precedes the intrusion of the ring-dykes and plutons.

In New Hampshire it has been possible in some cases to estimate the extent of subsidence from the degree of tilting of the lavas within the ring-structures near the peripheral ring-faults (Kingsley 1931). This method is not applicable in Nigeria, as the peripheral rhyolites have often been obliterated by later granite intrusions, and differential subsidence and tilting of segmented blocks within the cauldrons have modified the attitude of the lavas. Peripheral tilting of the early lavas has been recorded only in one complex, and there the exposures are too poor to permit a clear resolution of the stratigraphic succession of the flows.

From the study of the ring-complexes in the Oslo region, Oftedahl (1953) has demonstrated that considerable tilting of the blocks often occurs during cauldron subsidence, and in the Baerum cauldron an accurate estimation of the amount of tilting can be made. Steepening of the attitude of the peripheral lavas near the ring-fault is frequently recorded and, in the Glitrevan cauldron, this is attributed to an inward dip of the ring-fault. Unequivocal evidence of tilting during block subsidence has not been established in Nigeria but the form of some of the ring-intrusions strongly suggests that it may have occurred. In the Richa granite-porphyry of the Kaleri complex there is extensive crushing of the wall-rocks along the line of the ring-fault in the zone where no magma has entered, and the intrusion is widest at a point almost diametrically opposite to the crush zone. This could possibly indicate that the sinking block remained jammed against one side of the ring-fault and tilted during subsidence.

The closest parallels between the Nigerian granites and the ring-complexes in the British Tertiary province are found in the smaller volcanic complexes such as Liruei and Buji. An important feature of comparison is the localization of vents by ring-fractures, as is demonstrated by Buji in Nigeria and at Ardnamurchan and Slieve Gullion in the British province (Richey & others 1930, Richey 1932B). The Ard Bheinn complex of Arran (King 1955) has many structural features in common with the Buji and Liruei complexes. As in the case of Mull and Ardnamurchan, many of the Nigerian ring-complexes reveal a progressive shift of the focus of intrusion during the cycle of activity. Cone-sheets are less common in Nigeria and show greater irregularity of pattern in comparison with the cone-sheets in Britain. In addition, the Nigerian cone-sheets are entirely of acid composition and are of greater maximum thickness.

To sum up, it may be said that the importance of the Younger Granite province resides in two main aspects. Firstly, it provides a clear demonstration of the succession of magmatic activity from volcanism to high-level granite emplacement. Secondly, it exemplifies the great range of structural patterns and tectonic processes associated with the emplacement of granites by cauldron subsidence.

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V. List of References

Bain, A. D. N. 1934. The younger intrusive rocks of the Kudaru Hills, Nigeria. *Q.J.G.S.* **90**, 201–39.

Beer, K. E. 1952. The petrography of some of the riebeckite-granites of Nigeria. *Rep. Geol. Surv. Atomic Energy Div.* **116**, 1–38.

Billings, M. P. 1943. Ring-dikes and their origin. *Trans. N.Y. Acad. Sci.* **5**, 131–44.

——. 1945. Mechanics of igneous intrusion in New Hampshire. *Am. Journ. Sci.* **243A**, 40–68.

Bowen, N. L., & J. F. Schairer. 1935. The system MgO–FeO–SiO_2. *Am. Journ. Sci.* (5) **29**, 151–217.

—— & ——. 1938. Crystallization equilibrium in nepheline–albite–silica mixtures with fayalite. *Journ. Geol.* **46**, 397–411.

Chapman, R. W. 1935. Percy ring-dike complex. *Am. Journ. Sci.* (5) **30**, 401–31.
——. 1942. Ring structures of the Pliny region, New Hampshire. *Bull. Geol. Soc. Am.* **53**, 1533–68.
—— & C. R. Williams. 1935. Evolution of the White Mountain magma series. *Am. Min.* **20**, 502–30.
Clough, C. T., H. B. Maufe & E. B. Bailey. 1909. The cauldron-subsidence of Glen Coe, and the associated igneous phenomena. *Q.J.G.S.* **65**, 611–78.
Delany, F. M. 1955. Ring structures in the northern Sudan. *Eclog. Geol. Helv.* **48**, 133–48.
Falconer, J. D. 1921. The geology of the Plateau tin fields. *Bull. Geol. Surv. Nigeria*, **1**.
—— & C. Raeburn. 1923. The northern tinfields of Bauchi Province. *Bull. Geol. Surv. Nigeria*, **4**.
—— & others. 1926. The southern plateau tinfields. The geology of Mama. *Bull. Geol. Surv. Nigeria*, **9**.
Garde, G. 1911. Description géologique des régions situées entre le Niger et le Tchad et à l'est et au nord-est du Tchad. Paris.
Greenwood, R. 1951. Younger intrusive rocks of Plateau Province, Nigeria, compared with the alkalic rocks of New England. *Bull. Geol. Soc. Am.* **62**, 1151–78.
Jacobson, R. R. E., & E. H. Jaques. 1944. Report on wolfram investigations. *Geol. Surv. Nigeria, Ann. Rep. 1942*, 5–13.
—— & J. S. Webb. 1946. The pegmatites of central Nigeria. *Bull. Geol. Surv. Nigeria*, **17**.
——, A. Cawley & W. N. MacLeod. 1951. The occurrence of columbite in Nigeria. *Occas. Paper Geol. Surv. Nigeria*, **9**.
King, B. C. 1955. The Ard Bheinn area of the central igneous complex of Arran. *Q.J.G.S.* **110** [for 1954], 323–54.
Kingsley, L. 1931. Cauldron-subsidence of the Ossipee Mountains. *Am. Journ. Sci.* (5) 22, 139–68.
Lelubre, M. 1952. Recherches sur la géologie de l'Ahaggar central et occidental. *Bull. Serv. Carte géol. Algérie*, **22**.
Mackay, R. A., & K. E. Beer. 1952. The albite-riebeckite-granites of Nigeria. *Rep. Geol. Surv. Atomic Energy Div.* **95**.
——, R. Greenwood & J. E. Rockingham. 1949. The geology of the Plateau tinfields—Re-survey, 1945–48. *Bull. Geol. Surv. Nigeria*, **19**.
MacLeod, W. N. 1956. The geology of the Jos–Bukuru Younger Granite complex with particular reference to the distribution of columbite. *Rec. Geol. Surv. Nigeria*, 1954, 17–34.
Modell, D. 1936. Ring-dike complex of the Belknap Mountains, New Hampshire. *Bull. Geol. Soc. Am.* **47**, 1885–1932.
Oftedahl, C. 1953. Studies on the igneous rock complex of the Oslo region. XIII. The cauldrons. *Skr. Norske Vidensk.-Akad. Oslo, Mat.-Nat. Kl.* **3**.
Pitcher, W. S. 1953. The Rosses granitic ring-complex, County Donegal, Eire. *Proc. Geol. Assoc.* **63**, 153–79.
Raeburn, C. 1924. The tinfields of Nassarawa and Ilorin provinces. *Bull. Geol. Surv. Nigeria*, **5**.
——, A. D. N. Bain & W. Russ. 1927. The tinfields of Zaria and Kano provinces. *Bull. Geol. Surv. Nigeria*, **11**, 1–71.
Richey, J. E. 1927. The structural relations of the Mourne granites (Northern Ireland). *Q.J.G.S.* **83**, 653–88.
——. 1932a. Tertiary ring structures in Britain. *Trans. Geol. Soc. Glasgow*, **19**, 42–140.
——. 1932b. The Tertiary ring-complex of Slieve Gullion, Ireland, with petrological notes by H. H. Thomas. *Q.J.G.S.* **88**, 776–849.
—— & others. 1930. The geology of Ardnamurchan, North-West Mull, and Coll. *Mem. Geol. Surv. Scotland.*
Williams, F. A., & others. 1956. Economic geology of the decomposed columbite-bearing granites, Jos Plateau, Nigeria. *Econ. Geol.* **51**, 303–32.
Williams, H. 1941. Calderas and their origin. *Bull. Geol. Univ. Calif.* **25**, 239–346.

EXPLANATION OF PLATES

Frontispiece.—View of Younger Granite hills near Vom on the Jos Plateau.

Plate I

Fig. 1.—Aerial photograph of the southern boundary of the Vom–Ganawuri massif on the western side of the Jos Plateau. The Younger Granite forms a prominent escarpment and weathers into enormous exfoliation domes. The plains to the south are Basement Complex overlain by Newer Basalt. Scale, 1 : 20,000 approximately.

2.—Aerial photograph of part of the great polygonal Mongu ring-dyke on the eastern side of the Rop Younger Granite complex The dyke extends for 35 miles and forms a ridge rising several hundred feet above the plains. Note the sudden changes in strike and the branching character of the dyke. Scale, 1 : 20,000 approximately.

Plate II

Fig. 1.—Panoramic view of the central massif of the Rop complex on the Jos Plateau. The hills are composed of a series of flat-lying granite intrusions which represent the upper level of a major cauldron subsidence structure. The Shere Hills appear in the far distance on the right, and the Vom–Ganawuri complex can be seen on the horizon to the left of the Rop massif.

2.—View of a portion of the central massif of the Rop complex. In this photograph the flat-lying contact between the Kaskara biotite-granite and the Yelwa hornblende-fayalite-granite is clearly demarcated by the coarser-weathering form of the underlying biotite-granite. Narrow screens of an earlier biotite-granite are preserved along the horizontal contact.

Plate III

Fig. 1.—Younger Granite hills near Jos. The early biotite-granite of the Jos–Bukuru complex forms the boulders in the foreground. The hills on the skyline, with the smoother-weathering form, are composed of quartz-fayalite-porphyries forming the southern side of the Neil's Valley ring-complex.

2.—Younger Granite hills near Jos showing the typical weathering form. A laterite-capped hill representing one of the erosion surfaces can be seen on the skyline on the left-hand side.

Plate IV

Fig. 1.—Comendite from Liruei, showing flow-banding and axiolitic structure. Ordinary light, × 15 (X.572).

2.—Spherulitic structure in comendite from Liruei. The spherulites are composed of alkali-felspar, aegirine and soda-amphibole. Ordinary light, × 25 (X.506).

3.—Tuff, composed mainly of glassy fragments, from one of the vents in the Buji complex. Ordinary light, × 25 (L.920).

4.—Fine-grained crystal tuff from one of the Buji vents. Crossed nicols, × 25 (L.924).

5.—Tuff vein cutting rhyolite in one of the vents at Buji. Ordinary light, × 25 (L.929).

6.—Late intrusive rhyolite from the Buji complex. The groundmass is isotropic or cryptocrystalline and contains abundant minute angular fragments. Both the quartz and felspar crystals show evidence of disintegration, and the felspars show the mottled alteration characteristic of this rock. The presence of angular fragments in the groundmass is attributed to the incorporation of fine tuffaceous material during intrusion of the rhyolite. Ordinary light, × 25 (L.814).

Plate V

Fig. 7.—Granophyric texture of one of the cone-sheet porphyries at Buji. Crossed nicols, × 25 (L.820).

8.—Quartz-fayalite-hedenbergite-porphyry from D. Shetu, Liruei, showing typical fayalite and hedenbergite micro-phenocrysts. Ordinary light, × 50 (X.511).

9.—Quartz-hedenbergite-porphyry from Buji Plateau, showing abundant phenocrysts of quartz, orthoclase, sodic plagioclase and hedenbergite in a microcrystalline groundmass. Many of the hedenbergite crystals show alteration to secondary iron oxides. Crossed nicols, × 25 (L.903).

10.—Naraguta quartz-fayalite-hedenbergite-porphyry from Neil's Valley, showing a large crystal of fayalite mantled by blue-green soda-amphibole. Crossed nicols, × 25 (L.270).

11.—Rough Range biotite-granite, Amo. The lamellar exsolution perthite has been partly obliterated by late deuteric albite. Note the development of dentate albite around the borders of the perthite. Crossed nicols, × 25 (L.1822).

12.—Albite-biotite-granite from the Amo complex, showing the typical replacement perthite in this type of granite. Only residual " eyes " of the host microcline remain. The broadly-twinned laths of albite around the margins of the perthite belong to a later generation than the untwinned albite in the perthite. Crossed nicols, × 25 (L.946).

Plate VI

Fig. 13.—Albite-biotite-granite from the Afu Hills. The rock is rich in albite, and the texture is similar to that of the albite-riebeckite-granites. Crossed nicols, × 25 (L.1).

14.—Riebeckite-aegirine-granite from Liruei, showing riebeckite moulded on perthite. The amphibole and pyroxene are interstitial to the felspar and quartz and were the last minerals to crystallize. Note the irregular patchy replacement perthite. Ordinary light, × 12 (X.575).

15.—Albite-riebeckite-granite from Kaffo, with large grains of quartz and abundant well-twinned albite. Note the inclusions of cryolite in the quartz. Crossed nicols, × 20 (X.674).

16.—Arfvedsonite-fayalite granite-porphyry from the Liruei complex, showing large glomeroporphyritic aggregates of orthoclase and embayed crystals of quartz in a groundmass composed of quartz, alkali-felspar and arfvedsonite. The fayalite and hedenbergite are usually surrounded by reaction rims of arfvedsonite, except when they are enclosed in the orthoclase phenocrysts. Ordinary light, × 10 (X.592B).

17.—Riebeckite-biotite-granite from the Amo complex. The exsolution and replacement perthites are similar to those found in the riebeckite-granites. Crossed nicols, × 25 (L.1816).

18.—Early hornblende-biotite-granite from Amo, showing the typical lamellar exsolution perthite found in this facies. Late replacement albite is absent. Crossed nicols, × 25 (L.999).

Plate VII

Geological map of north-central Nigeria, showing the Younger Granite complexes. Scale : 1 inch to 18 miles.

Plate VIII

Geological map of, and sections across, the Rop Younger Granite complex. Scale : 1 inch to 3 miles approximately.

Plate IX

Geological map of the Sha–Kaleri Younger Granite complex, with a section across the Tof and Kaleri complexes. Scale : 1 inch to 3 miles approximately.

Note : The substance of this Memoir was read as a paper at the meeting of the Society on 16 January, 1957. The discussion which followed the reading is published in the Society's *Proceedings*, No. 1545, pp. 22–8.

Fig. 1.—PART OF THE GREAT POLYGONAL MONGU RING-DYKE, ROP COMPLEX

Fig. 2.—SOUTHERN BOUNDARY OF THE VOM-GANAWURI MASSIF

AERIAL PHOTOGRAPHS OF YOUNGER GRANITE RING-COMPLEXES, NIGERIA

[*Published by courtesy of the Aircraft Operating Company (Aerial Surveys) Ltd.*]

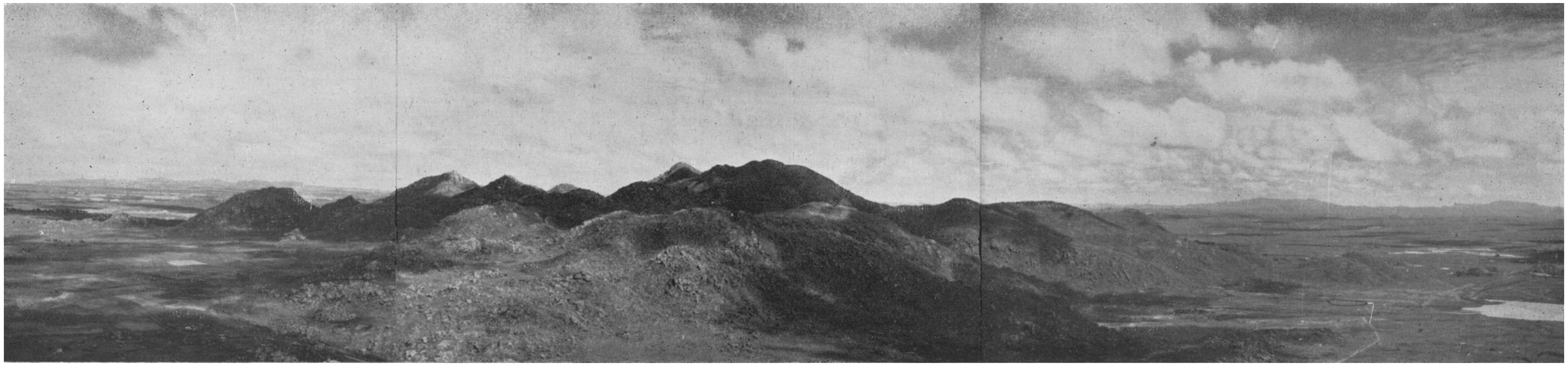


FIG. 1.—PANORAMIC VIEW OF THE CENTRAL MASSIF OF THE ROP COMPLEX

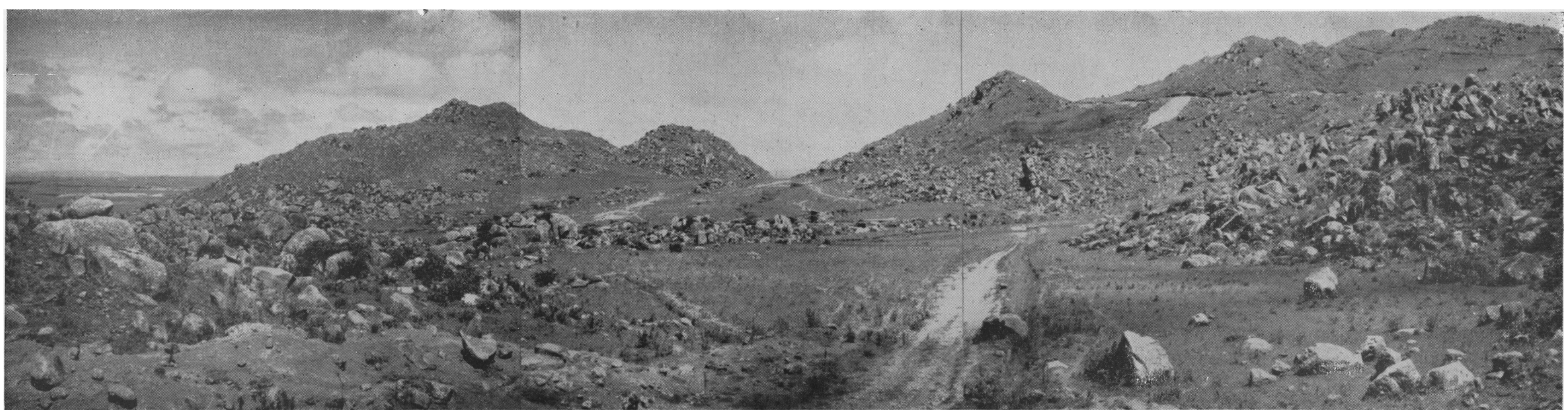


FIG. 2.—PART OF THE CENTRAL MASSIF OF THE ROP COMPLEX

PANORAMIC VIEWS OF THE ROP COMPLEX, JOS PLATEAU

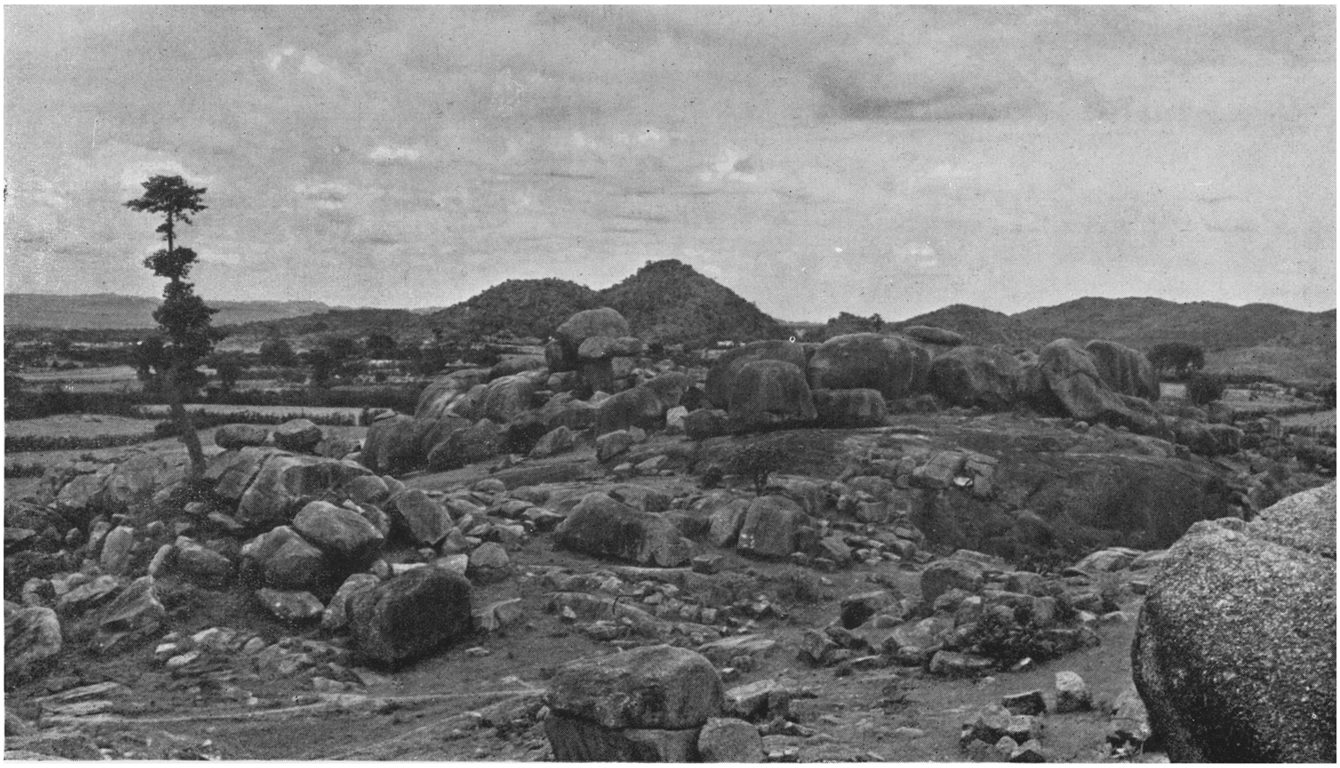


Fig. 1

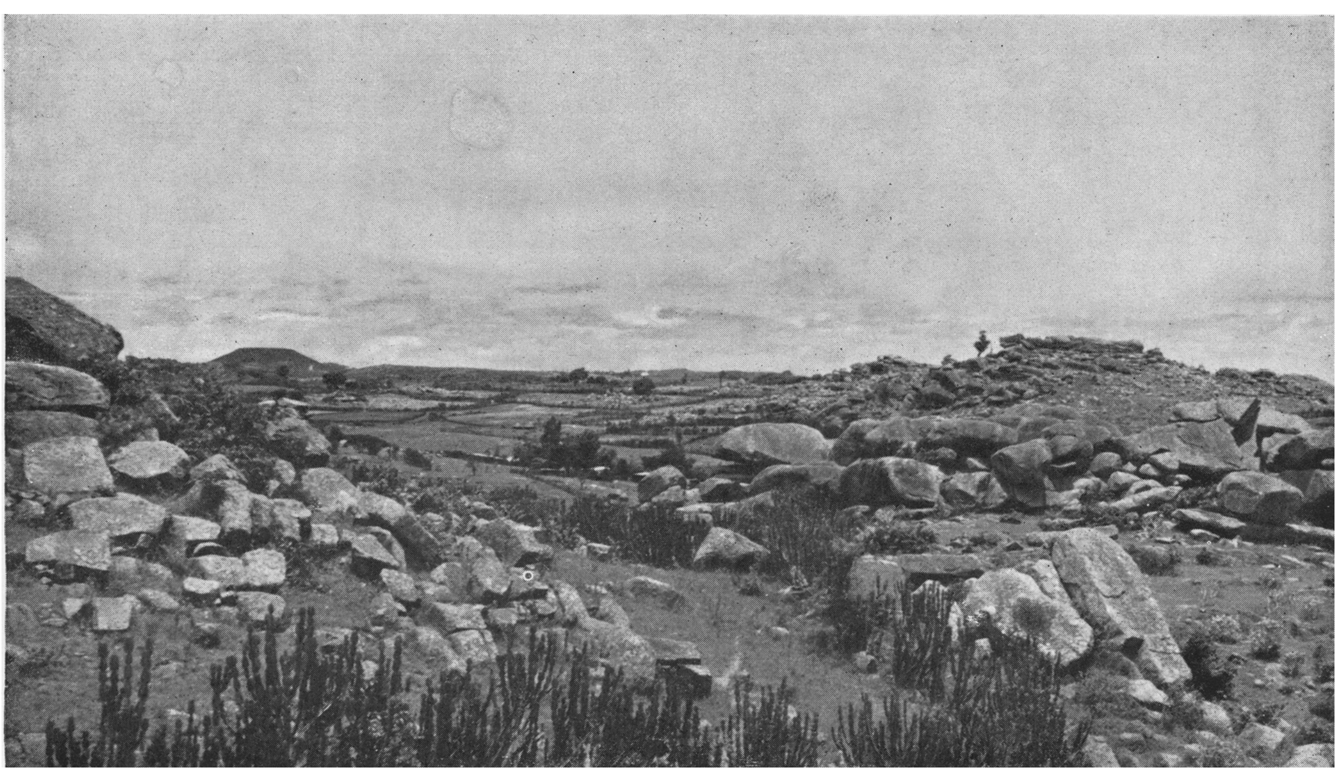
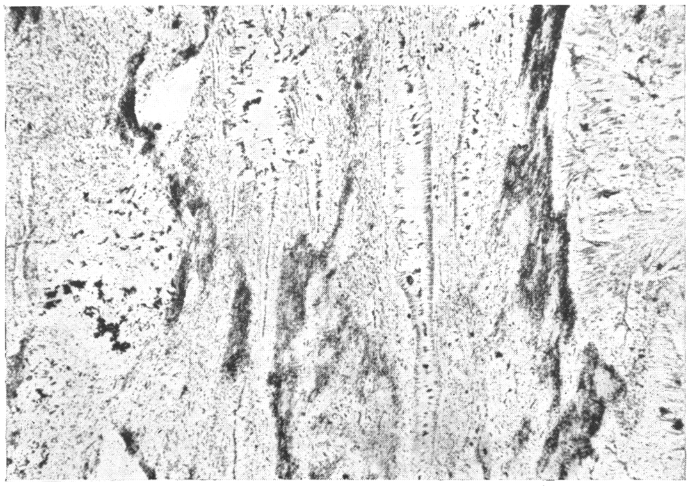


Fig. 2

YOUNGER GRANITE HILLS NEAR JOS, NORTHERN NIGERIA



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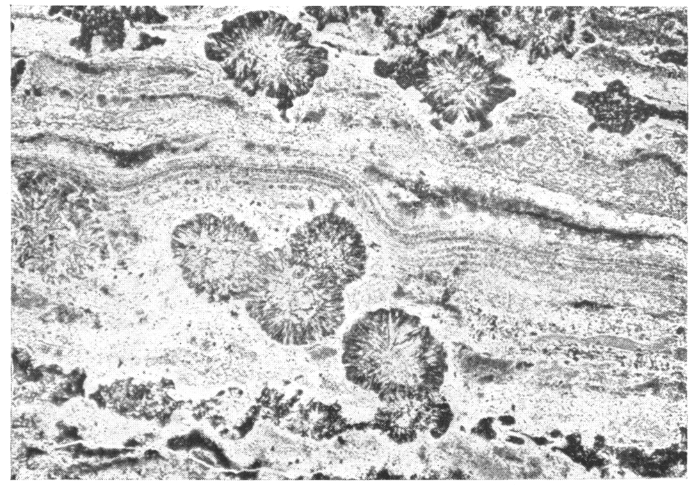

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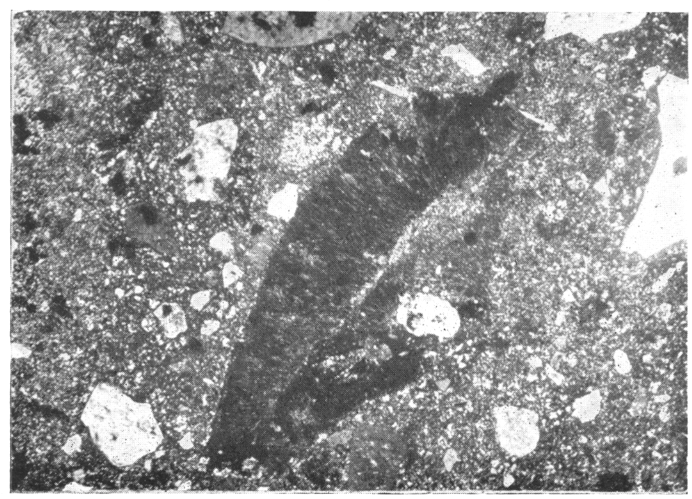

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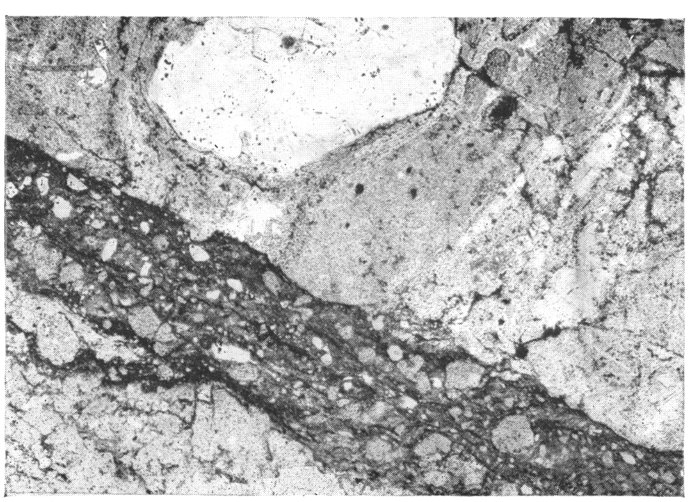

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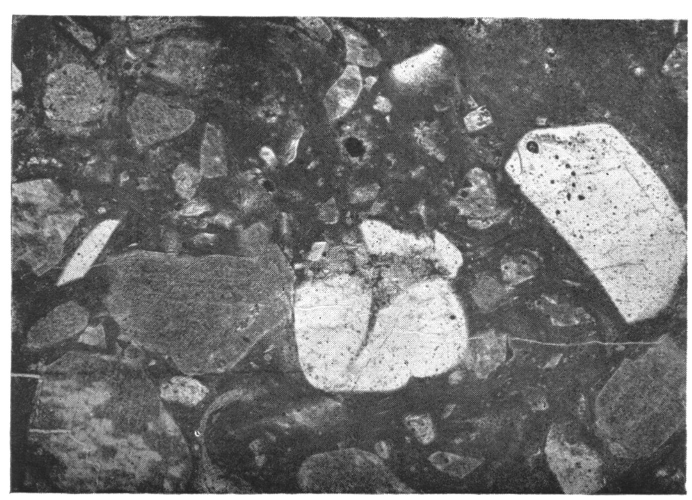

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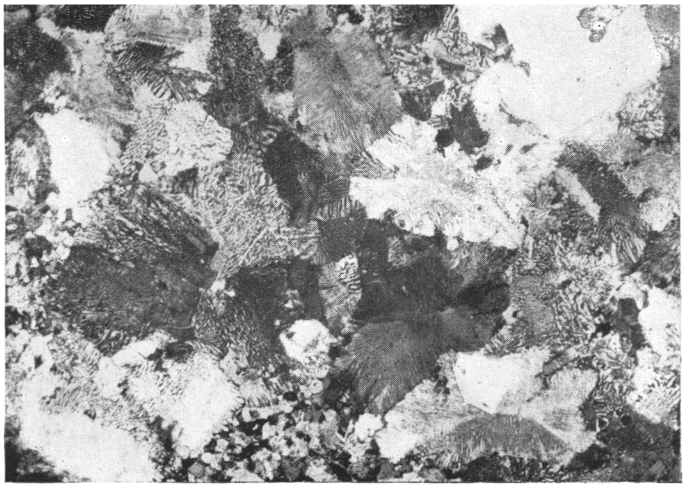
PHOTOMICROGRAPHS OF ROCKS FROM THE YOUNGER GRANITE RING-COMPLEXES, NORTHERN NIGERIA



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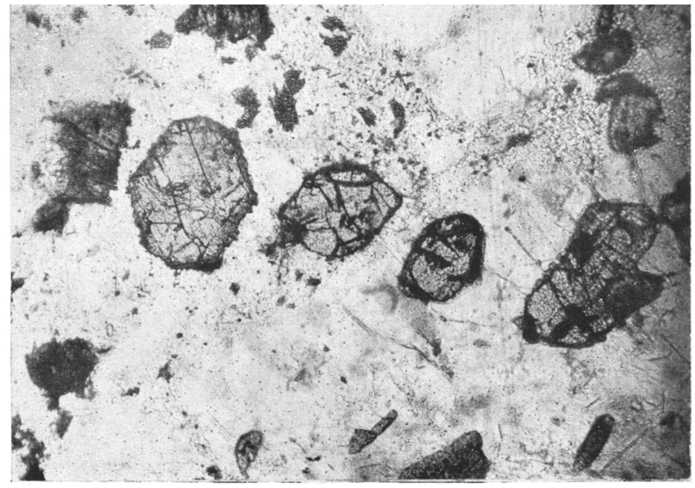

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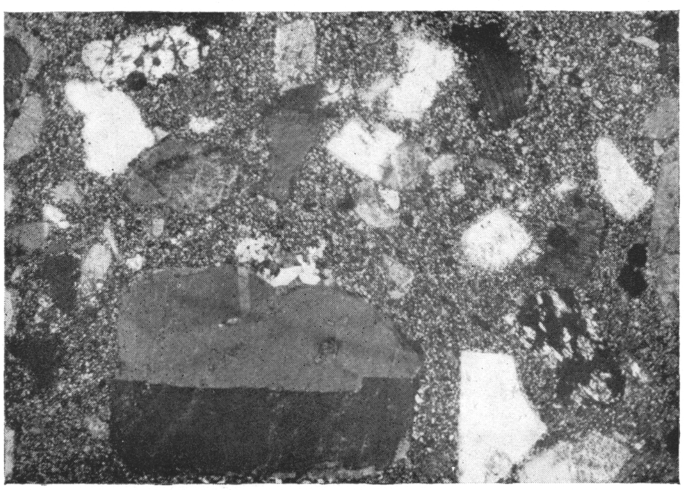

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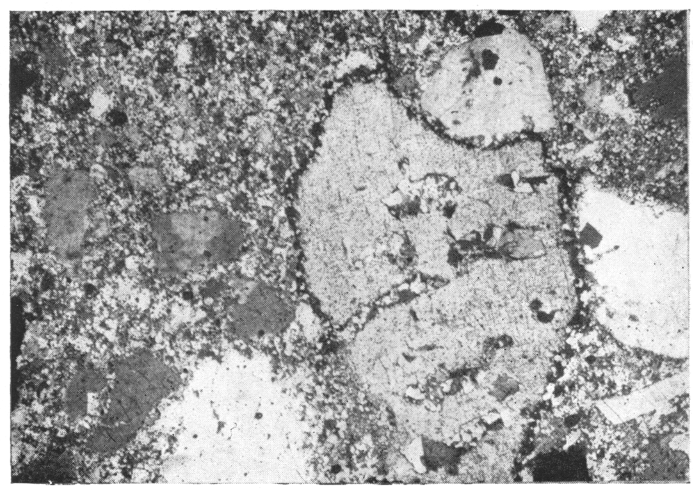

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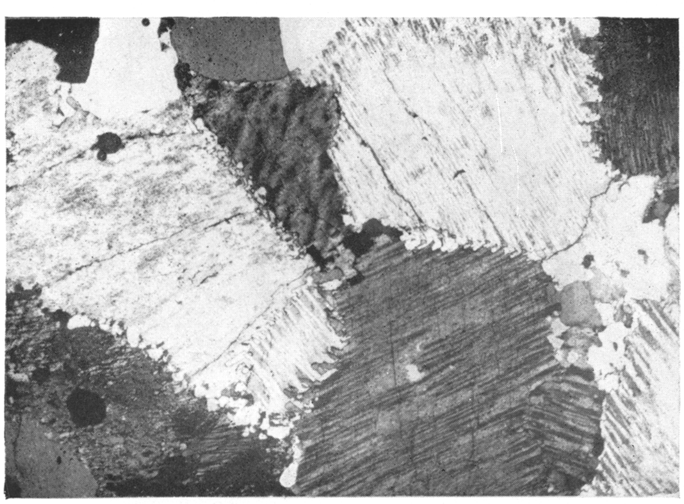

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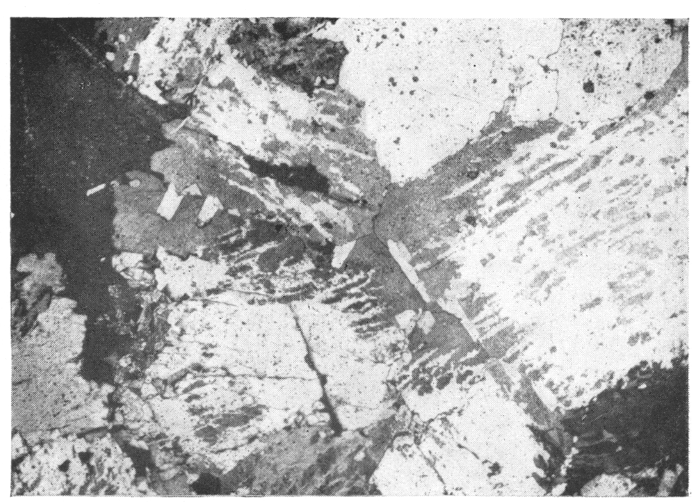

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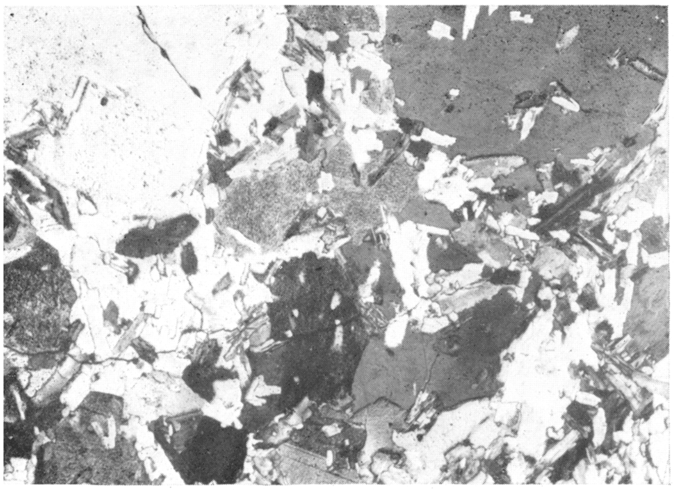

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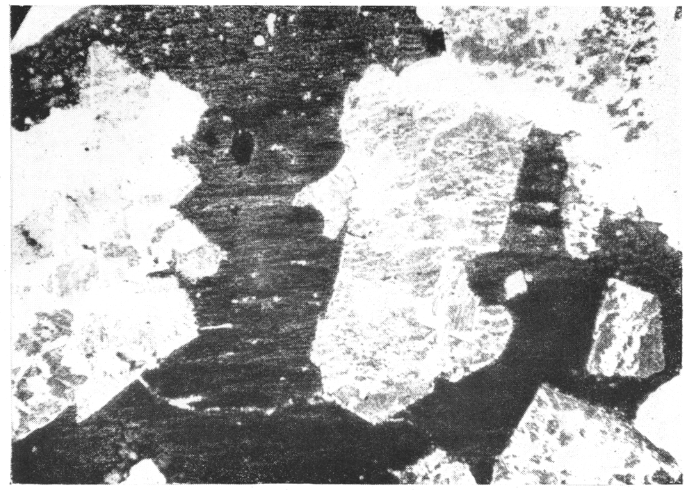

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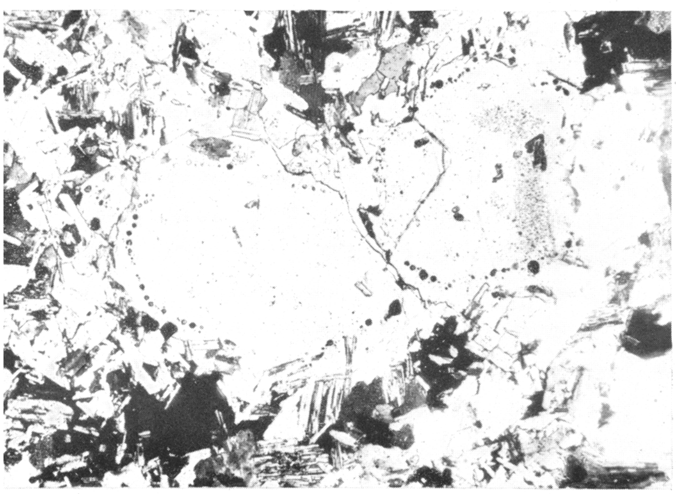

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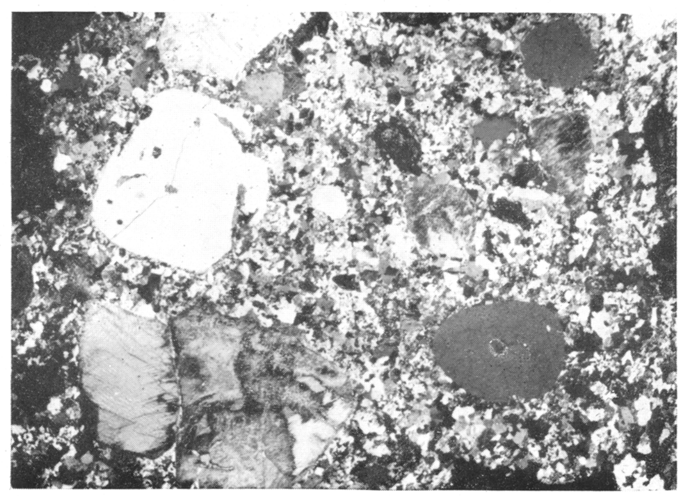

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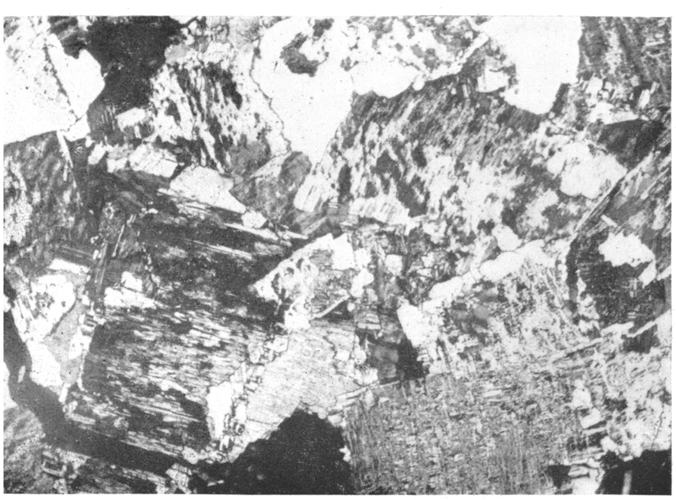

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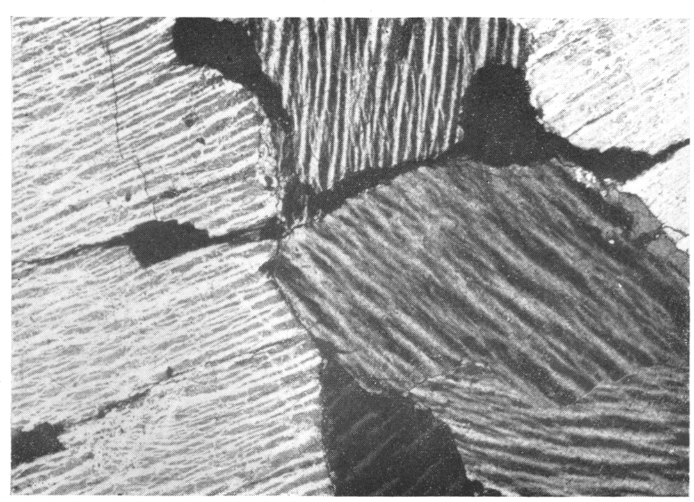

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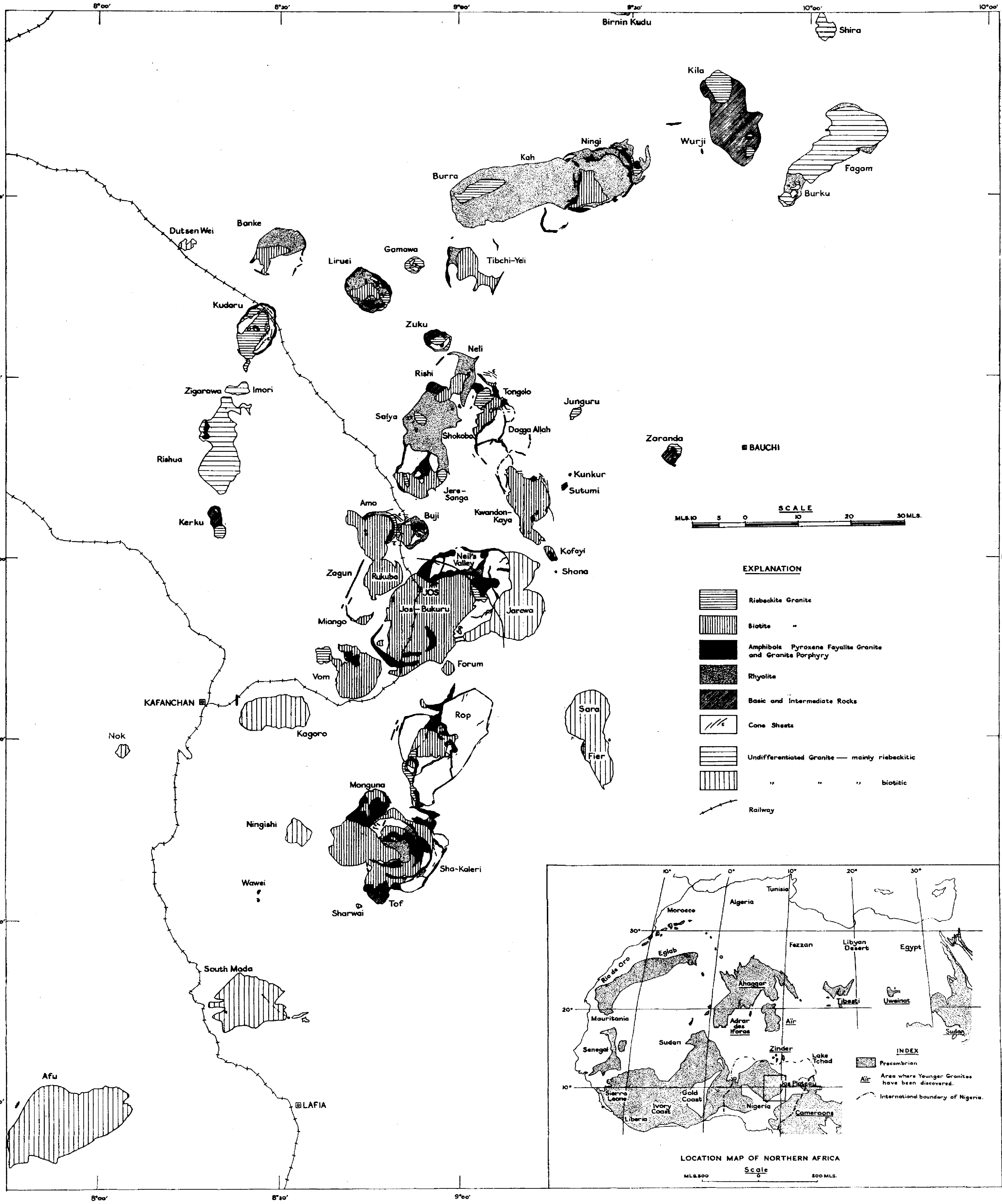
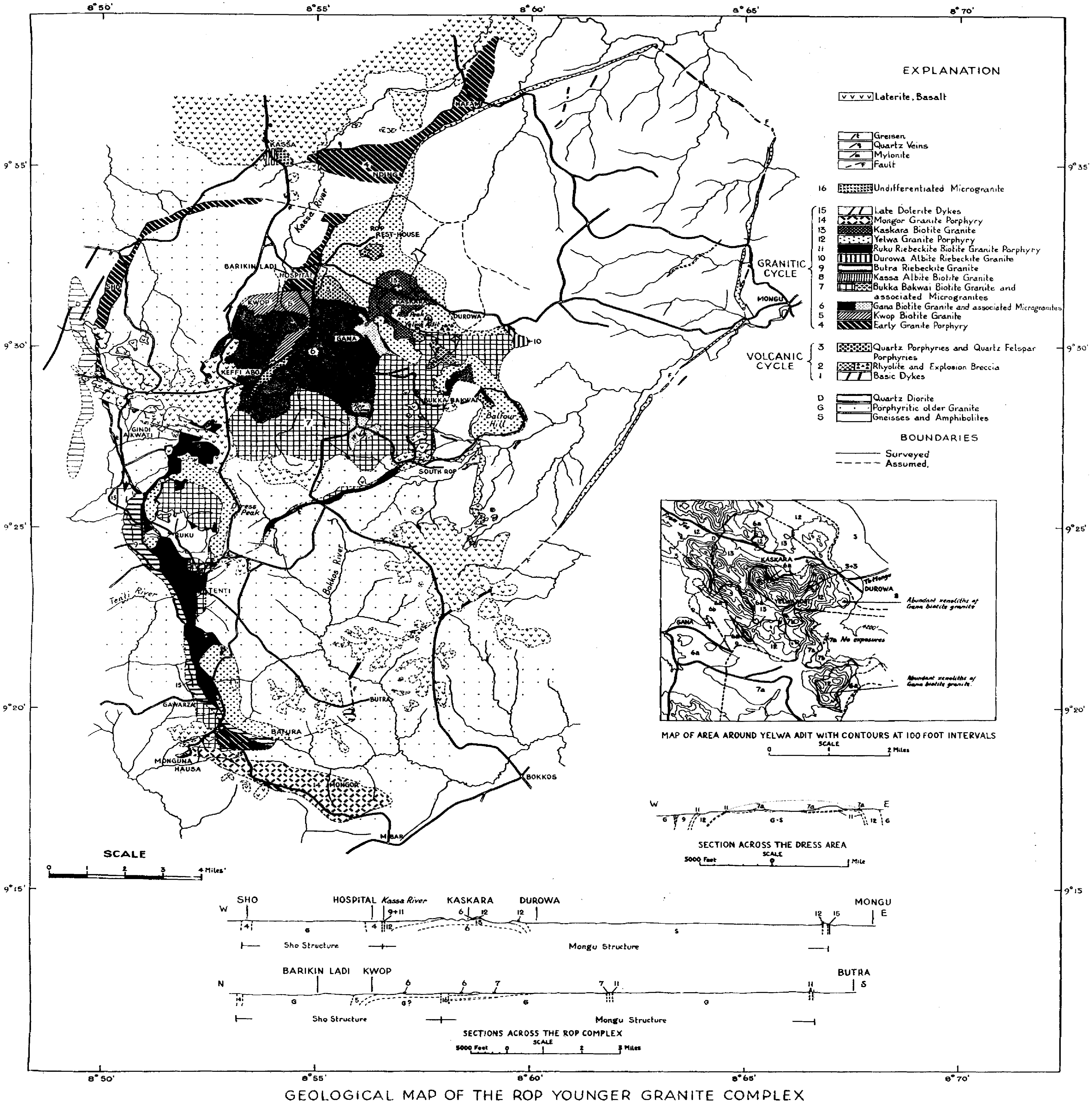
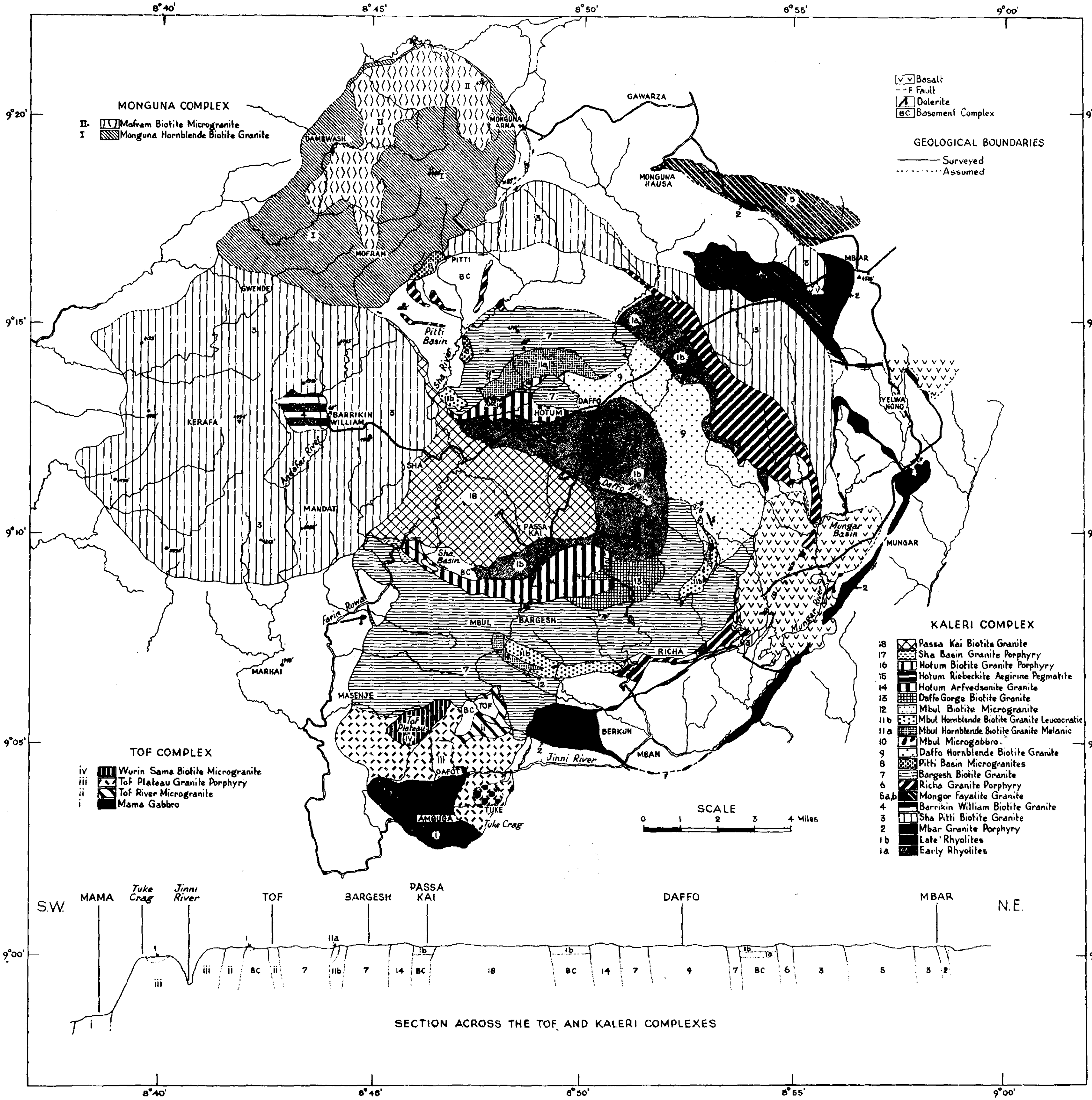
PHOTOMICROGRAPHS OF ROCKS FROM THE YOUNGER GRANITE RING-COMPLEXES, NORTHERN NIGERIA



GEOLOGICAL MAP OF NORTH-CENTRAL NIGERIA SHOWING THE YOUNGER GRANITE COMPLEXES



GEOLOGICAL MAP OF THE ROP YOUNGER GRANITE COMPLEX



GEOLOGICAL MAP OF THE SHA-KALERI YOUNGER GRANITE COMPLEX