A Geological Investigation of Some Nigerian Jurassic Granites and their Mineralisation

by

Judith A. Kinnaird. B.Sc.

being a thesis presented to the University of St. Andrews in application for the degree of M.Sc.

C e r t i f i c a t e

I certify that Judith A. Kinnaird has been engaged in research for the equivalent of nine terms at the University of St. Andrews, that she has fulfilled the conditions of Ordnance No. 51, and that she is qualified to submit the accompanying thesis in application for the degree of Master of Science.

I certify that the following thesis is based on the results of research carried out by me, that it is my own composition, and that it has not previously been presented for a higher degree.

Acknowledgements.

The author would like to thank all members of staff and colleagues of the Geology Department of St. Andrews University for their help and good humour during the seemingly never ending preparation of this thesis. In particular I would like to thank Dr. P. Bowden for much useful discussion, for his continuing interest and for critically reviewing and re-reading the manuscript.

Thanks are also due to Dr. D.C. Turner of Ahmadu Bello University, Zaria, who occasionally accompanied the writer in the field, and who also critically appraised part of the manuscript.

The generous grant given by the Overseas Development Ministry, which made this work possible, is gratefully acknowledged.

I would also like to acknowledge the help, friendliness and advice accorded to me by everyone I met in Nigeria, without whom this thesis would not have been possible. In particular thanks are due to Mr. D. Dent-Young of Amalgamated Tin Mines (Nigeria) who provided housing, useful discussion, and a Land Rover in times of need and to Mr. C.I. Cox for his help. Also to Mr. A. Thompson, Mr. Hugh Anderson and Mr. Fred Anderson of Jantar-Bisichi for unlimited access to their mines - and for the loan of some wellingtons! Thanks are also due to Mr. L. Gibb of Gold and Base Metals for arranging a visit to the Liruei mine. I would also like to record the help given by Mr. C.N. Okezie, Acting Director of the Geological Survey of Nigeria and his staff at the

Jos Office. I must also acknowledge the help given by Mallam Inuwe Gombe and Officials of the Ministry of Mines and Power and also the Nigerian Mining Corporation. The help given by the Surveyor General and his staff at the Ministry of Lands and Survey, Benue Plateau State proved invaluable.

No acknowledgements would be complete without thanks to Roger Barley, Mohammed Zakari and Gwanda Rim who all helped to keep me sane - also to the Harknesses and other members of Ladi Club for cheerful support!

Finally, my thanks to Allan my husband for his great patience, encouragement and understanding, and for punctuating my torrent of words.

Volume 1.

Photogeological and field studies of Jurassic granites and their mineralisation with special reference to the Bukuru/Ngell valley area.

Abstract.

The Jurassic granites in the Nigerian Younger Granite Province belonging to the Jos-Bukuru Complex - in the Ngell valley, are compared with granites from the more southerly Ropp Complex. Tabulated petrological characteristics of each of the variants from both complexes indicate identical - though widely separate - rock types in similar sequences. Satellite photography of central Nigeria suggests that the Jos-Bukuru and Ropp complexes may be connected. It is concluded that nine biotite granite phases of the Jos-Bukuru complex, previously believed to be separate intrusions by MacLeod, belong to two major biotite granite intrusive cycles separated by the emplacement of hastingsite-fayalite granite.

Mineralisation studies completed in the Bukuru/Ngell valley area were continued in the Ropp and Saiya-Shokobo complexes and led to a more detailed investigation of mineralisation in other rock types.

It is concluded that the peralkaline granites have only one dispersed phase of mineralisation. This is thought to be due to the retention of water and volatiles by a peralkaline magma until late stages, when a residual liquid separates and modifies the partially crystalline alkaline granite.

In contrast there are two distinct stages of mineralisation related to the cooling and consolidation of biotite granites; an early dispersed (apogranitic) phase and a later metasomatic replacement - vein forming stage.

The development of columbite in the Younger Granite Province is related to the apogranitic stage, which is a late-magmatic, pre-joint phase of mineralisation. Recrystallisation,

effected by a new growth of microcline and albite is accompanied by an introduction of xenotime, thorite and hafnium and uranium rich zircon in addition to columbite. Fifty analyses of Rayfield Gona granite affected by this type of mineralisation and recrystallisation showed a varying Nb_2O_5 content from less than 30 ppm to over 2,500 ppm with high ThO_2 values in those samples with an enhanced Nb_2O_5 content. In general columbite mineralisation is not accompanied by an extensive precipitation of cassiterite.

In contrast with the apogranitic phase, the replacement vein mineralisation is post-magmatic and predominantly post jointing. The veins consist of quartz, Li-Fe or Li-Al biotite, topaz and/or fluorite. In addition to a high cassiterite content in some of the veins, a mixed assemblage of any of the minerals sphalerite, chalcopyrite, galena, pyrite, monazite, greenockite, chalcocite, covellite, native copper, genthelvite, phenakite, arsenopyrite, molybdenite, bismuthinite and uraninite may occur. These veins are generated by biotite granite magmas and may be found in basement, pyroxene or fayalite granite, and riebeckite porphyry which surrounds or overlies biotite granite. Veins are only abundant, however, in medium to fine-grained biotite granites; this simplifies the search for the veins. In some cases it seems likely that the veins in one biotite granite have been generated by the intrusion of a later biotite granite phase emplaced at deeper levels (e.g. Liruei). This mechanism may account for the formation of veins that appear to have no definite spatial relationship to the host rock.

Occasionally, areas that contain numerous replacement veins can be identified on aerial photographs by the increased density of joints in the vein rich area, in contrast with that in the host rock.

Within these replacement veins there are definite stages of alteration affecting the host rocks. During argillic alteration, which is the first phase, there is a partial alteration of feldspars to clay minerals. This is followed by chloritic alteration when the original biotite of the host rock is chloritised and a massive input of fluorine may introduce a complex assemblage of sulphide ores in addition to some cassiterite. This is the main phase of ore deposition. During sericitic alteration, which follows the minor chloritic alteration, sericite is formed as a result of feldspar breakdown or by hydrogen ion metasomatism of the chloritic mica, and only minor amounts of ore minerals occur, usually sphalerite or galena. Greisenisation postdates this phase and is characterised by the development of new alumina minerals (topaz and siderophyllite or protolithionite) in association with quartz, and the disappearance of sericite. Cassiterite is the only ore mineral common to the greisen-stage of vein formation. Finally, silicification may affect the veins formed by the previous stages, or there may be a development of quartz fissure fillings, sometimes with cassiterite and occasionally with wolframite and sphalerite.

These sequences of alteration are shown to be almost the reverse of those described by Štemprok for the Bohemian massif and examples of Bohemian types of alteration are recorded throughout the world, in many other tin provinces. The degree of sericitic alteration in Nigeria, in comparison with other provinces is very weak; furthermore, the advanced argillic and propylitic stages of alteration recorded in other, orogenic, regions does not seem to occur in the Nigerian setting. Such differences may be fundamentally related to the tectonic environment, source and origin of the magmatic liquids and residual fluids.

CONTENTS.

Text Figures

APPENDICES.

List of Photographs

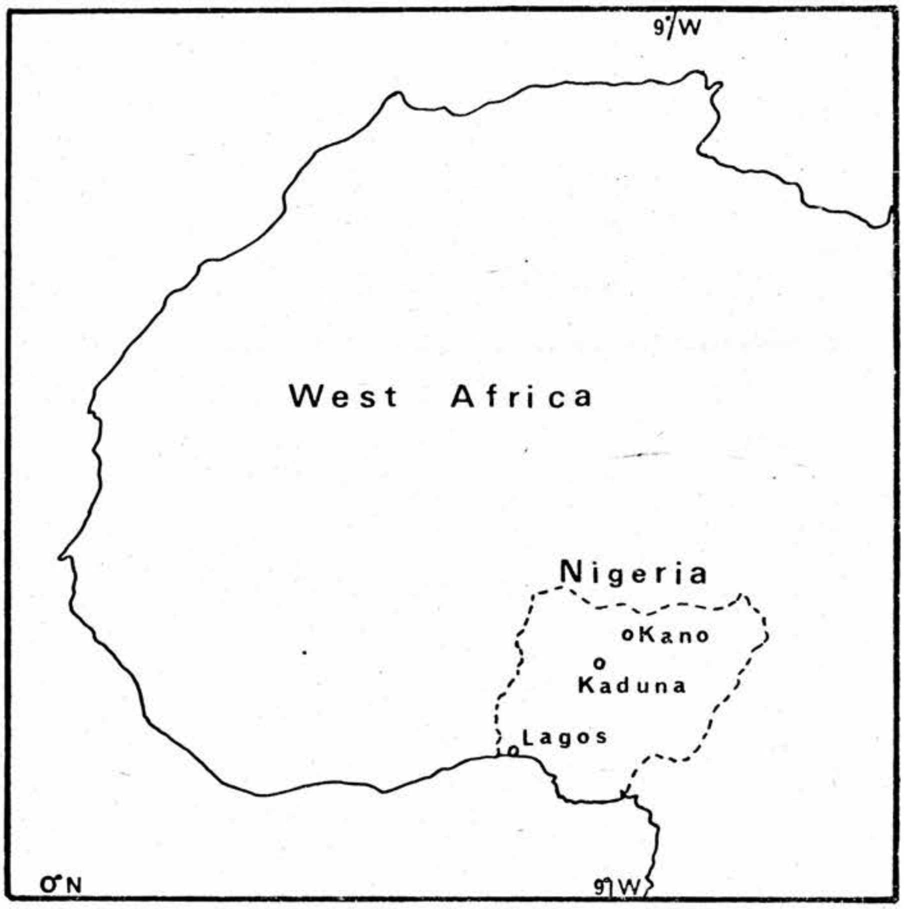


Figure I

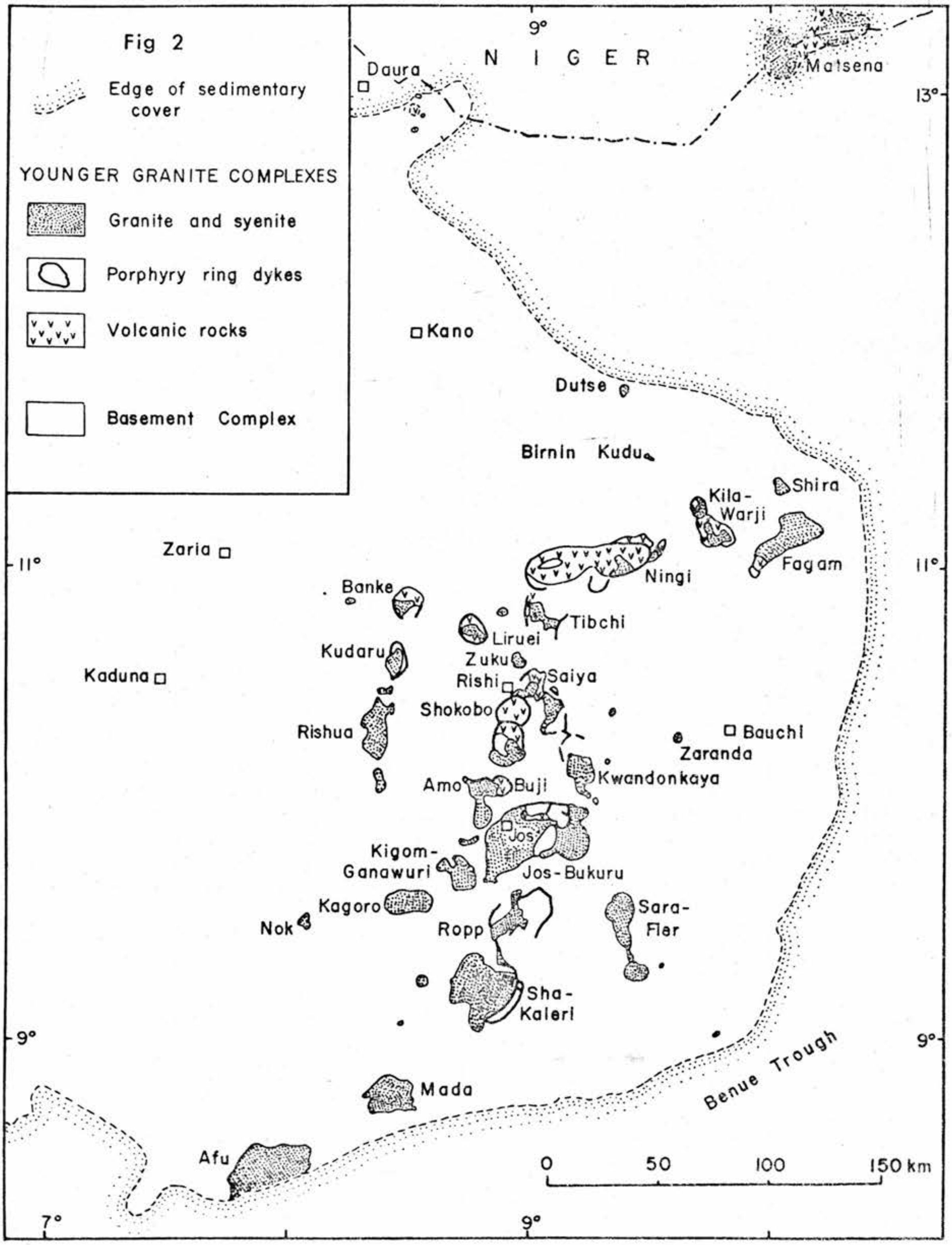


Fig 2
Edge of sedimentary cover
YOUNGER GRANITE COMPLEXES
Granite and syenite
Porphyry ring dykes
Volcanic rocks
Basement Complex
NIGER
Daura
Matsena
Kano
Dutse
Birnin Kudu
Shira
Kila-Warji
Fagam
Ningi
Zaria
Banke
Tibchi
Liruei
Kudaru
Zuku
Kaduna
Rishi
Saiya
Shokobo
Rishua
Bauchi
Zaranda
Amo
Buji
Kwandonkaya
Jos
Kigom-Ganawuri
Jos-Bukuru
Kagoro
Sara-Fier
Nok
Ropp
Sha-Kaleri
Mada
Benue Trough
Afu
0 50 100 150 km
7°
9°
11°
13°

CHAPTER 1.

General Introduction

Aims of the project

Previous mapping of the Bukuru-Ngell area by W.N. MacLeod had been on a scale of 1:50,000 and had concentrated largely on the different granite lithologies. The published geological sheet based on this work, in Bulletin 32 of the Geological Survey, is at 1:100,000 scale and shows only the distribution of different granite types. Areas of intrusive basic rocks, fluvio-volcanic sediments and mineralised veins in the area remained unmapped.

Previous information on the primary mineralisation was restricted mainly to mining company literature and the relationship between individual areas of mineralisation, especially those belonging to different mining companies, was not clearly understood.

The aims of this project therefore were:-

1). To make a more accurate and detailed geological map in the Bukuru/Ngell valley region as an area of known mineralisation, using part of the new, high resolution, large-scale 1:10,000 photography. This black and white photography includes approximately 100 km^2 and covers part of the map sheet 168 NE.

2). To study areas of known mineralisation and to examine their characteristics on these photographs in the hope that a pattern would emerge that would aid in the location of undocumented areas of mineralisation.

3). To combine new and existing information on mineralisation in an attempt to understand the processes of formation and distribution of the ore mineralisation.

To achieve these aims a composite of overlays was made of the Bukuru/Ngell valley from part of the 1:10,000 photo coverage, at the same scale, in conjunction with a field investigation. Areas of known primary mineralisation outside this project area were also examined both on the photographs and on the ground to gain more data on the characteristics of mineralised areas.

The ultimate aim to assist future project work was to try to identify areas containing mineralised veins from air photographs alone so that the technique could be used in relatively inaccessible areas, such as the Ningi complex.

General Geology of Central Nigeria

MacLeod _et al_., (1971) describing the general geology of the Jos Plateau in Bulletin 32 of the Geological Survey of Nigeria recognised the following successions:

5.	Quaternary -	Alkali olivine basalts $\simeq$ 1 my
4.	Tertiary -	Sedimentary succession with associated tholeiitic basalts.
3.	Jurassic -	Younger granite cycle 200-140 my with associated tin and columbite mineralisation.
2.	Lower Palaeozoic/ late Precambrian	Pegmatite mineralisation containing cassiterite and columbite/tantalite.
1.	Late Precambrian	Migmatites, diorites, gneisses, metasediments and older granites of the Basement Complex. >500 my.

Basement

The central area of Nigeria is composed of ancient crystalline rocks which were re-deformed and metamorphosed during the Pan African thermo-tectonic event which is regarded as an orogeny by some authors (e.g. Grant 1969). Rocks belonging to a phase of sedimentation within this event probably occur in the schist belts which lie to the west of the Jurassic granite complexes. (McCurry 1971). These were invaded by largely concordant granites lying in a 600-500 my zone between the cratons of West and Central Africa.

Until 1960 the Basement had remained unmapped but during the period 1960-1962 six 1:100,000 sheets covering the Jos Plateau and surrounding areas were mapped under the supervision of E.P. Wright. Since then, several authors have completed more detailed age-dating on the Basement and McCurry (1971) and others have discussed the effect of the thermo-tectonic event in Northern Nigeria.

Whole rock and mineral Rb-Sr and K-Ar analyses yield ages in the range 2,200-500 my, the last event being the wide-spread intrusion of weakly foliated 'older' granites which have yielded mineral and whole rock ages ranging from 618-417 my (Grant 1969). Van Breemen et al., (in press) suggest a peak of granite plutonism 610 my ago. Grant (1969) suggests that the Pan African orogeny resulted in the reactivation of the Nigerian Basement Complex and gneissic Dahomeyan with the emplacement of a granitic suite. He suggests from his geo-chronological data that the pre-reactivation Basement included rocks of Birrimian age - ca. 2,000 my old. Vachette (1964) has obtained ages for the Basement in Niger and elsewhere in the West African craton varying between 2,000 and 1,700 my which is the original age of the basement rocks before overprinting by the thermo-tectonic event affected the 'ages' of the old cratonic continental crust.

McCurry on Sheet 21-Zaria, (1973), divides the granites into two main groups according to their field relationship. The elongate, batholithic sheets which are partly concordant and show good foliation are considered to be 'syntectonic', whilst the poorly foliated, discordant bodies, rich in mafic xenoliths and having a lower proportion of potash feldspar are considered to be 'late tectonic'.

In the central area of Nigeria, around Jos, this tectonic division of the granites is not apparent. The 'older granites are much more abundant, which could be interpreted either as a marked difference in erosional levels or as an eastward increase in Pan African magmatism towards the centre of the orogenic zone.

In the Plateau region there is a succession of granulitic gneiss, followed by intermediate rocks, migmatites, granite gneisses and later intrusive members. The pre-migmatic rocks are postulated by MacLeod et al., (1971) to have been derived from a psammitic to semi-pelitic sedimentary series which was regionally metamorphosed to the biotite grade prior to migmatisation. The regional metamorphism has been shown by van Breemen et al., (op cit) to be Precambrian and there is no evidence in north central Nigeria for sedimentation continuing into the Cambrian. Also all magmatism had ceased by Cambrian times, except for the development of pegmatites.

Black and Girod (1970) demonstrate that the distribution of the eruptive rocks in Nigeria is closely related to the pattern of pre-Ordovician faulting in the Basement. This pattern, although masked by later superimposed faulting, extends over most of the Pan African zone to the east of the West African craton. In Aïr, Hoggar, Togo and Ghana these are in the form of northwest sinistral faults accompanied by a few complementary northeast trending dextral faults. They observe that the major faults in Nigeria and the Cameroons are northeasterly and east-northeasterly wrench faults that are complementary to the northwesterly sinistral faults that traverse Aïr. Many of these fractures have suffered renewed movements at intervals and have influenced the localisation of zones of subsidence and intermittend uplift. Black and Girod also believe that the north-south upwarping which took place in the early Palaeozoic formed an emerged land surface over most of Nigeria in Palaeozoic and early Mesozoic times. On a more detailed scale the basement trends appear to have influenced the location of the younger granite ring complexes. The Jos Plateau lies on a discontinuity within the basement; to the west the trend is north-south whereas to the east the lineations are east-west or northeast - southwest. McCurry (1971) concludes that minor structures imply at least two major episodes of deformation affecting both the crystalline complex and the younger metasedimentary cover. During the earlier phase ENE structures predominated with the axial planes of the folds dipping north and south. Later isoclinal folding has produced the north-south trending structures common over much of Nigeria.

Widespread pegmatite and aplite development characterised the latest stages of the older granite phase and marked the termination of the thermo-tectonic event, probably in the lower Palaeozoic (Tugarinov 1968). The most important mineralisation occurred along a central, east-northeast trending belt and was best developed at the eastern end near the southwestern edge of the Jos Plateau (Wright 1970). Principally the pegmatites consist of quartz, microcline, oligoclase, biotite, muscovite, garnet and black tourmaline but economically the most important minerals are those of the columbite-tantalite series and cassiterite with beryl, pink and green tourmaline, apatite and lepidolite.

The complete sequence of events is shown in Fig. 7.

Jurassic Granites

Distribution and History of Previous work

The anorogenic Jurassic granites of northern Nigeria were intruded at a high level into the late Precambrian to Lower Palaeozoic basement as ring complexes. Over 40 individual complexes range in size from 1,500 km^2 to less than 2 km^2. In general the suite of complexes from Daura and Matsena on the Niger border to Afu in the south are concentrate in a 200 km wide north-south zone. They form part of a north-south chain along the ninth meridian, extending from the Niger Republic 1,200 km south to the margin of the Benue trough in Nigeria (Fig. 2). This chain is structurally controlled by the main Pan African trends in the basement and is aligned with the zone along which crustal separation of southern Africa and South America took place in Mesozoic times. It seems probable that the granites lie on an extension of this ancient lineament on a zone of incipient faulting along which crustal separation did not take place (Black 1965). Although the granites are unrelated to orogenic activity it seems likely that their emplacement was associated with epeirogenic uplift. The granites all display similar joint patterns;

the major joints trend in a northwesterly direction which coincides with the planes of weakness that are complementary to the east-northeast wrench faults in the basement (Black and Girod 1970).

The younger granites were first defined by Falconer (1911). He described them as cross-cutting alkali granites containing riebeckite or biotite, characterised by chilled margins against their country rocks, and noted their undeformed post-tectonic character, contrasting them with the foliated calc-alkaline older granites of the basement.

The first geological survey began in 1919 immediately after the Geological Survey had been established. It revealed the essential geological features of the younger granites and recognised the biotite granites as a source of the abundant tin mineralisation which had inspired the survey. Falconer, Director of the Survey, recognised the pre-eminent position of the Jos-Bukuru complex as a source of cassiterite. He noted the heterogeneity of the complex but attributed the textural variations in the granite to the proximity of the batholith roof.

Bain (1934), Jacobson (1947) and predominantly Greenwood (1951) drew attention to the structural and petrological similarities between the younger granites of Nigeria and the White Mountain magma series of New Hampshire. More recently, the younger granites have been shown to be similar to complexes in Aïr and southern Niger (Black 1960) whilst Bonin (1973) has extended the similarity to the Corsican granites. Jacobson (1947) in the study of the Liruei complex also explained the structural relationships that exist between the volcanic, hypabyssal and plutonic members of the suite.

In 1950 the riebeckite granites, in view of their radioactive content, were studied by MacKay and Beer (1952) of the Atomic Energy Division of the Geological Survey of U.K. but it was decided that they were not an economic proposition.

Another resurvey of the Plateau and adjoining areas was begun by the Geological Survey in 1952. During this survey an area of 18,000 km^2 was mapped at a scale of 1:50,000, based on good aerial photography and more accurate topographic mapping.

MacLeod (1952), during an investigation of the biotite granites in the Jos-Bukuru complex showed that the variations in granitic texture and composition noted by earlier workers usually occurred as abrupt changes rather than as transitions within a single body. Similarly, he believed that other complexes were formed by a series of distinct intrusions, often with a concentric arrangement and having characteristic petrographic features.

A description of the younger granite province was published by Jacobson *et al.*, in 1958 as a memoir of the Geological Society of London. At this stage the younger granites were still believed to have been intruded during the Cambrian period but subsequent work by Snelling (1964, 1965), Jacobson, Snelling and Truswell (1963) and Bowden and van Breemen (1970) and others have conclusively proved the granites to be Jurassic in age.

In 1971 the detailed work on the younger granites and basement which had begun in 1952 was compiled as Bulletin No. 32 of the Geological Survey of Nigeria. This remains the most comprehensive overall work on the Province. However, there is still a large number of complexes, amounting to nearly a third of the total area, which have not been mapped in detail, some of which are currently being investigated by members of the Nigerian Granite Project sponsored by ODM.

Age Dating

Whole rock Rb-Sr isochron studies, with $\lambda = 1.39 \times 10^{-11}$ yr^{-1}, have been completed on samples from a number of complexes ranging from Aïr and Zinder-Gouré in Niger to widely spaced localities within Nigeria (van Breemen and Bowden 1973, Breemen *et al.*, 1975, Bowden *et al.*, 1976). The chronological evidence confirms a sequential age trend. Within the sub-volcanic provinces in Niger there is a variation from mid-Palaeozoic for Aïr in the north to Carboniferous for Zinder-Goure in the south. This trend is continued in Nigeria (Fig. 3) from Liruei (early Jurassic) and Sara Fier (mid-Jurassic) to Afu in the south (late Jurassic).

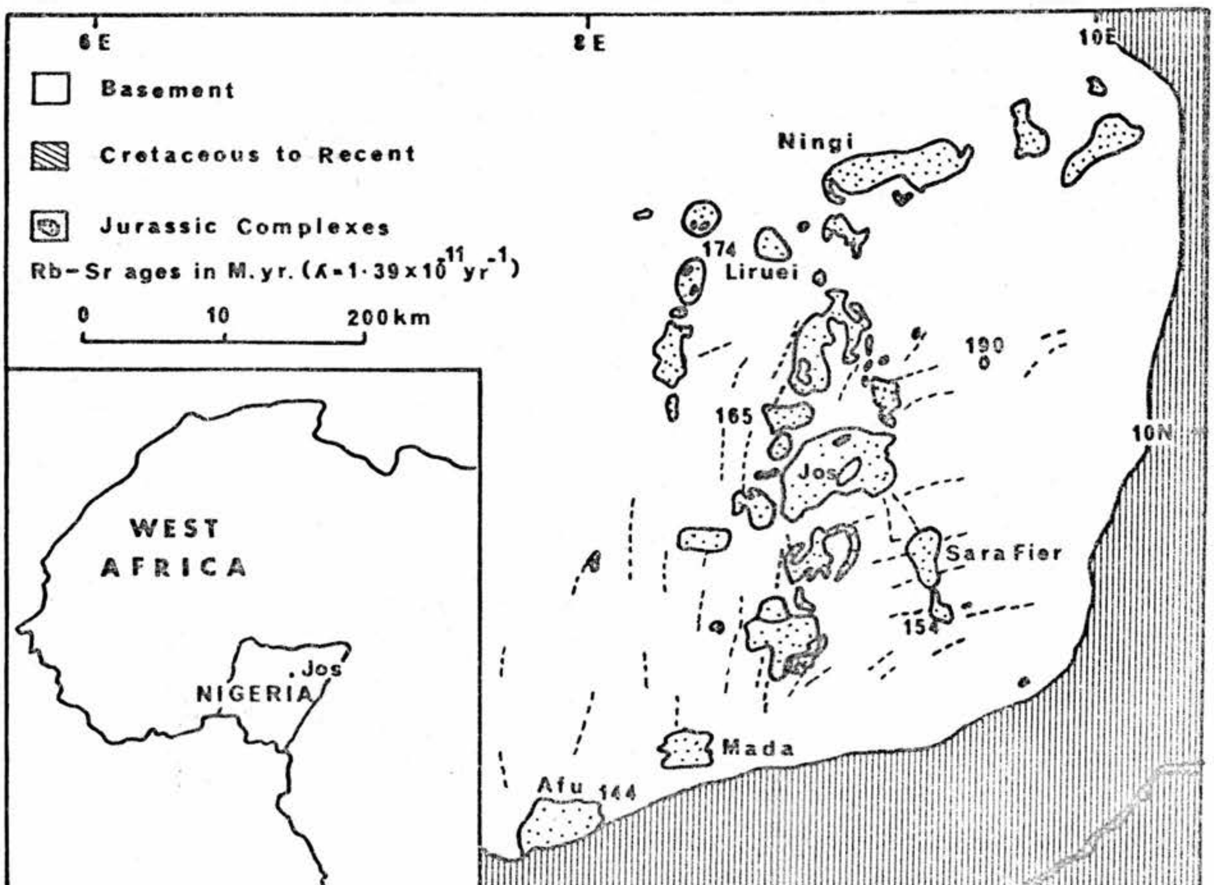


FIG 3 Age trends within the Nigerian Jurassic

Petrogenesis of the Nigerian granites

The Jurassic granites belong to two related, but sequential evolutionary trends (see fig. 4) which are thought to have evolved from a syenitic or more basic parental magma (Bailey, 1966). For the purposes of this discussion the actual source is not too critical but the evolution of the rock types leading to the development of residual mineralising fluids is important. A possible petrogenetic sequence is as follows:-

i) an early alkaline trend characterised by granites containing the iron-soda minerals aegirine, riebeckite, aenigmatite and arfvedsonite. They have an agpaitic coefficient of >1 and are characterised by <u>ac</u> and occasionally <u>ns</u> in the norm.

ii) a late aluminous trend characterised by granites containing iron-calcium-alumina minerals,- hastingsite and biotite. They have an agpaitic coefficient of <1 and are characterised by <u>c</u> and <u>an</u> in the norm.

The mineralogical and chemical changes which take place along these evolutionary trends are shown in figs. 5 & 6.

The petrological and structural sequence of many of the individual ring complexes follows the same general pattern. Early rhyolites, often ignimbritic and including the peralkaline comendites, form bedded sequences with minor associated basalts and trachytes. The later rhyolites are porphyritic and form thick, caldera-filling flows: they are closely associated with the emplacement of the vertical outer ring-dykes of granite porphyry which contain fayalite, hedenbergite and hastingsite or arfvedsonite. The main central part of each complex is occupied by granite intrusions, the number and structural complexity of which are very varied.

Where a number of different granites occur together in one complex there does appear to be a concentric sequence of granite types. Turner (1974) lists three main trends, noting that reversed sequences of concentricity sometimes occur.

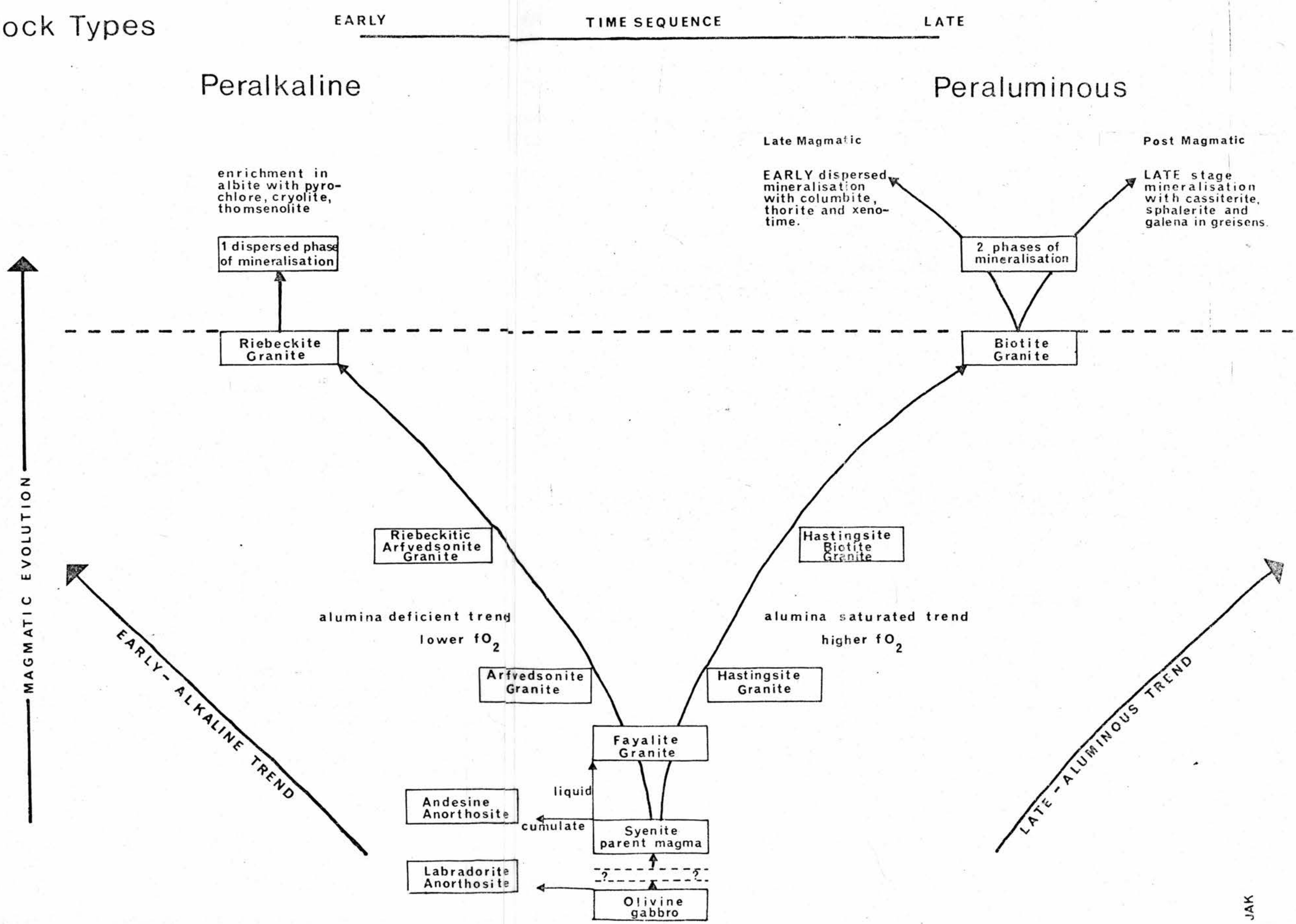
1. i) fayalite-hedenbergite-hastingsite (or arfvedsonite) granite porphyry.
   ii) aegirine-riebeckitic arfvedsonite porphyry
   iii) biotite granites.
2. i) fayalite-hedenbergite-hastingsite granite porphyry
   ii) hastingsite-biotite granite
   iii) biotite granites.
3. i) syenite
   ii) aegirine-riebeckitic arfvedsonite granite
   iii) biotite granite.

The concentric pattern does not necessarily reflect the order of intrusion, or more particularly the order of production from a high level magma chamber.

Within complexes where many biotite granites occur, Turner suggests that there is a trend from early coarse-grained granites through medium-grained varieties to the late fine-grained types.

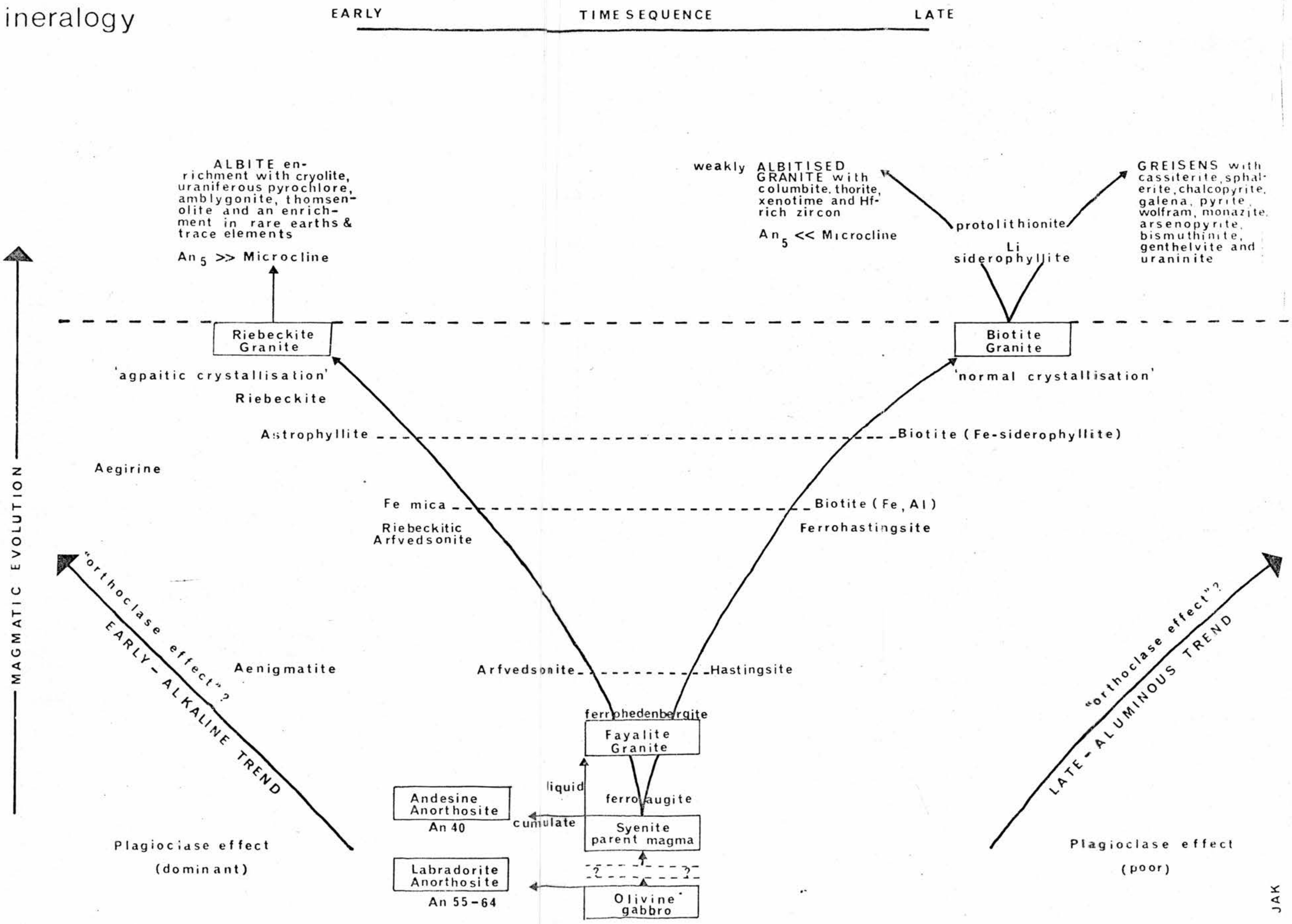
The northern complexes are exposed at a higher structural level than those of the Jos Plateau and further south, and abundant rhyolites are associated with fayalite-granite porphyries whilst only the roof zones of the biotite granites are exposed. In contrast, the complexes of the Plateau and south are composed mainly of massive biotite and hastingsite biotite granites whilst the volcanics generally are preserved only as small arcuate remnants between granitic

1. Rock Types

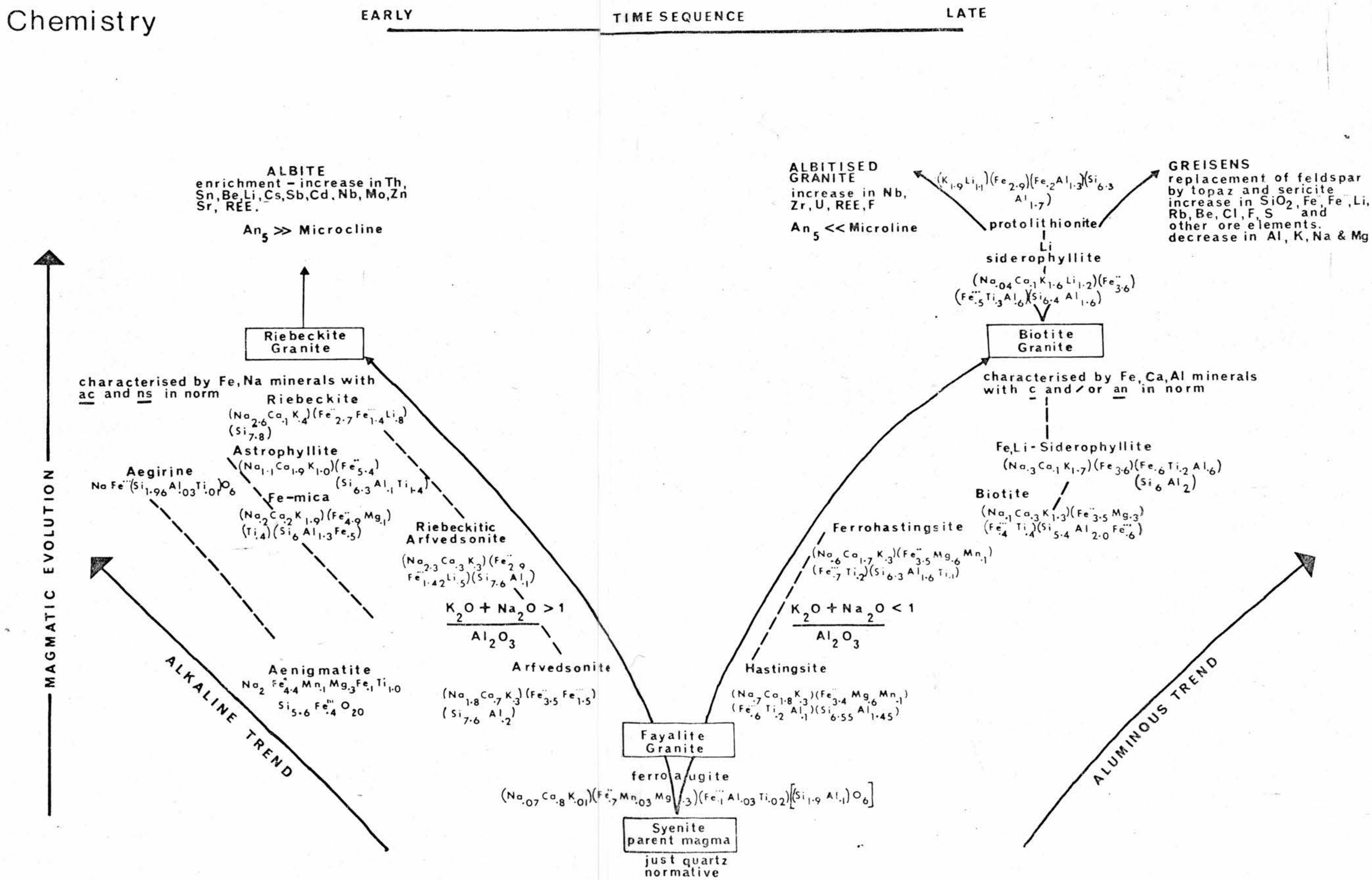


EARLY
TIME SEQUENCE
LATE
Peralkaline
Peraluminous
Late Magmatic
Post Magmatic
enrichment in albite with pyrochlore, cryolite, thomsenolite
1 dispersed phase of mineralisation
EARLY dispersed mineralisation with columbite, thorite and xenotime.
LATE stage mineralisation with cassiterite, sphalerite and galena in greisens.
2 phases of mineralisation
Riebeckite Granite
Biotite Granite
MAGMATIC EVOLUTION
Riebeckitic Arfvedsonite Granite
Hastingsite Biotite Granite
alumina deficient trend
lower fO_2
alumina saturated trend
higher fO_2
Arfvedsonite Granite
Hastingsite Granite
EARLY - ALKALINE TREND
LATE - ALUMINOUS TREND
Fayalite Granite
liquid
Andesine Anorthosite
cumulate
Syenite parent magma
?
?
Labradorite Anorthosite
Olivine gabbro
JAK

2. Mineralogy



Chemistry



EARLY
TIME SEQUENCE
LATE
MAGMATIC EVOLUTION
ALBITE
enrichment - increase in Th, Sn, Be, Li, Cs, Sb, Cd, Nb, Mo, Zn Sr, REE.
An5 >> Microcline
Riebeckite Granite
characterised by Fe, Na minerals with ac and ns in norm
Riebeckite
Astrophyllite
Aegirine
Fe-mica
Riebeckitic Arfvedsonite
K2O + Na2O > 1 / Al2O3
Aenigmatite
Arfvedsonite
ALKALINE TREND
ALBITISED GRANITE
increase in Nb, Zr, U, REE, F
An5 << Microline
protolithionite
Li siderophyllite
GREISENS
replacement of feldspar by topaz and sericite increase in SiO2, Fe, Fe, Li, Rb, Be, Cl, F, S and other ore elements. decrease in Al, K, Na & Mg
Biotite Granite
characterised by Fe, Ca, Al minerals with c and/or an in norm
Fe,Li-Siderophyllite
Biotite
Ferrohastingsite
K2O + Na2O < 1 / Al2O3
Hastingsite
ALUMINOUS TREND
Fayalite Granite
ferro augite
Syenite parent magma
just quartz normative

ring intrusions. This difference in depth of erosion is partly related to a north-eastward tilt towards the Chad basin and increasing erosion on approaching the Benue trough.

The distribution of exposed biotite granites is of economic significance since cassiterite and columbite mineralisation are generally associated with biotite granites.

Although they are not extensive and their total volume is very small, a number of dykes described as tholeiitic dolerite and basalt can be found cutting the granite, generally trending north-east and north-west within the younger granite complexes. During this project the writer also found microsyenite in dyke form cutting younger granite and trending north-west. These dykes appear to have utilised pre-existing planes of weakness in the basement. (Black and Girod 1970).

Rocks of basaltic and syenitic composition occur at various stages in the development of the Nigerian ring-complexes indicating that magma of these compositions was available continuously or intermittently during the evolution of the province.

Mineralisation

Economically, the younger granite province is of great importance as one of the richest tin and columbite producing regions of the world. Cassiterite is generally found in mineralised veins and greisens associated with biotite granites. (In past literature all mineralised veins, except for ore bearing quartz veins, have been defined as greisens. However this work uses the term greisens as a specific term which will be defined later in part 1.) It is also present as a fine-grained accessory mineral in some of the fine and medium-grained biotite granites and in mineralised veins in other rock types. Over three quarters of the total Nigerian tin production is derived from alluvial concentrations shed from the biotite granites and ore bearing veins of the Jos-Bukuru and Ropp complexes. (Dent Young 1974).

Niobium is abundant in albite rich granites and crystallises in the form of columbite in the biotite granites and as pyrochlore in the peralkaline granites. In addition to pyrochlore the albite-riebeckite granites may contain cryolite, thomsenolite, and fluorite and are enriched in a large number of rare and trace elements. As yet they have not been exploited. In contrast, the albitised biotite granites, where they have been decomposed to the consistency of clay, are being worked for columbite, xenotime, thorite and Hf rich zircon.

Despite the wealth of ore minerals there has been little published work on mineralisation. In 1943 Haag described numerous wolfram localities and during the years 1945-1948 a large part of the Plateau, considered important because of the tin, was re-surveyed. This information was published by MacKay et al., (1949) as Bulletin 19 of the Geological Survey and this described in detail two cassiterite-bearing lodes, as well as the distribution of alluvial tin and columbite. Jacobson (1947) gave a detailed description of the Liruei lode and MacLeod (1956) and Williams et al., (1956) discussed the columbite-bearing granites of the Jos-Bukuru complex. Wright (1970) in his discussions of the controls of mineralisation of Nigerian tin-fields summarised much of the existing data on ore distribution. Both the 1958 Memoir and Bulletin 32 of the Geological Survey note that 'greisens' occur in many of the granites, but no further description is given.

Tertiary Older basalts and Sedimentary Series of Tertiary to Quaternary age.

The name fluvio-volcanic series was used by Falconer in 1921 to describe a series of sediments and lavas laid down over a wide area of the Plateau, probably during mid-Tertiary. Gravels and sands were overlain by fluviatile clays. Widespread eruptions of basaltic lava covered these sediments and prolonged weathering decomposed the basalts to clay. Leached iron oxides were redeposited at lower levels as ironstone bands and the characteristic flat-topped hills of the fluvio-volcanic series were protected from erosion by these hard cappings of ironstone. The Tertiary sediments contain the oldest alluvial cassiterite, derived from the primary sources mentioned above.

MacKay et al., (1949) give the following as a representative sequence:-

1 metre	-	ironstone capping
36 "	-	basaltic clays derived from the older basalts
3 "	-	sedimentary clays with lenses of well sorted sands
1½ "	-	sands with cassiterite.

However, the beds vary considerably in thickness and from one locality to another. Dixey (1949) suggests that the original thickness of the fluvio-volcanic series was at least 350 metres although MacKay _et al._, (op cit) suggest that the total thickness was probably only 70-100 metres. They also estimate that the total area covered by the series is about 180 km^2.

Volcanic activity has taken place intermittently from Tertiary to Recent times. The resulting basalts have been divided into two groups; the older basalts, some of which are lateritised and the Quaternary Newer basalts. The lateritised older basalts represent lavas now decomposed to clay which are usually overlain by a thick cap of lateritic ironstone. The relationship of the unaltered older basalts to the old lateritised and the newer basalts is not clear but it does seem likely that each group covers a considerable age range.

The older basalts are possibly of tholeiitic affinities whereas the newer basalts are alkaline and contain ultramafic nodules containing $Ti\text{-}Fe^3$ rich hornblende, zircon, ferrisalite and Fe spinel. Wright (1972) describes tholeiitic older basalt from the south-west of the Plateau, containing 10% orthopyroxene (bronzite), 35% clinopyroxene and 45% plagioclase of approximately An 55 with little or no olivine - the remaining 10% is glass.

Black and Girod (1970) suggest that the Tertiary to Quaternary vulcanism in the unstable belt of orogenesis to the east of the west African craton has developed only in zones of pronounced epeirogenic uplift where deep pre-existing faults provide channelways for the rise of the magma. This epeirogenic uplift which took place in Cretaceous - see fig. 7 - would also explain the onset of sedimentation.

During the denudation of the Tertiary granitic landscape cassiterite was eroded from the primary sources and concentrated in the alluvials, often in small rich pockets, to form important areas of secondary mineralisation. Later erosion may have reworked these sediments and redeposited the cassiterite in complex patterns.

The alluvial ore-deposits in Nigeria are very important since virtually all the cassiterite and most of the columbite has been worked from modern streams and their old channels. Very few stream valleys are not overdeepened by the tin workings of individual miners.

The ore-bearing sediments are mined by drag lines, gravel pumps, dredging, hydraulicing, or are worked by hand. The content of the ore concentrate varies in different areas but may contain cassiterite, columbite, ilmenite, magnetite, zircon and small quantities of xenotime and occasionally monazite. Cassiterite and columbite are the most abundant and valuable minerals although concentrates of the others may be sold when the current world market price is high.

The tenor of the tin in the alluvials has been known to exceed 3,500 ppm although the grade, which has been gradually decreasing since tin mining began, is now commonly below 700 ppm. However, tin values along a channel can vary very rapidly.

In a modern stream it is not always possible to be sure whether a deposit has been derived directly by granite weathering or whether there has been reworking of the Tertiary sediments - which must account for some of the concentrates in the present streams.

Although the columbite is smaller in size than the cassiterite grains it nevertheless has a better crystal form in the alluvials than the cassiterite. It is also more widely distributed from its source because its finer grain size enables it to be transported a greater distance.

Columbite also occurs over a greater vertical range than cassiterite, presumably because it has a more general distribution in the source rocks.

Much of the cassiterite occurs in grains which are greater than 40 mesh in size, whereas over 90% of the alluvial columbite is finer than 60 mesh.

MacKay _et al_., (op cit) estimate that the ratio of columbite to cassiterite throughout the minesfield is between 1:20 and 1:25. However, as the columbite is of a finer grain size than the cassiterite estimates of this ratio are bound to be inaccurate since there will be a greater loss on recovery for columbite than for cassiterite.

The position of major concentrations within the modern valleys is influenced by the availability of ore material, the gradient of the profile and the velocity and volume of the river water. MacKay _et al_., (op cit) noted that all major deposits of tin located in stream profiles occurred where the average gradient was between 4.7 and 13 metres per kilometre.

Newer Basalts

The newer basalts of Quaternary age were so named by MacKay _et al_., (1949) to differentiate them from the older, tholeiitic, lateritised basalts of Tertiary age. These alkali basalts occupy approximately 350 km^2 in the western and southern Plateau and cover much larger areas below the escarpment in the west and south-east. Recent geochronological research suggests that both older and newer basalts cover a considerable age range. It has been suggested by Black and

Girod (1970) that the rise of the magma has been facilitated by the pre-existence of deep seated wrench faults. Volcanic craters are located where younger granite ring-faults intersect with pre-Ordovician transcurrent faults in the basement and may also be aligned along more recent north-northeasterly faults.

Most of the volcanic vents of the Plateau lie in a belt running from Bassa cone in the north-west to Panyam in the south east. Falconer (1926) regarded this as a line of structural weakness in the earth's crust which he termed the Sura volcanic line. MacLeod et al., (1971) describe another such lineation to the south-east - the Gu volcanic line which has six foci and a length of approximately 15 km.

Grant et al., (1972) suggest that the basalts of the Jos Plateau belong to a period of widespread basaltic activity extending back at least 7 my BP. The K/Ar ages from the Plateau date only the youngest activity. Two of the dated samples from the Plateau are from the newer basalts. The sample of the Vom basalt represents the 'more recent basalt' of MacKay et al., (1949) and gave an age of 0.9 ± 0.2 my whilst the sample from the 'earlier newer basalt' of the Bassa flow (outside the project area) gave an age of 1.5 ± 0.1 my.

The newer basalts erupted after the Plateau had almost assumed its present day topography. The flows were controlled by broad, shallow valleys and are therefore rather limited in depth, rarely exceeding 70 m in thickness. Much of the basalt, particularly the later flows, is unweathered, - the epoch of intense weathering and later lateritisation which affected the fluvio-volcanic series preceded the newer basalt flows on which there is rarely laterite.

Most flows can be traced to well preserved volcanic cones which are relatively small features. Eruptions were intermittent and in some cases two, three or more flows issued from one vent although in the Ngell cores there is no evidence for more than one flow. The volcanoes, which rarely rise more than 100 m above the Plateau surface, are steep sided and frequently show central craters. It seems likely that eruptions of ash preceded many of the newer basalt flows.

Petrologically the newer basalts are dark to black, porphyritic olivine or augite basalts with phenocrysts set in a groundmass composed of plagioclase laths, granular augite, olivine and iron oxides. Phenocrysts may be of olivine, augite or less commonly of plagioclase, usually labradorite, with combinations of all three. The olivine phenocrysts may be partly serpentinised and the augite phenocrysts commonly show zoning. They may also contain numerous ultramafic nodules of $Ti\text{-}Fe^{3}$ rich hornblende, zircon, ferrisalite and Fe spinel.

The newer basalts overlie the main alluvial deposits of the broad Plateau valleys which are a potentially rich source of buried cassiterite. Between 130 and 260 km^2 can be considered to be of economic interest and for many years small opencast workings have extracted cassiterite from beneath the margin of basalt flows. Geophysical methods have been applied in prospecting to reduce costly exploration drilling. Shaw (1951) used magnetic and electrical resistivity measurements whilst Masson Smith (1965) used gravity and seismic methods. None of the methods were very successful due to the variable decomposition of the basalt and the small difference between weathered bedrock and overlying alluvial wash.

Fig. 7. Summary of the main structural events, Igneous activity and Sedimentation relevant to the history of the Jos Plateau

		Age my	
13	Quaternary	2	Extrusion of alkali olivine basalts from volcanoes aligned on WNW and NNE fractures and younger granite ring faults.
12	Tertiary		Erosion of the Jurassic landscape and deposition of alluvium. Extrusion of tholeiitic basalts.
11			Senonian folding associated with NNE faulting in adjacent Benue troug which contains continental and marin sediments.
	Creteaceous		The rise of the Aïr-Jos Plateau axis
10			Reactivation of the pre-Ordovician wrench faults. Formation of Benue rift valley in Albian.
9	Jurassic	200-144	Intrusion of riebeckite, hastingsite and biotite granites with associated tin and columbite mineralisation.
8			NE and ENE trending dextral wrench faulting which is pre-Ordovician - N-S upwarping.
7	U. Precambrian - L. Palaeozoic	ca 450	Pegmatite mineralisation of older granites.
6		ca 610	Intrusion of weakly foliated syn-tectonic to late tectonic granites and granodiorites accompanied by local contact metamorphism of meta-sediments.
5			Two successive phases of deformation and metamorphism, with migmatisation and reactivation of the crystalline complex and metasediments resulting in a suite of orogenic granites (the older granites).
4			Geosynclinal deposition of younger metasediments, thick sands, muds and greywackes in a mobile belt. Formed schists, phyllites, quartzite & amphibolites during Pan African thermo-tectonic event.
3	Early Proter-ozoic	2,000 2,500	Folding & metamorphism of Birrimian sediments during the Eburnian orogen to form a crystalline complex of gneisses, migmatites and high grade metasedimentary relics. Reactivatio of Dahomeyam to produce a suite of orogenic granites.
2			Geosynclinal deposition of older metasediments-Birrimian
1	Archaean	2,800	Crystalline Basement - Dahomeyan and Liberian.

CHAPTER 2

The Bukuru/Ngell Valley Project

Location

Detailed field mapping, preceded by air photograph interpretation, covered an area of 145 km^2 west of Bukuru. Most of the project area lies within the Jos-Bukuru Jurassic granite complex, which together with its associated satellite ring structures covers an area of approximately 750 km^2 on the central Plateau. The Jos-Bukuru complex as a whole is elliptical with the longer axis extending from the Shere Hills in the north-east to the Vom Hills in the south-west. The project area is located in the south-west of this complex and encompasses rocks of the basement and Tertiary basalts west of the Jurassic granites (Fig. 8).

Topography

Within the Jos-Bukuru complex there is a range in elevation from 1,150 metres in the west and north-west to nearly 1,800 metres in the Shere Hills. The area of study lies between 1,250 and 1,370 m.

Rocks of the basement complex form a broad, shallow river valley, occupied by the Ngell river, with Jurassic granite to the east forming rocky, rugged hills and gently undulating terrain. To the west of the Ngell valley the lavas of the Ngell and Vom basalts form flat, featureless terrain.

Climate and Vegetation

The climate varies considerably, according to the month and season. There are three well-marked seasons and a less well-marked season between October and December.

i) Dec. - Feb. - a cool dry season with dust-laden Harmattan winds blowing from the Sahara. Max. temp. $30^{o}C$.

ii) Mar. - May - a hot dry season characterised by a change in wind direction from NE. to SW. Occasional heavy showers. Max. daily temp. $35^{o}C$.

iii) June - Sept. - a warm, wet season with heavy rains during July and August and heavy isolated storms in June, early July and Sept. Max. daily temp. $32^{o}C$.

iv) Oct. - Dec. - a less well marked season characterised by cessation of rainfall and gradually decreasing temperatures.

Vegetation is of the Sudan Savanna type. During the wet season the ubiquitous grasses rise to a height of 1 m. There is little natural woodland remaining.

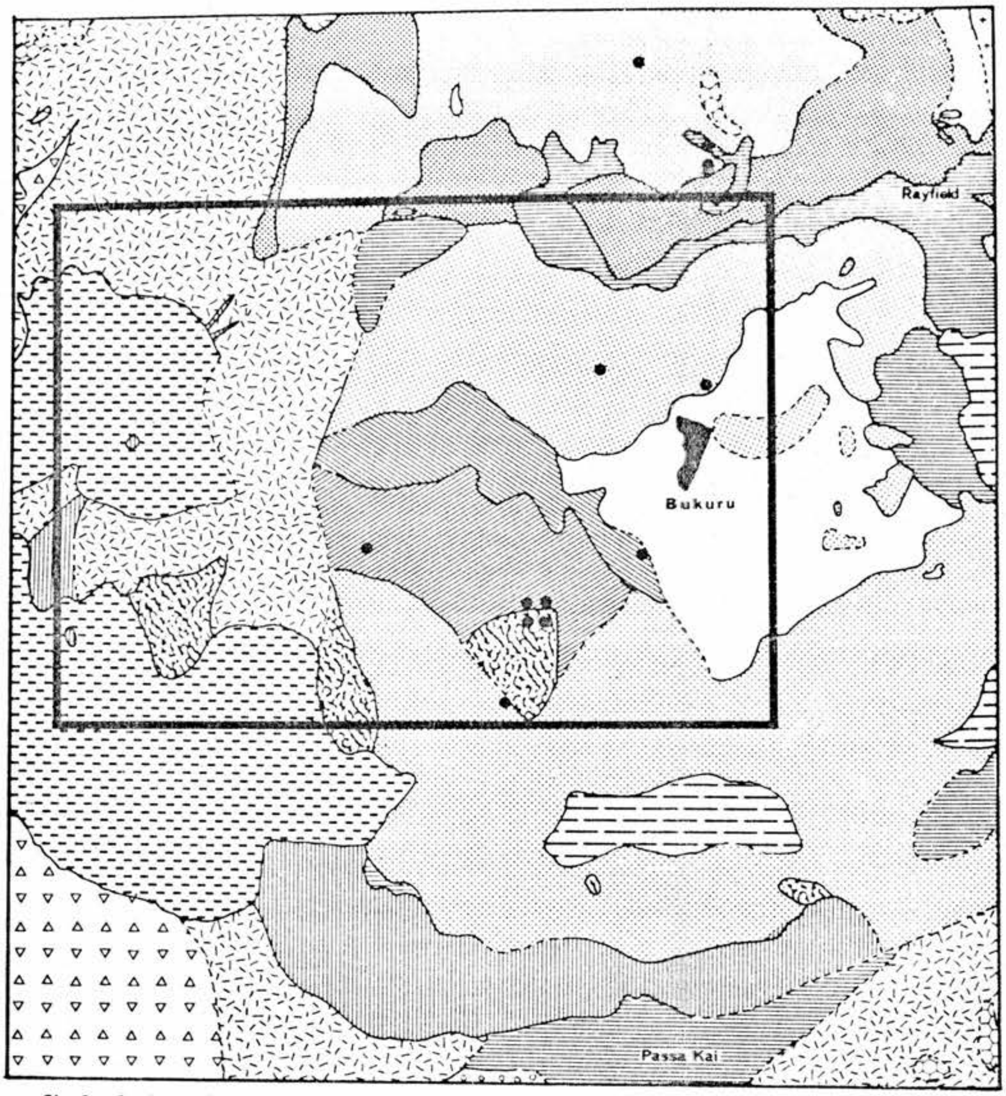


Fig 8 Geology of part of the Jos-Bukuru Jurassic Complex and surrounding areas taken from the 1:100,000 sheet 168 in Bulletin 32 Geological Survey of Nigeria 1971

Quaternary - Newer basalt

Tertiary - Older basalt

Microgranite

Sabon Gida north granite

Sabon Gida south granite

Bukuru granite

Shen granite

Delimi granite

Rayfield-Gona granite

Kuru granite

Ngell granite

Jos granite

Vom granite

Undifferentiated granite

Basement

Greisen locality

Area covered by 1:10,000 project map

Scale

0 1 2 3 4

kms

Photogeology.

A large part of Sheet 168 is covered by high resolution photographs on a scale of 1:10,000 taken by Meridian in 1971. These were used to make a geological base map of the area to be studied as no suitable large scale base map existed. From the photographs, areas from which the maximum ground information could be obtained were selected for field work checking. Also it was hoped that it would be possible to locate areas of mineralisation.

Initially smaller scale photographs at 1:40,000 were used to make a rapid preliminary interpretation since a small number of photographs covered a large area (Footnote).

The project area around Bukuru was studied in detail on the large-scale photographs and it was found possible not only to differentiate different rock types but separation of some of the granite units proved very accurate. This was achieved by noting subtle differences of tone and texture, structure and jointing and form of outcrop. Where there are few rock outcrops, relief, landforms, drainage pattern and vegetation changes may all be indicative of the underlying lithology.

The rock types described below occur to a greater or lesser extent within the project mapping area. As it was hoped to project information gained in this study to areas in the far north of the province it was considered necessary to gain as much detail on different rock types as possible.

Footnote. (Using a camera with a 6" lens, a flying height of 20,000 feet results in a scale of approximately 1:40,000. At 1:20,000 the number of photographs involved is x6, allowing for overlap. At 1:10,000 however, the number of photos now becomes x40).

The following criteria were established:

Basement Rocks.

These seldom occur as large outcrops except on the escarpment and have no economic potential on the Plateau, and so have not been considered important by the writer. They appear an even, light to medium grey producing a featureless, mildly undulating landscape. The older porphyritic granite member of the group forms occasional small or medium sized hills and is usually found as a smooth-faced, dull grey rock, frequently displaying dyke networks. Similar smooth surfaces are observed on the few gneissose outcrops. More soil is normally associated and vegetation is more abundant than on the younger granite, which is strongly jointed, the older granite being foliated and of an overall rough character.

It is impossible to draw accurate boundaries either between members of the group, or around the group as a whole, even after ground checking. However, after checks on the ground, fairly accurate boundaries can be drawn on the air photographs between the Jurassic and older granites where they occur in contact.

Long major streams form the general make-up of the drainage pattern, few short tributaries occurring.

Younger Granites.

Whether as single boulders, bare rocky ridges or high hills, most of the Plateau outcrops are formed from hard Jurassic granite, resistant to erosion. Smooth surfaces do occur but loose boulders and jointed outcrops are more common. At ground level the boulders and slabs seem randomly strewn, but on aerial examination a parallel arrangement is evident, with the same alignment as the predominant joint sets. It is occasionally possible to identify granite variants in isolation from air photographs and frequently possible when they are in contact with one another. The appearances on the air photographs of the granites found in the project area are described later.

Where the granite has a thin soil cover there is little evidence of the identity of the underlying rock apart from occasional hills and smaller outcrops, practically the only vegetation being grass.

In hilly regions streams form straight gullies following major joints, suddenly swinging, often widely, into a different joint set and heading off along another straight channel. Even on flatter ground where the younger granite is exposed the streams meander less than on the basement and overall a much more dense pattern is shown.

An attempt was made to use the joint patterns apparent on the air photographs to distinguish the granites in the project area.

With the aid of a geological map (Sheet 168 from Memoir 32 - 1971) to locate outcrops of each granite type on the air photos, rose-diagrams were constructed of the joint directions for each type. These directions were later verified by field work. No definite pattern emerged - each granite showed a wide range of joint directions with major sets orientated either north-east or north-west.

One useful fact did emerge from these studies. It was noted that in certain granites there were zones in which there was a marked increase in jointing intensity and that occasionally the joints became so closely spaced it was impossible to tell their orientation from the photographs. Subsequent field work showed that where mineralised veins occurred in the project area they were located within these zones.

Fluvio-volcanic Series.

Since alluvial tin is concentrated in basal members of this series their identification on air photographs could be economically valuable.

The series is formed of unconsolidated sediments and weathered lavas, and outcrops are invariably small. Complete series occur characteristically as flat topped hills whilst flat horizons at or near the ground surface mark the ironstone horizon. The boundary of the ironstone is clearly marked by a low serrated scarp where the ground slopes away from the edges of these flat horizons with the slopes often covered with ironstone slabs. Recognition can be difficult when erosion has removed the ironstone capping leaving only the lowest horizons. The remaining outcrop forms a smooth, low curving ridge or hillock.

The series has a typical dull grey tone and smooth surface, quite distinct from those of all other rock types although old paddock dumps also have the tone and texture. MacKay (1949) noted that remnants of this series could be picked out on air photographs, even when buried, by their lighter tones, vegetational differences and much less intense cultivation due to the presence of laterite rubble. Several of the occurrences he inferred were later proved by drilling.

Newer Basalts.

The air photographs show as a distinctive dark, almost black tone, the flat flow surfaces of the younger basalts, the edges often being marked by low irregular scarps. Where the edge of the flow is thin the margins cannot be recognised with certainty. Small basalt exposures are found only at flow edges along river banks or in river beds. They are characterised by flat upper surfaces and vertical walls of black rock. It is more usual to find basalt as black boulders on the flow surface, giving a particular surface appearance where there are many, but too small to be individually distinguishable on air photographs. Unmistakable dark crescent-shaped hills usually surrounded by flat lava plains (e.g. Vom) are formed by the volcanic vents.

Another characteristic of the lava flow is the almost complete lack of drainage. Typically the stream follows the margin of the flow with no tributaries from the basalt, only from the surrounding landscape. A classic example is the Ngell river channel which follows the east and north margins of the Ngell basalt.

On the Plateau the lack of natural selectiveness of vegetation makes it impossible to determine accurately the underlying lithology from vegetational changes. However, clear changes in land use pattern occur on the almost undetectable boundary between basalt and older rocks. Perceiving changes in land use pattern it proved easier and more accurate to map the boundary of the Vom basalt on the aerial photographs than was possible on the ground.

Summary

On the 1:10,000 photographs it was found that areas covered by basalt and sediments of the fluvio-volcanic series are readily identifiable. Areas underlain by granite gneiss are not so apparent but can sometimes be distinguished with difficulty, although it is impossible to draw accurate boundaries between this and other rock types, including others from the basement. No distinction between the porphyritic and muscovite granites of the basement could be drawn on the photographs but only the porphyritic variety formed large bouldery outcrops.

It was found possible with practise to distinguish some differences between two Jurassic granites when they were in contact. However, only with the Jos granite and sometimes the Ngell can small isolated outcrops be identified as a particular granite variant. Within these granites, individual ore-bearing veins can rarely be identified from air photos alone. However, potential areas of mineralised veins can be located in some of the granites by field examination of the areas which show an unusually close pattern of joints.

Geology of the Ngell Valley Area

Basement

The Basement igneous and metamorphic granitic rocks of the area include porphyritic hornblende-biotite granite, fine-grained muscovite granite and granite gneiss which has been mapped by the Survey as a fine-grained granite. Outcrops are poor and except for the porphyritic granite largely restricted to paddock floors.

The porphyritic granite is well exposed in the hills to the west of Kafo Peak, (Fig. 13), as a largely homogeneous, foliated granite with feldspar phenocrysts up to 4.5 cm long set in a dark coloured, medium grained matrix. It contains two generations of feldspar; the large megacrysts, up to 4.5 cm in length, are randomly orientated whilst the smaller crystals have a subparallel, approximately 350' orientation. The smaller crystals may be an earlier phase of development formed under regional stress whilst the later, larger crystals, which often show zoning, may have been formed after the stress had been removed.

In thin section the large, subhedral phenocrysts are oligoclase/andesine with minor amounts of microcline microperthite set in a finer feldspar mass often displaying a micrographic texture. The quartz occurs as a fine mosaic or as large anhedral grains showing strain extinction. Biotite and hornblende are abundant: both are strongly pleochroic and show strain cleavage. The biotite is pleochroic from very dark brown to pale yellow brown and the hornblende from dark olive green to pale yellow brown. The abundant hornblende, which is altered at the edges to biotite, contains laths of feldspar and anhedral ilmenite. Sphene, zircon and apatite occur as accessory minerals with a few small epidote crystals distributed in the fine-grained quartz. The ilmenite always occurs within, or adjacent to, the ferromagnesian minerals.

To the east of the porphyritic older granite, the rock type is still clearly granitic, but with a finer grain size, and is composed of muscovite, biotite, quartz and feldspar. The boundary between these two different types of granites is not observed but examination of closely spaced sub-basalt cores suggests that the boundary between the two is probably fairly sharp. Petrologically the muscovite granite differs little from the porphyritic granite except that muscovite is the predominant mica and hornblende is absent.

Part of the area mapped as fine-grained granite on the 1:100,000 Geological Survey map is clearly a gneiss and is petrologically distinct from the granites. Sillimanite and garnet bearing samples have been described by the geologists of the Amalgamated Tin Mines (Nigeria) and the relationship of this gneiss to the Basement granites has not been determined and no boundaries have been located.

Jurassic Granites

Within the Jos-Bukuru complex, MacLeod (1971) differentiated 13 different intrusive phases which he separated into an early granite cycle of eight phases and a central granite cycle of five phases (Table 2). The granites were preceded by rhyolites and pyroclastics. The main plutonic cycle began with the emplacement of porphyries and hastingsite biotite granite, generally in the form of discontinuous ring dykes intruded into a major elliptical fracture zone. These ring dykes were undoubtedly more extensive than present outcrops show. The first emplacements were followed by a series of intrusions of biotite granite beginning with the extremely coarse grained Jos granite, followed by successively finer-grained varieties.

The recurrence of hastingsite fayalite granite characterised the beginning of the second intrusive cycle and it forms a broad, arcuate ring dyke. A series of medium to fine grained biotite granites and microgranites succeeds this intrusion.

Within the project area only a very small exposure of volcanics is seen and no porphyries occur, so the first of the phases represented is hastingsite-biotite granite. The sequence is:-

Table 1.

9. Microgranite
8. Sabon Gida North biotite granite
7. Sabon Gida South biotite granite
6. Bukuru biotite granite
5. Shen hastingsite-fayalite granite
4. Rayfield Gona biotite granite
3. Ngell biotite granite
2. Jos biotite granite
1. Vom hastingsite-biotite granite.

It has long been noted that many of the biotite granite types of the Jos-Bukuru complex are identical in hand specimen and in thin section to granite types from the Ropp complex. The sequence in both complexes as established by MacLeod and Black in Bull. 32 is compared in Table 2.

Table 2.

	Jos-Bukuru Complex after MacLeod		Ropp Complex after Black
14.	Microgranite		
12, 13	Sabon Gida granites		13. Mongor granite porphyry
11.	Bukuru biotite granite		12. Kaskara biotite granite
10.	Shen/Kuru hastingsite-fayalite granite	≡	11. Yelwa pyroxene granite porphyry
			10. Ruku riebeckite biotite granite porphyry
9.	Delimi biotite granite		9. Durowa albite riebeckite granite
8.	Kuru stock biotite granite		8. Butra riebeckite biotite granite
7.	Rayfield Gona granite	≡	7. Kassa biotite granite 6. Bukka Bakwai granite
6.	Ngell granite	≡	5. Gana biotite granite
5.	Jos granite	≡	4. Kwop granite
4.	Naraguta qu. pyroxene-fayalite porphyry	≡	3. Sho porphyry and hastingsite biotite granite
3.	Vom hastingsite-biotite granite		

It is the writer's opinion that the Jos-Bukuru and Ropp complexes probably form part of the same batholith at depth and that similar processes near the surface formed comparable, though widely separated, rock types. Evidence in support of this theory has come from satellite photography.

On the ERTS photo of Central Nigeria, centred on 08.30E and 10.00N the ring fracture, clearly evident between the Shere Hills and Jos in the north of the complex, appears to extend in an arc southwards. If the arc were continued it would intersect the Ropp and Sha Kaleri complexes where these two are adjacent (Fig. 9). It suggests therefore that the Jos and Ropp complexes are part of the same major batholith. If the two complexes do form part of the same batholith at depth, the comparable succession of rock types and identical granite variants is easily understood. Also the similarity in abundance of tin and columbite and other accessories (Williams et al., 1956) is obvious.

MacLeod divided the biotite granites within the project area into 9 phases (Table 1), and the writer agrees that whilst at least nine types can be recognised by variations in texture, grain size, feldspar type and accessories, it is very often difficult to accept the precise petrographic boundaries that are shown. There is often more variation between samples of the same granite from different areas than between samples of different granites. The boundary between two different granite types may sometimes be of hairline sharpness but a few kilometres away the same boundary may be very diffuse - the Jos/Ngell boundary is a good example of this phenomenon. Many of the boundaries between granites also suggest a fairly sharp demarcation but a transition zone up to several hundreds of metres in width may occur. Mapping of the granites is complicated in many crucial areas by lack of exposure.

To make comparisons easier it is proposed to describe the different granites using the same names that MacLeod

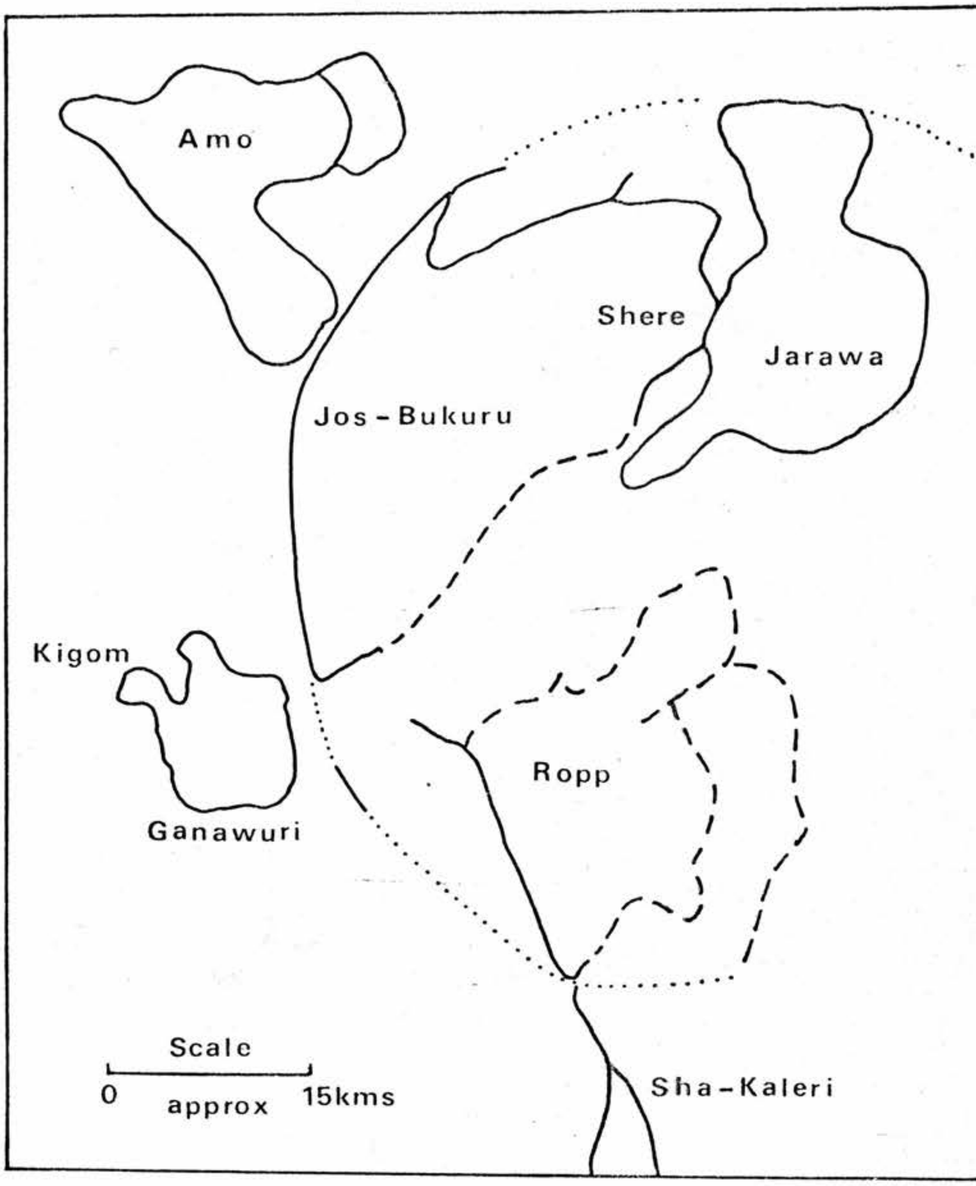


Fig 9 Structural features visible on ERTS satellite photograph of central Nigeria

.... suggested batholith margin

— definite contact

-- apparent contact

proposed for them although different conclusions about the relationship between these granites and their mineralisation will be drawn.

The following tables briefly describe the essential petrological features of the main granite types that occur within the project area.

Table 3.

Biotite Granite	Feldspar	Mica	Quartz	Accessories
Rayfield Gona (medium to fine grained)	Microcline has been partially replaced by albite or may form micrographic intergrowths with quartz. The lamellar perthitic structure is only rarely preserved and the microcline appears as marginal rims surrounding a predominantly albitic core containing small remnants of potash feldspar. It appears that late stage albitisation has destroyed the original lamellar structure. The albite is characterised by fine twin lamellae of composition approximately $Ab_{90}An_{10}$.	Pale green to colourless except in the Bisichi area where it develops a brownish tinge	Clustered anhedral glassy grains, fine to medium grain size 1-2 mm.	Columbite Thorite Xenotime Hafnium-bearing zircon Cassiterite
Ngell (medium grained)	In the project area large feldspars impart a porphyritic texture but to the north there is a greater textural variation and a greater degree of albitisation. In the project area range in size between 0.2 and 1 cm, set in a finer grained groundmass. Described in Bull. 32 as orthoclase perthite but many sections have well developed albite crystals marginal to the above and there is almost a complete transition between idealised Ngell and idealised Rayfield Gona.	Biotite occurs as large isolated plates or as fine dispersions within the feldspars. Dark greenish brown to pale green and occasionally contains minute zircons with pleochroic haloes.	Composite quartz forms large clusters and chains of subhedral crystals between the feldspars	Fluorite, commonly associate with large biotite flakes also as irregular patches in feldspar. columbite zircon ilmenite
Jos (Coarse grained)	Coarse subhedral crystals of orthoclase and microcline microperthite 0.5-2 cm in size considerable variation in amount of plagioclase but most perthites show a regular lamellar structure characteristic of exsolution. Occasional small crystals of albite/oligoclase occur at the margins of the perthites and large subhedral crystals of these are not uncommon.	Less abundant than in later granites it forms clusters of ragged plates which are either dark green or very dark greenish brown and is pleochroic to straw yellow, Pleochroic haloes surround abundant included zircons.	As clusters of coarse anhedral grains up to 1 cm in size.	Fluorite is common varying from euhed crystals 1 mm in s in mica to larger anhedral patches a mica margins. Occasional allanite intimately associated with mica. Also ilmenite magnetite with hornblende altered to zoisite and chlorite. Fergusonite, ferrohastingsite, leucoxene and zircon also occur and monazite has been recorded by Williams et al., (1956).

Table 4.

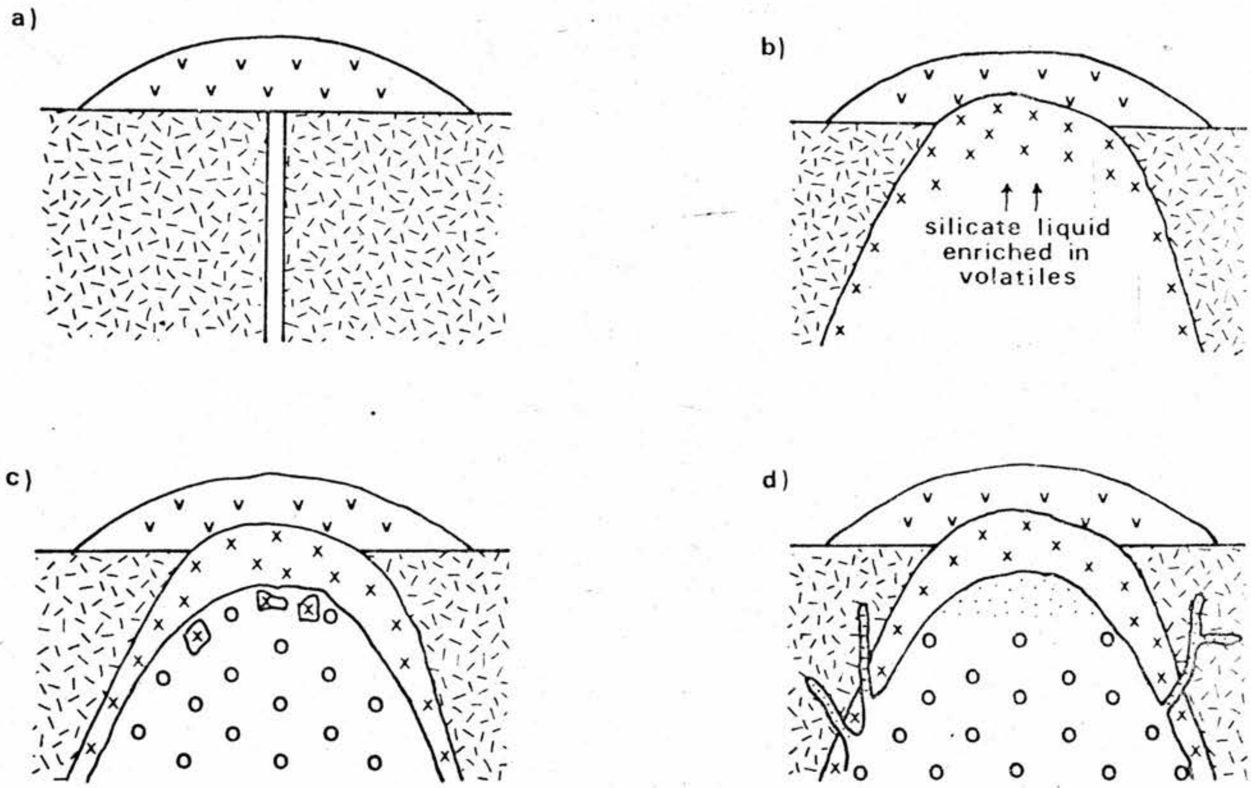
Biotite Granite	Feldspar	Mica	Quartz	Accessories
Sabon Gida North (fine grained)	Microcline microperthite with albite, either as trains of interstitial crystals or as rims around the perthites.	Usually pale green, commonly clustered, aggregates up to 1 cm in druses.	Usually fine grained and clustered. Occasionally large crystals in pegmatitic knots.	
Sabon Gida South (fine to medium grained)	Albite perthites with euhedral albite crystals as discrete grains marginal to the perthites and as chains of interstitial crystals 1 mm in size.	Dark brownish or pale green and may show wavy cleavage. Disseminated flakes 1 mm in size.	Composite quartz form medium size clusters with chains or small to medium crystals between the feldspars.	Zircon
Bukuru (medium grained porphyrite)	Albite, large euhedral phenocrysts of orthoclase microperthite with microcline set in a fine-grained groundmass rich in albite.	Brownish with green to pale green pleochroism	Large and distinctive aggregated grains	Zircon Anatase (Williams et al., 1956) Columbite

Webb (1974) has recently suggested that the Rayfield Gona granite was not an independent intrusion but a roof facies of the Ngell granite. He noted that the Ngell and Rayfield Gona phases pass transitionally and complexly into each other. He showed petrographic evidence which suggested that the Rayfield Gona was formed at the expense of the Ngell by a process of <u>in situ</u> modification when the Ngell was completely or nearly solid. Hybrids between the two i.e. relict Ngell feldspars, biotite or quartz in a Rayfield Gona groundmass, represent incomplete modification.

However, the Rayfield Gona and Ngell granites are not the only two that form hybrids. Whereas previously the formation of these hybrids has been attributed to mechanical disintegration (Williams <u>et al</u>., 1956) it is suggested here that there were not nine separate biotite granites as MacLeod suggested (op cit) but only two major intrusions of biotite granite. These two intrusions were separated by an intrusion of hastingsite-fayalite granite and there were a number of facies variants in each.

The first intrusion was very large and the early crystallisation gave rise to the Jos facies which was emplaced at a very high level into volcanics so that crystallisation proceeded from the walls and the roof (Fig. 10 a & b). At depth there remained a still liquid portion more enriched in volatiles than the Jos facies which then invaded the cooled apical portions and crystallised more rapidly than the earlier facies (Fig. 10c). During this crystallisation there was a progressive build up of residual fluids enriched in Th, Nb, etc. which modified the roof zone of the Ngell facies to give the Rayfield Gona facies (Fig. 10d) and probably the Kuru stock and Delimi facies also. The granite of the Kuru stock is strikingly

Fig 10



Sketch diagram to illustrate the suggested mechanism of formation of the Jos, Ngell and Rayfield-Gona facies.

Basement **Volcanics** **Jos facies** **Ngell facies** **Rayfield-Gona**

similar petrographically to the Ngell but in addition it contains a high columbite content and heavy mineral assemblage similar to that found in the Rayfield Gona.

Also the Delimi granite shows microcline perthite with a mottled replacement texture and abundant coarse lath albite at perthite boundaries similar to the Rayfield Gona granite in thin section.

During these modifications there is a gradual transformation in mineralogy. There appears to be a progressive change from orthoclase microperthite in Jos granite to microcline microperthite in Ngell with the gradual destruction of perthite by albite in the Rayfield and Delimi facies. Also there is a change from deep brown ferroan siderophyllite in the Jos granite and deep brown or dark green mica in the Ngell to a pale green or colourless protolithionite in the Rayfield Gona and pale greenish brown mica in the Delimi facies.

The second major biotite granite intrusion began with the Bukuru facies followed by the Sabon Gida north and the Sabon Gida south facies and lastly by the Vom microgranite which is a modification of the Sabon Gida south. Again the same progressive changes of the earlier intrusion are repeated. Orthoclase perthite forms large phenocrysts in the Bukuru granite whereas the feldspar of the Sabon Gida north granite is microcline with abundant lath albite. The mica of the Bukuru granite is brown in contrast with that of the later Sabon Gida facies in which they are greenish brown in the Sabon Gida south facies and pale green in the Sabon Gida north facies (Table 4).

The varying clarity of the boundaries between different granite facies can be explained by this hypothesis, and also why there is sometimes greater variation within one granite (e.g. Rayfield Gona) than there is between supposedly different granites (e.g. Ngell and Kuru facies).

Examination of a number of 'sharp' contacts within the Bukuru/Ngell valley area has also shown that mineralogically the contact is not as sharp as the texture implies. In some cases where there appears to be a decrease in grain size of the younger facies against the older there is actually an increase in the size of the biotite whereas the decrease in grain size applies only to the feldspars. This gives the rock the appearance of being finer-grained. Thin section examination of the 'sharp' contact between the Rayfield Gona and Ngell phases show that immediately adjacent to the boundary the biotite in the Rayfield Gona shows the clustered distribution of the Ngell phase and it is several centimetres from the contact before the mica becomes more disseminated and paler in colour.

Parallel to the northern limb of the Rayfield Gona intrusion, MacLeod (op cit) describes a persistent shear zone intruded by microgranites, which he relates to the intrusion of the Rayfield Gona granite. However, in the region of the twin hills loose boulders of Shen hastingsite-fayalite granite were found and it is suggested here that the shear zone is probably the result of the hastingsite-biotite granite intrusion. If the arc of this intrusion which occurs further south, were projected, then it would in fact intersect the twin hills where the loose boulders of hastingsite biotite granite were found. Also, shearing has been noted within the Rayfield Gona facies to the north of Yelwan Feranti village (see 1:10,000 scale map).

The following section describes the distribution, photographic expression, mineralisation and joint directions of each of the granite facies using the names designated by MacLeod (1956) to avoid confusion. The numbering system for the granites not only refers to the order of formation but also relates to the numbering of the outcrops on the 1:10,000 scale accompanying map.

1. Vom hastingsite biotite granite

The Vom hastingsite-biotite granite ring-dyke is a broad, arcuate intrusion defining the south-west perimeter of the Jos-Bukuru complex (see Fig. 8). It has been covered in part by the Vom and Ngell basalts and the largest exposures in the project area is to the east of Kafo peak. North of the Ngell basalt the Geological Survey 1:100,000 sheet (1971) shows that the continuation of the ring-dyke bifurcates. From this it is inferred that the two small dykes merge below the basalt to form the one dyke that is observed south of the basalt. However, there is no field evidence to support the continuation of the more easterly of the two dykes south of the Ngell river and drilling by ATMN has not located this second dyke either within the basement or beneath the basalt. The western dyke has been cored by sub-basalt plugs at a depth below surface of 41.8 - 39.3 metres whereas the basement is cored at depths of greater than 42.5 m.

The boundary between the ring-dyke and the basement is nowhere observed as is suggested by the solid line of the survey.

Numerous thin ($<$ 5mm) black veins cut the ring-dyke trending either north-northeast or, more commonly, varying between east-northeast and east-southeast. Originally they were considered by the writer to be mylonite veins but thin sections show them to be black greisen veinlets. These are analagous to the mineralised greisens described by Weir (1974) cutting the Sho granite porphyry ring-dyke of the Ropp complex.

An analysis of the hastingsite appears in Appendix 3.

2. Jos biotite granite

The Jos granite outcrops in a broad, discontinuous east-west band along the northern margin of the project area and covers 4 km^2. It is the only granite that is immediately recognisable throughout the complex on account of its pink colour and extremely coarse grain size. It displays little variation in texture over its entire extent. The feldspars range between 0.5 cm and 2.0 cm in length and the quartz is aggregated in clusters up to 1 cm long. The biotite forms large plates and coarse clusters. Whole rock analyses appear in Appendix 4.

The Jos granite, the largest intrusion in the whole Jurassic granite province, has equivalents in many of the other complexes and the Kwop granite of the Ropp complex is indistinguishable from the Jos granite. In all these complexes the very coarse-grained granite is always the earliest phase of the biotite granite intrusions and contains only low quantities of dispersed columbite. Only rarely are mineralised veins found and then they are restricted to the contacts with the earlier intrusives or the basement. The area that these different coarse-grained granites cover in the different complexes depends on the degree of erosion.

On aerial photographs, although it only covers a small proportion of the project area, the Jos granite is quite distinctive. It has a prominent regular open joint system with two equally developed joint sets, one east-west and the other at 340^{o}-360^{o}, accompanied by horizontal sheeting in weathered outcrops. This produces 'towers of perched boulders' which have a constant colour and texture on the photographs and are therefore quite distinctive. Even on relatively unjointed surfaces there are invariable smaller piles of boulders and the Jos granite can be identified from the photographs even on small isolated outcrops. Minor joint sets orientated east-northeast and west-northwest are also common.

The contact between the Jos and Ngell facies is best seen outside the project area north of the new road to the Jos township reservoir where the contact can be followed for nearly 5 km. It dips northwards at a low angle whereas in the hills south of the Vom volcano the contact dips south between 20^{o} and 30^{o}. In the project area the contact is either poorly exposed or complicated by microgranites or large scale xenolith inclusions. In one area north of Yelwan Feranti the contact between the Jos and Rayfield-Gona granite was more obvious on the aerial photographs than it was on the ground.

3. Ngell granite

The Ngell granite covers the largest area of any of the granites within the project area and occurs in two broad continuous east-west bands, one to the north and one to the south of Bukuru with an area of 32 km^2. Despite the fact that in thin section there is sometimes little distinction between the Jos facies the Ngell granite is finer grained, less equigranular and consistent in texture.

On air photographs it can be a distinctive granite unit, darker grey in colour than the Jos granite with a more mottled appearance. Although - like the Jos facies - the dominant joint direction is also east-west, combined with secondary less persistent sets trending north-northwest and north-northeast, it does not have the prominent horizontal joints of the Jos granite and so a 'chimney stack' type of weathering is characteristic. Because it appears the darkest grey of all the granites on air photographs and because of the weathering pattern it is possible to recognise fairly small isolated outcrops on the photos. Contacts with some rock types, particularly the Rayfield-Gona granite are impossible to draw accurately on the photographs.

The Ngell weathers to rough boulder strewn hills which in the case of the Ngell peak rise 100 metres above the surrounding terrain. It is well exposed on Ngell peak at locality 9, where it includes several micro-granites. These trend 220^{o} and the broadest is 14 cm wide.

The contact between the Jos and Ngell facies has been discussed in part previously. Near the contact with the Jos granite there is commonly a zone in the Ngell granite in which pegmatites, quartz knots and veins and microgranites are extensively developed. It is a highly irregular contact and there is a complex intermingling of microgranites and porphyritic facies with xenoliths of the Jos granite. Sometimes this variable contact zone is absent and normal textured Ngell facies, with a narrow chilled margin, is in contact with unaltered Jos granite. Microgranite development is variable. Where this occurs it is invariably associated with pegmatites and thin veins of quartz. In some xenoliths the microgranite can be seen penetrating along crystal boundaries. South of Sabon Gida, at locality 58, a roof feature of the Ngell granite can be observed where the basement is cut by dykes of Ngell granite. The Ngell granite dykes are very altered, bright red in colour with rounded quartz grains set in a hard haematite groundmass and may be accompanied by quartz veins at the margin. Associated quartz-veining is abundant along north-south joint planes and numerous sinuous stringers of aplite and microgranite also occur. Occasionally the quartz veins widen out to give drusy cavities filled with large quartz crystals, but more commonly the veins are narrow and show a comb texture. The explanation for this area is not entirely clear since these basement hills cut by Ngell dykes are surrounded on all sides, at the same topographic level, by typical unaltered Ngell granite. It is presumed to be a feature of a highly irregular, undulating roof.

There is a marked variation in the Ngell granite throughout the complex. North of Jos airport, outside the project area, it is a medium-grained equigranular granite, pinkish red in colour, whilst in the project area it is commonly almost coarse-grained with large feldspars which give a porphyritic texture to the rock and make it more pink than red in colour. In its porphyritic form it is unmistakable but the finer grained varieties can be confused with other biotite granites of the complex. Like the Jos granite the medium to coarse-grained Ngell has its equivalents in many other complexes, particularly the Gana biotite granite in the Ropp complex, from which it is indistinguishable in hand specimen and thin section.

The Ngell granite is probably the most important granite economically within the Jos-Bukuru complex. It contains small quantities of primary cassiterite and columbite and also contains ilmenite and zircon. Although not as rich in accessory cassiterite and columbite as the Rayfield Gona granite it has probably contributed far more to the alluvials due to its much larger surface area. The Ngell granite and Sabon Gida south facies contain the most ore-mineralised veins within the complex and numerous small greisen veinlets occur in addition to the massive veins described later. They commonly follow the east-west joint set although any of the joint sets may have thin, discontinuous veinlets and mineralised veins. Many of the joints show reddening without any further alteration or mineralisation.

4. Rayfield-Gona biotite granite

The Rayfield-Gona granite which is phase 4 on the 1:10,000 scale map covers approximately 5 km^2 in the north of the project area and extends southwards beyond it in a broad semicircle (Fig. 8). On aerial photographs it is difficult to distinguish where exposed - it is very light in colour and of even tone and it passes transitionally into Ngell and Jos granites. Jointing is close and irregular and the granite usually weathers to low outcrops of white boulders.

Type specimens show a distinctive sacchroidal appearance, fine to medium grain size with clustered glassy quartz grains and fine grained pale brown or green to white mica which is evenly distributed. However, the granite as mapped by MacLeod may vary from an undecomposed medium-grained variant, almost indistinguishable from Ngell granite in hand specimen to a very weathered granite which is a very soft clay. Of all the granite types it is the most enriched in columbite although the Nb_2O_5 content may vary from 150 ppm for much of the granite to 0.27 per cent locally. High columbite values are associated with thorite, Hf-rich zircon and xenotime.

The coarser variations of the granite show Ngell granite characteristics with clustered quartz, microcline microperthite and clustered pale brown biotite with very little evidence of albitisation. Even in a fresh sample the K constituent of the perthites shows extensive alteration and the typical cross-hatched twinning of the microcline is only rarely seen. This alteration is thought to be of deuteric origin rather than as a result of weathering. The albite component does not exceed that of microcline and so samples show the extensive albitisation of the albite riebeckite granites.

In the area of the twin hills, east of Danbagarmi, at locality 20 a sharp contact can be seen between fine-grained Rayfield-Gona type and a coarse grained Jos. Here the Rayfield Gona appears to form a low dipping sheet, but elsewhere there is a complex transition between the two granite variants.

In both the Rayfield and Passa Kai areas which are outside the project area (Fig. 8) the granite has been decomposed to the consistency of clay. Kaolinite veins are numerous but patchy in distribution. It is thought that all these are supergene in origin. The intensity of decomposition at these localities precludes a precise petrographic study and chemical variations throughout the granite are bound to occur. Analyses from MacLeod <u>et</u> <u>al</u>., (1971) are shown in Appendix 4.

Both these areas although outside the project area were considered necessary for study on account of their economic importance. In the Passa Kai area the granite has been cut by pegmatite veins with coarse quartz and green mica. After a period of faulting and basic dyke intrusion, quartz veins either in massive form or showing comb texture were intruded along basic dykes and pegmatites, along joint planes, or formed irregularly shaped and variable sized knots. The joints are often lined with kaolinite. In the Rayfield area, the sequence of events is similar but two phases of pegmatite formations can be distinguished. The first consists of albitites which are less than 30 cm wide with sinuous irregular junctions whilst the later microcline pegmatites in contrast have sharp straight contacts and can be traced for a greater distance along an east-west strike. Amazonite is abundant in these and the occasional genthelvite crystal may be seen - microlite has also been recorded.

Basic dykes are more numerous in the Rayfield area than in the Passa Kai region and vary in size from 1 cm to 230 cm. They have all been completely kaolinised and heavily lateritised.

There is a very large variation in columbite content even within these two areas and the analyses of 50 samples varied from less than 30 ppm to over 2200 ppm Nb_2O_5 (Appendix 9). High columbite content coincides with high thorite content but there was no correlation between high columbite and SnO_2 content which proved generally less than 50 ppm in the Passa Kai area and between 100 and 150 in the Harwell area where Nb_2O_5 content was lower. However, in the Passa Kai samples that had very high Nb_2O_5 values there were also higher than average values of SnO_2. These high values were restricted to a single zone in one paddock. Possibly part of this SnO_2 is not in the form of cassiterite but is found within the columbite. It does seem likely however, that this zone of high tin values may be due to greisenisation.

The columbite-rich material is believed to be a modified roof zone of a biotite granite and evidence for this is found in the Passa Kai area. In one of the paddocks - PCP 10 - downfaulting of purple and black decomposed basement is clearly observed in the paddock floor, the fault plane on the east side has been lined with kaolinite and shows slickensiding. In the vertical north paddock wall between these two faults the white granite can be seen in the overlying basement as sills and irregularly branching dykes feathering out upwards into small white veinlets cutting the dark coloured basement. Further east in the Bisichi area in one paddock - ML 16020 - which is predominantly basement, the white albitised granite occurs as a series of irregular branching dykes and veinlets. Good columbite values have occurred sporadically through these dykes. The Geological Survey 1:10,000 sheet has clearly oversimplified the broad arc of Rayfield-Gona granite which extends discontinuously from Passa Kai to Bisichi and Rayfield - it is too broad in the south and the complex intermingling of the granite with the basement is not suggested.

To the north of Yelwan Feranti a band of mylonite approximately 1 m wide cuts the Rayfield Gona facies and minor cassiterite mineralisation is also related to the fracture. The mylonite does not seem persistent and is not well exposed partly because it appears to have been worked for its cassiterite content. It trends parallel to a dyke in the north of Rayfield Gona facies cutting the Jos facies.

5. Shen hastingsite fayalite granite

There are no <u>in situ</u> outcrops of this granite in the project area although several boulders have been found by the writer and Dr. Turner in the region of the twin hills north of the Ngell river bridge on the Jos-Bukuru road, at locality 20. A sample has been found west of the road and to the north of the twin hills in the region of locality 22. The main exposure of this rock type occurs several kilometres to the south and south-east (fig. 8) where it occurs in an arc of 180^{o}. It is envisaged that the ring fractures into which the hastingsite fayalite granite was intruded extend discontinuously into the project area - if the arc described by the intrusion is traced northwards then it intersects the Rayfield/Jos phases in the area of the twin hills.

The rock is dark green in hand specimen when fresh and has a medium grain size, not to be confused with the dark green fine variant found locally at the Jos/Rayfield contact.

6. Bukuru biotite granite

The Bukuru granite has a rather triangular shaped exposure within the project area, covering an area of approximately 12 km^2 and centred on the township of Bukuru where good exposures are to be found. It contains numerous 'pendants' of the Ngell granite, mainly to the east of the project area.

On aerial photographs it has a similar appearance to the Sabon Gida granites and the contact with these is not usually apparent on the photographs partly because of the similarities and partly because of lack of exposure. The contact between the Ngell and Bukuru granite can be seen clearly at locality 8 to the north of the Bukuru/Jos and Bukuru/Rayfield road junction. Where exposed the contact with the Ngell granite is of hairline sharpness, steeply dipping, and is much more precise than any of the other interphase contacts in the complex. The contact between the Bukuru and Sabon Gida north granite is well exposed at locality 86 south west of the ATMN mill. Elsewhere the contact is too poorly exposed for it to be apparent on the aerial photographs.

The Bukuru granite is closely jointed, particularly in microgranite areas and it weathers to low bouldery hills except where it is in contact with the more resistant Ngell.

The Bukuru granite is very variable in texture and sometimes may resemble the Ngell granite quite closely, so that where the outcrop is very decomposed it may be difficult to distinguish the two. However, the large coarse clustered quartz grains of the Bukuru granite locally prove a useful mapping aid. The quartz clusters are more resistant to erosion than the other minerals and on weathered rock surfaces they stand out in relief as trains of crystals up to 1 cm long.

The Bukuru granite varies from an inequigranular, fine-grained granite to a medium-grained porphyritic rock with large euhedral feldspar phenocrysts. Microgranites are common but lack of exposure prevents them being mapped separately. They are best seen at location 6 near the tennis court in Bukuru.

Unlike many of the other granite variants the Bukuru granite has no direct equivalent in the Ropp complex.

Columbite occurs as an accessory and except for the Rayfield-Gona granite is the richest in accessory columbite in the whole complex. A few mineralised veins were located in this granite type but none were persistent or more than a few centimetres wide and do not warrant separate descriptions.

7. Sabon Gida south biotite granite

This granite is exposed entirely within the project area. It covers an area of approximately 13 km^2 between Bukuru and Sabon Gida and is well exposed around the mining camp at Sabon Gida. It is a medium-grained biotite granite and although the feldspars are larger than the quartz and biotite it does not have a striking porphyritic appearance.

Mineralised veins are numerous throughout the whole of this granite. Unmineralised siliceous greisens are extensively developed south and east of Sabon Gida camp and may exceed 300 metres in length. The largest of these is apparent on the aerial photographs. Ore mineralised-micaceous veins are also common but these are on a much smaller scale appearing as narrow parallel bands a few centimetres in width. Both types are well exposed and abundant south of the Bukuru/ Sabon Gida road 2 km south-west of Bukuru at locality 64.

Although in general these veins are too small to pick out on the photographs mineralised areas can be recognised by the extremely close joint sets that invariably appear in extensively vein-mineralised areas. This particular locality shows such an intensity of jointing that on the aerial photographs it is impossible to determine the directions. More generally the Sabon Gida south granite is not a distinctive granite on the photographs. Like the Bukuru granite it has a medium grey tone and similar texture. However, the boundary with the Ngell granite can be drawn approximately and part of the contact with the Sabon Gida north granite can be distinguished on the photographs too. The circular outcrop of Sabon Gida north granite within the Sabon Gida south granite, immediately to the north-east of Sabon Gida mining camp, is as apparent on the air photots as it is on the ground.

8. Sabon Gida north biotite granite

The Sabon Gida north biotite granite is also exposed in its entirety within the project area covering 7 km^2. It forms a small arc extending from the Bukuru/Vom road junction where it is poorly exposed, through Gyel village towards the Ngell basalt. It is usually difficult to distinguish on aerial photographs and can only be identified in those exposures where it is in contact with the Sabon Gida south granite.

The Sabon Gida north granite is finer grained than the Sabon Gida south granite with phenocrysts of pink microcline. Whereas in the latter the albitic component of the perthites is slightly lower than microcline the reverse is true in the Sabon Gida north granite. Unlike virtually all the other granites, zircon does not seem to be an accessory.

A few mineralised veins are associated with this granite facies, the most notable being the two parallel veins at locality 118 described later. However, towards the south-west occasional quartz veins may locally contain one or two tiny cassiterite crystals.

The contact with the Ngell is clearly exposed in the Ngell river and in two north-flowing tributaries. It shows a variable but gentle northward dip. East of Gyel village there is a sharp steeply dipping contact with the Bukuru facies. The contact with the Sabon Gida south facies is extremely sharp but the attitude is variable and ranges from horizontal to sub-vertical.

9. Microgranites

Microgranites occur in two areas covered by the project. The North Vom microgranite forms a prominent hill 3 km north of the Vom volcano and is surrounded by the Vom basalt. It is a fine-grained biotite granite with a grain size <1 mm except for occasional feldspar rich zones with crystals up to 8 mm in size. At location 25, prominent gullies follow the main joint directions which vary between west-southwest/west-northwest and the granite walls within these gullies show well-developed exfoliated weathering surfaces.

At location 34, to the north of the right angle bend on the Vom-Miango road the granite is less well jointed. Near the boundary with the porphyritic basement granite, quartz-feldspar knots, veinlets and stringers which pinch and swell, are common. Whilst farther east, thin mineralised veins with reddened margins, trend either north-south or northwest-southeast.

The granite is unlike any of the others within the project area and MacLeod (1956) has suggested that it is possibly related to the later granites of the Ganawuri complex to the south-west.

In contrast, the Vom road microgranite which occurs to the south of No. 5 dam and on the edge of the Vom basalt, is similar to the Sabon Gida north granite although it is finer grained. It is thought therefore that it has been intruded at the same time as the Sabon Gida group of granites. Abundant cavities are filled with large, poorly terminated quartz crystals intermeshed with a few well formed ones and the ground between the exposures is littered with quartz crystals.

Acid and Basic dykes

Apart from the abundant microgranitic dykes associated with the various phases of granite emplacement there are numerous acid and basic tholeiitic dykes which are believed to represent the closing stages of magmatic activity. Usually these are less than 50 cm thick and cannot be traced far. They appear to have followed dominant joint directions closely, the general trend appearing to lie between north-west and north-east.

The largest of these dykes cuts the Ngell granite south of Barakin Sabon Gida. It is 9 metres wide, trends 330^{o}, can be traced for almost a kilometre and is clearly seen on the aerial photographs. It is of superior resistance to the granite and for part of its length appears as a low discontinuous ridge. In hand specimen the dyke rock is black, extremely fine-grained and pyritous. Small fragments of unaltered Ngell facies have been included. In thin section the dyke rock is seen to be composed essentially of microcline, oligoclase and quartz with a heavily decomposed ferromagnesian mineral and accessory pyrite. Despite the field indication of dolerite the dyke rock is microsyenite and it seems likely that many of the dark coloured dykes, previously mapped as dolerite may be microsyenitic in character. This is the first observation of syenite on the central Plateau.

Some of the thin dykes which have been heavily decomposed, show structures and texture more suggestive of an original doleritic composition. In the Tuke gulley, south of Danbagarmi, the dark-brownish faulted dyke shows columnar jointing and amygdaloidal cavities.

Thin quartz veins are common in every phase of the granites and although some may be traced over a distance of a hundred metres they have not generally been mapped because of their abundance and narrow width. However, the quartz dyke which occurs in the hills to the north of Gona village locally attains a width of 15 metres and can be traced along its strike for 33 metres. The quartz veins may be composed of milky quartz or of crystals which form a comb textured vein.

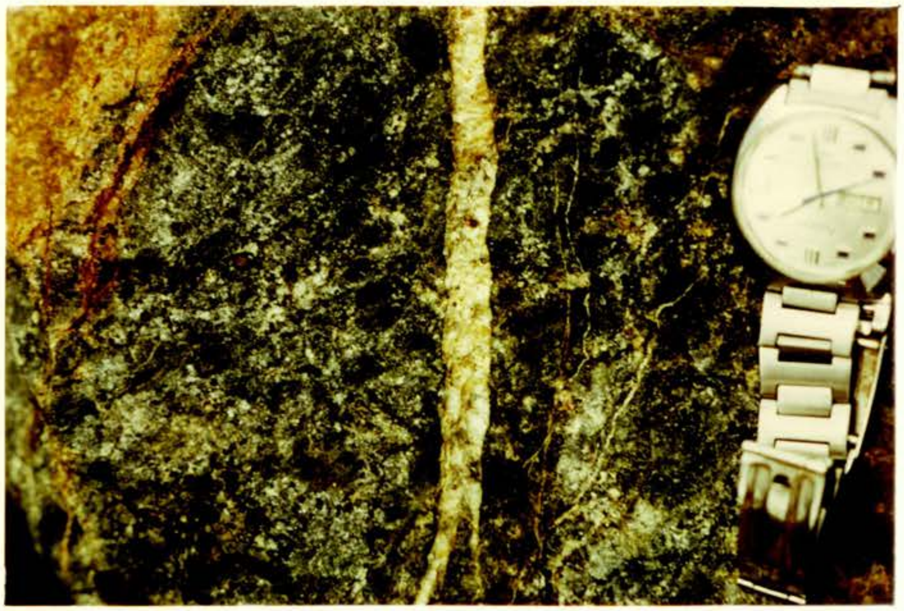
Mineralised veins in the Bukuru area

Altered granite, including mineralised replacement veins, has been studied at ten localities in the Bukuru area (Fig. 8). Although several of these lie outside the project area they have been included below because they occur in the same granite types as those within the project area. The mineralised veins which include greisens, show a wide variation in composition depending on the presence or absence of chlorite, fluorite, green mica, and topaz, and varying quartz content. The term greisen is used by the writer specifically to describe a rock which is formed in one particular phase of mineralisation and which consists of quartz, Li-rich mica, with accessory topaz and a little fluorite. The greisens and other mineralised veins may also contain cassiterite, sphalerite, chalcopyrite, galena or molybdenite. In contrast, the altered granite contains feldspars which show a varying degree of alteration to white mica and topaz and may also contain a variety of ore minerals.

The veins and greisens are formed by hydrothermal metasomatism and are restricted in the Bukuru area to biotite granites, but examples have been found elsewhere in virtually all rock types from basement to volcanics.

At Anglo-Jos, north of the Nigerian Department of Agriculture office on the Anglo-Jos/Miango road, cassiterite bearing altered granite was once worked as a payable proposition. The mineralised body trends 280° and cannot be traced for more than 30 metres. Although the replacement vein is rather weathered, it appears to have a porphyritic texture with large quartz grains. It is medium grained, greenish grey, rich in chalcopyrite and sphalerite, with malachite and azurite on all the weathered surfaces. The host Ngell granite has been very reddened near the vein contact. In thin section perfect chalcopyrite cubes 0.1 mm in size, are seen exsolved along cleavage traces in sphalerite. Pyrite, cassiterite and chalcopyrite are also distributed in the more quartzose areas of the altered granite. Sericite is seen replacing mottled feldspar although some quite fresh feldspars still remain zoned mica flakes are common.

At Gyantagere Quarry at mile 5 on the Jos-Bukuru road, both Rayfield Gona and Ngell granite can be seen. Siliceous replacement veins can be found in the Rayfield Gona granite and in hand specimen appear to be composed almost entirely of quartz with scattered flakes of reddish brown mica, occasional specks of chalcopyrite, and tiny brownish black crystals of sphalerite only 1 mm in size. Locally molybdenite is abundant. In thin section the veins are shown to be composed either of quartz and chlorite with a little fluorite, or of quartz and brown biotite with deep red sphalerite, haematite and chalcopyrite. In both types the recrystallised quartz may be very large, some grains being in excess of 5 mm, large in comparison with most of the Nigerian mineralised veins



Photograph 1 shows the fine-grained quartz, chlorite, fluorite replacement vein near Danbagarmi, with the late quartz vein, centrally placed. Marginal quartz veins (not shown in the picture) also occur.

Photograph 2 There is a sharp contact between the dark fine-grained replacement vein, shown above, and silicified, reddened granite.

South of this quarry, thin black vertical mineralised veins with a little reddening of the Ngell granite host rock are seen at locality B5.

North of Danbagarmi, and south of the above veins, a 3 metre wide, fine grained, black mineralised vein trends 204°. (See Photos 1 and 2). The zone of reddened Jos granite varies from 2 cm to 8 cm in width. Marginal quartz veins with a fine comb structure are only about 2 cm wide. Irregularly shaped, relatively unaltered xenoliths of Jos granite occur within the fine-grained vein. A thin section shows this vein to be composed essentially of quartz and chloritised mica with occasional topaz grains and slightly more fluorite which becomes purple in patches. Monazite is a common accessory.

In the Ngėll granite boulders to the west of the Gyel Commercial College, Bukuru, thin dark coloured replacement veins can be seen near the contact with the Bukuru granite. The veins follow two directions, both related to joints. The major set has a 270° trend whilst a minor set is orientated at 288°. A zone of reddening surrounds these veins, extending from 2-5 cm from the narrower veins to 5-8 cm from the broader ones. In thin section the veins are seen to be composed of quartz, altered feldspar, brown mica and chlorite with accessory fluorite, topaz and zircon. The quartz is marginal to the vein and the biotite is concentrated towards the centre. The accessory minerals are interspersed between the quartz.

To the north of the Ngell river bridge on the Bukuru-Yelwan Feranti road, Ngell granite has been altered. At locality 71 quartz veins 1 cm wide and a mineralised vein 30 cm wide trend 310°. The mineralised replacement vein is composed of several milky quartz veins 1 cm thick with porphyritic green replacement veins between. A similar green, unbanded vein - approximately 10 cm thick trends 220°. In thin section the green replacement vein consists of large quartz up to 3 mm in size set in a fine-grained groundmass of sericite and topaz. Large patches of fluorite are irregularly distributed between large quartz grains, and small rounded cassiterite crystals, generally <0.1 mm in size, occur in quartz and in the few large mica flakes.

South-west of Bukuru, along the Sabon Gida road, two large parallel mineralised veins, approximately 20 metres apart are found at locality 118 in the Sabon Gida north granite near the contact with the Bukuru granite. Both veins appear vertical, have strong perpendicular joints and poor cross joints. Both appear to die out rapidly. The one to the south can be traced for 30 metres along its 240° strike and at its maximum is about $2\frac{1}{4}$ metres wide. It is very siliceous, white or grey in colour and appears to have had a central micaceous band approximately 6 cm wide, which has now decomposed on the surface to a soft earthy brown material. The vein contains abundant fine-grained galena and a little disseminated sphalerite. In thin section the quartz appears as large recrystallised grains. Turbid areas of very fine-grained sericite or greenish brown mica appear to have replaced feldspar. The original brown mica of the granite has been chloritised. The sphalerite is yellow in colour and has tiny chalcopyrite blebs along cleavage traces, the angular galena fragments being randomly distributed. Accessory apatite forms small six-sided prismatic crystals in the quartz.

The vein to the north has the same 240° strike and can be traced for nearly 50 metres. It is 3.7 metres wide at maximum and does not have any apparent micaceous bands. It is more variable in colour than the southern vein, varying from white to green with no regular pattern of colour distribution. It is also very siliceous and contains abundant galena with sphalerite and traces of chalcopyrite. Thin sections show the feldspar has all been replaced by an extremely fine aggregate of chlorite with some topaz, quartz and fluorite. The fluorite is also seen as larger patches between quartz grains. The difference between white and green varieties of mineralised vein appears to be due to the degree of chloritisation.

West-southwest of these two veins albitised Sabon Gida south granite is extensively greisenised, a feature which is apparent from the aerial photographs. A series of thin greisens trend 320° and in the face of one small mining pit five of these vertical greisens, the widest of which is 5 cm thick, are exposed over a width of 45 cm. The intervening granite has been reddened and decomposed and is a very soft material, reminiscent of the columbite rich, albitised Rayfield-Gona granite from the Harwell area. Two conjugate sets of greisens are orientated north-south and east-west along the major joint sets and where the greisens are most numerous the spacing of the joint sets is correspondingly much denser than elsewhere. The east-west set is predominant and possibly earlier than the minor north-south set which at one locality can be seen displacing the east-west set. Local miners have dug numerous trenches through the lateritised surface to expose the underlying greisens. Two hundred metres south of the Kirana hedge in the rubbly rock exposure near the stream, a greisen 60 cm wide trends 240°. It is separated from several centimetres of reddened wall rock on one margin by a 30 cm wide quartz-protolithionite 'pegmatite' whilst the other margin is characterised by a comb textured quartz vein 15 cm wide (Fig. 11).

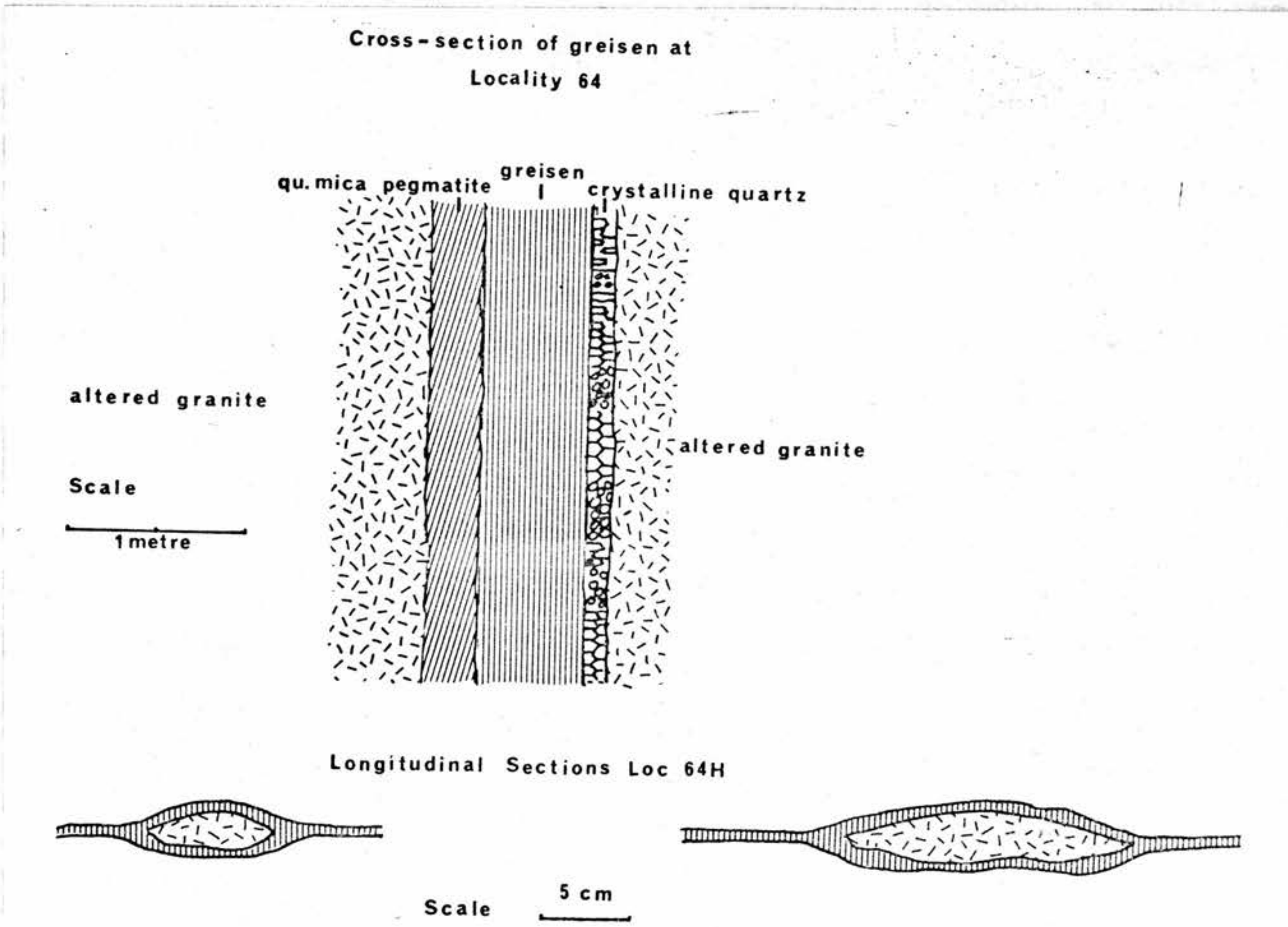


Fig. 11.

In thin section the greisen is seen to consist mainly of large, interlocking quartz. Pale green protolithionite replaces original brown biotite whilst colourless sericite mica formed by the breakdown of feldspar forms either a mosaic of tiny flakes with topaz or larger flakes surrounded by quartz. Topaz is abundant and occurs both as anhedral patches interstitial to quartz or as an extremely fine-

Photograph 3 shows an east-west trending, quartz mica pegmatitic vein cutting Sabon Gida south biotite granite. The granite has been albitised and is rather soft and decomposed. In the veins the quartz is centrally placed, with sheaves of mica occurring marginally. Occasionally the veins bifurcate and include fragments of altered and reddened granite.

grained mosaic with or without mica, which is probably feldspar replacement. Small cassiterite grains occur and zircon surrounded by pleochroic haloes is common in the large mica flakes.

Immediately to the north of this locality a whole series of east-west trending quartz mica pegmatitic veins is well exposed and locally four of these veins occur within 120 cm. Maximum width of these bands is 2 cm. The veins enclose angular fragments of altered and reddened granite. The mica in these veins is white in colour and has grown in a peculiar sheaf-like pattern. Compositionally, it has been shown to be protolithionite - (Fig. 24). (Photo 3).

To the north-east of Sabon Gida mining camp a massive siliceous vein trends east-west and can be traced westwards for over 800 metres. It is being mined for cassiterite at several points along the strike and fresh rock can be obtained from the small pits. In hand specimen the rock appears to be vesicular quartz with a greenish yellow chlorite infilling in the interstices. In thin section a few tiny cassiterite crystals <0.01 mm in size are accompanied by several very pale green to colourless mica flakes but the rock is 99% quartz, no chlorite being seen in thin section. It has been identified by XRD.

To the north of a small village on the Vom-Bukuru road at mining lease peg 14008 greisenised Sabon Gida south granite forms a low outcrop which is largely loose boulders. The dark grey quartz rich greisen is orientated north-south. In hand specimen, clustered quartz grains 1 mm in size are observed set in a fine-grained dark grey micaceous groundmass. In thin section the greisenised granite shows abundant feldspar, partially replaced by mica and topaz, whereas in the greisen, feldspar has been completely replaced by a mosaic of fine-grained mica and topaz. In a few of the large mica flakes the brown mica is partly replaced by green.

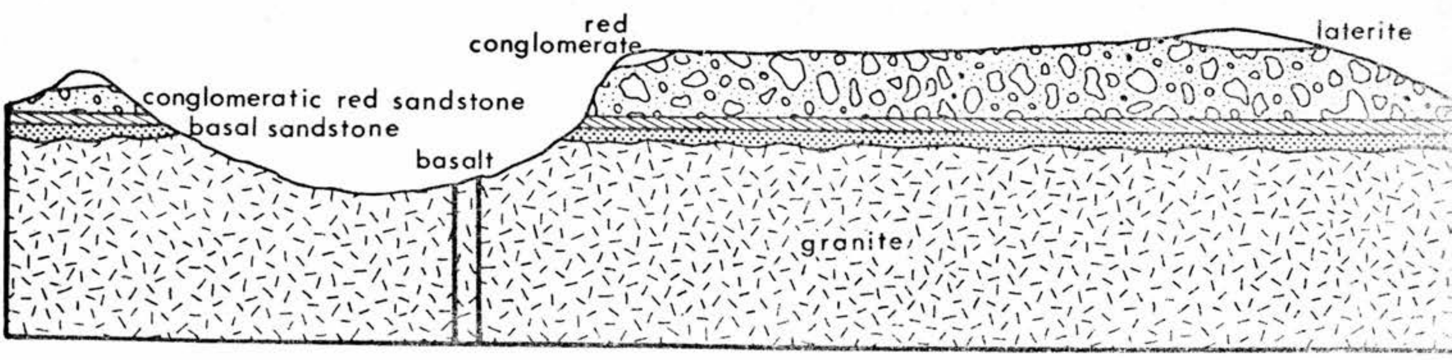
Tertiary Fluvio-Volcanic Series

Although as the 1:10,000 map indicates there are several remnant mounds of this sedimentary series exposed, the best cross-section of the series occurs about 1½ km north of Bukuru on the Rayfield road, where two small, rounded hills, reddish brown in colour and covered in gravel, have been pitted by local tin workers.

The fluviatile sedimentary rocks, which were probably deposited by a large, braided river, are horizontal and rest on rotten granite of Rayfield Gona type. The basal sandstone represents a high energy environment followed by a lower energy phase of sedimentation when the mudstone was deposited. Renewal of deposition in a high energy environment resulted in the formation of the conglomeratic sandstone.

Fig. 12

Diagrammatic Section Across Two Sedimentary Hills
Bukuru



The succession at this locality is at least 4.5 metres thick and is as follows:-

5.		Red conglomerate and laterite.
4.		Conglomeratic red sandstone.
3.	60-100 cm	Yellow-green mudstone, weathering to red with ironstone bands about 1 mm thick.
2.	1 cm.	Ironstone band, either within or at base of mudstone.
1.	75-100 cm.	Basal red sandstone.

1. The reddish brown sandstone, which has been deposited on an undulating weathered granite surface, is poorly sorted, poorly bedded and has been indurated by a mixture of iron oxides and well consolidated clayey material. It is obviously very cassiterite rich and has been excavated by local tin workers for a distance of several feet beneath the overlying sediments.
2. The hard undulating ironstone horizon probably represents the old water table level at which the iron leached from the superposed material was redeposited.
3. The mudstone is very variable in colour from yellow, grey and green to red, pink and white, often with definite bands of colour- the colouration being due to iron staining. Several ironstone bands are contained within this well indurated mudstone.
4. The conglomeratic red sandstone contains poorly sorted angular and subangular quartz grains dispersed in a coarse sand matrix and reddish clay. It is poorly bedded, loosely consolidated material and grades upwards into a hard brown crust of laterite.

5. Occurring at the same horizon at the surface are patches of red conglomerate and dark reddish brown laterite, locally grading into each other. The conglomerate consists of pebbles of lateritised sandstone and ironstone, quartz fragments and laterite pebbles, which have been cemented by iron oxide. The laterite is spongy and dark brown on the hillside and more massive and reddish brown on the hill top. It seems likely that these sediments have formed as a result of deposition in streams cutting into the underlying conglomeratic red sandstone.

Quaternary Sediments

In the Sabon Gida-Ngell area a sedimentary sequence up to 35 m thick underlies Ngell basalt which is almost certainly less than 1 my old. The nature of these sediments can be clearly seen in the steep quarry-like faces of the deep paddocks. Further information on the sediments comes from the sub-basalt cores which ATMN have taken during prospecting.

The pattern of sediments is complex: it is known that the Ngell basalt covers the valleys of the ancient Ngell and Rafin Bauna streams so there is a range of gravels, sands and muds associated with a complex and shifting braided drainage system. The sedimentary sequence is variable as would be expected in this type of environment since coarse and fine sediments can be deposited at the same time in different parts of the braided river bed. Also Leopold and Wolman (1957) noted that in a short length of stream showing both meanders and braids the braided reach had coarser sediments on the bed than on the meandering reach showing the same discharge. Naidu and Borreswara (1965) show that the material deposited in a channel may change its shape. High silt/clay ratios increase the degree of sinuosity of the river course and decrease in sinuosity takes place as a result of coarsening of the load.

At the base of the sedimentary sequence there is a coarse gravel or cobble horizon which is termed 'wash' by the miners. It is with this horizon that the bulk of the cassiterite is associated although some re-working has taken place so that a little cassiterite appears in a higher wash horizon. The wash lies on an uneven basement surface and is variable in thickness from 0-3 metres - mainly from 120-180 cm. A barren, yellow sandy wash overlies the basal grey sand or gravel wash locally or sometimes rests directly on bedrock where the gravel is absent. The washes, particularly the cobble bearing ones, suggest the existence of very fast moving stream or flood conditions and heavy erosion. In the first phase of these conditions a great amount of comparatively coarse material is transported which settles immediately upon a slight decrease of the competence of the stream. During the further lowering of the stream level and the velocity of flow the grain size of the detritus deposited decreases. (Kukal 1971).

This phase was followed by a series of sediments laid down in a low energy environment: fine compact silts with thin ironstone horizons are representative of this period and these are comparatively poorly mineralised. The overlying black carbonaceous mudstone, up to 25 m in thickness must have been deposited in a stagnant water lake, perhaps with an oscillating floor. These mudstones contain occasional plant fragments and huge tree trunks at the base. They are not fissile, contain no rootlets and no mud cracks and the tree trunks at the base are believed by the writer to represent the first flooding of the area by lake water. The cause of lake formation is not known but seems likely to be as a result of damming of the Ngell river by basalt outpouring from the Vom or Miango cones. The black mudstone from ML 6114 has been analysed and the following results were obtained:

SiO_2	50.00%
TiO_2	1.17
Al_2O_3	22.77
Fe_2O_3	5.03
FeO	n.d.
MnO	0.02
MgO	0.76
CaO	0.37
Na_2O	0.08
K_2O	1.01
P_2O_5	n.d.
H_2O^+ / H_2O^-	13.10
Total loss on ignition	18.79
	100.00

The sequence in paddock 1373 (see 1:10,000 scale map) shows:

18.5 m greyish brown mottled sand with gritty lenses and a neptunian dyke

9.25 m hard compact black mudstone with occasional sand grains. Shows a sharp boundary down into:-

0.3 - 1.8 m	grey sandy clay variable in thickness from 1.8 m in the west thinning very rapidly to 0.3 m in the east.
0.3 - 1.0 m	brown ferruginous fine sandy silt with concretionary banding especially near the top and base.
1.8 m	tin rich sandy wash with fragments up to 2 cm dispersed in a sandy clay which is either greyish or brown in colour.

In NG 6 paddock (see 1:10,000 scale map) the sequence is similar but the thickness of black mudstone is much reduced:

15.3 - 18.5 m	grey brown mottled sandstone
3 m	compact black mudstone
1.8 m	grey brown sand
3 m	grey sandy clay with numerous quartz splinters, no concretionary banding as at 1373
2 m	sandy wash with tin
1 m	gravel wash with tin

In NG 5 paddock however, the succession is more variable. The height of the basement bedrock changes constantly and is locally very hard and unweathered almost like younger granite. In the west the succession is as follows:

3. greyish brown sandy clay of variable thickness
2. black mudstone, locally directly overlying bedrock. Rich in fossilised wood at the base.
1. red conglomerate with coarse angular and feldspathic fragments dispersed in a clay matrix. Locally grey clay directly overlies bedrock and this is overlain by the red conglomerate.

In the east of the paddock a white quartz sand overlies bedrock and is succeeded by a brown and black ferruginous horizon; only low grade or trace mineralisation is encountered.

The accumulation of heavy minerals in the basal sands and gravels is based on the differences in the specific weights of light and heavy fractions which makes possible differential transport and deposition of two fractions. According to Kukal (1971) a contributory factor is the dropping of heavy mineral grains into the interstices of much coarser underlying sediments. When a mixture of sandy and silty material is transported along the gravelly bottom, large grains of quartz and smaller grains of heavy minerals, being heavier than the competency of the stream can carry, are laid down. The smaller grains of the heavy minerals sink into the interstices although the larger quartz grains may subsequently continue their travel.

Concentrations of tin and columbite therefore are to be expected in the 'wash' horizons but they will also occur on sand banks and in marginal shoals (as on beaches). Increased concentrations may also occur where there is a sudden decrease in velocity of a stream due to rock bars or near the mouth of tributaries. Locating the confluences of tributaries with the main streams beneath the Ngell basalt may therefore provide likely ore deposits (see section on Recent Basalts). Although mineral concentrations may be likely in minor streams there is not the amount of reworking that has taken place in the major stream and the heavy mineral concentration is unlikely to be as high in the former as in the latter.

The age of the Ngell basalt which overlies these sediments has not been determined but it is likely to be of a similar age to the Vom basalt which is less than a million years old. It seems likely therefore that all of these sediments were Quaternary in age and that they owe their preservation to a cover of basalt which was extruded before the sediments had been subjected to extensive erosion. However, the only reliable way to age date these sediments would be to use some of the wood from the base of the black mudstone for dating. A preliminary age obtained for Kotanski (pers. comm.) from this wood was 5,000 years which is even younger than was anticipated.

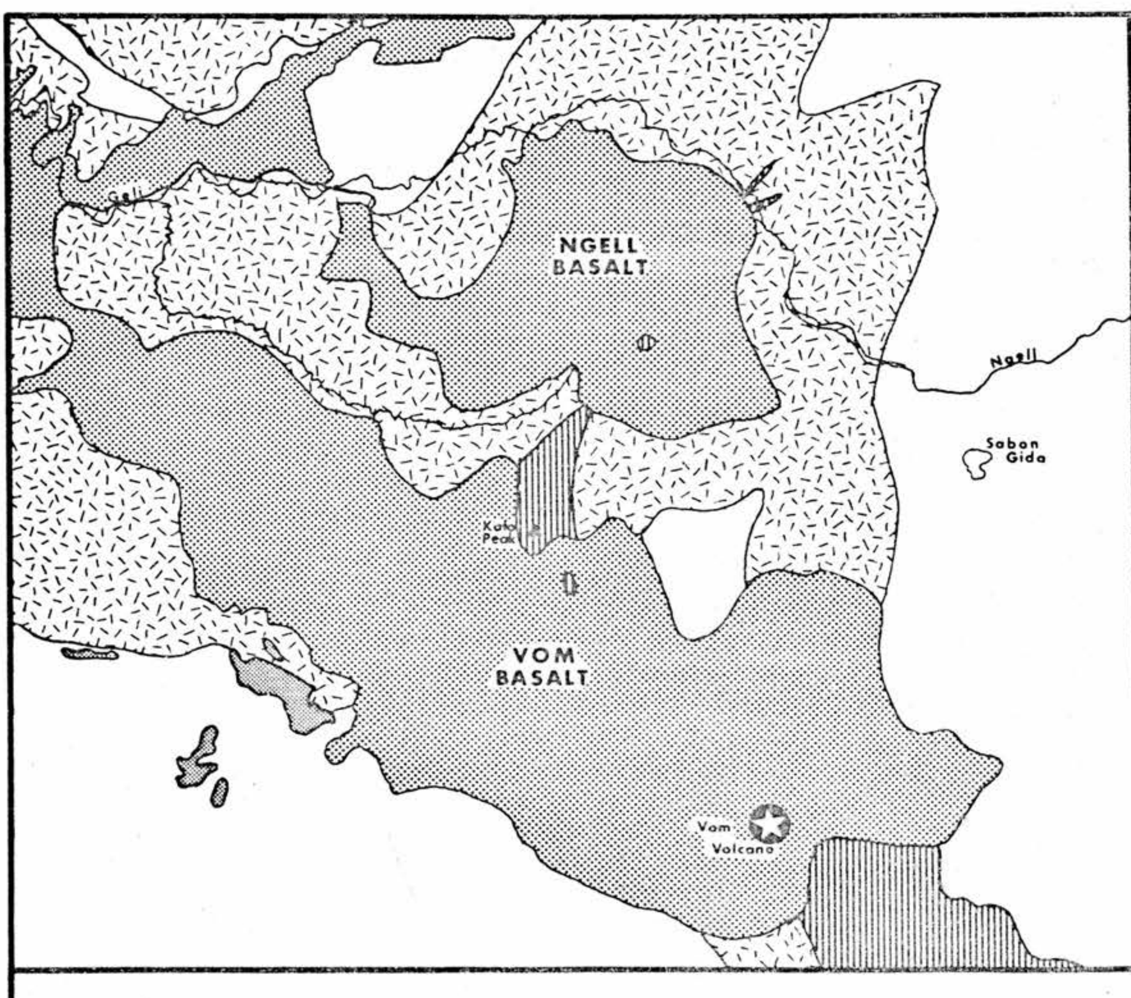


Fig 13 Distribution of Ngell & Vom Basalts, taken from Geol. Survey Sheet 168.

SCALE 1 : 115,000

Kilometres

0 1 2 3 4 5

	Newer basalt
	Older basalt
	Undifferentiated Jurassic granite
	Hastingsite biotite granite

Recent Basalts

Two separate alkali basalt flows cover part of the project area in the west. In the south-west the basalt of the Vom flow has clearly emanated from the well preserved cones of the Vom volcano which is outside the project area to the south (Fig. 13). The Vom volcano rises 130 m above the surrounding terrain, and has steep sided slopes to the south-west, aloping more gently to the north-east. The Vom basalt has been dated by Grant et al., (1972) and has an age of 0.9 ± 0.2 my. No age data is available for the Ngell flow.

The Ngell flow which lies to the south and west of the modern valley of the Ngell has no related cone. It is sited over the ancient course of the Ngell and Rafin Bauna streams and these ancient channels are at present being prospected as a source of cassiterite. The Ngell basalt is separated from the Vom basalt by a range of hills composed of basement porphyritic hornblende biotite granite and of the Vom hastingsite biotite granite (Fig. 8).

Both the Ngell and Vom basalt have clearly buried part of the early Vom hastingsite-biotite granite ring-dyke. The presence of the ring-dyke sporadically under the basalt has been established from well logging by ATMN. It has been suggested that in the absence of any related cone, the Ngell basalt has emanated from a series of fissures along a zone of weakness in the basement. If such a zone existed it would most likely have been the contact zone between the granite ring-dyke and basement. This is a definite possibility since the volcanic cones at Vom are known to be associated with the contact of the dyke in this locality where the dyke swings round to form the Kuru Hills. The highest point of the Ngell basalt lies close to where a small inlier of ring-dyke is exposed and the flow surface slopes gently away from this point in all directions except southwards where the basalt maintains the same elevation. From this highest point the bulk of the flow is to the north and west where the bedrock was lowest in the old Ngell and Rafin Bauna valleys.

The Vom and Ngell flows are drawn as two separate extrusions by the Geological Survey although prospecting by ATMN suggests that the flows are continuous in the Geli headwater region. The possibility therefore, that the Ngell basalt is part of the Vom flow must not be excluded. Petrologically the two basalts do show differences, but the comparison of a few thin sections is not conclusive evidence for the Ngell and Vom flows to be of differing origin.

Fig. 14 Comparative Petrology of Ngell and Vom flows.

Thin Section characteristics	Ngell Basalt	Vom Basalt
Texture	porphyritic	porphyritic
Phenocrysts	Abundant olivine which is usually fresh and euhedral, augite occasionally with colour zoning showing a pale brown core and darker rim. Max. size 0.5 mm	Smaller and fewer phenocrysts than in Ngell flow. Otherwise olivine and augite characteristics are the same. Max. size 0.3-0.5 mm
Groundmass	Dark brown groundmass. composed of laths of labradorite up to 0.3 mm in size (the largest laths occur in Sample JB 72 from the north of the flow), small rounded olivines generally fresh but a few may be partly serpentinised, granular augite and abundant iron oxide.	Lighter brown groundmass compose of labradorite laths, rarely more than 0.1 mm in size, small rounde olivines-usually fresh, granular augite and abundan iron oxides which are finer in grain size than those of the Ngell flow.

Sub-Basalt ore reserves

Cassiterite-bearing alluvial reserves in sediments below the Ngell basalt have attracted attention for many years. Both the Ngell and Rafin Bauna streams have their former courses beneath the basalt, the Rafin Bauna lying to the north-east whilst the former Ngell channel enters the basalt immediately south of the present day confluence of the Gona/Ngell streams. The buried Ngell and its tributaries are the site of major alluvial ore-bodies. High concentrations of tin occur in a series of basins separated at intervals by well defined rock bars, some of which may be of the Vom hornblende biotite granite. As thin black mineralised veins are known to cut this granite they may be the source of the pockets of enrichment in the ML 17707 deposit and part of ML 6114 reserve and could have contributed to enrichment in the centre of the basalt flow.

All the sub-basalt cassiterite mineralisation located so far has been associated with coarse quartz gravels and cobbles (see previous section) and it is not thought that this type of alluvial mineralisation is deposited far from its source. It is the writers opinion that the quartz-mica pegmatites and mineralised veins east of Sabon Gida must have contributed a large part of these cobble washes. The narrowness of the wash band combined with rapidly varying cassiterite values makes the reserve assessment difficult. However, whilst it is certain that the sub-basalt leads are potentially a rich source of tin, to mine them presents a number of problems due to the decomposition both of the base of the basalt and of the bedrock beneath the tin-bearing wash.

Summary

The Basement in the Bukuru-Ngell valley project area varies from gneiss to muscovite and porphyritic granites and has no mineralisation.

The Jurassic granites were intruded into this ca. 165 my ago and are richly mineralised with columbite and tin. Small amounts of columbite are dispersed through all the granites but reach economic proportions locally in the Rayfield-Gona granite. Minor amounts of cassiterite are also disseminated throughout the granites but cassiterite is concentrated, in addition to sphalerite and galena, in vertical mineralised veins which cut the granites. These veins although rarely visible directly on air photos can be inferred in areas of very close jointing.

It is suggested in this work that the granites which have previously been divided into a number of separate intrusions are variants related to two major intrusive phases and that the mineralisation is related to marginal and roof zones within these intrusions. It is also postulated that the Jos-Bukuru and Ropp complexes belong to the same batholith at depth thus offering an explanation for the similarities between sequence of intrusions and comparative abundance of mineralisation.

A period of erosion and deposition during the Tertiary followed the intrusion of these granites. Remnant mounds of this series are composed of fluviatile sediments, of which the basal sandstone is rich in derived cassiterite.

Basalts were extruded in Recent times after the plateau had more or less reached its present day topography

and the flows infilled broad, shallow valleys, thus burying the fluviatile tin rich sediments.

Economically the alluvial tin reserves are of great importance and the Bukuru area is one of the richest cassiterite producers of the Nigerian Province. However, as the alluvial reserves are slowly being depleted and the price of tin increases it seems likely that attention will once again turn to primary sources, especially those in replacement veins. Future assessments of primary ore reserves however may take into consideration other ore minerals, particularly sphalerite, in the mineral assemblages which could form valuable by products to cassiterite production.

These other minerals seem to have been largely ignored in the past. Little information has been written in the past about these mineral assemblages within replacement veins, about their distribution, or why they related to biotite granites. These problems will be discussed in Chapter 3.

Chapter 3 - Mineralisation

Introduction

During the process of crystallisation it is envisaged that the last material to crystallise is essentially a fluid mixture containing, in addition to water, silica and the constituents of feldspar, dissolved volatiles whose compositions can be inferred from volcanic gases, fluid inclusions and wall rock alteration. These volatiles consist predominantly of water with CO_2, HCl, HF, CH_4, sulphur compounds, alkali halides and halides of the 'incompatible' trace elements which are not readily accommodated in crystal lattices (Krauskopf 1967).

The amount of magmatic water in a residual fluid is strongly dependent on the level of the intrusion. According to the experimental data of Burnham and Jahns (1962) the amount of dissolved water in subvolcanic granites would not exceed 2% and may be even lower. Since the syenitic parent magma may have risen from subcrustal or mantle regions (van Breemen et al., 1975) to higher levels in the upper crust the magma must have been relatively undersaturated with water otherwise it would have frozen at depth. Consequently, the magmatic water content must have originally been low and at high crustal levels some meteoric water input may occur (Sheppard pers. comm).

At first if temperature and pressure are sufficiently high, the magma is a single silicate liquid phase but as crystallisation begins the water content and other components are concentrated in the residuum. At some later stage the watery components may separate from the silicate liquid phase and according to the experimental work by Wyllie and Tuttle (1961), Koster van Groos and Wyllie (1965), Burnham (1967) and Kogarko (1974) the chloride phase fractionates to the aqueous phase while the fluoride phase partitions to the silicate phase.

Mineralisation in Peralkaline Granites.

In their experimental work on the granite system, Tuttle and Bowen (1958) and Luth and Tuttle (1969) have shown that the more peralkaline the magma the more water can be retained within the silicate melt to low temperature. This continuous line of descent of residual fluids is applied to the genesis of peralkaline granites by Kovalenko (1968) who stated that, as the temperature drops and further crystallisation occurs the residual fluid becomes increasingly enriched in volatiles, changing continuously without supercritical phenomena from an agpaitic magma to a sodium-silicate rich hydrothermal solution. Thus he suggests that it is possible to progress from magmatic to hydrothermal processes without water separating off.

Analyses confirm that albitised peralkaline granites have ns in the norm and may evolve in this way. However, Roedder and Coombs (1967) have pointed out that other components such as Fe, not present in the synthetic experimental systems are available in the residual magma. Furthermore, at near surface conditions a second phase (or possibly phases) could separate from peralkaline residual magmas by 'second boiling' (Kogarko *et al.*, 1974) as the confining pressure decreases below the hydrostatic pressure. However, only at late stages in the crystallisation of alkaline magmas can a second immiscible liquid consisting predominantly of salts and volatile components separate.

This liquid phase differs profoundly in its chemistry and metasomatic action on earlier solidified minerals. It may freeze before it can modify the existing rocks or it may lead to the appearance of an exotic rock.

Such a process could account for the one late period of mineralisation of the Nigerian peralkaline granites which have been recrystallised with albite and microcline and may contain pyrochlore, fergusonite, cryolite, fluorite and thomsenolite and are enriched in many other elements eg. Th, Sn, Be, Li, Cs, Sb, Cd, Mo, Zn, Rb and Sr.

There are no aplitic dykes or pegmatitic veins in the peralkaline granites, which indicates that there has been no separation of a silicate liquid or of a water-rich supercritical phase.

Kogarko's (1974) thermodynamic calculations, together with a survey of experimental data for systems with H_2O, F, Cl, S and CO_2 attest to the high capacity of alkaline melts to dissolve and retain volatile components, which leads to a decrease in their concentration in the co-existing gas phase. This probably explains the absence of ores in alkaline rocks.

There are only five of these peralkaline granites in the Nigerian younger granite province, all of them adjacent to or near biotite granites with associated tin mineralisation. They have not been studied in detail by the writer.

Mineralisation in biotite granites.

As the biotite granites are aluminous the retention of a miscible aqueous phase appears to be severely limited. As fractional crystallisation continued so the concentration of volatile constituents would increase in the residuum until saturation when an aqueous phase would readily separate. This situation would be particularly important during sub-volcanic crystallisation of the biotite granites, the formation of pegmatitic veins and the development of aplite-micro-granite dykes. The cooler crystalline portions of the sub-volcanic granites, particularly in the roofs of the intrusions would be invaded by the separated phases from the crystallising granite at depth. Thus aplites represent the silicate liquid where there has been no watery separation; pegmatites represent the silicate liquid and water rich supercritical phase separation whilst the ore-mineralised veins represent the subcritical phase where there are three phases with crystals, a silicate liquid, water liquid and water vapour.

Of the mineralised veins studied in Nigeria none have yet been observed to cut aplites. This has however, been observed by Nockolds and Richey (1939) in the Mourne Mountain granites in Northern Ireland. They describe aplites 2.5 to 15 cm in width with a composition similar to the enclosing granite which are cross-cut by narrow vertical greisen veins less than 5 cm thick.

It has already been stated that fluorides strongly partition towards the silicate phase but that chloride compounds fractionate into the aqueous phase. The distribution of these 'incompatible' elements between the two phases is reflected by Goldschmidt's chalcophile (chloride) and litho-phile (silicate) classification and for the Nigerian model it appears that Nb, Th, Zr, Hf, and Y partition strongly towards the silicate phase whilst Zn, Pb, Cu, Mo, Bi and Cd are more stable as chloride compounds and fractionate into the aqueous phase. The uncertainty about the partitioning of tin is discussed later but it is suspected that the majority partitions towards the aqueous chloride phase.

As the temperature of the residua decreases further at subvolcanic levels, the aqueous chloride phase may itself become subcritical and separate into a chloride rich solution containing an immiscible sulphide rich assemblage of ore minerals. Such a separation may not actually occur until the watery fluid is passing through the fissure. The distribution of ore metals would therefore be highly localised and confined to zones of tensional fractures or cooling joints in the related biotite granites.

Two distinct stages of mineralisation are therefore recognised; the early apogranitic phase is a late magmatic, pre-joint phase of mineralisation whereas the later metasomatic phase takes place after the host rock has been consolidated and usually after jointing.

Phase 1 Apogranitic Stage of Mineralisation.

This is a late magmatic, autometamorphic (deuteric) phase which takes place during the cooling of biotite granites. It is a pre-joint, dispersed phase of mineralisation, with columbite, xenotime, thorite and hafnium and uranium rich zircon introduced. There is a new growth of microcline and albite (An_5) and a replacement of perthite by K feldspar. A textural change is effected by recrystallisation and silicification. The biotite is progressively altered from an iron biotite to a lithium aluminium biotite.

During, or slightly later than this phase, there follow the formation of albitites, microclinites and pegmatitic veins.

The dimensions of these are small and have no economic value. Varlamoff (1972) attributes this to the shallow depth of formation and shows that in granites crystallising at relatively shallow depths, these small pegmatites (and partially the quartz veins and associated mineralised veins) are located in the granite bodies. Whereas if they had formed at greater depths the pegmatites can reach gigantic proportions and may not be restricted to the granite intrusions.

The apogranitic stage of mineralisation is represented by many of the fine-grained biotite granites in the Nigerian Jurassic province but with the exception of limited areas of the Jos-Bukuru and Afu complexes the degree of mineralisation is insignificant.

Only three areas are known to be enriched in minerals belonging to this phase. Of these, Rayfield (Harwell paddocks) and Passa Kai areas (Fig. 8) of the Jos-Bukuru complex have already been described under the section on Rayfield Gona granite in Chapter 2. Little is known about the enrichment of columbite in the Odegi Hills of the Afu complex but it is to be investigated further by members of the Nigerian granite project, supported by the Overseas Development Ministry.

Despite the enrichment of the Rayfield Gona granite in minerals of this phase, values are generally too low for fresh undecomposed granite to be considered as an economic source for primary columbite. There are however, extensive areas within the above complexes where the granite is decomposed to a gritty clay and these are the areas richest in columbite and associated minerals. In the Jos-Bukuru complex these zones of decomposition occur mainly along the lines of two major watersheds and are preserved under remnants of the 1,300 m erosion surface (Dixey 1949). In such zones decomposition to depths exceeding 45 m is frequently found. The decomposed granite is covered by a shallow overburden of laterite and detritus and is mineable by opencast methods in the same way as an argillaceous alluvial deposit.

There is a definite geochemical correlation between niobium and the late soda-iron rich fluids that effected the extensive albitisation of the potash feldspars, it is significa that columbite is restricted to albitised biotite granites. It is envisaged therefore, that there was an introduction of soda-iron rich solutions, from unconsolidated magma at depth into the upper part of an irregularly shaped biotite granite cupola. These solutions were rich in columbite, xenotime and thorite and very small quantities of cassiterite were also disseminated throughout the granite. It is the writer's conclusion that monazite is not associated with this phase of mineralisation.

Phase 2 - Hydrothermal Phase of Mineralisation

This is a post-magmatic, metasomatic phase which takes place after the host rock has been consolidated and is predominantly a post-joint phase of mineralisation.

This type of mineralisation may form fissure fillings or involve a progressive replacement process in which the original host rock texture may be preserved. Although the resulting veins are generated within and by biotite granites, such veins can occur in any rock type ranging from basement gneiss to volcanics. These replacement processes take place in a distinct sequence although in many cases the processes overlap in time and space and early deposits of economic minerals may be diluted by later ore-free stages.

The term 'replacement vein' is a general description used to define any vein formed as a result of a progressive replacement process whether or not is contains ore minerals. These are akin to the carbonas of the Cornubian province and are generally vertical.

In contrast, the term 'mineralised vein' is used to describe veins which contain a mixed assemblage of any of the minerals - sphalerite, cassiterite, chalcopyrite, galena, pyrite, monazite, greenockite, chalcocite, covellite, native copper, genthelvite, phenakite, arseno-pyrite, molybdenite, bismuthinite and uraninite.

Fissure filling veins are simple veins generally composed of quartz and usually in a sub-vertical or vertical fracture with a constant trend. Associated mineralisation is sporadic.

The term 'greisen' is used very specifically to describe a mineralised vein formed during one of the five replacement processes (see later) and consisting of quartz, siderophyllite (or protolithionite) with a little accessory topaz and/or fluorite. Although compositionally they are similar to some of the greisens from other tin provinces of the world, in hand specimen they are much finer grained than the coarse 'pegmatitic' greisens found in the Altenberg area of the Erzgebirge. Neither do they contain the abundant muscovite which characterises the greisens from Tasmania, Australia, the Erzgebirge and Cornwall.

A lode consists of a series of mineralised and quartz veins, usually containing an economic concentration of ore minerals.

The replacement processes involve a gradual alteration of the feldspars of the host rock by tiny flakes of sericite, fluorite and/or topaz and there is a gradual development of siderophyllite. The annitic micas of the granitic host rock are gradually enriched in lithium and alumina and the feldspar and sericite eventually are completely replaced by quartz and a little topaz and fluorite.

Replacement veins have been examined from the Liruei complex, the Saiya-Shokobo complex, the Jos-Bukuru complex and the Ropp Hills and they are known to occur in many of the other ring complexes.

The veins are generally vertical in attitude although two horizontal veins have been identified, one in the Ladini area of the Saiya-Shokobo complex and the other in the Banke complex. The veins may consist of quartz, Li-Fe or Li-Al micas, chlorite, topaz and/or fluorite or contain the exotic suite of minerals described above. Sphalerite, chalcopyrite, cassiterite, galena, arsenopyrite and molybdenite may occur in the same mineralised vein at the same structural level together with the rarer minerals which have been recorded either in the veins or in the altered wall rock. Contrary to existing data on Nigerian mineralisation the writer has found that sphalerite is by far the dominant mineral and is far more abundant than cassiterite and wolframite.

The mineralised veins vary from light to dark grey or green and are occasionally black when very micaceous. The texture of the host rock may be preserved and together with the observation in thin section of feldspar in various stages of replacement, the replacement nature of the veins is clearly indicated.

Part of the replacement zone may contain veins of massive or drusy quartz which appear to have been formed by fracture filling. Most of the quartz in these veins is a clear, glassy variety, usually displaying a crude comb structure although massive milky quartz may also be present. Large individual crystals of cassiterite or sphalerite are sometimes found within this quartz. Commonly the quartz is enclosed by a replacement vein although it may also be marginal to veins, and replacement veins with no associated quartz vein are not uncommon. Marginal quartz veins are occasionally associated with green micaceous bands although micaceous bands and pods are more commonly found at the centre of veins.

In some cases, there are zones of wall-rock alteration marginal to, and earlier than, the mineralised vein. This wall rock may vary from a pale yellow to a brick red colour and contains mainly feldspar stained with haematite. This is best developed at Liruei. However, the extent of wall-rock alteration is very small in comparison with that associated with the porphyry copper deposits. The width of the mineralised vein and altered wall-rock is not proportional to the size of the quartz vein. All these features indicate that the fluid which caused the replacement veins was introduced earlier than the quartz vein infilling although the formation of both was probably close in time and space.

The lateral and vertical extent of the individual veins varies greatly. With the exception of the Liruei lode, which can be traced over 5 km, the veins can rarely be traced for more than 20 metres. Also, with the exception of the Liruei lode, part of which has been proved by underground exploration to extend over 300 m vertically, the depth to which the veins have been worked does not usually exceed 10 m.

Evidence from the Rishi area of the Saiya-Shokobo complex demonstrates that vein distribution is related to granite margins and their upper contacts with pre-existing rocks. Southwards, where erosion has proceeded to geologically deeper levels and where successive intrusions of granite magma have tended to modify earlier contacts, replacement veins are less abundant and their relationship to the host rock is less obvious. In the Rishi area, highest ore concentrations seem to occur less than 30 m below the roof of the granite.

This metasomatic mineralisation is related to, but not restricted by, biotite granite although the majority of mineralised veins are within this rock type. Veins can be found in any rock type which reacts in a similar way to the penetration of ore bearing fluids. Thus mineralised veins have been found in pyroxene granite, riebeckite porphyry and basement where ring fractures, faults or cooling joints have acted as channelways. Even the regional foliation of the basement may be exploited and preserved as at Gindi Akwati in the Ropp complex.

These types of deposit are categorised as xenothermal by Park and MacDiarmid (1975). They envisage that plutons were intruded to shallow depths expelling high temperature fluids into low pressure environments. Under these conditions the temperature and pressure gradients are exceptionally steep, causing ore fluids to undergo rapid cooling and sudden loss of pressure during their ascent.

As a result the ore minerals are deposited over a short distance and in a confused paragenesis. The earliest minerals to form are high temperature varieties and rapid cooling to near surface temperatures results in the deposition of typical low-temperature minerals during the waning stages of hydrothermal activity. True telescoping of deposits is described by Baumann (1976) as a zonal arrangement of ore minerals with the highest temperature minerals towards the outside of a deposit and the zones towards the centre being composed of lower temperature minerals. This may accurately describe only a few of the Nigerian occurrences. More commonly the process described as 'dumping' by Park and MacDiarmid (op cit) appears to have taken place where minerals that are not usually found together have been precipitated practically simultaneously. However, in some Nigerian veins there has been a distinct sequence of ore deposition and more than one depositional phase of several of the minerals. Examples Park and MacDiarmid give of xenothermal deposits are in Japan and Bolivia and in the mineral assemblages these are definitely closely analagous to the Nigerian occurrences. However, both these Japanese and Bolivian deposits and parts of the Australian tinfields, which also have close similarities to Nigeria (Taylor and Stevenson 1972) (Hesp 1974) differ tectonically from Nigeria since they are situated in orogenic environments. Within each of these provinces however, the cassiterite-bearing intrusives have been emplaced at different levels and different styles of mineralisation are related to different depths of intrusion. Despite the difference in tectonic setting the cassiterite-bearing intrusives at the highest level of emplacement e.g. Herbeton

Province, Australia (Taylor 1972) and central and southern Bolivia (Sillitoe et al., 1975) are similar to the Nigerian setting.

Mineralisation Processes.

It is clear that many of the areas that will be described have a complex history of late stage fluids and hydrothermal solutions and as yet it is difficult to distinguish whether the different types are produced by a single, continuous hydrothermal phase or by a series of separate injections. Obviously a particular hydrothermal solution will cause differing types of alteration at differing distances from its source due to changing pH, temperature and pressure effected by reactive wall rock and may itself separate into vapours and fluids.

Six stages of replacement have been distinguished (Fig. 14) although each replacement vein may not have gone through all of the stages or may have ceased alteration after having been affected only by the earliest stages. These stages have been put in a preliminary order. Further work outside the scope of this thesis will support or destroy this order.

Stage 1. Potassic ~~ARGILLIC~~ ALTERATION (Fig. 14).

The first stage is k-feldspar alteration ~~argillisation~~ of the granite host which involves the partial alteration or replacement of feldspars to form clay minerals. This may be associated with haematite staining due to the liberation of the very small amount of iron in the feldspar structure which has not been accommodated in the clay mineral lattice. In the field, this change can sometimes be observed as wall-rock reddening or as a zone of opaque feldspars adjacent to the vein. No experimental work has been done by the writer to determine the nature of the clay minerals but Deer, Howie & Zussman (1966) indicate that at low temperatures and pressures, acid conditions favour formation of clay minerals of the kaolinite group, whilst alkaline conditions promote the formation of smectites or, if sufficient potassium is present, mica. They also state that field occurrences indicate that acid rock types such as granites alter to kaolinite whilst calcium or sodium rich rocks generally yield montmorillonite. (Photo 4).

This first stage of alteration is equivalent to the intermediate argillic stage of Meyer and Hemley (1967). Stringham (1953) believes it takes place in an acid solution at temperatures below 350°C.

The hydration of the feldspar to form clay minerals results in the release of silica, sodium and potassium and small amounts of calcium. The silica may form new minerals in later stages of alteration or may be deposited in Stage 5 as vein quartz. The released sodium appears from chemical analyses to be almost completely removed, probably as NaCl; the released calcium however is converted in stage 2 into fluorite. The released potassium also forms new minerals in later stages.

Analyses by the writer and by Jacobson (1947) have shown that during this stage of alteration in addition to losses of silica, sodium and calcium in comparison with an average unaltered biotite granite there is also a depletion in alumina, ferric iron, magnesia, water and perhaps titanium.

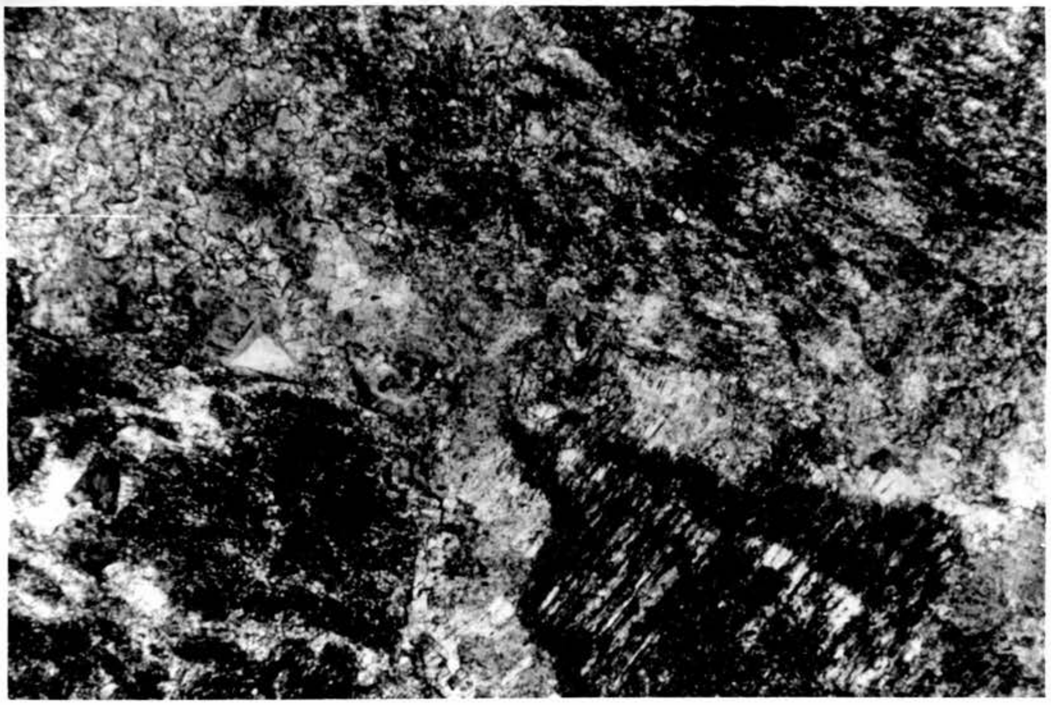


Photo 4. Photomicrograph of granite undergoing argillic alteration. The feldspars, which appear cloudy in plane polarised light, are seen decomposing to kaolinite under crossed nicols. Scale x 20.

Photo 5. Photomicrograph of part of a sphalerite veinlet - 2 mm in width - cutting a replacement vein which consists of quartz, fluorite and chloritised mica. Locality 106, Rishi.

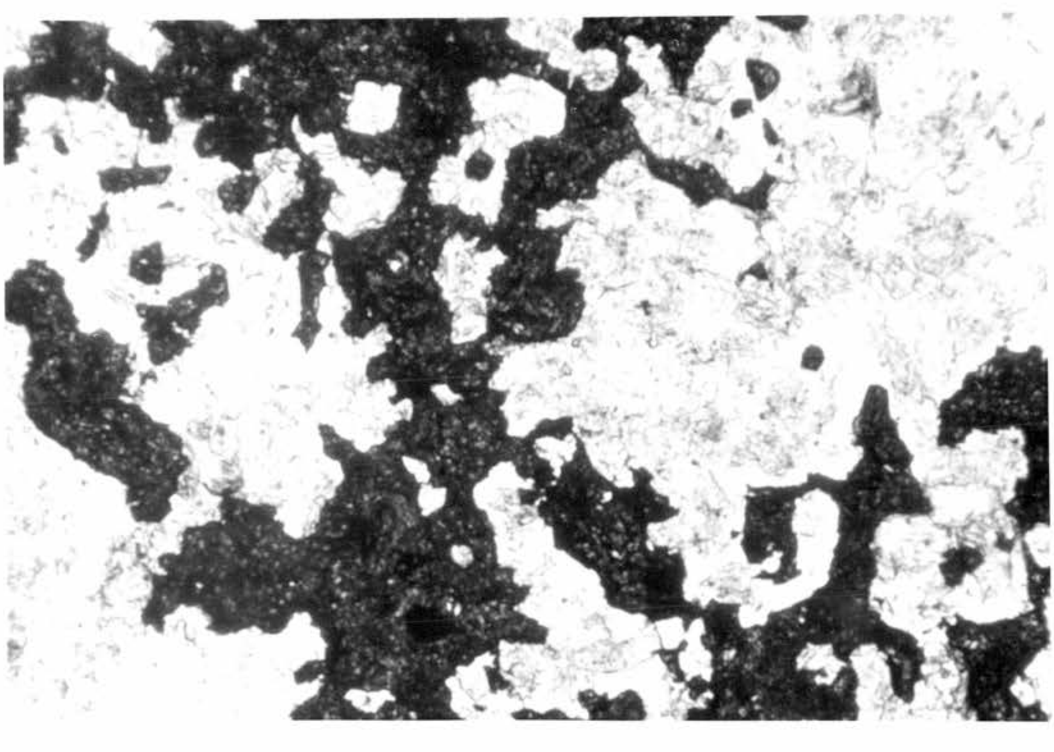
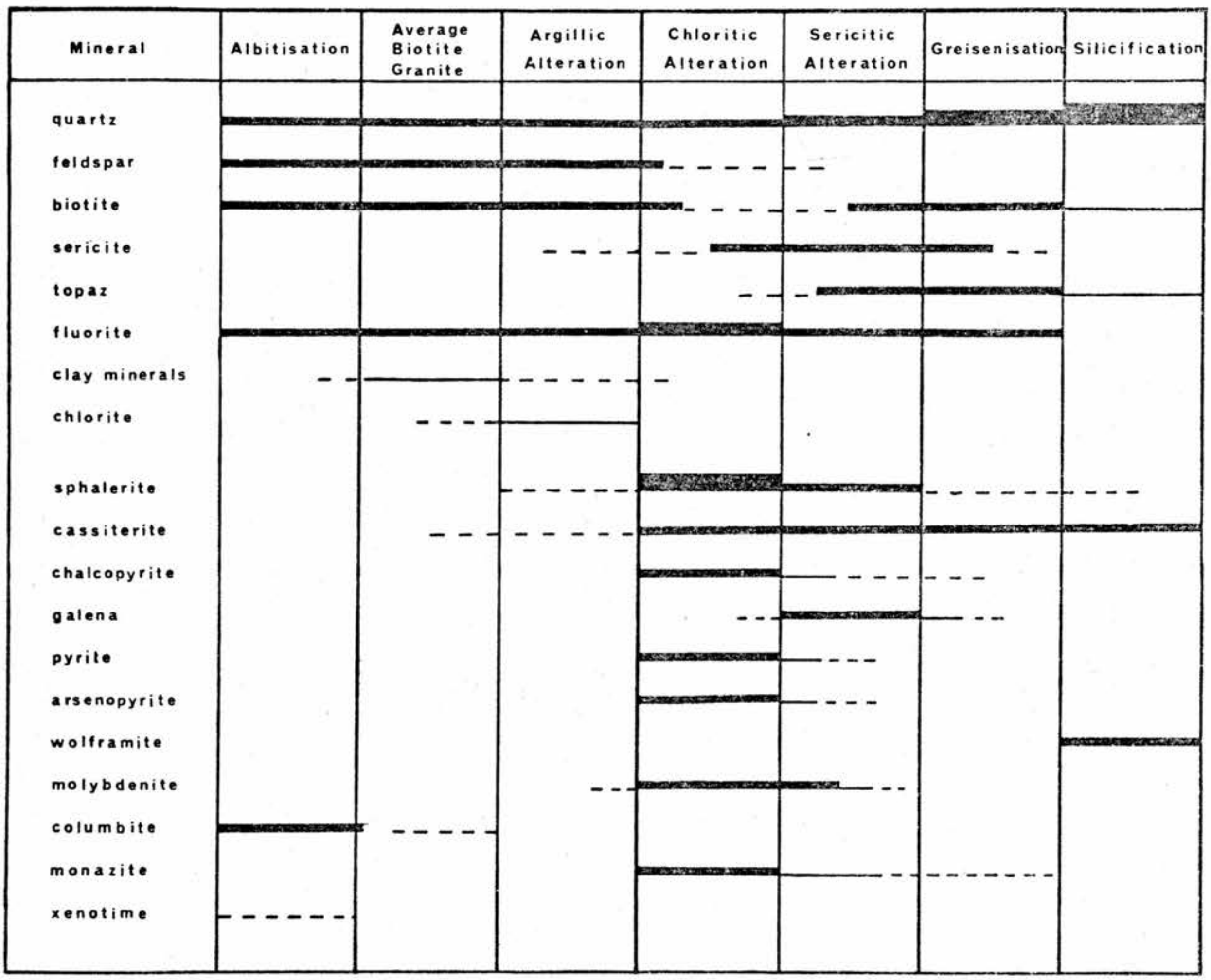


FIGURE 14


Mineral
Albitisation
Average Biotite Granite
Argillic Alteration
Chloritic Alteration
Sericitic Alteration
Greisenisation
Silicification
quartz
feldspar
biotite
sericite
topaz
fluorite
clay minerals
chlorite
sphalerite
cassiterite
chalcopyrite
galena
pyrite
arsenopyrite
wolframite
molybdenite
columbite
monazite
xenotime

Similarly the writer and Jacobson (op cit) have recorded minor increases in ferrous iron, manganese and fluorine.

Stage 2. CHLORITIC ALTERATION (Fig. 14).

The second stage of mineralisation is chloritisation which involves addition of varying amounts of iron accompanied by very minor sericitisation and the amount of alteration varies widely. The original biotite of the host granite may be partially chloritised or may undergo only partial replacement and some of the original biotite appears very resistant.

Meyer and Hemley (1967) quote chloritisation of biotite as an example of hydrogen metasomatism and give the following equation:-

$$2K(MgFe)_3AlSi_3O_{10}(OH)_2 + 4H^+ \rightarrow Al(MgFe)_5AlSi_3O_{10}(OH)_8 + (MgFe)^{2+} 2K^+ + 3SiO_2$$

The chlorite may also be altered by H^+ metasomatism to form sericite which is described under the next phase of alteration.

There is usually a massive input of fluorine associated with this stage and there is a direct correlation between fluorine content and ore concentration. Highest enrichment in sulphide ores, particularly of sphalerite, pyrite, arsenopyrite and chalcopyrite are always associated with fluorite rich chloritised veins. During deposition of the sulphide ores local cracks may have formed resulting in the streaming of sulphide bearing solutions causing the formation of solid sulphide veinlets. (Photo 5).

In hand specimen mineralised veins of this type are dense, dark green to nearly black and some may be extremely fine grained.

Lovering and Grüner (in Stringham 1953) believe that chlorite forms in neutral to slightly alkaline solutions at temperatures anywhere between 500-100°C so although the essential minerals give no indication of the physico-chemical conditions of formation the sulphide minerals may give a clearer definition. However, there is obviously more than one phase of mineralisation so that any attempt at deduction of conditions from the sulphide paragenesis may encounter difficulties.

In addition to the input of fluorine there is a significant increase in iron content from < 2% for the average of biotite granites to >25% in some of the mineralised replacement veins of this type. Increases in Cu, Sn, Pb, Li, Ce, Zn and As are also recorded in this stage and all form separate minerals except Li which is accommodated in the mica lattice. The composition of the chloritic minerals is not known but it seems likely that they will prove to be daphnites or Fe-rich ribidolites since the biotites from which the chloritic minerals have formed are very poor in magnesia.

Stage 3. SERICITIC ALTERATION (Fig. 14).

The sericitic stage of alteration appears to follow the chloritic stage and again amounts of alteration appear to differ widely, the most noticeable effects appearing where extensive chloritisation has not taken place. However, the amount of sericitisation is very small in comparison with the degree that has been described in Bolivia by Sillitoe et al., (1975) and in Cornwall by Alderton et al., (1976).

Sericite forms as a result of breakdown of feldspar that has not been argillised and may be associated with a few flakes of chlorite or fluorite or may form mica/topaz aggregates with quartz. Nockolds & Richey (1939) give an equation representing the change from microperthite to sericite and topaz assuming that no alumina is added or removed:

$$6(K_{.66}Na_{.33})AlSi_3O_8+3Fe+2\underset{}{\overset{\text{added}}{F_2}}+2(OH)\longrightarrow K_2Fe_3Al_2(AlSi_3O_{10})_2(OH_{.5}F_{.5})_4$$

$$+AlF_2AlSiO_4+\underbrace{K_2SiO_3+Na_2SiO_3+9SiO_2}_{\text{removed}}$$

The distribution of sericite flakes within the feldspar is completely random. (Photo 6).

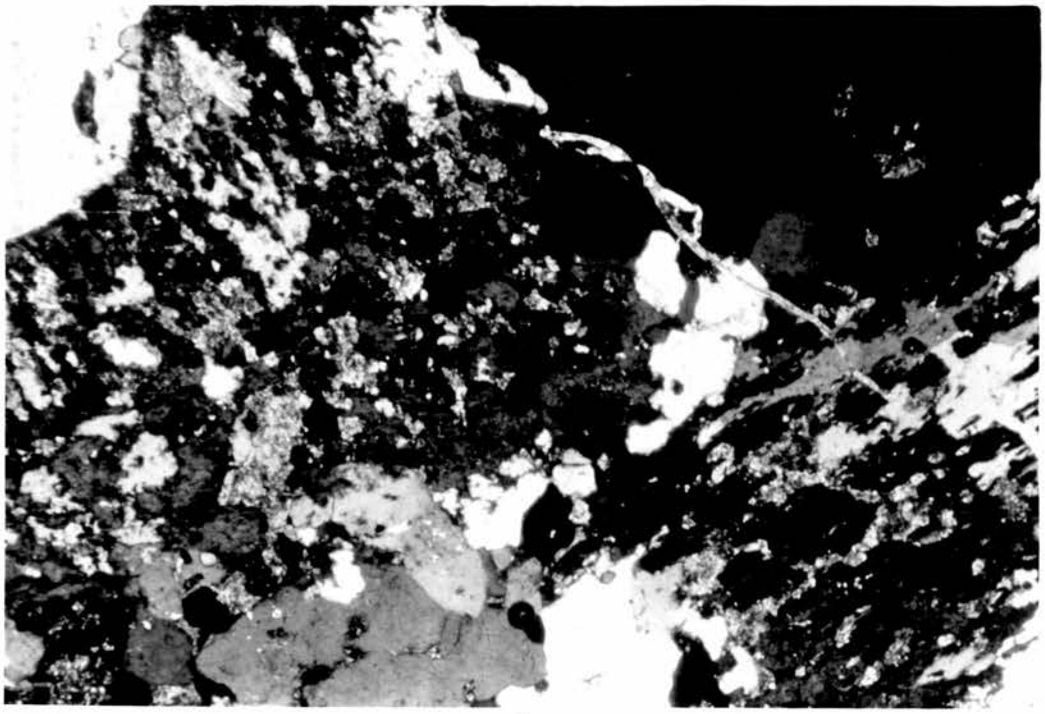
Sericite may also be formed by hydrogen ion metasomatism of chlorite according to Meyer and Hemley (1967) who give the equation for approximately constant volume of the solid phases and with mobilisation of aluminium:

$$2Al(Mg,Fe)_5AlSi_3O_{10}(OH)_8+5Al^3+3Si(OH)_4+3K^++2H^+$$
$$\longrightarrow KAl_2AlSi_3O_{10}(OH)_2+10(Fe,Mg)^{2+}+12H_2O.$$

In comparison with the chloritic stage of alteration only minor amounts of sulphide minerals are associated with the sericitic phase and of these only sphalerite and galena are common. Cassiterite appears to have a similar distribution in both phases.

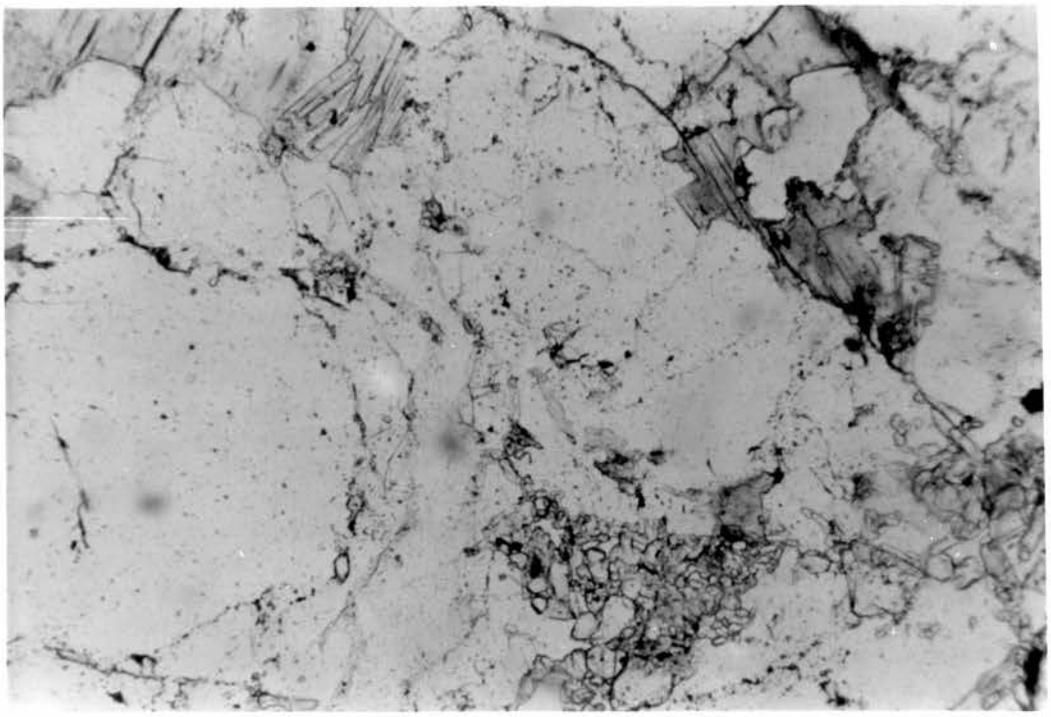
It has been established by Grüner (1944) that sericite probably forms in acid solutions above 350°C and in alkaline solutions below 350°C. However, without fluid inclusion data there is no means of deducing either temperature or pH.

In hand specimen mineralised veins of this type vary from greyish white to medium grey depending on ore content and percentage of inherited unaltered biotite.



Photograph 6. Sericite is seen randomly replacing the remaining feldspar in this photomicrograph of part of a mineralised replacement vein. Sphalerite fills the top right corner of the photograph. Cross nicols x 20. Locality Anglo Jos.

Photograph 7, shows a typical greisen with large, clear quartz grains, small clustered topaz (bottom centre), pale coloured protolithionite (top left) and green siderophyllite (upper right) x 20. Locality 64, Sabon Gida south granite, near Bukuru.



Stage 4. GREISENISATION.

The next phase of alteration is greisenisation and is characterised by the development of new alumina minerals in association with quartz. Greisen veins consist of large interlocking unstrained quartz, green siderophyllites or less commonly white protolithionite, and topaz which is usually only in small proportions. Also minor fluorite and cassiterite may occur as accessories (Fig. 14). (Photo 7).

The sericite of the previous phase has almost completely disappeared, possibly due to silicification as suggested by Meyer & Hemley (1967):

$$KAl_2AlSi_3O_{10}(OH)_2+3Si(OH)_4+10H^+ \longrightarrow 3Al^3+K^++6SiO_2+12H_2O.$$

The siderophyllite forms large bright blue green flakes and has clearly replaced relic brown annitic mica, in some cases with the formation of haematite along the cleavage traces. Not all the siderophyllite, however, can have formed by the replacement of original brown biotite since some greisens are exceptionally siderophyllite rich e.g. Ladini sample 5A. An analysis of both whole rock and mica appears in appendix 12 and the mica plots in the siderophyllite field of the diagram devised by Lange _et al._, (1972). It is possible that some of the siderophyllite has been formed by the modification of sericite.

In some cases the original brown annitic mica appears to have been bleached and then mantled with blue-green-siderophyllite.

The abundant quartz generally forms large anhedral grains except within the mica clusters where it forms mosaics of small interstitial crystals with topaz. The quartz has a metamorphic texture and appears to be completely recrystallised.

Cassiterite is the only ore mineral common to the greisens and its concentration is directly linked to mica distribution. It is found within the mica clusters as twinned and zoned crystals which are generally brown at the centre and colourless at the margin. Small anhedral grains are also numerous.

Chemically the greisens show a wide range in composition but this is due to the differing proportions of the siderophyllite. Analysis 1 in Appendix 2 shows a SiO_2 content of 90.9% whereas Analysis 2 shows 54.2%. However, the decrease in silica and corresponding increase in lithium, potassium, alumina and total iron is largely due to a much increased siderophyllite content. Hand specimen characteristics reflect the chemical composition. The more siliceous greisen is light grey with a granitic texture and appears to be composed of quartz and mica with a little haematite staining. In contrast the micaceous greisen is very dark green to almost black, coarse textured and so mica rich that quartz is not evident except on close inspection.

Stage 5. SILICIFICATION.

The final phase in the mineralisation sequence is undoubtedly silicification and quartz veins infilling fissures can be seen cross-cutting all previous stages of alteration. Silicification involves an increase in the proportion of quartz to other minerals in an altered rock - this may result due to silica being added hydrothermally. In other cases quartz may increase without an overall increase of silica due to alteration of feldspar to sericite or to selective hydrothermal leaching of bases leaving residual silica as quartz. There is evidence at Liruei supporting the latter suggestion and it is believed by the writer that the quartz of the lode has been derived from another biotite granite crystallising at depth.

The differing amounts of quartz in the previous-greisen-stage (i.e. 50-90%) probably reflect the effect of the silicification stage on the greisens. It is with the late stage quartz veins that the bulk of the wolfram is associated and cassiterite is also not uncommon, either with the wolfram or on its own. Less commonly sphalerite occurs in some of the quartz veins, suggesting a later generation than that associated with the chloritic phase of alteration. The cassiterite is also believed to be a later generation and a preliminary investigation indicates that the cassiterite associated with silicification is much lighter coloured than the earlier generation and likely to contain impurities of quartz.

Occasionally lithium rich biotite mica remains in some of the small veins and a mineral of the chlorite group is associated with the massive quartz vein at Sabon Gida. It seems likely to the writer that there is also a very minor second generation of chloritic development at this stage which is responsible for the thin chloritic veins cross-cutting earlier stages of alteration. Chlorite has been recorded in fissure veins in some hydrothermal veins of the alpine type in low grade metamorphosed sediments in association with adularia and quartz (Deer et al., 1966). Although a chlorite mineral has not been found in association with adularia in Nigeria, Jacobson (1947) records adularia associated with late-stage quartz veins. "It sometimes occurs in aggregates of euhedral crystals lining vugs in the quartz and is often associated with wolfram. The adularia is salmon pink in colour and is easily identified by its characteristic rhomboidal form".

In hand specimen the small quartz veins usually display a crude comb structure with colourless, transparent crystals, but tend to become more massive and milky in the larger veins and rarely becoming amethystine. The quartz veins may occur alone or as fracture infilling cutting earlier stages. There seems to be no direct relationship between the width of alteration and the width of the quartz vein. As yet there is no information on the temperature of formation of these veins but the material collected proves promising for fluid inclusion techniques.

Discussion

Nigel Grant (Grant et al., 1976) during his studies of Bolivian tin mineralisation has used fluid inclusion data to indicate the temperature and salinity conditions that prevailed during vein formation. He and other co-workers have found that the earliest veins form around 500°C and at high salinity - these have no associated mineralisation. As salinity and temperature decrease so cassiterite begins to form. Gradual temperature and salinity decrease may be responsible for the sequence of phases that have just been described.

It also seems likely that some of the veins described above are due to pneumatolysis by a supercritical fluid. Some veins may have developed before a joint system was established and joints may have formed along the veins which formed a linear weakness. The replacement veins in the south-west of the biotite granite at Banke may be of this type which would explain, in relation to Grant's work (op. cit.), why there is no associated mineralisation since the salinity and temperature of formation would have been too high for separation of cassiterite and other ore minerals as separate phases. In contrast, the veins at Rishi and Liruei would be considered as having formed at lower temperatures and salinity. Further work, outside the scope of this thesis, is planned to prove this hypothesis. However, it does seem likely that where joints and fissures developed there would be a corresponding drop in both temperature and salinity thus increasing the possibility of ore deposition.

These veins show stages of mineralisation similar to those observed in other tin provinces (e.g. Bolivia and Czechoslovakia) although the order in which they take place is not necessarily the same. The Nigerian setting however is unique in that the veins which contain cassiterite contain no tourmaline which is attributed to boron deficiency in the parental liquids of the province (Bowden 1970).

The sequence of stages as suggested by the writer is in fact almost the reverse of that proposed by Štemprok for the stages that have taken place in the Erzgebirge. He suggests the following sequence of events:

1. pegmatite formation
2. feldspar growth
3. silicification
4. greisenisation
5. tourmalinisation
6. chloritisation
7. sericitisation

kaolinisation

In contrast the writer has suggested that in Nigeria the sequence is:-

1. argillisation and haematite formation
2. chloritisation
3. sericitisation
4. greisenisation
5. silicification (rarely with feldspar growth).

There is no tourmalinisation stage in Nigeria since tourmaline is absent and there is no distinct phase of pegmatite formation although pegmatitic knots and lenses do occur. These may have formed in the early apogranitic stage of mineralisation either pre- or post-jointing; also pegmatitic lenses are associated with at least one of the later mineralisation stages listed above since the greisens in the Ladini area of the Saiya-Shokobo complex (Fig. 22) may have pegmatitic lenses at their centre or parallel to one of the margins.

The apparent reversal of the alteration phases may be related to alkalinity since the Erzgebirge mineralisation is related to an initially low alkalinity whereas in the Nigerian province the alkalinity is initially much higher. In the Erzgebirge the original host rock is calc-alkaline and as the alkalinity increases there is a progression of alteration phases from 1, which is pegmatite formation, to stage 8, which is argillisation (Fig. 15a). However, in Nigeria the reverse is true. Mineralisation is associated with decreasing alkalinity. Since late-stage argillisation in the Erzgebirge is related to high alkalinity perhaps it is therefore not unreasonable to find argillisation related to high alkalinity in Nigeria i.e. forming one of the first phases of mineralisation rather than the last as in Czechoslovakia. viz.

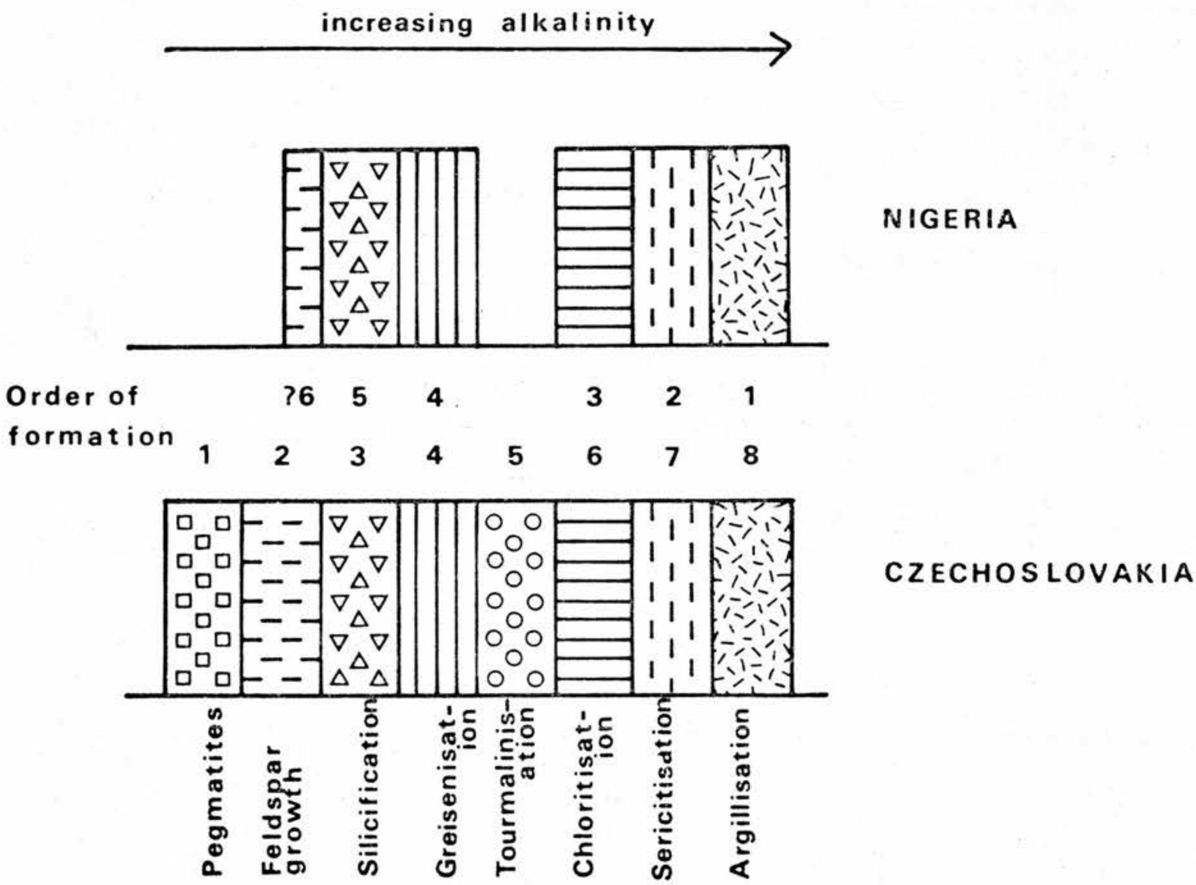


Fig. 15 Comparison between stages of mineralisation in Nigeria and in the Erzgebirge.

Thus in the Erzgebirge and Nigerian Provinces argillisation takes place at maximum alkalinity which in the Erzgebirge is late in the sequence and in Nigeria is related to the early mineralisation stages (Fig. a and b).

Therefore, stages 1-8 in the Erzgebirge take place as the alkalinity increases. However the stages in Nigeria are reversed and take place in response to a decreasing alkalinity.

Chapter 4. Characteristics of the Replacement Veins in the Complexes that were studied.

Liruei

The Liruei lode is the largest of the vein systems. The lode can be traced along its east-west strike for over 5 km (Fig. 16) and has been proved at depths of 300 m west of the shaft. The lode dips to the south at 70-80°. The total width of the vein system varies from 1 m to 8 m but it is commonly 2.5 m wide. It comprises parallel quartz veins which are enclosed by bands of greisen which grade into a

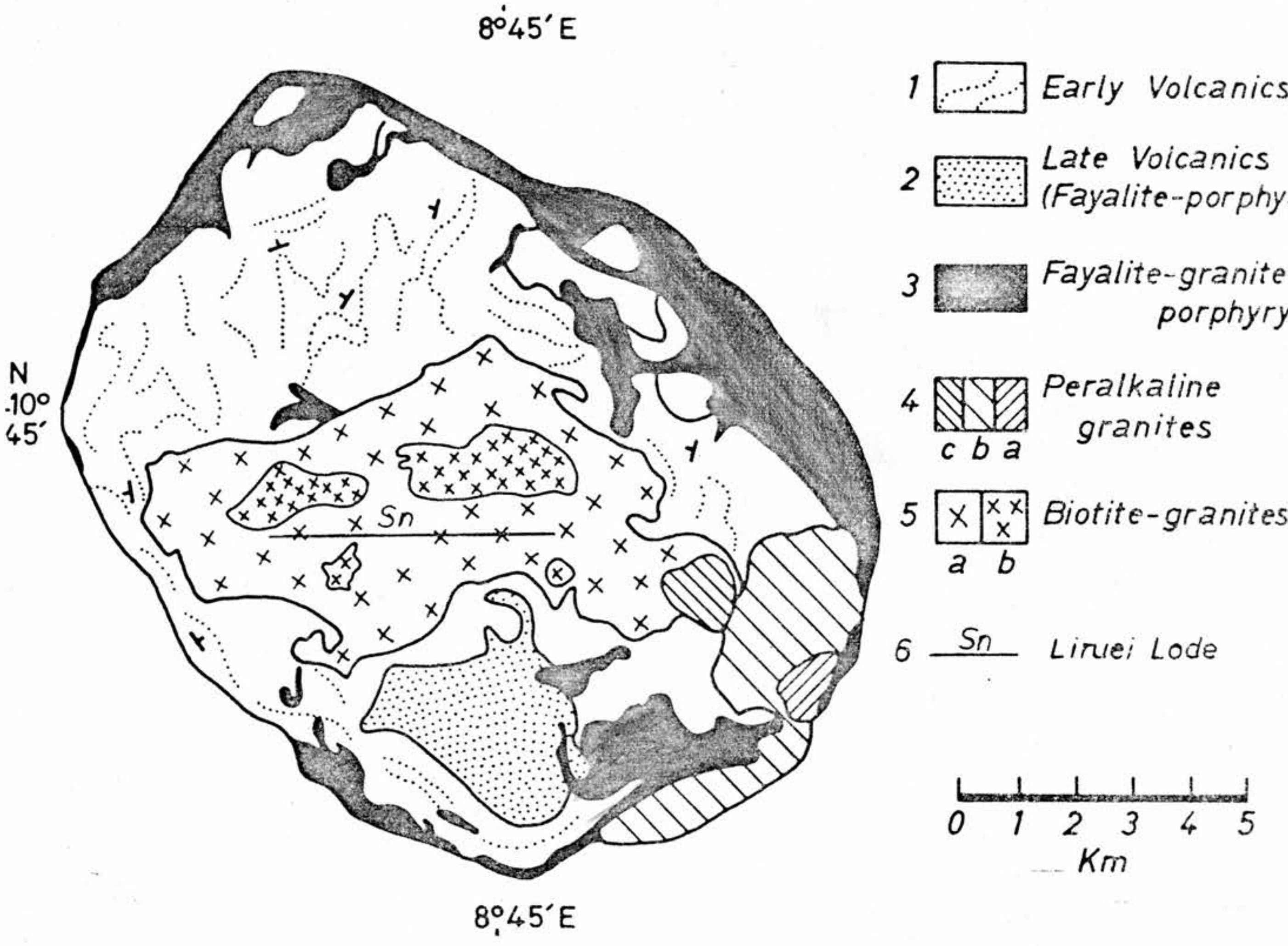
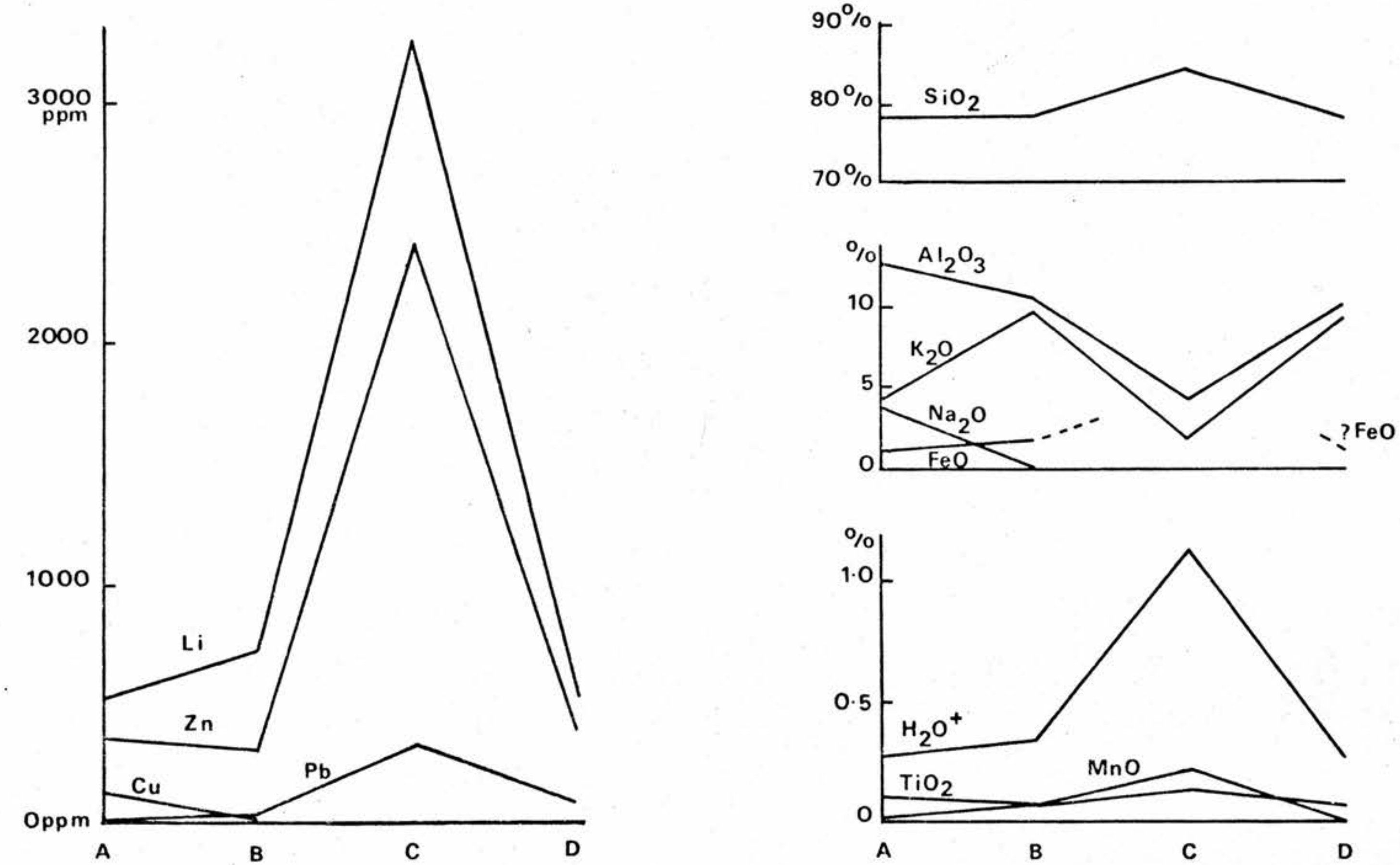


Fig. 16. The Liruei Younger Granite Complex.

Fig 17 Chemical changes from an average of biotite granite across a mineralised vein – Liruei

A – Average of five analyses of Liruei biotite granites
B – Altered wall rock on one side of vein
C – Quartz vein with cassiterite
D – Altered wall rock on opposite side of vein



Photograph 8. Cross section across one of the minor Liruei veins showing grey greisen, with a central quartz vein, grading sharply into reddened granite. Scale x $\frac{1}{2}$.

Photograph 9. Cassiterite crystals taken from kaolinite-filled vugs in the Liruei lode. x 5.

zone of reddened granite. Jacobson (1947) describes "the contact between the quartz vein infilling and greisenised wall-rock as fairly sharp and the junction between the greisen and the reddened wall-rock, although not as sharp as a normal intrusive contact, is very well defined. The junction between the reddened wall-rock and the unaltered host granite is also surprisingly sharp." (Photos 8 and 9).

At one point underground, over a horizontal distance of 7 m, nine or ten separate lodes can be seen. Parallel stringers are common and offshoots sometimes occur but they are narrow and impersistent - at the adit they are orientated in a north-northeast - south-southwest direction. The quartz veins vary from 5 mm to 75 cm in thickness. Generally the narrower ones show a comb structure with glassy crystals whilst the wider ones show a more massive type of quartz which may be cloudy or milky. Occasional large cavities occur in these massive quartz veins and may contain adularia crystals and wolfram. The quartz veins may also contain sphalerite, cassiterite, a little galena and disseminated chalcopyrite. Commonly the width of the greisen zone is inversely proportional to the width of the quartz vein. R.G. Taylor (pers. comm.) has suggested that where there is a wide fracture there is less reaction of the ascending fluids with the wall-rock and where the fracture is narrow ascending fluids react with the wall rock so that there is little deposition of ore minerals.

Chemical variations between an average of five biotite granite samples and altered wall-rock on either side of a mineralised quartz vein show marked increases in Li, Zn, Si, and H_2O from the normal granite, probably also in SnO_2

although this has not been analysed. Minor increases are recorded in Pb, Fe and Mn whilst sharp decreases in K_2O and Na_2O have been found in the vein (Fig. 17). It must be concluded that K^+ and Na^+ were released by feldspar breakdown and possibly removed in solution in the form of chlorides. However, the wall rocks enclosing the vein have a marked increase in potassium although they show evidence of argillic alteration which would involve a net loss in potassium. It seems likely that the potassium from the vein may have migrated into the surrounding wall rock. Despite the increase in potassium in the wall rock, it is not considered to be akin to the potassium silicate alteration of Meyer and Hemley (1967) since there is no new feldspar formation. (Appendix 12).

The greisen is dark green or greyish and always has a granitic texture. It consists essentially of quartz and green mica. Despite the fact that topaz is rare within the lode the veins are still considered as greisens since they are composed of quartz and "new" alumina minerals in the form of protolithionite which has not formed at the expense of the biotite in the original host rock. This fits with the definition of a greisen given in the previous chapter although not necessarily in agreement with other authors.

Cassiterite has been exploited in the alluvial deposits along the lode on several levels to a depth of 150 m. It has been estimated that the mine would produce 1,600 tonnes of tin metal a year and 6000 tonnes of zinc metal. This gives an approximate grade of 0.5% Sn and 1.5-2% Zn. The metal values of the wall rock between the lodes has not yet been assessed. The cassiterite occurs as coarse crystals in the quartz veins and is also widely disseminated in the greisens. It is also found underground in vugs as large, lustrous black twinned crystals associated with kaolinite. The distribution of the cassiterite is highly irregular and rich pockets of ore are separated by long stretches of barren quartz.

Sphalerite is the most abundant ore, widely distributed in quartz veins and greisens, and occasionally found in the altered wall-rock. It occurs in massive form up to 1 m across and may be pure or associated with massive galena, especially in the western end of the lode. In the quartz veins the sphalerite may occur marginally or at the centre and for short distances the lode becomes solid sphalerite. In hand specimen the sphalerite is very dark brown with a characteristic greasy lustre. In thin section it is always yellow or yellowish brown.

Chalcopyrite has been observed widely but is not abundant. Azurite and malachite are common stains at the surface especially around the adit.

Molybdenite, bismuthinite and wolframite are known to occur in the Liruei lode although they are rare in comparison with cassiterite and sphalerite. Molybdenite appears to be more common in the altered wall-rock than in the lode although it has been recorded in veins to the west. Wolfram has been mined at Liruei but the tenor has never been very high. It is restricted in occurrence to the late-stage quartz veins and it occurs as dark brown to black crystals either in the veins or in drusy cavities associated with adularia. Like cassiterite its distribution is very variable but the highest values occur in the west end of the lode where it is richest in galena.

Despite the fact that wolfram is most abundant in the west and sphalerite is most common in the central part of the lode there is no zonation of ores as in Cornwall. However, a three-dimensional survey of the whole lode would now be possible with the opening up of a mine and would establish a distribution pattern of each of the ores.

Jacobson (1947) has noted the occurrence of genthelvite in greisens at Kerigateri Hill near the contact between a fine-grained granite and an earlier rhyolite. Individual greisens are only developed on a small scale and become more abundant towards the rhyolite contact. Some of the greisens are extremely irregular in form and are not related to definite fissure fillings. They are predominantly siliceous and sulphide-bearing. The occurrence of genthelvite close to the upper contact of the granite is very similar to occurrences at Rishi where the beryllium mineralisation is restricted to the upper 30 m of granite.

The host rock of both the lode and of the greisens at Kerigateri Hill is biotite granite. At the surface this is a relatively uniform medium to coarse grained biotite granite, generally pink in colour. However, at depth, fine-grained white or pale grey variants and micro-granite may form sharp irregular boundaries with the normal granite both in texture and colour. Small, thin pegmatitic pods may also occasionally occur. This variable granite appears to represent a distinct intrusion emplaced within the normal Liruei biotite granite and clear effects of hydrothermal alteration within this intrusion suggest that it must have been emplaced earlier than the formation of the lode.

Associated with the microgranite are fine-grained whitish bands composed almost entirely of feldspar. They contain numerous cavities which may be the result of leaching out of silica. The cavities may contain crystals of albite and books of green mica. These feldspar bands are akin to the albitised granites formed by late stage metasomatism and it has been suggested by D.C. Turner (pers. comm.) that the silica of the lode has been derived from the silica deplete feldspathic rocks.

The fine-grained granites show evidence of albitisation and of replacement where feldspar has been partially replaced by quartz and green mica and original brown biotite has a green rim or is partially replaced by green mica. It is suggested therefore that the mineralising solutions which formed the Liruei lode are directly related to this fine-grained intrusion at depth. It is envisaged that the roof of this fine-grained granite was mineralised before joint development by ascending solutions from a still liquid portion at depth and that as these solutions continued to rise they mineralised the overlying granite along a series of fissures which had developed as a result of the fine-grained intrusion at depth, thus forming the lode.

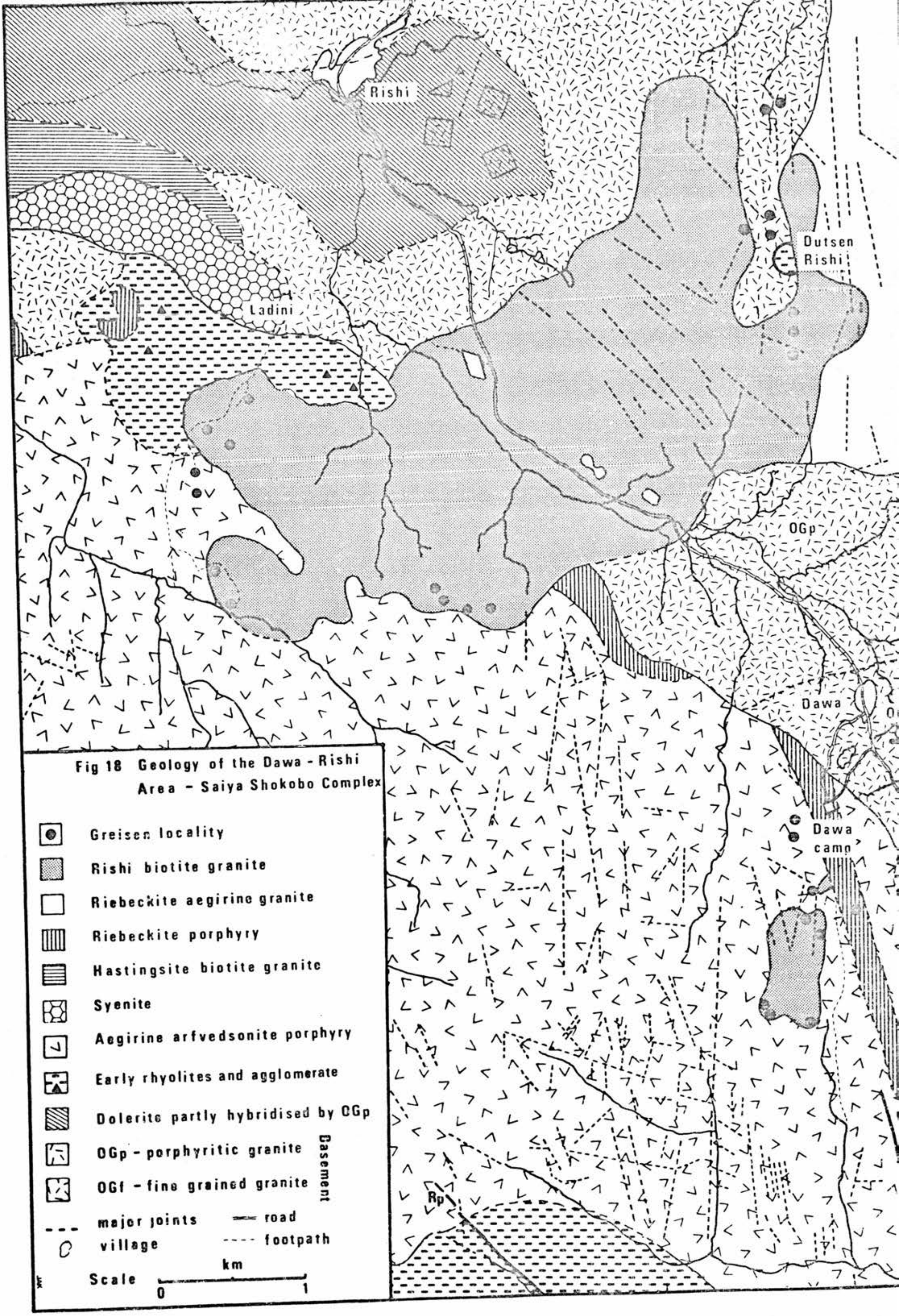


Fig 18 Geology of the Dawa - Rishi Area - Saiya Shokobo Complex

The Rishi biotite granite, which is medium-grained, appears to be the most extensively mineralised granite in the province and the mineralised veins contain the most exotic suite of minerals. All the veins located fall within three distinct groups with one group in the vicinity of Dutsen Rishi (Fig. 19), one group south and west of Dawa (Fig. 21) and one group south of Ladini (Fig. 22). In all cases the veins occur near the granite contact with other rock types and all the veins are parallel locally to that contact whether they are within the contact or beyond it. Figure 18 shows the distribution of these veins which have been mapped onto air photographs and then located on the survey map by photographically increasing it from a scale of 1:100,000 to the same 1:40,000 scale as the air photos. At this scale the geological boundaries shown are not very accurate and have thus presented problems in mapping. Sketch maps of each area have therefore been added (Figs. 19-22) and where possible amended geological boundaries drawn.

It seems significant that the vein localities in the Dutsen Rishi and Dawa areas appear to lie in a north-south zone in which joints and lithological contacts are also predominantly of a similar orientation. It seems likely therefore that major lineations in the basement have exerted an effect not only on the location and form of the intrusive rocks but also on the mineralisation related to them.

Dutsen Rishi Area.

The Dutsen Rishi group (Fig. 19) is composed of a series of veins occurring either at the surface in basement and Rishi biotite granite or in the biotite granite at shallow depth beneath a narrow basement rib. This is

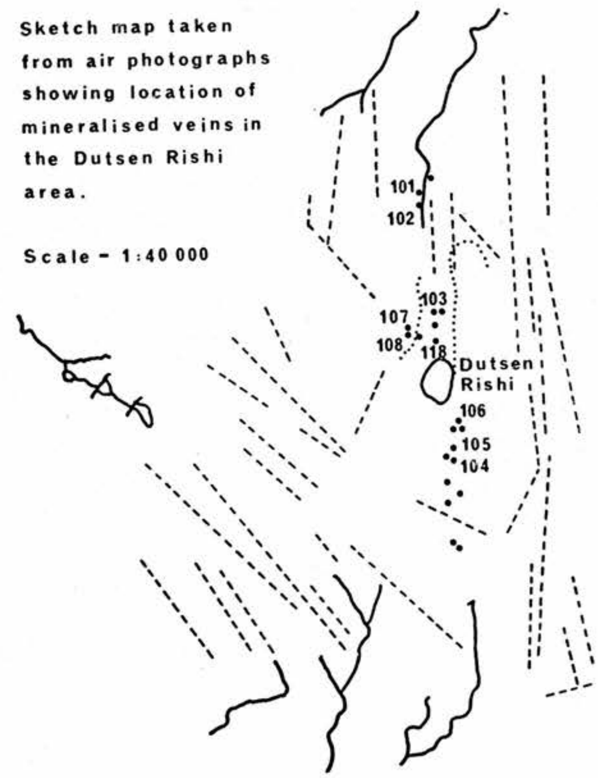


Fig. 19.

described by Buchanan (1971) as "an unusual cross-section of the granite roof provided by a narrow arched rib of porphyritic older granite which extends from the line of the outer contact to the top of the hill. This is a horizontal distance of $2\frac{1}{2}$ km and a vertical rise of 300 m. The attitude of the contact shows a progressive change from 45^{o} at the lower end of the rib to horizontal at the top". A small cap of weathered, grass covered rhyolite overlies the older granite and forms the summit of Dutsen Rishi (Fig. 18) but its contact with the adjacent rocks is nowhere exposed.

At the base of the slope, dark coloured quartz veins trend 320^{o} in basement (Fig. 18). Locally, one of these veins is 3 m wide and has been worked for tin and tungsten. Nearer the contact with the younger granite there is a profusion of aplitic veins with varying thickness and trend. East-west orientated mineralised veins vary in thickness from 2.5-7 cm and the wider veins are often composite with two narrow replacement veins enclosing a thin central quartz or aplite vein.

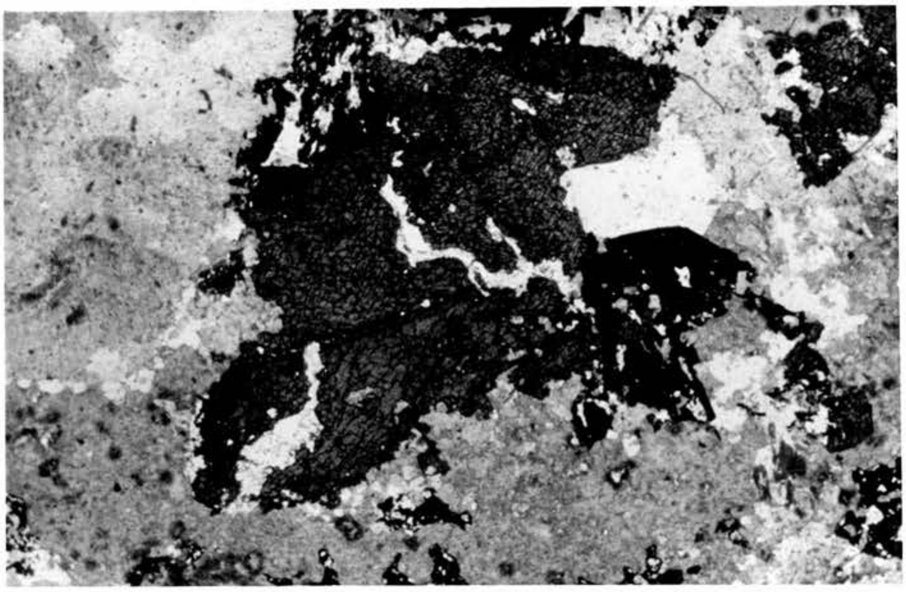
Following the basement rib up the river valley a number of workings expose mineralised veins, in underlying granite, which appear to trend 300-320^{o} and continue up the hill parallel to the stream valley. The underlying granite, exposed in pits, is seen to be within a few metres of the surface.

At locality 102 the exposed vein is grey and micaceous with abundant sphalerite and chalcopyrite as large anhedral masses and pyrite as small dodecahedra. Locally pods or streaks of milky quartz are enclosed and small clear, iron-stained crystals may occur along fissures.

An enormous spoil heap fills the valley and younger granite boulders from the pits show numerous cross-cutting and irregular mineralised veins. Further up the hill at locality 103 two mineralised veins within 15 metres of each other are clearly exposed at the head of the valley. The lower one is 1.8 metres wide with no apparent ore minerals and has thin offshoots whilst the other one is 3 metres in width.

There is an irregular distribution of ore minerals both across this lode and along its strike. Dark brown to black sphalerite is abundant with cassiterite and chalcopyrite; chalcocite has also been identified from polished ore sections of this material. Very little galena has been observed although it is known to have been mined from these pits.

In thin section the veins from the basement, which are dark, almost black, fine-grained varieties, have very little quartz and topaz. They are extremely rich in brown mica, fluorite and ore minerals. Under high power the brown mica shows minor replacement by siderophyllite and part of the mica may also be chloritised. The feldspar has been altered into turbid areas of clay minerals, or has undergone sericitisation. Cassiterite is common to abundant as small grains varying in colour between brown, red and colourless. Occasionally these crystals are twinned - see photomicrograph 10. Sphalerite is extremely abundant and may vary from small grains which are yellow to orange in colour and rimmed with chalcopyrite to large red areas with exsolved chalcopyrite. The two different types probably represent two different generations of sphalerite. Chalcopyrite is also extremely abundant. It occurs as large or small anhedral patches and occasional small euhedral crystals and also along the partings and cleavage in sphalerite or as rims around other minerals. Monazite is also abundant usually occurring as a mesh of crystals or as rosettes. Small dark brown prismatic crystals of allanite may occur and tiny zircons are numerous. Greenockite has also been identified. Thin sections suggest that the most altered zones are also the richest in sulphide deposits and as the hydrolitic effect



Photograph 10. Twinned cassiterite with chalcopyrite in a groundmass of quartz, fluorite and chloritised mica. x 25.

Photograph 11. Monazite crystals forming a mesh surrounded by chalcopyrite with large anhedral fluorite and chloritised mica.

diminished the quantity of sulphide deposited was also reduced.

In contrast, the lighter coloured siliceous greisens which occur only in the Rishi biotite granite are not enriched in ore minerals, the amount of fluorite is small and there is an abundance of topaz. The greenish brown lithium rich biotite is extremely fine-grained and has been partly chloritised.

Much further up the hill more veins have been excavated and pitted although they are now very overgrown. At locality 107 Rishi biotite granite has been extensively altered although no distinct boundaries can be determined - streaky quartz and a dark fine-grained unmineralised greisen are completely intermixed. The greisen is vertical and trends 320°. Above this locality and on the same strike, a well exposed composite vein 3 metres wide has a variable texture across the strike. The outer margin is characterised by a discontinuous zone of quartz-mica which has a vesicular texture, the cavities being due to the preferential weathering of mica - small brown crystals of cassiterite can be found in this zone. The quartz occasionally becomes massive and is streaked with amethyst. There is a gradual westwards transition into a very quartz-mica rich streaky variant which in turn grades into a light grey coloured fine-grained greisen and eventually into a dark grey fine-grained material. It is not known whether there is a further westward zonation because the ground falls away steeply at this point. In thin sections of the quartz-mica streaky variant, topaz is absent, there is a little fluorite and cassiterite but essentially the minerals are quartz and fine-grained brown or greenish mica pleochroic to pale yellow and almost colourless. The light and dark grey varieties differ little in hand specimen but the lighter type is rich in topaz and quartz with extremely fine-grained brown mica and a little fluorite whilst the darker variety has no topaz and only a little fluorite with micas varying from reddish brown to light green. Both contain minor sulphide ores and almost no cassiterite.

Below Dutsen Rishi at locality 118 a dark grey fine-grained replacement vein trending 260° has been blasted out forming a gulley, and again the younger granite can be seen below the basement granite at the surface. It contains pyrite and chalcopyrite, and cassiterite rich quartz was collected from the spoil heap.

To the south of Dutsen Rishi a fine-grained variant of Rishi biotite granite contains replacement veins. Many of the north-south joints or 320° joint planes have been reddened and quartz veins are abundant. At locality 104 a one metre wide mineralised vein, trending 250° grades from light coloured almost pure quartz into a grey fine-grained or streaky material with alternating quartz and medium to dark red or blackish streaks of replacement vein. The grey fine-grained variant contains abundant chalcopyrite, a little pyrite, cassiterite and galena. Further up the hill at locality 105 the same vein is 1.5 metres wide. It is streaky at the margins and the granite contact is very decomposed.

Across the valley from Dutsen Rishi at locality 106, a massive mineralised vein trending 214° cuts a fine-grained marginal variant of the Rishi biotite granite. The vein which is approximately 1.8 metres wide is exceptionally sphalerite and cassiterite rich - the cassiterite in the form of massive pockets is concentrated on the eastern margin whilst the sphalerite forms veinlets associated with quartz and purple fluorite in the centre and becomes massive on the western margin. The distribution of chalcopyrite is similar to that of sphalerite although it is less abundant. The quartz veins which are variable in thickness have a honeycomb texture and may contain masses of cassiterite 2.5-5 cm across, stringers of cassiterite and irregular patches of sphalerite.

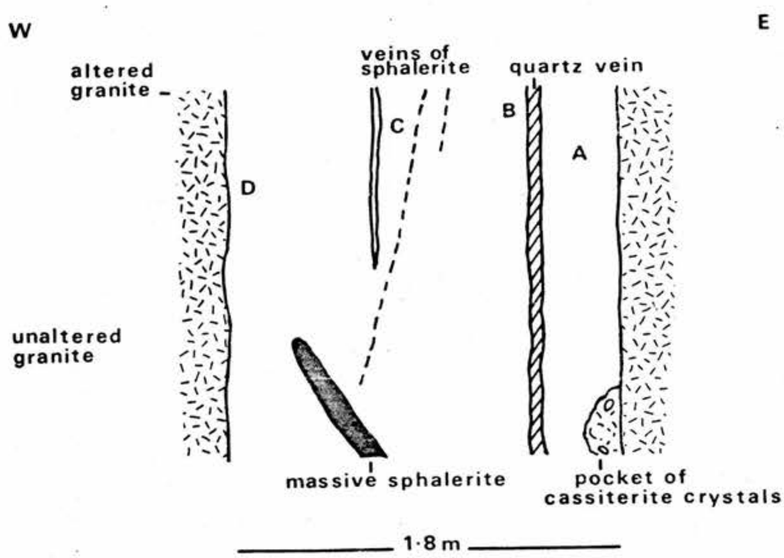


Fig 20 Section across Locality 106 showing location of specimens

In thin section Sample A (Fig. 20) shows medium-sized strain free quartz with minute fluid inclusions. No feldspar now remains and fine-grained sericitic mica associated with quartz and topaz is abundant whilst occasional large mica flakes, which are either white or pale green (probably protolithionite), may be associated with fluorite. Patches of chlorite with sericite are also formed during feldspar breakdown. Both cassiterite and sphalerite occur, the cassiterite is light in colour and the sphalerite forms small anhedral yellow masses apparently replacing mica/topaz/quartz.

Sample B in thin section shows a greater range of size in the quartz grains. Not all the feldspar has been replaced and locally sericitic mica is seen replacing turbid feldspar, forming also a very fine grained mosaic of quartz with some topaz and purple fluorite. There is no cassiterite but it is rich in yellow anhedral sphalerite which also forms a vein cross-cutting the micas. In contrast to sample A there is almost no chlorite.

In thin section sample C shows a more patchy distribution of quartz grains, which are smaller than in previous samples and shows kaolinised feldspar. It is darker in colour than the other samples and this is due to an abundance of extremely fine-grained pale green mica associated with white mica and some chlorite, which is equally fine-grained. These are too fine-grained for identification. A little brown biotite survives and is overgrown by pale green mica, which is probably siderophyllite. This may also be overgrown by a white tri-octohedral mica which is probably protolithionite. Fluorite forms one large patch, there is no cassiterite and only a little sphalerite.

Sample D is partially altered granite. The quartz grains are medium sized, similar to those in sample A. The feldspar is largely unaltered although local incipient alteration to sericite takes place. Ragged plates of surviving mica are small and partially chloritised. Small green flakes probably siderophyllite, pleochroic from dark green to colourless also occur but neither are abundant.

From the cross-section it is obvious that the ore minerals are rich locally, cassiterite being richest marginally and sphalerite richer towards the centre of the vein, which is contradictory to evidence found in Liruei where sphalerite may be marginal. It is not completely understood why partially unaltered feldspar is in the centre of the greisen whilst it has been completely replaced at the margin. It must be concluded that the ascending greisenising solutions did not affect the host rock uniformly, since the controls of ore deposition were obviously changing within the channel in response to changing conditions of temperature, pressure or wall rock reaction during migration of fluid through the system. It seems probable that within the wall rocks adjoining the channel transfer of chemical components is probably chiefly by diffusion so that chemical gradients will be different around different minerals in the altering rock. The most important changes taking place probably relate to H^+/OH balance. Hydrogen metasomatism has obviously been important; firstly, in the chloritisation of the biotite and secondly, in sericitisation of the mica (Meyer & Hemley 1967). The level of H^+ metasomatism can only be maintained in an ore deposit if the temperature is increasing upward or if oxidation, owing to mixing with oxygenated ground water produces more highly ionised sulphuric acid from less ionised H_2S. As both factors are probably involved, local variations in the effect of hydrogen metasomatism are bound to occur and would possibly explain why chloritisation has been more extensive adjacent to the margins of the vein.

Meyer and Hemley (1967) show that there is a close correlation between hydrogen metasomatism and high sulphur fugacity in the sulphide assemblage and that strong H metasomatism exists only when the S/O fugacity ratio is relatively high, not merely when oxygen fugacity is high. Therefore, changing content of total sulphur in the hydrothermal solution is probably responsible for variations within this mineral assemblage. Localised removal of sulphur from the ascending solutions by the wall rocks may account for lack of sulphide deposit along the western margin. This relatively high sulphur fugacity would also explain the lack of wall rock reddening as very low sulphur fugacities and higher oxygen fugacities are favourable to haematite formation. High sulphur ratios also favour the stability of chalcopyrite as opposed to pyrite (Sales and Meyer, 1948). However, the mixing of the ores observed strongly suggests that rapid changes in pressure and temperature dominated over these slower, nearly steady state reactions.

Dawa

Eight hundred metres south-southeast of Barakin Dawa (Figs. 18 and 21) riebeckite-feldspar porphyry contains replacement veins near its contact with a fine-grained offshoot of Rishi biotite granite. The host porphyry is characterised by phenocrysts of pink feldspar up to 1 cm long with quartz and occasional laths of blue riebeckite set in a fine-grained dark groundmass. The adjacent fine-grained

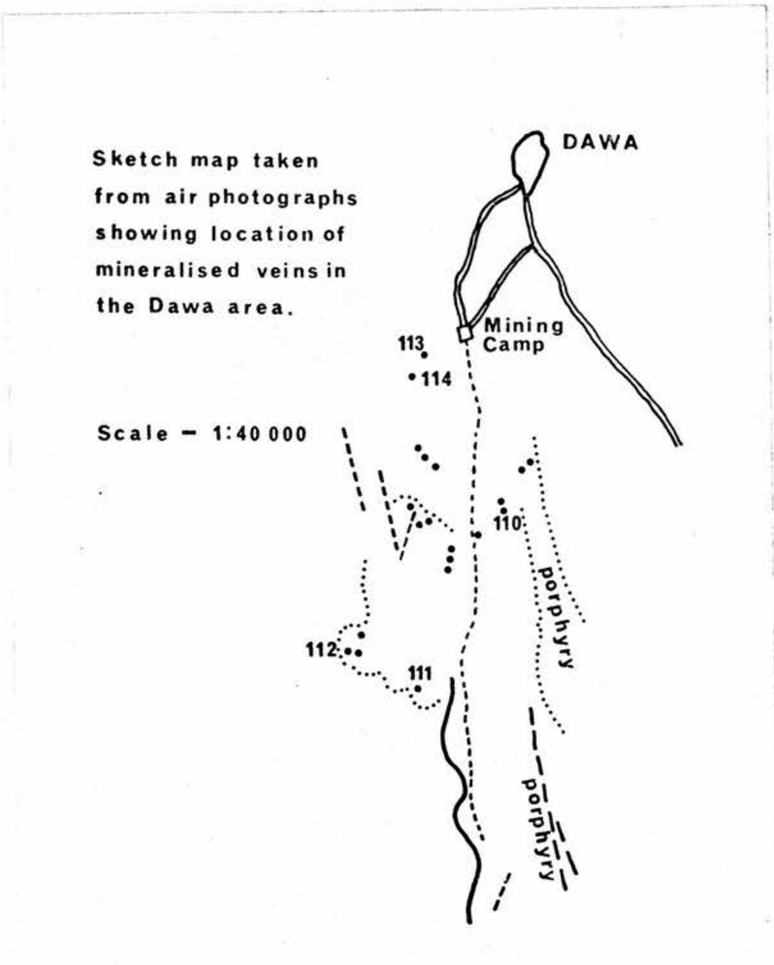


Fig. 21.

granite has a variable texture and when altered the feldspars are replaced by quartz, mica and topaz producing a rock which is less micaceous and finer grained than altered porphyry. The replacement veins in the porphyry are very micaceous and many of the feldspar phenocrysts have been preserved although they are rather rounded.

At locality 110 mineralised veins parallel to the porphyry contact can be seen in a series of pits excavated in the hillside, the most persistent of which consists of a vuggy quartz vein 8 cm wide with selvedges of altered wall rock 30 cm wide which can be traced up the hillside for 25 metres. Mineralisation is sporadic. Cassiterite is localised and is very fine-grained. It is most abundant in the grey veins in association with small crystals of yellow or brown sphalerite, and pyrite also occurs occasionally. The quartz rich parts of the vein system are reddened with haematite. Genthelvite occurs in thin red, greasy-looking streaks up to 5 cm long in altered porphyry adjacent to joint planes crossing the porphyry dyke.

South of Dawa (Fig. 18) the margins of the granite outlier are extensively reddened or slightly altered along joints and fissures, but at locality 111 in the south-east, reddened quartz veins and grey, siliceous mineralised veins with a remnant granitic texture have been worked for tin. Minor sporadic mineralisation is apparent although it seems insufficient to warrant working. The veins are more siliceous and coarser grained than those at locality 110. In addition to cassiterite and sphalerite a little chalcopyrite and traces of molybdenite were found.

In the extreme south-west corner of the granite, tin bearing quartz veins and vertical replacement veins trending between north-northeast and northeast have been worked extensively for cassiterite along a strike distance of approximately 25 metres. Genthelvite occurs in the veins that lie within 30 metres of the granite contact, rapidly dying out at a greater distance. Taylor (1961) also records phenakite in association with the genthelvite at this locality. No copper or zinc minerals were collected here but cassiterite is abundant. These veins are siliceous and similar to those from locality 111 above. On the hillside immediately to the west of Barakin Dawa an area of extensively mineralised porphyry is proving to be a rich but sporadic source of tin. The lode at locality 114, near the contact between riebeckite-porphyry and aegirine-arfvedsonite porphyry has been the source of a massive lump of pure cassiterite weighing over 130 kilos and was currently producing cassiterite when visited. The lode trends northwest parallel to the porphyry contact; excavations have destroyed much of the major lode <u>in situ</u> and it is difficult to estimate its width. Altered host rock grades into a streaky variant which appears to become fine-grained in part and has either micaceous bands or pods, rich in cassiterite, within it. Unfortunately sampling has largely been confined to pit heaps. An analysis of the greisen whole rock gave only 0.05% SnO_2 which shows that the cassiterite distribution is sporadic.

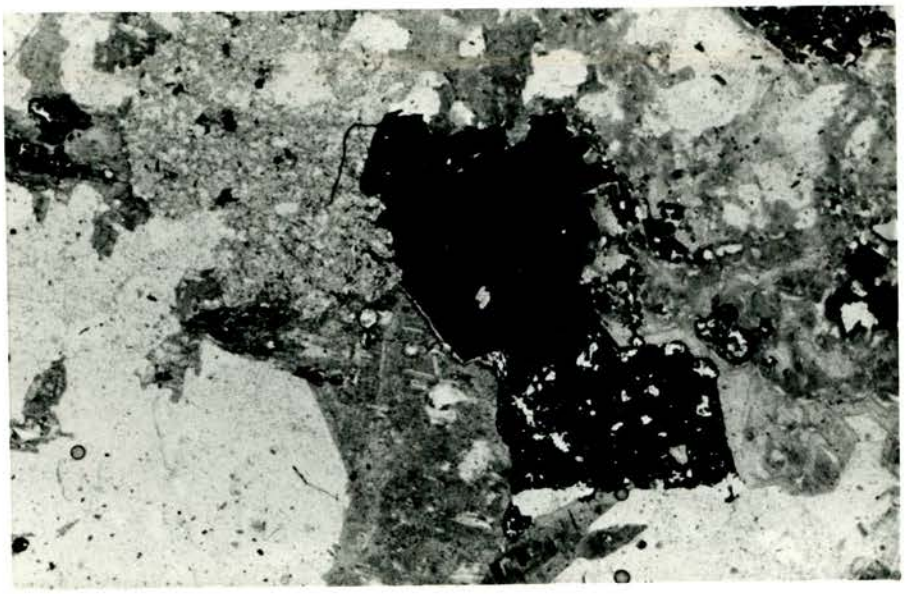
The major element analysis proved very similar to that of a sample collected at locality 117 Ladini. See Appendix 12.

Parts of the fine-grained variant become very sulphide rich with abundant sphalerite and chalcopyrite accompanied by molybdenite in the altered wall rock. Cassiterite also occurs and in thin section is shown to be associated with fine-grained clusters of fine-grained brown or blue-green mica, and fluorite is a common but minor accessory. (Photo 12).

Further down the hillside at locality 113, numerous steeply dipping quartz-mica veins cut the porphyry. The one photographed is 2 cms wide trends 230^{o} and dips 74^{o}. It consists of a central dark micaceous band enclosed by glassy quartz surrounded by a thin selvedge of greisen less than half a centimetre wide on either side. In contrast, a narrower quartz-mica vein only 1 cm thick trending 330^{o} and dipping at 50^{o} has a 2 cm wide greisen selvedge.

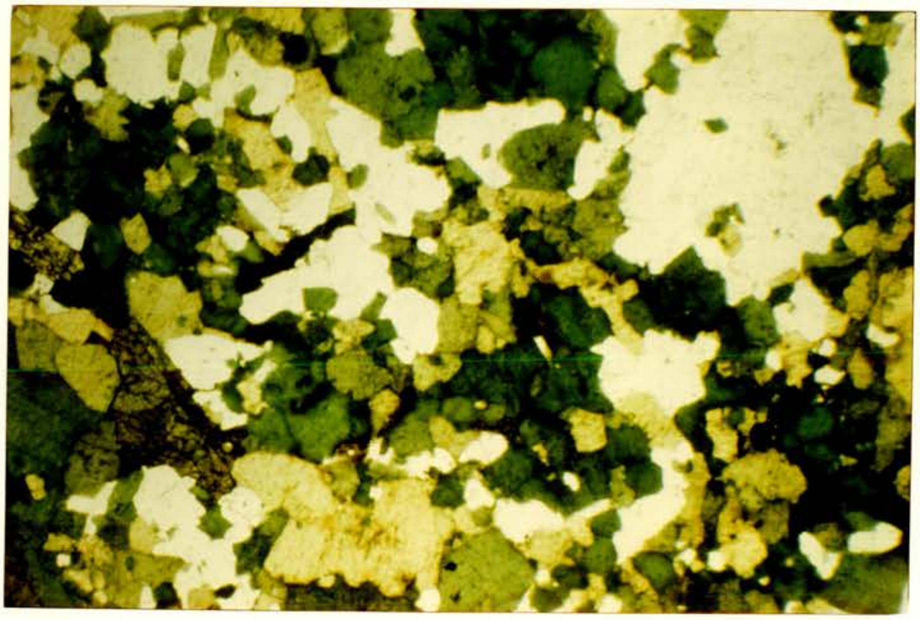
Photograph 12. Locality 113. Quartz-mica vein, 1 cm wide with a 2 cm wide greisen selvedge grading into altered host rock.

Samples from some of the veins in this area show features slightly different from those observed in veins elsewhere. In addition to quartz, mica is extremely abundant; it may be in the form of small sericitic flakes associated with a little fine-grained topaz and quartz, or it may form large white or pale-green flakes with haematite formed along the cleavage traces. Microprobe analyses indicate that both white and pale green varieties are siderophyllite although optically the white mica would appear to be protolithionite. In other specimens the mica is in the form of large brownish-more iron rich-mica, which is undergoing chloritisation. Fluorite is abundant in some specimens and these also show the highest concentration of



Photograph 13. A photomicrograph of a sample from locality 113, Dawa, shows sphalerite, full of inclusions, adjacent to molybdenite (opaque, centre). Cassiterite (top right) is also abundant. The groundmass is composed of blue-green siderophyllite replacing biotite with haematite along the cleavage traces, quartz, fluorite and siderite. x 20.

Photograph 14. Photomicrograph of a greisen from locality 115 Ladini showing cassiterite with blue-green siderophyllite and large quartz grains. x 20.



ore minerals, particularly sphalerite. In addition, siderite has been observed in several thin sections and secondary feldspars, probably adularia, which have grown at a late stage in mineralisation are not uncommon although in other complexes this feature is rare.

Ladini

South and south west of Ladini (Fig. 22) the fine-grained margin of the Rishi biotite granite contains numerous

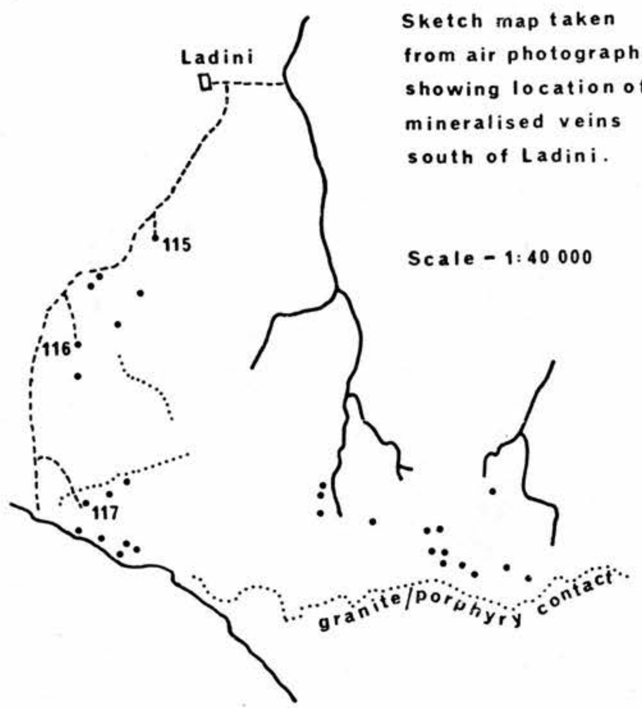


Fig. 22.

mineralised veins which extend into the surrounding aegirine-arfvedsonite porphyry. The majority of the veins have proved to be greisens which are grey and very siliceous, occasionally becoming black in very micaceous segregations. Cassiterite is the only mineral that occurs abundantly.

There is an abundance of these veins as Fig. 22 indicates, and each of these localities may contain many veins. Only a few of these veins have been chosen for detailed description.

At locality 115 a 2 metre wide, light grey, siliceous greisen with a granitic texture trends 230°, parallel to the granite/porphyry contact. Occasionally thick books of siderophyllite reach 5 mm in size, although they are not usually greater than 2 mm. In thin section the mica is blue-green in colour and replaces original brown biotite with haematite along the cleavage traces. Smaller flakes of blue-green second generation siderophyllite do not show brown cores. A few clusters of unaltered brown biotite with interstitial fluorite remain. Quartz is abundant as large anhedral grains with a little interstitial fine-grained topaz. Small rounded cassiterite crystals occur within the micaceous clusters. (Photo 14).

Further south, at locality 116 the east-west trending greisen - also parallel to the granite/porphyry contact - is very similar to that at locality 115 but occurs within porphyry host rock.

Extensive workings expose both a horizontal and a vertical greisen in granite at locality 117. The extent of the greisenisation appears to be due to the flat lying q joints in the granite which have been greisenised as well as the vertical dyke-like form which trends approximately 240°. Generally the greisen is grey and very siliceous, but black micaceous lenses very rich in cassiterite occur. The cassiterite which is strongly zoned and twinned is concentrated in the mica clusters and is occasionally associated with a few small patches of fluorite. In thin section mica from the lenses is blue-green which on analysis proved to be siderophyllite (see Appendix 6), and only a few relics of brown biotite remain. The abundant quartz, which has been completely recrystallised and has a metamorphic texture, forms medium sized anhedral interlocking grains except within the mica clusters where it forms a mosaic of interstitial granules.

The normal grey greisen in thin section has characteristics similar to the one described from locality 115.

It is not possible to determine the thickness of the horizontal greisen although it is known to be at least 1 metre thick. The overlying granite has become very altered and friable for approximately 0.5 metres. Locally however, the upper contact is irregular with no such alteration of the granite. A coarse pegmatite, composed of oligoclase up to 1 cm across, quartz, siderophyllite, genthelvite and rare black crystal clusters of uraninite - 1 mm in size, can be found on the spoil heaps but not <u>in situ</u>. Since the upper contact of the greisen is exposed and there is no evidence of pegmatite at this contact it is presumed that the pegmatite horizon either underlies the greisen or forms pods or lenses within it. It seems possible that there was an accumulation of greisenising fluids along one of the horizontal joint planes, and subsequent migration of these fluids upwards along vertical joints to a higher level would have left a void in which large crystals could grow. Two greisens from this locality were analysed (Appendix 12). One (5 Lad) was light grey in hand specimen and obviously very siliceous, the other (5A Lad) being dark greenish grey, almost black in hand specimen and obviously more mica rich. Thin sections show the light grey sample to be composed of abundant large anhedral quartz with occasional small interstitial topaz grains. The scattered mica flakes are predominantly blue-green and are clearly replacing brown mica with the formation of haematite along cleavage traces. Some brown mica survives and is associated with fine-grained clusters of fluorite. Cassiterite occurs as small rounded grains.

In contrast the dark micaceous greisen contains less quartz and is exceptionally rich in cassiterite. The blue green mica which has a higher RI than the brown mica has virtually replaced the latter. Cassiterite distribution is related to that of the mica and twinned and zoned crystals are found adjacent to mica flakes or within mica clusters. Crystals are generally brown at the centre and colourless at the margin. Analysis of the micaceous greisen showed an SnO_2 content of 0.88% in contrast to the siliceous greisen (5 Lad) above, which contained only 0.14%. Increased mica is reflected in the chemical analyses, which show increased alumina, total iron, potassium and lithium content with a 36% decrease in silica in comparison with the siliceous greisen. A photomicrograph of the micaceous greisen is shown in Photo 14.

It is considered that the light grey siliceous greisen has been affected by silicification which is responsible for the much increased silica content.

Summary

Mineralised veins related to the Rishi biotite granite show a wide variation in size and mineralogy. These mineralised veins contain a mixed assemblage of ore minerals which may include sphalerite, cassiterite, chalcopyrite, galena, pyrite, monazite, greenockite, chalcocite, covellite, genthelvite, phenakite, arsenopyrite, molybdenite and uraninite. All the veins are near the contact between the Rishi biotite granite and earlier rock types and are locally parallel to the contact whether they occur within or outside the granite. In the Dawa area where the veins occur in the porphyries they are believed to be related to the granite at shallow depth.

In the larger veins there does appear to be a crude zonation of ore minerals, with cassiterite marginally deposited and sphalerite and other sulphides centrally placed, although it is also possible to find sphalerite in partially altered host rock. In the smaller veins there appears to be more definite zoning with a dark cassiterite-rich micaceous band enclosing a central quartz vein, both of these being surrounded by a thin selvedge of greisen.

It was originally believed by the writer that each of the mineralised veins was of a distinct type - e.g. quartz-chlorite-biotite, quartz-siderophyllite-topaz or quartz-mica-fluorite, but from the samples that have been taken across the wider replacement veins it appears that each of these variants may occur within one vein without any obvious zonation, and it therefore appears that the host rock was not affected uniformly by the mineralising solutions and that mineralisation has proceeded in several phases.

Of the veins that do appear fairly uniform in composition, the more siliceous, light grey granitic textured greisens ($>80\%$ quartz) are less rich in sulphides, and usually less rich in cassiterite too, than the dark coloured, finer grained less siliceous greisens ($<65\%$ quartz). In the light coloured greisens cassiterite may occur, closely related to mica distribution, and in the extremely mica-rich greisens the cassiterite reaches its highest concentrations.

Minor Areas.

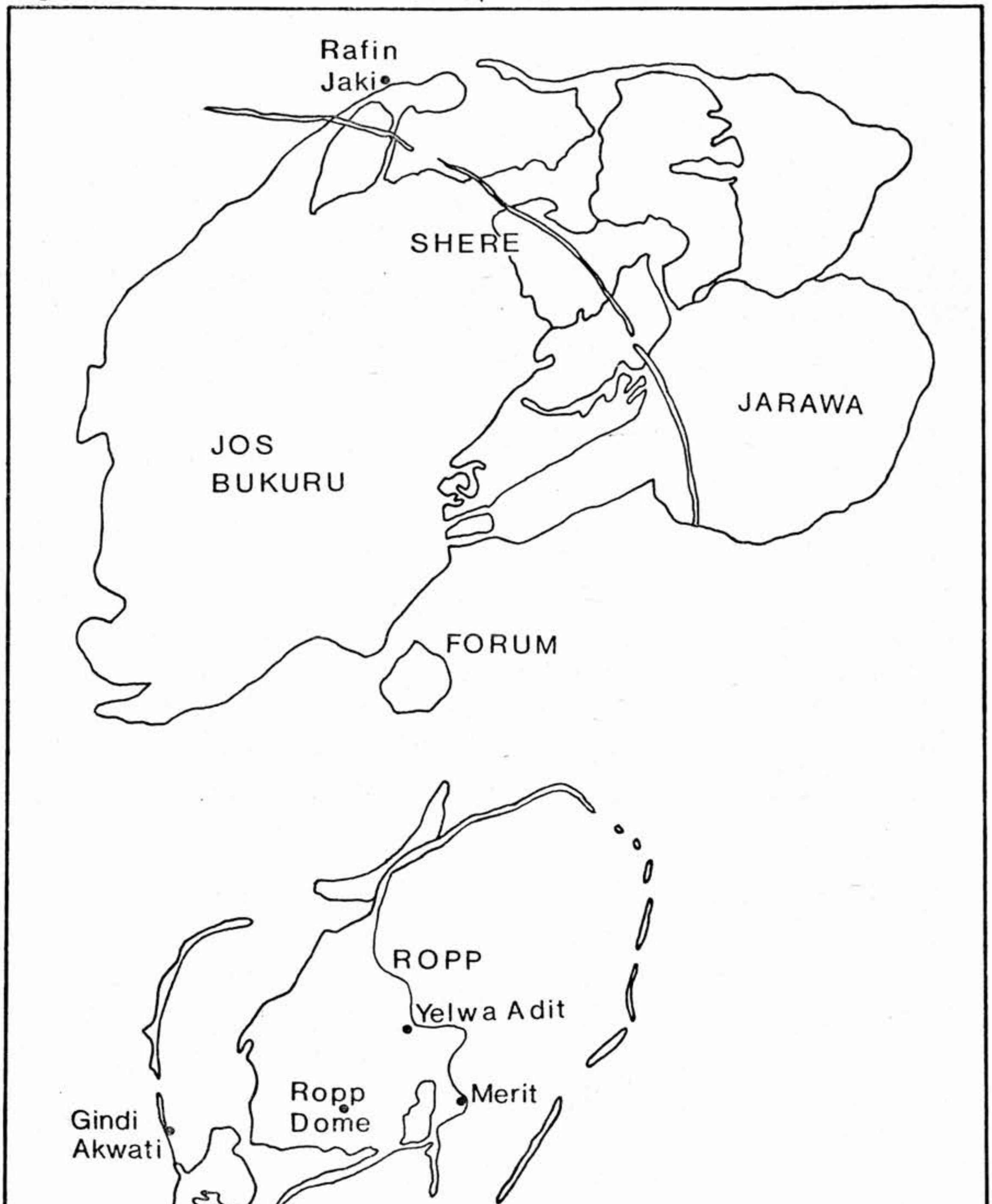
In addition to the areas that have been described from the Liruei and Saiya-Shokobo complexes where mineralised replacement veins occur in abundance, there are numerous widely scattered mineralised veins throughout the Plateau, some of which have been worked for cassiterite.

Mineralised veins in the Bukuru area have already been described in Chapter 2. They proved to be far more abundant than anticipated and further work in some of the other complexes may reveal a similar abundance of mineralised veins. Descriptions of a few vein mineralised localities on the Plateau are included here as an indication of the similarity of these replacement veins to those from a wide area of the younger granite province.

Rafin Jaki

Stockworks in the hills south-east of Rafin Jaki (Fig. 23) can be reached by turning off the main Jos-Bauchi road onto a small bush road between the Bauchi State and Plateau State notice boards. Between the road and main scarp two areas have been worked for primary and alluvial tin - visible tin is coarse grained, + 25 mesh and is black, highly lustrous and commonly twinned.

Fig 23 Location of the minor replacement veins



The stockworks occur at the contact of gneiss and granite porphyry with a later aplite. The aplite trends north-northeast and appears to be $7\frac{1}{2}$ metres wide. It has a granitic texture whilst the earlier porphyry contains phenocrysts of pink feldspar in a finer-grained groundmass.

Silicification and a little greisenisation is apparent along fractures and crystals of cassiterite with a little wolfram can be found at the points of maximum alteration. Thin quartz veins, which do not show a distinct comb structure characteristic elsewhere, may also carry cassiterite. Pyrolusite may be seen forming a brownish black dendritic growth on the fracture surfaces of the aplite and botryoidal malachite also forms a coating on many aplite surfaces although no primary copper minerals were observed by the writer. MacKay _et_ _al_., (1949) record chalcopyrite, bornite and a little galena from this locality.

Jarawa Hills

In the Jarawa granite (Fig. 23), 25 km east-south-east of Jos, Berridge (in Buchanan _et_ _al_., 1971) describes extensive mineralisation with cassiterite, wolfram, molybdenite, helvite and topaz and concludes that the present erosion surface is close to the roof of the intrusion. Extensive mineralisation was not observed in the course of the writer's brief visit, although alteration along joint planes was observed in several localities.

Near Jala village on the west bank of a deeply incised stream, a lenticular pod of altered granite trending 110° follows a prominent joint direction. It can be followed over 40 metres and is on average about 3 metres wide and vertical in attitude.

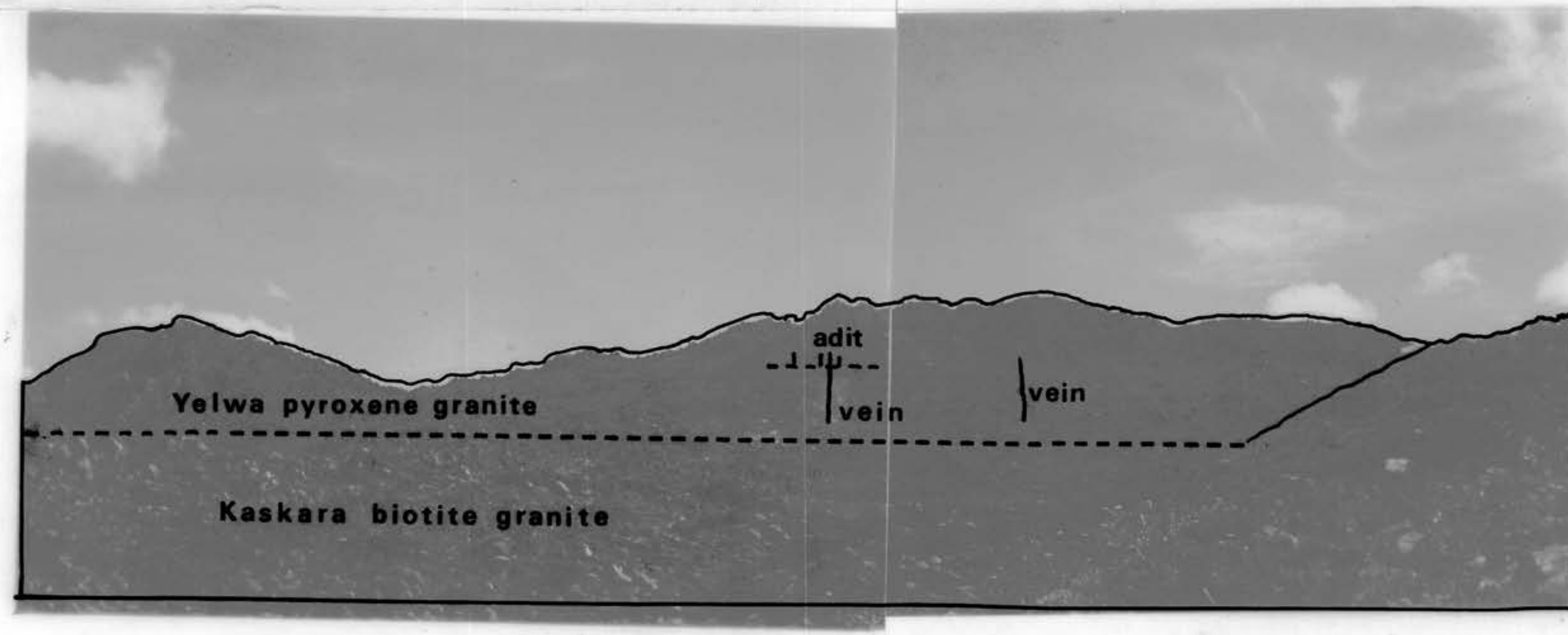
Discontinuous streaks of genthelvite occur parallel or subparallel to the long axis of the replacement body and may be separated by up to a metre of barren quartz. Fine-grained mica is distributed sparsely through the quartz and no other accessory minerals were observed. The genthelvite is dark brownish-red in colour when fresh but tends to be rather rusty and decomposed to a mixture of Fe and Mn oxides. It may occur as an irregular knot up to 2 cm across replacing the quartz or form euhedral crystals 3 mm in size. Weathered hollows with a characteristic triangular cross-section indicate the abundance of genthelvite at this locality. Alteration of the granite along joint planes is limited to the Rudos, Dogon Daji, Zebir and Zundi areas and only in the Rudos area was any primary cassiterite visible. However, coarse alluvial cassiterite is common in the Dogon Daji and Zigam areas.

The greisens visibly consist of quartz, green biotite and topaz. Abundant large water worn pebbles of topaz can be found along the Zebir River.

<u>Ropp Hills</u>

<u>Yelwa adit</u> (Fig. 23).

Replacement veins and alteration along joint planes can be seen in the Yelwa pyroxene granite. The veins are directly related to the underlying sheet of Kaskara biotite granite and the horizontal contact between the two granites can be seen below the adit. The veins do not appear to cross this boundary but can be traced to a few metres above it. See photo 15. The veins are essentially vertical and trend 220°. The broadest of these is 1.5 metres thick and has been mined by adit into the hillside for approximately



Photograph 15. Yelwa adit, with replacement veins cutting Yelwa pyroxene granite. The veins are directly related to the underlying Kaskara biotite granite.

100 metres and several others have been mined for lesser distances.

The fine-grained grey vein has the characteristic quartz veins either marginally or centrally placed and they may be massive or possess a comb structure. The central massive quartz vein is visibly rich in cassiterite and crystals up to 3 mm in diameter were collected. Sphalerite and galena are abundant in the mineralised vein and azurite, molybdenite and malachite occur in small amounts - no primary copper sulphide minerals were observed in hand specimen. However in the host rock marginal to the broadest vein, disseminations of native copper were collected. The largest of these disseminations was 3 mm across and of negligible thickness - the colour was that of a newly minted 'copper' coin.

Locally the veins become very micaceous and there is a corresponding darkening in colour. Pods of almost pure mica are found as infilling towards the centre of the veins.

The host rock has been reddened for a short distance from the veins and reddened joint planes at 320° are common where no veins are apparent.

In thin section one of the veins is shown to be very siliceous with large interlocking quartz grains forming $>80\%$ of the rock. The mica is very pale yellowish brown, pleochroic to almost colourless; aggregates of small plates form clusters which have survived from the original granite. Frequently the cleavage traces are enhanced by haematite. Accessory fluorite occurs within the mica clusters and a euhedral monazite crystal, surrounded by a pleochroic halo occurs in a mica flake.

Ropp Dome

Several small veins occur in a mineralised zone in the Ropp Dome (Fig. 23) area of the Ropp complex. They are found in the Gana biotite granite which is almost identical to the Ngell granite of the Jos complex and is related by Black (1958) to the underlying sheet of Bukka Bakwai biotite granite.

A sample was collected from a vein about 1 km north of Ropp Dome, from a pit where the rock was being worked for tin. The sample is greyish in colour and fine-grained with abundant disseminated cassiterite, pyrite, sphalerite, chalcopyrite and traces of molybdenite and galena. An analysis of the ore content of the sample shows a cassiterite content of 5.47%.

The width of the vein is approximately 30 cm and a central discontinuous zone of mica pods was proving to be cassiterite rich on mining. These micaceous pods appear identical to those described in the Dawa area.

In thin section the vein sample shows abundant sphalerite apparently of two generations; large deep red anhedral patches are abundant and may be surrounded by later small rounded grains or aggregates which are colourless. As in many other veins the feldspar has been completely altered to topaz and sericite with quartz whilst the original quartz remains unchanged. A little brown biotite, occasionally clustered, survives and is pleochroic from medium greenish brown → pale greenish brown → pale green. Accessory fluorite appears to survive from the granite. Whole rock analysis of the sample gave the following results:

SiO_2	57.7%			
TiO_2	0.1			
Al_2O_3	14.1			
total Fe as FeO	4.3		Sulphides	
MnO	0.13	Cu		0.31%
MgO	0.02	Zn		2.82
CaO	0.1	Fe		2.31
Na_2O	0.1	Mn		0.05
K_2O	1.04	Cd		483 ppm
SnO_2	5.47	Pb		77 ppm
H_2O^+	0.56			
	83.62			
Li	170 ppm			
Be	6 ppm			

The low total is due to the sulphur content; an analysis of the sulphides content is shown above.

In comparison with the Rishi vein the alumina content is higher and the total iron content lower despite the amount of pyrite and sphalerite. The increased alumina content can be directly related to the greater proportion of topaz in the Ropp sample and the decreased iron is related to the low percentage of 'original' mica.

Merit/Balfour Hill.

Mineralised fractures and joint planes are found in the Merit area of Balfour Hill (Fig. 23) orientated north-south with very short strike length. They are parallel to the contact between the quartz porphyry and Yelwa pyroxene granite. In colour they are almost white, and apart from a few grains of cassiterite no ore minerals are apparent. In thin section they are seen to consist of very fine grained brown mica which is probably a Li-Fe biotite, quartz and a little topaz.

South of Balfour Hill, north-south orientated quartz veins in basement are locally wolfram and cassiterite rich. The veins in the basement both here and at Tenti lie within 450 metres of granite - similar to the mineralised quartz veins in basement at Rishi. The veinlets and stringers are very narrow and the distribution of cassiterite and wolfram is very uneven. The ratio of cassiterite to wolfram is not known.

Tenti

Black (1958) believes that the walls of the South Ropp/Tenti dyke are extensively mineralised on account of the repeated injection of biotite granite along the fissure. Small quartz stringers carrying cassiterite are found at the contact between the Ruku riebeckite-biotite granite porphyry ring-dyke and the basement.

Summary of Minor Areas

These areas of minor importance, widely scattered, demonstrate how mineralising fluids utilise vertical fractures in the host rock whether the host is basement - e.g. Rafin Jaki-or biotite granite- e.g. Yelwa Adit. At the latter locality it is evident that the replacement veins are related to an underlying granite rather than the host rock. Weir (1974) also describes mineralised veins in the Gindi Akwati area of the Ropp complex which have utilised fractures within the basement. In all these areas the replacement veins are vertical. They may also be parallel to granite/basement contacts except for the Jarawa Hills area where mineralisation appears to be related to the roof of the intrusion.

At all these localities, cassiterite appears the dominant ore mineral of the replacement veins although sphalerite is abundant in the Yelwa Adit and Ropp Dome areas of the Ropp complex. Nowhere, however, has massive sphalerite been found akin to that from the Dutsen Rishi or Liruei areas.

There is no implication intended that as these are the only replacement veins described from a wide area of the Plateau, that these are the only ones to exist. These veins were studied and included as a comparison to the sulphide rich veins of the Rishi area and the Liruei complex. Replacement veins are known to exist in the Sara-Fier and Sha-Kaleri complexes and probably also in the Ganawuri and other complexes, but sufficient areas had been examined to provide a basis for an understanding of the processes involved in mineralisation. Also it is unlikely that a major lode is yet to be discovered at the surface.

Summary of Conclusions.

During late Precambrian, geosynclinal deposits were laid down in Central Nigeria on a crystalline complex probably at least 2,000 my in age. Two successive phases of deformation and metamorphism, with migmatisation and reactivation of the crystalline complex and metasediments, resulted in a suite of orogenic granites (the older granites).

Dextral wrench faulting and north-south upwarping during the Lower Palaeozoic was followed by extensive erosion during the Upper Palaeozoic.

The anorogenic Jurassic granites of Central Nigeria (the Younger granites), which were intruded at a high level, form over 40 individual complexes which are concentrated in a 200 km wide north-south zone. This zone is structurally controlled by the main Pan-African trends in the basement and is aligned with the zone along which crustal separation of southern Africa and South America took place in Mesozoic times. Chronological evidence confirms a sequential age trend from mid-Palaeozoic for Aïr in northern Niger to late Jurassic for Afu in the south of Nigeria.

The Jurassic granites belong to two related but sequential evolutionary trends which are thought to have evolved from a syenitic or more basic parental magma. The early alkaline trend is characterised by granites containing the iron-soda minerals aegirine, riebeckite, aenigmatite and arfvedsonite. The agpaitic index is > 1 and ac and occasionally ns appear in the norm. In contrast the late auminous trend is characterised by granites containing the iron-calcium-alumina-minerals, hastingsite and biotite. Cassiterite and columbite are related to the latter. The agpaitic index is < 1 and c and an appear in the norm.

A series of sediments and tholeiitic lavas were laid down over a wide area of the Plateau, probably during mid Tertiary, and these were followed by the extrusion of alkali basalts of Quaternary age (newer basalts).

This succession was examined in part of the Jos-Bukuru Complex, west of Bukuru, first on aerial photographs and then on the ground. The air photographs, at a scale of 1:10,000, were used to make a base map, to draw a preliminary geological map and to select areas for ground examination. Areas covered by basalt and Tertiary sediments proved readily identifiable on the air photographs and whilst some of the Jurassic granites could also be identified in small outcrops it was only found possible to distinguish some differences when two granites are in contact. Areas underlain by basement rocks could sometimes be mapped, especially if they were granitic. The photography proved a useful aid to locating ore-bearing veins. Whilst individual veins could not be recognised on air photographs, potential areas containing mineralised veins could be located in some granites as areas which showed an unusually close pattern of joints.

In the Bukuru/Ngell valley area the Basement was shown to include granitic gneiss, porphyritic hornblende-biotite granite and fine-grained muscovite granite with no ore mineralisation.

The Jurassic granites which were intruded into these rocks ca. 165 my ago show sharp contacts and rapidly cooled margins against the older rocks. They are richly mineralised with columbite and cassiterite. Small amounts of columbite are dispersed through all the granites but galena, in mineralised veins which cut the granites. It is postulated in this work that the biotite granites which had previously been divided into a number of separate intrusions are variants related to two major intrusive phases and that the mineralisation is related to marginal and roof zones within these intrusions. It is further concluded that the Jos-Bukuru and Ropp complexes may belong to the same batholith at shallow depth thus offering an explanation for the similarities between sequence of intrusions and comparative abundance of mineralisation.

A period of erosion and deposition during the Tertiary followed the intrusion of these granites. Remnant mesas of this series are composed of fluviatile sedimentary rocks of which the basal sandstone is rich in derived cassiterite.

Two alkali basalts were extruded in Recent times after the Plateau had more or less reached its present day topography and the flows infilled broad, shallow valleys, thus burying tin rich sediments. The flows have also preserved thick Quaternary sediments which are partly fluviatile and partly lacustrine in origin and also contain cassiterite and columbite.

Mineralisation studies completed in the Bukuru/Ngell valley area were continued in the Ropp and Saiya Shokobo complexes and led to a more detailed investigation of mineralisation in other rock types.

It is concluded that the peralkaline granites have only one dispersed phase of mineralisation. This is thought to be due to the retention of water and volatiles by a peralkaline magma until late stages when a residual liquid separates and modifies the partially crystalline

In contrast there are two distinct stages of mineralisation related to the cooling and consolidation of biotite granites; an early dispersed (apogranitic) phase and a later metasomatic replacement-vein forming stage.

The development of columbite in the Younger Granite Province is related to the apogranitic stage, which is a late-magmatic, pre-joint phase of mineralisation. Re-crystallisation, effected by a new growth of microcline and albite, is accompanied by an introduction of xenotime, thorite, and hafnium and uranium rich zircon. Only three areas are known to have enhanced columbite values and samples collected from two of these areas showed a varying Nb_2O_5 content from less than 30 ppm to over 2,500 ppm with high ThO_2 values in those samples with an elevated Nb_2O_5 content. In general, columbite mineralisation is not accompanied by an extensive precipitation of cassiterite.

In contrast with the apogranitic phase, the replacement vein mineralisation is post-magmatic and predominantly post-jointing. The veins consist of quartz, Li-Fe or Li-Al biotite, topaz and/or fluorite. In addition to a high cassiterite content in some of the veins, a mixed assemblage of any of the minerals sphalerite, chalcopyrite, galena, pyrite, monazite, greenockite, chalcocite, covellite, native copper, genthelvite, phenakite, arseno-pyrite, molybdenite, bismuthinite and uraninite may occur. These veins have been studied in detail in a number of complexes and it is concluded that sphalerite is the most abundant ore mineral, followed by cassiterite and chalcopyrite, whilst the other ore minerals are found in much lesser amounts. Further it is concluded that these veins are generated by biotite granite magmas and may be found in basement, pyroxene or fayalite granite and riebeckite porphyry which surrounds or overlies biotite granite. Veins are only abundant, however, in medium to fine-grained biotite granites.

Within these replacement veins there are definite stages of alteration affecting the host rocks. During argillic alteration, which is the first phase, there is a partial alteration of feldspars to clay minerals. This is followed by chloritic alteration when the original biotite of the host rock is chloritised and a massive input of fluorine may introduce a complex assemblage of sulphide ores in addition to some cassiterite. This is the main phase of ore deposition. During sericitic alteration, which follows the minor chloritic alteration, sericite is formed as a result of feldspar breakdown or by hydrogen ion metasomatism of the chloritic mica, and only minor amounts of ore minerals occur, usually sphalerite or galena. Greisenisation postdates this phase and is characterised by the development of new alumina minerals (topaz and siderophyllite or protolithionite) in association with quartz and the disappearance of sericite. Cassiterite is the only ore mineral common in the greisen-stage of vein formation. Finally, silicification may affect the veins formed by the previous stages, or there may be a development of quartz fissure fillings, sometimes with cassiterite and occasionally with wolframite and sphalerite.

The Liruei lode is the largest mineralised body in the Younger granite province and as such has received most attention. It is rich in sphalerite and cassiterite and contains up to 2% of zinc and 0.5% of Sn. Chalcopyrite and galena occur widely whilst bismuthinite, molybdenite, and wolframite are also recorded. Despite localised concentration of certain ores there is no apparent zonation of ores either along the strike or at depth.

Within the Saiya-Shokobo complex the Rishi biotite granite covers an area of approximately 12.5 km^2. Mineralised replacement veins related to this granite are abundant and show a wide variation in size and mineralogy. All the veins are near the contact between the Rishi biotite granite and earlier rock types and are locally parallel to the contact whether they occur within or outside the granite. In the Dawa area where the veins occur in porphyries they are believed to be related to the granite at shallow depth.

Other areas of minor importance which are widely scattered demonstrate how mineralising fluids utilise fractures in the host rock whether the host is basement or Jurassic granite. In some cases it seems likely that the veins in one biotite granite have been generated by the intrusion of a later biotite granite phase emplaced at deeper levels (e.g. Liruei). This mechanism may account for the distribution of the veins that appear to have no definite spatial relationship to the host rock.

It is concluded therefore that whilst the sequence of mineralisation in central Nigeria has its analogues elsewhere in the world the style of mineralisation is rather different. The sequences of alteration during mineralisation are the reverse of those described by Stemprok for the Bohemian massif. The degree of sericitic alteration in Nigeria in comparison with other provinces is very weak, and furthermore the advanced argillic and prophylitic stages of alteration recorded in other regions does not seem to occur in the Nigerian setting. These contrasts may be fundamentally related to the tectonic environment, source and origin of the magmatic liquids and residual fluids.

Bibliography.

Alderton, D.H.M., Halliday, A.N., Jackson, N.J., Sheppard, S.M.F. 1976. The Evolution of the Cornubian Metallogenic Province, South-West England. In preparation.

Bailey, D.K., Shairer, J.K. 1966. The system Na_2O-Al_2O_3-Fe_2O_3-SiO_2 at 1 atmosphere and the petrogenesis of alkaline rocks. J. Petrol. 7, p. 114-170.

Bain, A.D.N. 1934. The Younger Intrusive Rocks of the Kudaru Hills, Nigeria. Q. Jl. geol. Soc. Lond., 90, p. 201-239.

Baumann, L. 1976. An Introduction to Ore Deposits. Scottish University Press.

Black, R. 1958. The Geology of the Rop Complex, Northern Nigeria. Unpubl. Ph.D. thesis. Univ. of Aberdeen.

Black, R. 1960. Rapport provisoire sur les Younger Granites de la région Zinder Gouré. Paris: Bureau des Récherches Geologiques et Minieres.

Black, R. 1965. Sur la signification pétrogénetique de la découverte d'anorthosites associées aux complexes annulaires sub-volcaniques du Niger. C.R. Acad. Sc. Paris 260, p. 5829-5832.

Black, R., Girod, M. 1970. Late Palaeozoic to Recent Igneous Activity in West Africa and its relationship to Basement structure. In: "African Magmatism and Tectonics", Eds. T.N. Clifford and I.G. Gass, p. 185-210. Oliver & Boyd, Edinburgh.

Bonin, B. 1973. Le Complexe Granitique subvolcanique de la région de Tolla Cauro (Corse) Ecole Normale Superieure.

Bowden, P. 1970. Origin of the Younger Granites of Nigeria. Contr. Mineral and Petrol. 25, p. 153-162.

Bowden, P., Breemen, O. van. 1970. Isotopic and Chemical Studies on Younger Granites from Northern Nigeria. in Proceedings on the Conference on African Geology. Dec. 1970.

Bowden, P., Breemen, O. van., Hutchinson, J., Turner, D.C. 1976. Palaeozoic and Mesozoic Age Trends for Some Ring Complexes in Niger and Nigeria. Nature, 259, No. 5541, p. 297-299.

Breemen, O. van. Bowden, P. 1973. Sequential Age Trends for Some Nigerian Mesozoic Granites. Nature Physical Science 242, No. 114, p. 9-11.

Breemen, O. van Hutchinson, J. Bowden, P. 1975. Age and Origin of the Nigerian Mesozoic Granites: A Rb-Sr Isotopic Study. Contrib. Mineral. Petrol. 50, p. 157-172.

Breemen, O. van Pidgeon, R.T. Bowden, P. Age and Isotopic Studies of some Pan-African Granites and Related Rocks, North Central Nigeria. (In press).

Buchanan, M.S. MacLeod, W.N. Turner, D.C. 1971. The Geology of the Jos Plateau volume 2 Younger Granite Complexes. Bull. Geol. Surv. Nigeria 32.

Burnham, C.W. 1967. Hydrothermal fluids at the magmatic stage. in "Geochemistry of Hydrothermal Ore Deposits" Ed. H. Barnes, p. 36-76. Holt, Reinhart and Winston, New York.

Burnham, C.W. Jahns 1962 A method for determining the solubility of water in silicate melts. Am. J. Sci. 260, p. 721-745.

Deer, W.A. Howie, R.A. Zussman, J. 1965. An Introduction to the Rock Forming Minerals. Longmans.

Dent-Young, D. 1974. Tin and Nigeria. Unpubl. Paper for Amalgamated Tin Mines (Nigeria).

Dixey, F. 1949. The Morphology of the Jos Plateau in "The Geology of the Plateau Tinfields" by R.A. Mackay , R. Greenwood and J.E. Rockingham. Bull. 19, Geol. surv. of Nigeria.

Falconer, J.D. 1911. The Geology and Geography of Northern Nigeria. London, McMillan & Co.

Falconer, J.D. 1926. The Southern Plateau Tinfields and the Sura Volcanic Line. Bull. No. 9. Geol. Surv. of Nigeria.

Grant, N.K. 1969. The late Precambrian to early Palaeozoic Pan-African orogeny in Ghana, Togo, Dahomey and Nigeria. Bull. Geol. Soc. Am. 80, p. 45-56.

Grant, N.K. Rex, D.C. Freeth, S.J. 1972. K-Ar ages and Sr isotope ratio measurements from volcanic rocks in Northeastern Nigeria. Contr. Mineral. and Petrol. 35, p. 277-292.

Grant, J.N. 1976. Igneous Geology and Evolution of Hydrothermal Systems in sub-volcanic deposits of Bolivia (in press).
Halls. C.
Avila, W.
Avila, G.

Greenwood, R. 1951. Younger Intrusive Rocks of Plateau Province, Nigeria Compared with the Alkalic Rocks of New England. Bull. Geol. Soc. Am. 62, p. 1151-1178.

Grüner, 1944. The hydrothermal alteration of feldspars in acid solution between 300-400°C. Econ. Geol. 39, p. 578-589.

Haag, H.L. 1943. Wolfram in Nigeria: With notes on cassiterite, wolfram and columbite. Trans. Inst. Min. Metall. lii.

Hesp, W. 1974. Geochemical Features of Sn-Ta-Nb Mineralization Associated with Granitic Rocks in South-Eastern Australia.

Jacobson, R.R.E. 1947. The Younger Granite Complex of the Liruei Hills, Nigeria. Unpubl. thesis Univ. of London.

Jacobson, R.R.E. 1958. Ring Complexes in the Younger Granite Province of Northern Nigeria. Mem. Geol. Soc. Lond. No. 1.
MacLeod, W.N.
Black, R.

Jacobson, R.R.E. 1963. Age determinations in the geology of Nigeria with special reference to the Older and Younger Granites. Overseas Geol. Miner. Resour., 9, p. 168-182.
Snelling, N.J.
Truswell, J.F.

Kogarko, L.N. 1974. Liquid Fractionation in "The Alkaline Rocks". Ed. H. Sørensen p. 488-499. John Wiley, New York.
Ryabchikov, I.D.
Sørensen, H.

Kogarko, L.N. 1974. Role of Volatiles in "The Alkaline Rocks". Ed. H. Sørensen p.474-487, John Wiley, New York.

Koster, van Groos, A.F. 1965. The system $NaAlSi_3O_8$-NaCl-H_2O at 1 Kb pressure. Abstr. Trans. Am. Geophy. Union, 46, 179-180.
Wyllie, P.J.

Kovalenko, V.I. 1968. On the Chemical Composition Properties and Mineral Paragenesis of Riebeckite and Arfvedsonite. I.M.A. Volume 1966, p. 261-284.

Krauskopf, K. 1967. Geochemistry. McGraw-Hill, Chapter 15.

Kukal, Z. 1971. Geology of Recent Sediments. Academic Press, London & New York.

Lange, H.L., Tischendorf, G., Pälchen, W., Klemm, I., Waltraut, O. 1972. Zur petrographie und geochemie der granites des Erzgebirges - Fortschritte der Metallogenie in Erzgebirge, B. Geologie, 21, p. 457-493.

Leopold, L.B., Wolman, M.G. 1957. River channel patterns; braided, meandering and straight. U.S. Geol. Surv. Profess. Papers, 282B, p. 39-85.

Luth, W.C., Tuttle, O.F. 1969. The hydrous vapour phase in equilibrium with granite and granite magmas. Poldervaart Memorial Volume. Geol. Soc. Am. Mem. 115, p. 513-548.

MacKay, R.A., Beer, K.E. 1952. The albite-riebeckite granites of Nigeria. Geol. Surv. of Britain Atomic Energy Division. Report No. 95, p. 1-95.

MacKay, R.A., Greenwood, R., Rockingham, J.E. 1949. The Geology of the Plateau Tin-fields. Resurvey 1945-1948. Geol. Surv. of Nigeria Bull. 19.

MacLeod, W.N. 1952. Unpubl. report Geol. Surv. of Nigeria.

MacLeod, W.N. 1956. The Geology of the Jos-Bukuru Complex with particular reference to the distribution of columbite. Rec. Geol. Surv. Nigeria 1954, p. 17-34.

MacLeod, W.N., Turner, D.C., Wright, E.P. 1971. The Geology of the Jos Plateau, Vol. 1 General Geology. Geol. Surv. of Nigeria, Bull. 32.

McCurry, P. 1971. Pan-African Orogeny in northern Nigeria. Bull. Geol. Soc. Am. 82, p. 3251-3262.

McCurry, P. 1973. Geology of Degree Sheet 21 Zaria, Nigeria. Overseas Geol. Min. Res. 45, HMSO.

Masson-Smith, D. 1965. Geophysical prospecting for basalt covered alluvial cassiterite on the Jos Plateau - Northern Nigeria. Overseas Geol. Surv. London Geophys. Rep. No. 27.

Meyer, C., Hemley, J.J. 1967. Wall rock alteration, in "Geochemistr of Hydrothermal Ore Deposits" Ed. H. L. Barnes, p. 166-235, Holt, Rein-

Naidu, A.S. Borreswara, R.C. 1965. Some Aspects of the Lower Godavari River and Delta Sediments. India Bull. Am. Ass. Petrol. Geol. 49, 35A, Abstr.

Nockolds, S.R. Richey, J.E. 1939. Replacement veins in the Mourne Mountain granites, Northern Ireland Am. Journ. Sci. 237, No. 1, p. 27-47.

Park, C.F. MacDiarmid, R.A. 1975. Ore Deposits. W.H. Freeman, San Francisco & London.

Roedder, E. Coombs, D.S. 1967. Immiscibility in granitic melts, indicated by fluid inclusions in ejected granitic blocks from Ascension Island. J. Petrol. 8, p. 417-451.

Sales, R.H. Meyer, C. 1949 Wall rock alteration at Butte, Montana: Am. Inst. Min. Engr. Trans. 178, p. 9-35.

Shaw, S.H. 1951. Report on magnetic and Resistivity Work in the Plateau Tinfield. Unpubl. Rep. Overseas Geol. Surv. London.

Sillitoe, R.H. Halls, C. Grant, J.N. 1975. Porphyry tin deposits of Bolivia. Econ. Geol. 70, No. 5, p. 913-927.

Snelling, N.J. 1964. Annual Report. Overseas Geol. Surv 1963. Age Determination Unit, p. 30-40.

Snelling, N.J. 1965. Annual Report. Overseas Geol. Survs 1964. Age Determination Unit, p. 28-38.

Štemprok, M. 1976. Suggestions for the classification of tin, tungsten and molybdenum deposits of the plutonic type. Unpubl. paper.

Stringham, B. 1953. Granitization and Hydrothermal Alteration at Bingham, Utah. Bull. Geol. Soc. Am. 64, p. 945-992.

Taylor, J. 1961. Investigations of the Economic Potentialities of Danalite-Genthelvite. Occurrences in Northern Nigeria. Geol. Surv. of Britain Atomic Energy Div. Rept. No. 231.

Taylor, R.G. 1972. The Relationship Between Structure and Ore Body Type in the Ardlethan Tinfield New South Wales. Econ. Geo 67, p. 116-118.

Taylor, R.G.
Stevenson, B.G. 1972. An analysis of Metal Distribution and Zoning in the Herbeton Tinfield North Queensland, Australia. Econ. Geol. 67, 1972, p. 1234-1240.

Tugarinov, A. 1965. Age absolu et particularites genetiques des granites du Nigeria et du Camerous Septentrional. Prob. of Symposium on Granites of West Africa. In "Granites of West Africa", UNESCO Vol. VIII, 1968, Paris.

Turner, D.C. 1974. Structure and Petrology of the Younger Granite Ring Complexes Ahmadu Bello University Unpubl. paper.

Tuttle, O.F.
Bowen, N.L. 1958. Origin of granite in the light of experimental studies in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O. Geol. Soc. Am. Mem. 74.

Vachette, M. 1964. Essai de synthèse des determination d'âges radiometrique de formations cristallines de l'Ouest Africain (Côte d'Ivoire, Mauritanie, Niger). Ann. Fac. Sci. Clermont Ferrand Vol. 25, Sér Geol. 8.1.

Varlamoff, N. 1972. Central and West African Rare-Metal Granitic Pegmatites, Related Aplites, Quartz Veins and Mineral Deposits. Mineralium Deposita 7, No. 2, p. 202-216.

Webb, P.K. 1974. Roof modifications of a high level granite, Jos-Bukuru Younger Granite Ring Complex, Nigeria. Geol. Mag. Vol. III No. 1, Jan. 1974.

Weir, J. 1974. The Geochemistry and Mineralisation of the Younger Granites at Dress, Ropp Complex, Northern Nigeria. Unpubl. Honours Research Essay Univ. of St. Andrews 1974.

Williams, F.A.
Meehan, J.A.
Paulo, K.L.
John, T.U.
Rushton, H.G. 1956. Economic Geology of the Decomposed Columbite Bearing Granites, Jos Plateau. Econ. Geol. 51, No. 4, p. 303-332.

Wright, J.B. 1970. Controls of Mineralisation in the Older and Younger Tin Fields of Nigeria. Econ. Geol. 65, p. 945-951

Wright, J.B. 1972. Tholeiite from the Cenozoic Alkaline Volcanic Province of Nigeria. Geol. Mag., 109 (3), p. 243-246.

Wyllie, P.J. Tuttle, O.F. 1961. Experimental investigation of silicate systems containing two volatile components. Am. Jl. Sci. 259, p. 189-191.

Appendix 1 — Determination of Tin in Decomposed Mineralised Granites by Atomic Absorption Spectrophotometry.

Summary

This is a rapid technique in which the rock is dried, powdered, and a portion heated with ammonium iodide. The volatile tin iodide sublimes and the sublimate is dissolved in dilute hydrochloric acid. The solution is sprayed directly into the A.A. Spectrometer.
This method has a detection limit of 20ppm Sn.

Method

Break up the rock sample into small chunks and place in a flat vessel for drying. Heat the broken sample in an oven at 120°C for about 2 hours, or until dry.

Powder down the dry material to approximately 200 mesh in a TEMA mill, mix well and bottle.

Weigh out approximately 1g. accurately and transfer to a dry 180 x 18 mm Pyrex test tube by means of a funnel. One gram of ammonium iodide is added and mixed with the powder using a long spatula.

Stopper the test tube with a one-holed rubber bung and heat the end of the tube in the flame of a bunsen or Meker burner. The tube should be moved in and out of the flame, with occasional shaking to promote an even gentle heating.

The volatile components vapourise and condense on the cooler parts of the tube. When the activity cases the test tube is allowed to cool.

Pipette 10 mls of 1M hydrochloric acid into the test tube and shake to dissolve the sublimate.

Stopper the test tube and immerse it into a bath of water at 60-70°C for an hour to ensure complete dissolution.

Shake the test tube to homogenise the solution and allow the sediment to settle.

The supernatant liquid is then sprayed into the A.A. Spectrometer and the results compared to a range of tin standard solutions.

The working range is 5 µg/ml - 200 µg/ml. Sn.

Determination of Niobium in Decomposed Granites by X-Ray Fluorescence.

Summary

This is also a fairly rapid method in which the sample is prepared and pelleted for XRF.

Method

a) Initial Preparation: The rock sample is crushed into small chunks and placed in a flat tray for drying. The sample is heated in an oven at 120°C for at least 6 hours to ensure dryness.

The dry material is then powdered down to approximately 200 mesh in a Tema mill, mixed well and bottled.

A pellet is then prepared for the XRF process in the following way.

b) Disc preparation: The pellet press which is used in this process consists of a base, an evacuatable die, 2 stainless steel discs, one stainless steel ram, a soft iron ram and a perspex collar. The base die are fixed together and one of the steel discs is placed in the bottom of the dish. A large teaspoon of boric acid crystals are placed in the die and a cup-shaped impression is formed in the crystals by using a soft metal ram to a pressure of 2000 lb per sq. inch in a metallurgical press.

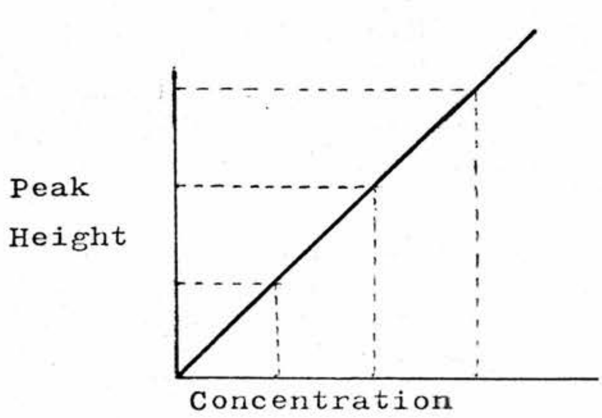
2.7 grms of the sample powder of approximately 200 mesh are weighed out. The weighed powder is transferred to a mortar and two drops of distilled water are added to assist in binding the powder. This water is then evenly distributed throughout the powder and the powder transferred to the die. Care is taken to ensure that the powder is enclosed within the boric acid 'cup'.

The second steel disc and steel ram are now added in the die. The powder is compressed in 30 ton press to a pressure of 20 tons for approximately 10 seconds, with a vacuum pump evacuating the dye during compression. The pressure is gradually released.

The die is removed from the press, inverted and the base removed. The perspex collar is placed over the bottom disc and slowly pressure is applied by the metallurgical press, ensuring that the ram and the discs are in position.

The two discs and the pellet will emerge from the top of the die.

c) XRF procedure: The pellet is passed through the XRF, under optimum conditions, and the peaks displayed on a recorder. The peak heights are then calculated from the print out and plotted on a graph of concentration/peak height, which has previously been calibrated using three standards.



Appendix 3.

Chemical Analysis of Hastingsite
from Vom hastingsite-biotite granite

SiO_2	38.08
Al_2O_3	7.67
Fe_2O_3	6.41
FeO	28.81
MgO	1.09
CaO	9.45
Na_2O	1.85
K_2O	1.52
H_2O^+	0.65
H_2O^-	nil
TiO_2	2.23
P_2O_5	nil
Cl	1.98
F	0.58
MnO	0.54
	100.86
Less O	0.69
	100.17

Formula calculated to 23O

Si	6.274	8.000
Al	1.489	
Ti	0.237	
Al	-	5.000
Ti	0.039	
Fe'''	0.818	
Fe''	3.876	
Mn	-	
Mg	0.267	
Ca	1.668	2.747
Na	0.590	
K	0.320	
Mn	0.075	
Fe''	0.094	

Analyst: Mrs. G. Borley (Borley and Frost 1973).

Appendix 4.

Chemical Analyses and Norms

of some of the granites

	1	2	3	4	5
SiO_2	74.36	74.36	73.48	76.19	74.52
Al_2O_3	12.44	12.40	13.10	13.51	13.55
Fe_2O_3	0.62	1.10	0.72	0.43	0.46
FeO	1.81	1.83	1.79	0.61	1.03
MgO	0.15	0.09	0.21	0.08	0.10
CaO	0.33	0.84	0.49	0.10	0.12
Na_2O	3.83	3.71	4.23	4.23	4.98
K_2O	5.31	4.94	5.19	4.61	4.03
H_2O^+	0.38	0.30	0.35	0.13	0.29
H_2O^-	0.04	n.d.	0.03	0.15	0.24
CO_2	0.14	-	0.06	0.01	0.03
TiO_2	0.16	0.17	0.16	0.04	0.02
ZrO_2	n.d.	0.03	n.d.	0.04	0.18
P_2O_5	0.01	n.d.	0.03	tr	tr
Cl	0.03	0.13	0.03	0.02	0.01
F	0.18	0.13	0.20	0.22	0.16
S	0.01	-	0.01	0.02	0.01
MnO	0.06	0.06	0.06	0.01	0.02
	99.86	99.96	100.14	100.40	99.75
Less O	0.09	0.05	0.09	0.09	0.07
Total	99.77	99.91	100.05	100.31	99.68
Q	29.79	31.28	26.76	33.31	29.05
or	31.40	29.17	30.67	27.22	23.83
ab	32.41	31.42	35.77	35.77	42.16
an	1.06	2.59	1.45	0.50	0.58
C	-	-	-	1.39	0.79
ac	-	-	-	-	-
di	0.34	1.23	0.68	-	-
hy	2.84	1.86	2.70	0.91	1.75
mg	0.90	1.60	1.04	0.63	0.67
il	0.30	0.32	0.30	0.07	0.05
ap	0.03	0.07	0.07	-	-

	6	7	8	9	10	11
SiO_2	73.2	70.4	75.5	70.1	75.4	76.5
Al_2O_3	14.18	16.69	13.48	16.98	13.25	12.38
Fe_2O_3	0.67	0.90	0.59	0.78	0.08	0.12
FeO	1.19	1.74	0.84	1.65	1.33	1.28
MgO	0.08	0.18	0.06	0.10	0.02	0.02
CaO	0.73	0.83	0.47	0.72	0.50	0.56
Na_2O	3.45	3.46	3.26	3.57	3.50	2.97
K_2O	5.32	5.34	4.74	5.56	5.03	4.95
H_2O^+	0.41	0.31	0.29	0.26	0.19	0.24
H_2O^-	0.10	0.10	0.07	0.05	0.04	0.11
TiO_2	0.18	0.24	0.18	0.26	0.15	0.17
P_2O_5	0.03	0.04	0.00	0.03	0.02	0.00
MnO	0.02	0.03	0.01	0.03	0.02	0.01
	99.56	100.26	99.49	100.09	99.53	99.31

	12	13
SiO_2	70.05	75.52
TiO_2	0.26	0.18
Al_2O_3	16.98	13.48
Fe_2O_3	0.78	0.59
FeO	1.65	0.84
MgO	0.10	0.06
MnO	0.03	0.01
CaO	0.72	0.47
Na_2O	3.57	3.26
K_2O	5.56	4.74
P_2O_5	0.03	0.01
P_2O^+	0.26	0.29
P_2O^-	0.05	0.07
	100.04	99.52

Li	130 ppm	283
Rb	280	441
Sr	47	12
Y	44	
Zr	275	250
Cu	130	
Zn	124	
Pb	33	
U	22	
Th	22	

1. Shen hornblende fayalite granite - Jos-Bukuru Complex. Analyst D.J.O'Leary (MacLeod 1971).
2. Vom hornblende-biotite granite Jos-Bukuru Complex. Analyst Mrs. M. H. Kerr (MacLeod 1971).
3. Jos Biotite granite - Jos-Bukuru Complex. Analyst D.J.O'Leary (MacLeod 1971).
4. Rayfield-Gona biotite-granite, Jos-Bukuru Complex. Analyst G. Jefford (MacLeod 1971).
5. Altered Rayfield Gona biotite-granite. Analyst G. Jefford (MacLeod 1971).

6-12 Jos Biotite granite - Jos-Bukuru Complex. Analyst R. Batchelor.

13. Ngell Biotite granite - Jos-Bukuru Complex. Analyst R. Batchelor.

Analysis of the micas from some of the granites.

	1	2	3	4	5 (dark greenish brown / red brown)	6	7 (opaque to straw yellow)
SiO_2	35.94	33.10	35.36	30.72	35.14	37.58	37.38
Al_2O_3	11.71	9.77	10.90	11.54	6.44	15.43	11.89
Fe_2O_3	5.00	12.19	3.76	11.62	4.40	4.96	4.38
FeO	23.91	24.48	31.38	26.49	34.92	25.00	28.65
MgO	6.35	1.95	1.06	0.15	0.43	0.32	0.22
CaO	1.65	2.37	n.d.	1.70	0.97	1.15	0.16
Na_2O	0.42	0.41	0.97	0.44	0.74	1.67	0.39
K_2O	6.95	5.43	9.04	4.35	8.92	7.34	8.78
H_2O^+	4.15	5.55	3.74	8.27	3.12	-	1.84
H_2O^-	0.03	1.94	n.d.	0.27	0.06	0.52	0.67
TiO_2	3.33	2.96	3.04	3.04	2.87	1.42	1.84
P_2O_5	nil	nil	nil	0.06	0.03	tr.	n.d.
F	n.d.	n.d.	n.d.	n.d.	n.d.	2.01	4.36
MnO	0.50	0.64	0.65	0.64	0.53	0.20	0.41
Li_2O	n.d.	n.d.	n.d.	n.d.	n.d.	-	0.77
	99.94	100.55	99.90	99.29	101.04	101.85	97.60
Less O					1.04	1.86	
					100.00	99.99	
R1	-254	-275	-1146	(-1147) -232	-1160	-661	-654
R2	721.	542	266	(416) 416	251	441	261

Formula calculated to 24

	1	2	3	4	5	6	7
Si	5.616	5.282	5.798	4.744	5.984	6.05	6.03
Al	2.156 } 8.0	1.842	2.107 } 8.0	2.106	1.274 } 7.72	1.95 } 8.0	1.97 } 8.0
Fe'''	0.228	0.876	0.095	1.150	0.544	-	-
Al	-	-	-	-	-	0.98	0.29
Ti	0.392	0.354	0.374	0.352	0.362	0.17	0.22
Fe'''	0.360	0.588	0.368	0.202	-	0.64	0.53
Fe''	3.124 } 4.418	3.268 } 4.728	4.303 } 5.395	3.428 } 4.10	4.912 } 5.452	3.36 } 5.26	3.86 } 5.
Mn	0.066	0.054	0.091	0.084	0.074	0.03	0.06
Mg	1.476	0.464	0.259	0.034	0.104	0.08	0.05
Li	-	-	-	-	-	-	0.50
Ca	0.276	0.406	-	0.284	0.172	0.20	0.01
Na	0.128 } 1.690	0.126 } 1.638	0.309 } 2.201	0.128 } 1.268	0.240 } 2.320	0.52 } 2.23	0.12 } 1.
K	1.286	1.106	1.892	0.856	1.908	1.51	1.81
OH	4.328	5.902	4.091	8.544	3.498 } 4.798	3.01	1.98 } 4.
F					1.300		2.22

Appendix 6.

Analysis of the micas from greisens and pegmatitic veins

	8	9	10	11 light olive green	12 dark olive green	13
SiO_2	39.2	36.10	45.50	41.11	42.24	43.60
Al_2O_3	12.24	13.26	10.42	16.59	19.62	19.09
Fe_2O_3	2.98	7.29	2.48	2.00	2.02	2.57
FeO	29.0	25.30	28.10	22.61	18.64	14.80
MgO	0.03	0.05	0.13	0.13	0.08	0.10
CaO	0.15	0.20	0.40	n.d.	0.11	0.21
Na_2O	0.10	0.11	0.10	0.16	0.14	0.18
K_2O	8.15	8.82	6.09	9.92	8.84	9.54
H_2O^+	2.28	1.40	2.50	1.12	2.35	4.58
H_2O^-	1.61	1.27	1.56	0.29	0.48	0.82
TiO_2	2.58	3.07	2.47	0.30	0.18	0.88
F	-	-	-	5.49	5.02	-
S	-	-	-	-	0.02	-
MnO	0.43	0.51	0.40	0.67	0.30	0.84
Li_2O	1.40	2.73	1.96	1.85	1.90	3.34
	99.57	100.27	98.87	102.24	101.94	98.93
Less O	-226 258	-660 284	665 254	1.85	2.11	
				99.93	99.83	
Be	6ppm	16ppm	19ppm	-324	124	112 32ppm
Cr	10ppm	20ppm	30ppm	332	401	402 10ppm
Zn	1660ppm	2510ppm	3140ppm			1350ppm
Cd	6ppm	10ppm	30ppm			<6ppm

Formula calculated to 24

	8		9		10		11		12		13	
Si	6.36	8.00	5.74		6.96	8.00	6.30		6.22	8.00	6.16	
Al	1.64		2.26		1.04		1.70		1.78		1.84	
Al	0.69		0.22		0.84		1.30		1.62		1.34	
Ti	0.31		0.37		0.28		0.03		0.02		0.09	
Fe'''	0.39	6.30	0.93	6.71	0.30	6.31	0.23	5.72	0.22	5.33	0.29	5.
Fe''	3.93		3.36		3.60		2.90		2.29		1.75	
Mn	0.06		0.07		0.05		0.09		0.04		0.10	
Mg	0.01		0.01		0.03		0.03		0.02		0.02	
Li	0.91		1.75		1.21		1.14		1.12		1.90	
Ca	0.26	1.98	0.03	1.85	0.07	1.29	-	1.97	0.01	1.71	0.03	1.
Na	0.03		0.03		0.03		0.03		0.04		0.05	
K	1.69		1.79		1.19		1.94		1.66		1.72	
OH	2.47		2.80		2.55		1.15	3.81	2.30	4.63	5.09	
F							2.66		2.33			

1. Fe-biotite from Fier hastingsite biotite granite, Sara Fier. Analysis taken from Bull. 32 of Geol. Survey.
2. Lepidomelane (Foster) from Kula hastingsite biotite granite, Pankshin. Analysis taken from Bull. 32 of Geol. Survey.
3. Annite from early hastingsite biotite granite, Amo. Analysis taken from Bull. 32 of Geol. Survey.
4. Lepidomelane taken from Daffo hastingsite biotite granite, Sha Kaleri. Analysis taken from Bull. 32 of Geol. Survey.
5. Annite taken from riebeckite biotite granite, Amo. Analysis taken from Bull. 32 of Geol. Survey.
6. Li-siderophyllite from Kudaru biotite granite. Analysis taken from Bain (Jacobson, Imperial Institute).
7. Li-siderophyllite from Liruei biotite granite. Analysis taken from Bull. 32 of Geol. Survey.
8. Li-siderophyllite from greisen in Rishi biotite granite, Saiya/Shokobo Complex. Analysed by R. Batchelor, St. Andrews.
9. Li-Fe-siderophyllite from pegmatitic vein in Rishi biotite granite. Analysed by R. Batchelor.
10. Li-siderophyllite from greisen in Rishi biotite granite, Saiya/Shokobo Complex. Analysed by R. Batchelor.
11. Protolithionite from Rayfield Gona granite, Harwell area, Jos/Bukuru Complex. Analysed by von Knorring and Dyson (1959).
12. Protolithionite from greisen in biotite granite, Liruei. Analysis taken from Bull. 32 of Geol. Survey.
13. Protolithionite from quartz-mica pegmatitic vein, Sabon Gida South biotite granite - Jos/Bukuru Complex. Analysed by R. Batchelor.

Appendix 8.

	1	2	3	4	5	6	7	8	9	10
SiO_2	76.15	74.80	74.01	198.75	196.72	200.57	- 2.03	+ 1.82	- 0.78	+ 0.70
Al_2O_3	12.48	11.25	10.13	32.57	29.59	27.45	- 2.98	- 5.12	- 1.14	- 1.96
Fe_2O_3	0.50	0.37	0.37	1.31	0.97	1.00	- 0.34	- 0.31	- 0.13	- 0.12
FeO	0.73	1.47	4.33	1.91	3.87	11.73	+ 1.96	+ 9.82	+ 0.75	+ 3.76
MgO	0.19	0.10	0.15	0.50	0.26	0.41	- 0.24	- 0.09	- 0.09	- 0.03
CaO	0.51	0.38	0.11	1.33	1.00	0.30	- 0.33	- 1.03	- 0.13	- 0.39
Na_2O	4.06	0.21	0.19	10.60	0.55	0.52	-10.05	-10.08	- 3.85	- 3.86
K_2O	4.43	9.84	6.41	11.56	25.88	17.37	+14.32	+ 5.81	+ 5.49	+ 2.23
H_2O^+	0.33	0.26	0.55	0.86	0.68	1.49	- 0.18	+ 0.63	- 0.07	+ 0.24
H_2O^-	0.20	0.32	0.19	-	-	-	-	-	-	-
CO_2	0.02	0.02	0.03	0.05	0.05	0.08	-	+ 0.03	-	+ 0.01
P_2O_5	tr.	tr.	nil	-	-	-	-	-	-	-
TiO_2	0.06	0.06	0.03	0.16	0.16	0.08	-	- 0.08	-	+ 0.03
MnO	0.01	0.03	0.12	0.03	0.08	0.33	+ 0.05	+ 0.30	+ 0.02	+ 0.11
Cl	0.01	0.01	0.01	0.03	0.03	0.03	-	-	-	-
F	0.35	0.45	1.40	0.91	1.18	3.79	+ 0.27	+ 2.88	+ 0.10	+ 1.10
Li_2O	0.08	0.14	0.40	0.21	0.37	1.08	+ 0.16	+ 0.87	+ 0.06	+ 0.33
ZrO_2	0.04	0.04	0.03	0.10	0.10	0.08	-	- 0.02	-	- 0.01
S	0.02	0.14	0.55	0.05	0.37	1.49	+ 0.32	+ 1.44	+ 0.12	+ 0.55
Pb	nil	0.26	0.88	-	0.68	2.39	+ 0.68	+ 2.39	+ 0.26	+ 0.91
Zn	nil	0.15	0.67	-	0.40	1.82	+ 0.40	+ 1.82	+ 0.15	+ 0.70
Cu	nil	0.01	0.02	-	0.03	0.05	+ 0.03	+ 0.05	+ 0.01	+ 0.02
SnO_2	nil	0.03	0.10	-	0.08	0.27	+ 0.08	+ 0.27	+ 0.03	+ 0.10
Totals	100.18	100.35	100.68	260.93	259.18	260.50				
Less O	0.15	0.19	0.59							
	100.03	100.16	100.09							
Sp. Gr.	2.61	2.63	2.71							

Chemical Analyses of Biotite Granite, Reddened Granite and Greisenised Granite Liruei - after R. Jacobson (1947).

Localities:-

1. Biotite granite, old shaft, Liruei Lode. (Imperial Institute).
2. "Reddened granite", M.L. 5693, Liruei Lode. (Imperial Institute).
3. Semi-greisenized granite, M.L. 5693, Liruei Lode. (Imperial Institute).
4. Composition in grams of 100 cc. of
   4. Granite.
   5. "Reddened granite".
   6. Semi-greisenized granite.

Gain or loss in grams in alteration to

7. "Reddened granite".
8. Semi-greisenized granite.

Gain or loss in percentage of total original rock mass.

9. "Reddened granite".
10. Semi-greisenized granite.

Appendix 7.

Chemical Analyses of Liruei biotite granite, mineralised vein and altered wall rocks.

	1	2	3	4	5	6
SiO_2	76.2	84.4	76.0	95.8	75.9	76.8
Al_2O_3	10.89	4.28	10.69	1.85	12.85	11.99
Fe_2O_3	0.0	total 7.71	0.00	0.73	0.33	0.47
FeO	1.76	iron	1.21	0.25	1.05	0.97
MgO	0.01	0.01	0.01	0.00	0.02	0.01
CaO	0.05	0.18	0.19	0.02	0.24	0.24
Na_2O	0.00	0.00	0.98	0.00	3.91	3.92
K_2O	9.76	1.58	9.78	0.58	4.30	4.31
H_2O^+	0.36	1.15	0.27	0.37	0.46	0.17
H_2O^-	0.00	0.05	0.03	0.08	0.06	0.05
TiO_2	0.08	0.17	0.07	0.11	0.11	0.07
P_2O_5	0.06	0.08	0.07	0.01	0.00	0.00
MnO	0.06	0.18	0.03	0.01	0.05	0.03
	99.23	99.71	99.33	99.81	99.28	99.03
Cu	21ppm	49ppm	10ppm			
Pb	98	320	98			
Zn	292	2436	331			

Analyst R.A. Batchelor.

1 = 58a altered wall rock adjacent in mineralised vein
2 = 58b mineralised vein
3 = 58c altered wall rock adjacent to vein
(1–3: see Fig. 15)
4 = N74 quartz vein in biotite granite
5 = N75 Liruei biotite granite
6 = N77 Liruei biotite granite

Appendix 9.

Nb_2O_5/SnO_2 results
from Rayfield Gona granite

ATMN

8838 - present paddock	ppm Nb_2O_5	ppm SnO_2
A	90	25
B	770	200
C	510	165
D	460	165
E	470	70
F	610	140
G	55	50
H	470	130
J	770	50
K	520	56
L	1115	50
M	590	120
N	630	120

8838/1127B		
A	100	-
B	1300	1433
C	1140	830
D	1000	650

Appendix 9 Contd.

	Nb_2O_5	SnO_2
Jantar	ppm	ppm
No. 1 GP		
A	50	50
B	33	
C	33	
D	50	
PCP 10		
A	40	20
B	30	20
C	30	20
D	900	520
E	2290	1450
F	1200	68
G	30	<20
H	1280	350
J	1720	430
K	750	360
L	500	20
M	1050	28
N	820	<20
O	320	<20
P	40	20
Q	40	<20
R	430	<20
S	33	<20
T	33	<20
U	450	<20

Appendix 10.

Chemical Analyses of Sulphides from
Rishi & Liruei Mineralised Veins.

	Rishi	Liruei
Cu	4.21%	0.25%
Pb	0.14	0.96
Zn	52.5	60.9
Fe	10.2	6.48
Mn	0.02	0.04
Cd	0.19	0.59
Co	137ppm	<16ppm
Ag	61ppm	5ppm

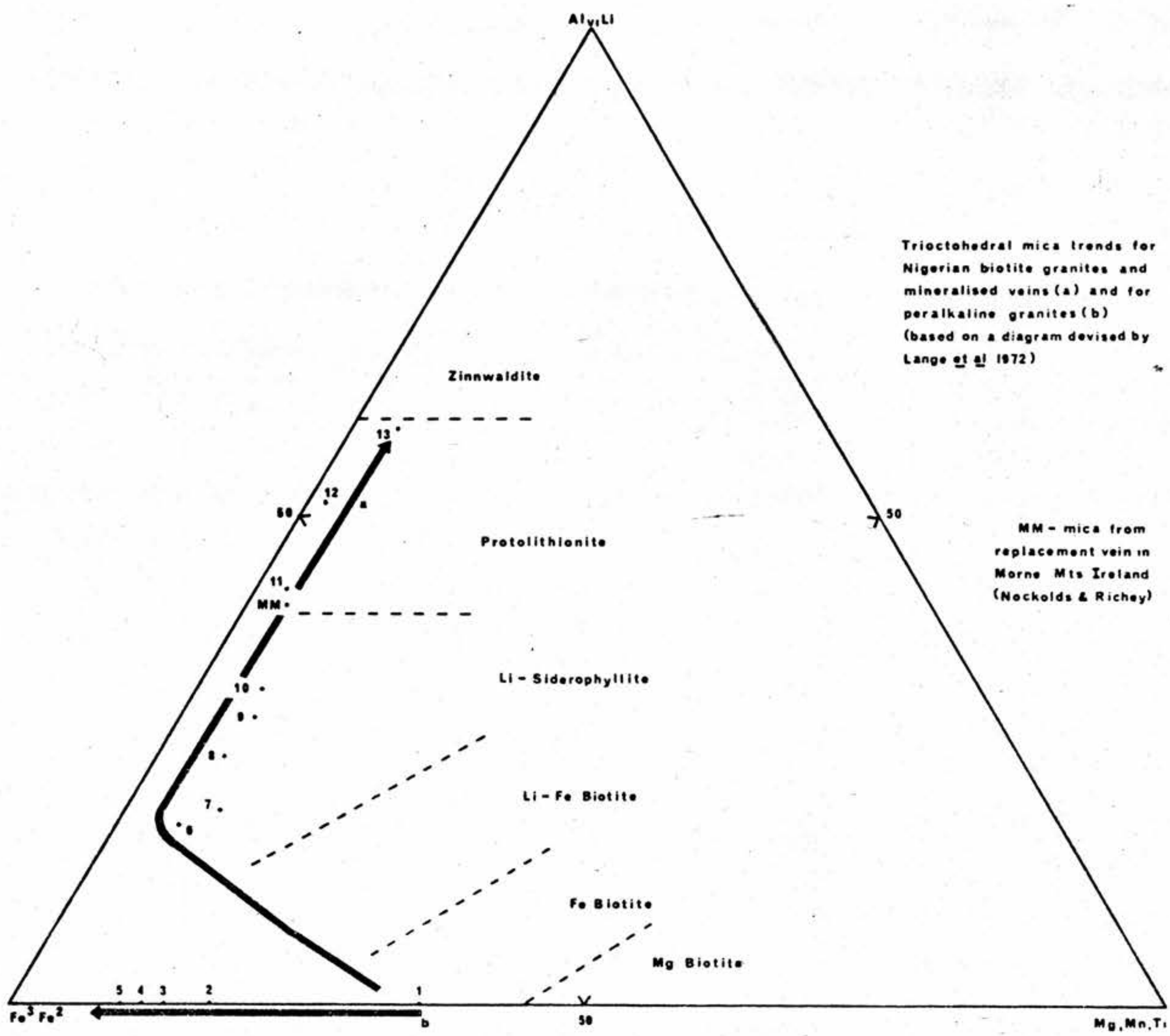

Al$_{VI}$,Li
Zinnwaldite
Protolithionite
Li - Siderophyllite
Li - Fe Biotite
Fe Biotite
Mg Biotite
Fe^3 Fe^2
Mg,Mn,Ti
50
50
50
a
b
MM
Triooctohedral mica trends for Nigerian biotite granites and mineralised veins (a) and for peralkaline granites (b) (based on a diagram devised by Lange et al 1972)
MM - mica from replacement vein in Morne Mts Ireland (Nockolds & Richey)

Figure 24

Appendix 12

Chemical Analyses of Mineralised Veins.

	1	2	3	4
SiO_2	90.9	54.2	52.3	57.7
TiO_2	0.1	0.1	0.1	0.1
Al_2O_3	1.2	9.7	9.7	14.1
Total Fe as FeO	3.4	27.3	21.1	4.3
MnO	0.05	0.31	0.23	0.13
MgO	<0.02	0.02	0.02	<0.02
CaO	0.24	0.12	2.57	0.10
Na_2O	0.15	0.11	0.10	0.10
K_2O	0.81	5.85	4.08	1.04
SnO_2	.14	.88	.05	5.47
	97.01	98.59	90.25	83.05
Li	760	4645	5090	170
Be	2	6	10	6

Mica from above vein (2)

SiO_2	39.2
Al_2O_3	12.24
Fe_2O_3	2.98
FeO	29.0
MgO	0.03
CaO	0.15
Na_2O	0.10
K_2O	8.15
H_2O^+	2.28
H_2O^-	1.61
TiO_2	2.58
MnO	0.43
Li_2O	1.40
	99.57

Sulphide fraction

Cu	0.31%
Zn	2.82
Fe	2.31
Mn	0.05
Pb	77 ppm
Cd	483
Co	<16
Ag	27

Low totals are due to insoluble sulphide residues which were not analysed, and F and OH contents also.

1 = Sample 5 Locality 117 Ladini

2 = Sample 5A Locality 117 Ladini

3 = Sample 2A Locality 114 Dawa

A Geological Investigation of Some Nigerian Jurassic Granites and their Mineralization

by

Judith A. Kinnaird, B.Sc.

Volume 2.

Economic Minerals in the Nigerian Jurassic Granites.

C O N T E N T S.

List of photographs

Volume 2 - Mineral descriptions.

Introduction

This volume incorporates descriptions of economically important minerals, and those of mineralogical interest, related to mineralisation in biotite granites and replacement veins. It summarises the existing data and adds information that has been gained as a result of this research programme. Each mineral is treated separately although associated minerals are also noted. The mineral associations have already been discussed in Chapter 3. **(Volume 1)**

It was not possible in this compilation to follow a standard format with the mineral descriptions since for each mineral the important aspects varied and therefore the emphasis is placed on important new information for each of the minerals.

Although previous literature on Nigerian mineralisation includes descriptions of cassiterite, columbite and wolfram, most of the other minerals have been noted only briefly, whilst greenockite, bismuthinite and some of the copper minerals have not been recorded hitherto.

It is therefore the intention of this volume to present as much data as possible about the minerals that have been studied, both from the apogranitic phase of mineralisation and the hydrothermal vein-forming phase.

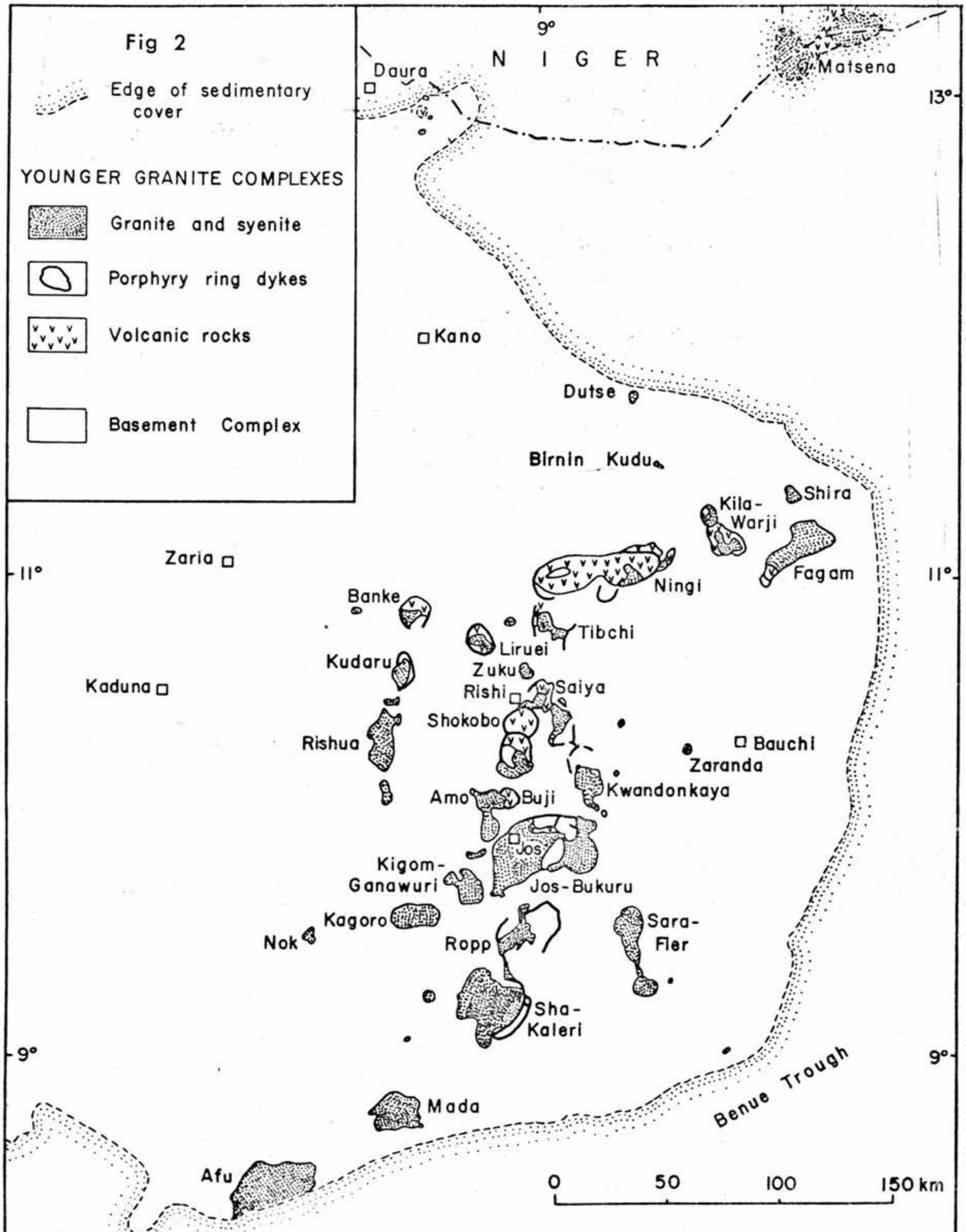
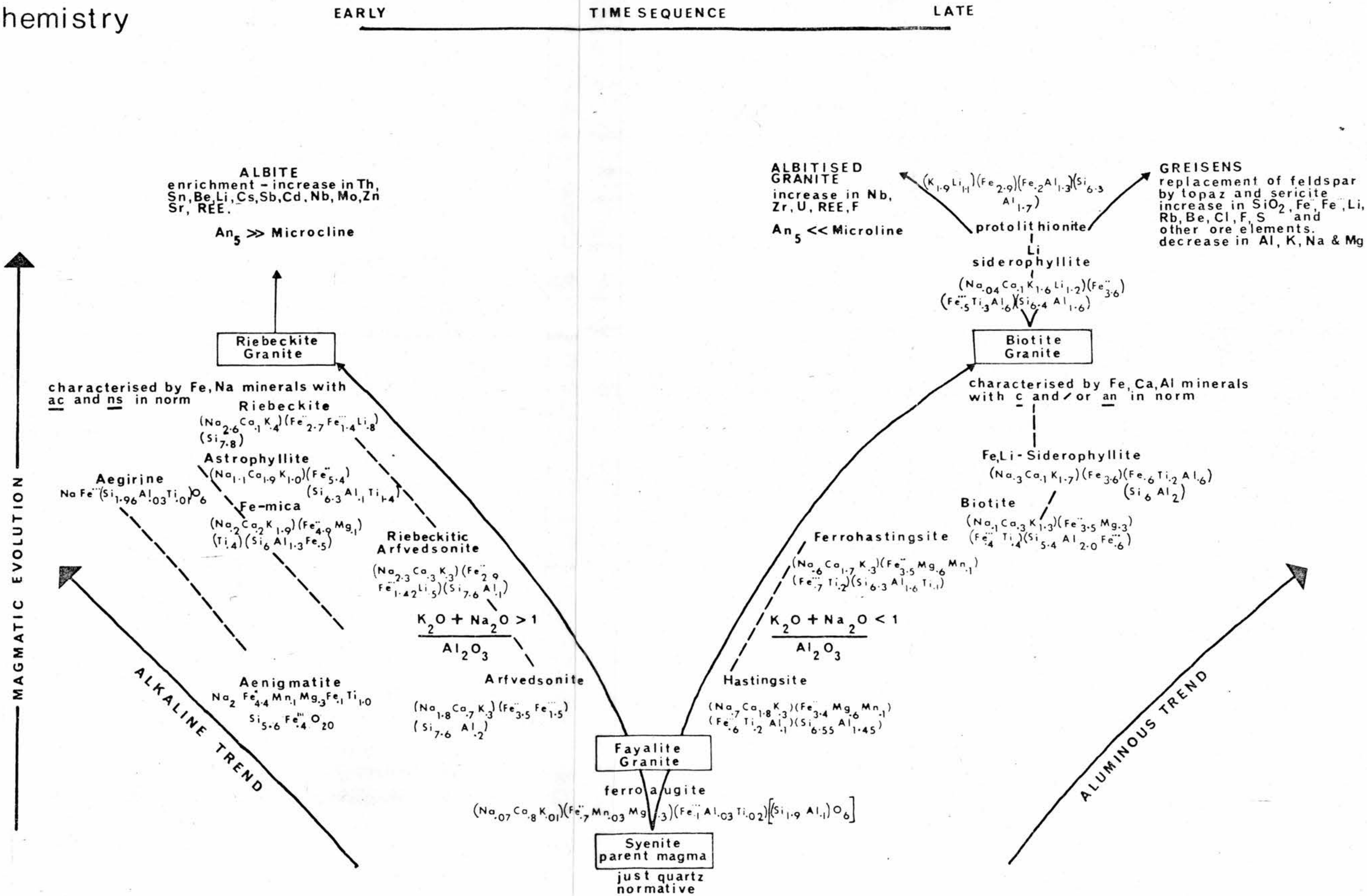


Fig 2
Edge of sedimentary cover
YOUNGER GRANITE COMPLEXES
Granite and syenite
Porphyry ring dykes
Volcanic rocks
Basement Complex
N I G E R
Daura
Matsena
Kano
Dutse
Birnin Kudu
Shira
Kila-Warji
Fagam
Ningi
Zaria
Banke
Tibchi
Liruei
Kudaru
Zuku
Kaduna
Rishi
Saiya
Shokobo
Rishua
Bauchi
Zaranda
Kwandonkaya
Amo
Buji
Jos
Kigom-Ganawuri
Jos-Bukuru
Kagoro
Sara-Fler
Nok
Ropp
Sha-Kaleri
Mada
Benue Trough
Afu
0
50
100
150 km
9°
13°
11°
9°
7°
9°

FIG 5

Chemistry



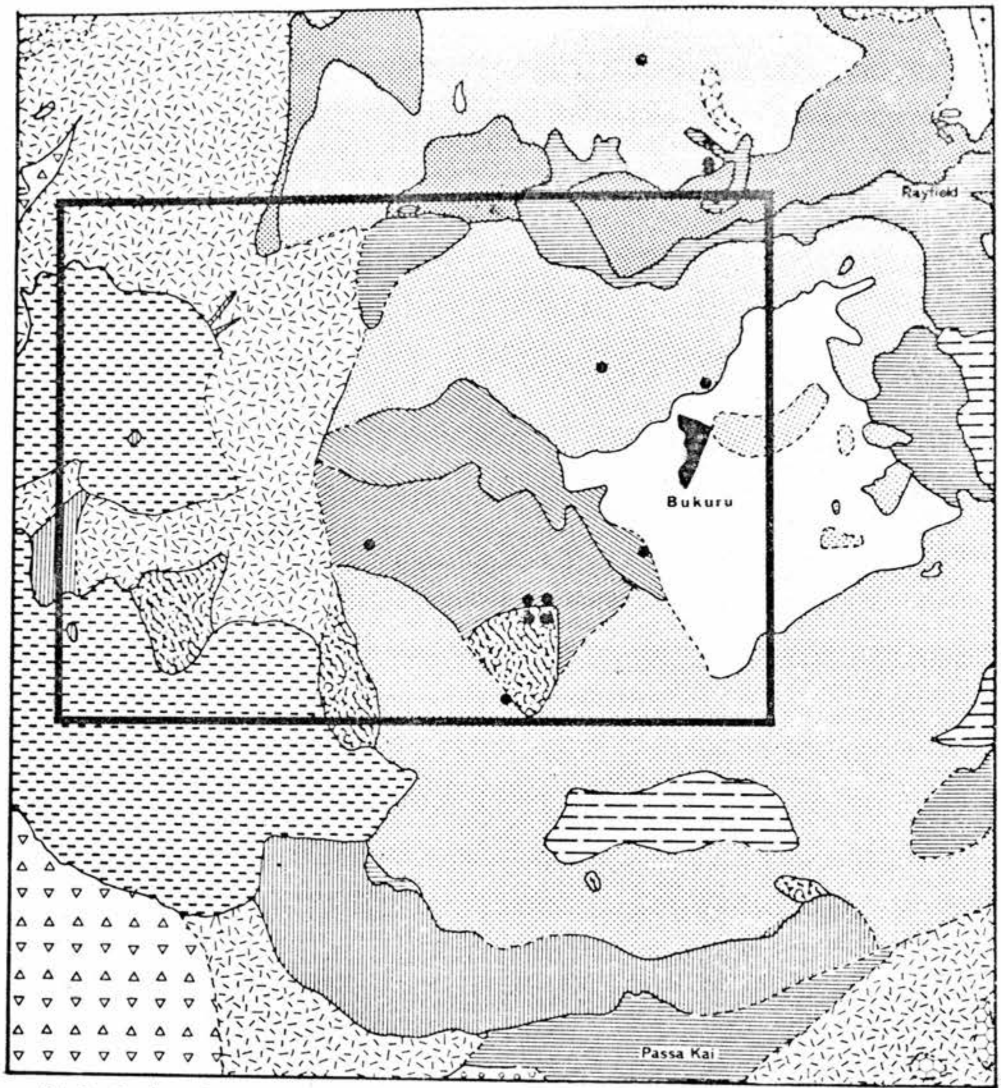


Fig 8 Geology of part of the Jos-Bukuru Jurassic Complex and surrounding areas taken from the 1:100,000 sheet 168 in Bulletin 32 Geological Survey of Nigeria 1971

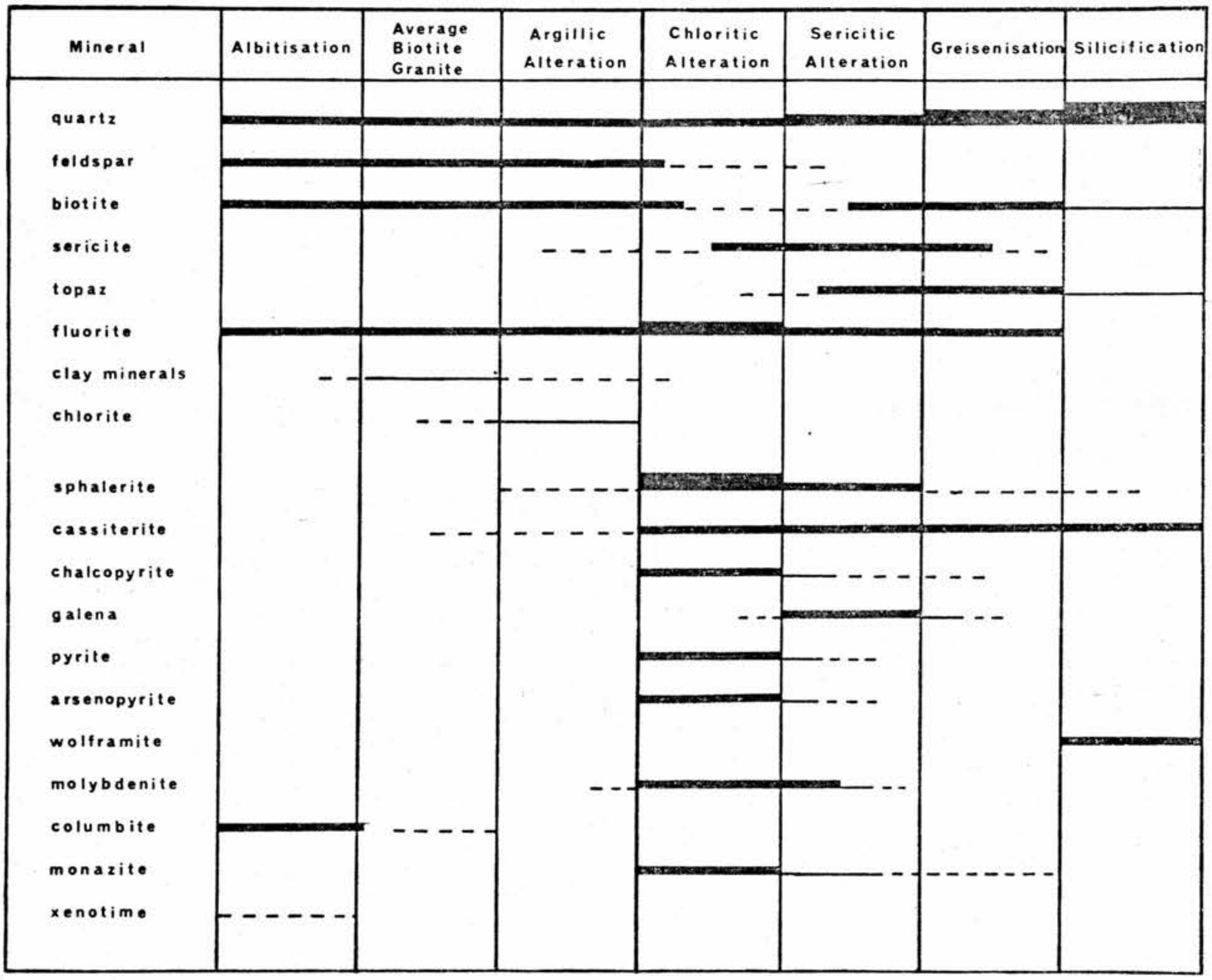
- Quaternary - Newer basalt
- Tertiary - Older basalt
- Microgranite
- Sabon Gida north granite
- Sabon Gida south granite
- Bukuru granite
- Shen granite
- Delimi granite
- Area covered by 1:10,000 project map
- Rayfield-Gona granite
- Kuru granite
- Ngell granite
- Jos granite
- Vom granite
- Undifferentiated granite
- Basement
- Greisen locality

Scale

0 1 2 3 4

kms

FIGURE 14



Mineral
Albitisation
Average Biotite Granite
Argillic Alteration
Chloritic Alteration
Sericitic Alteration
Greisenisation
Silicification
quartz
feldspar
biotite
sericite
topaz
fluorite
clay minerals
chlorite
sphalerite
cassiterite
chalcopyrite
galena
pyrite
arsenopyrite
wolframite
molybdenite
columbite
monazite
xenotime

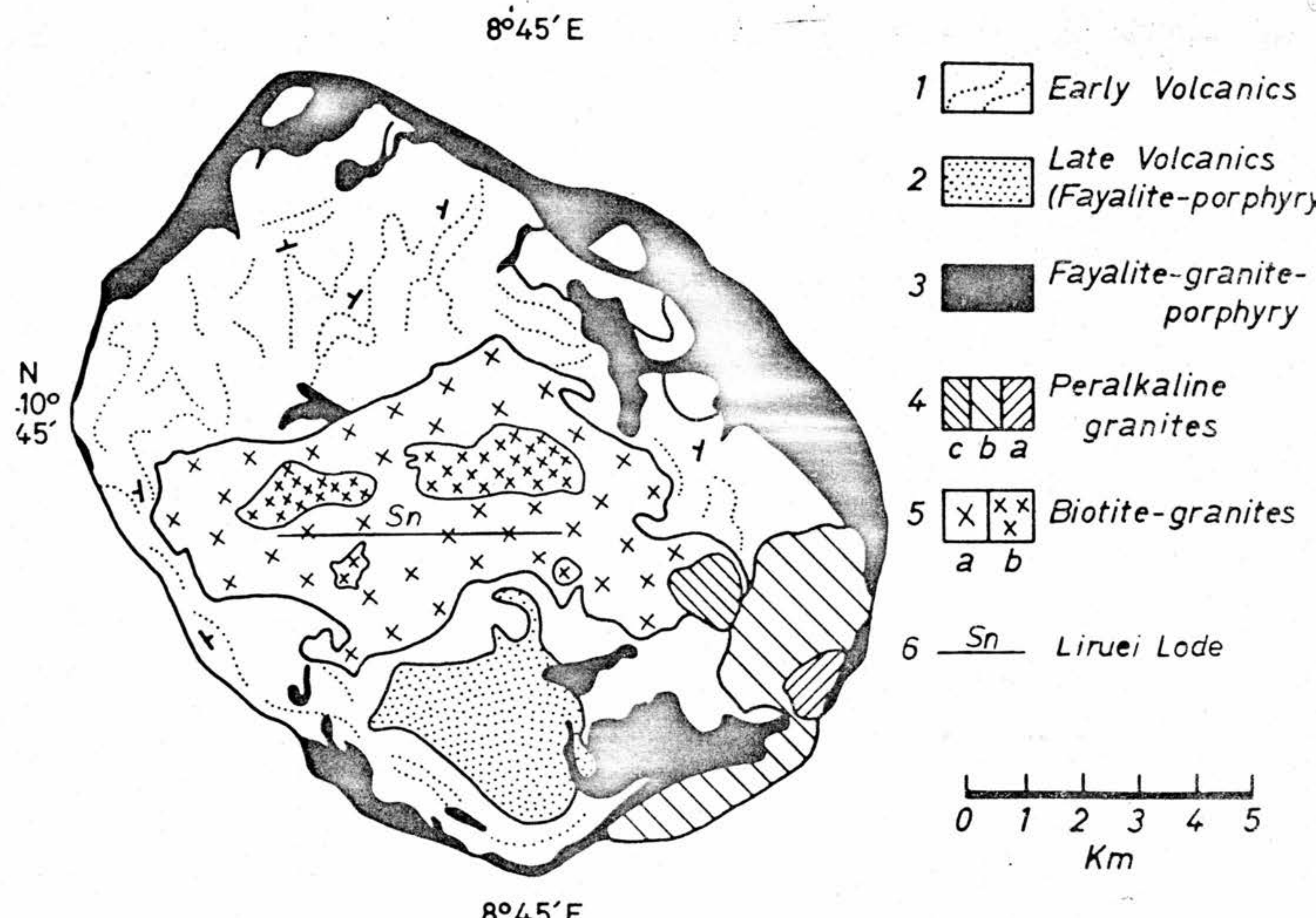


Fig. 16. The Liruei Younger Granite Complex.

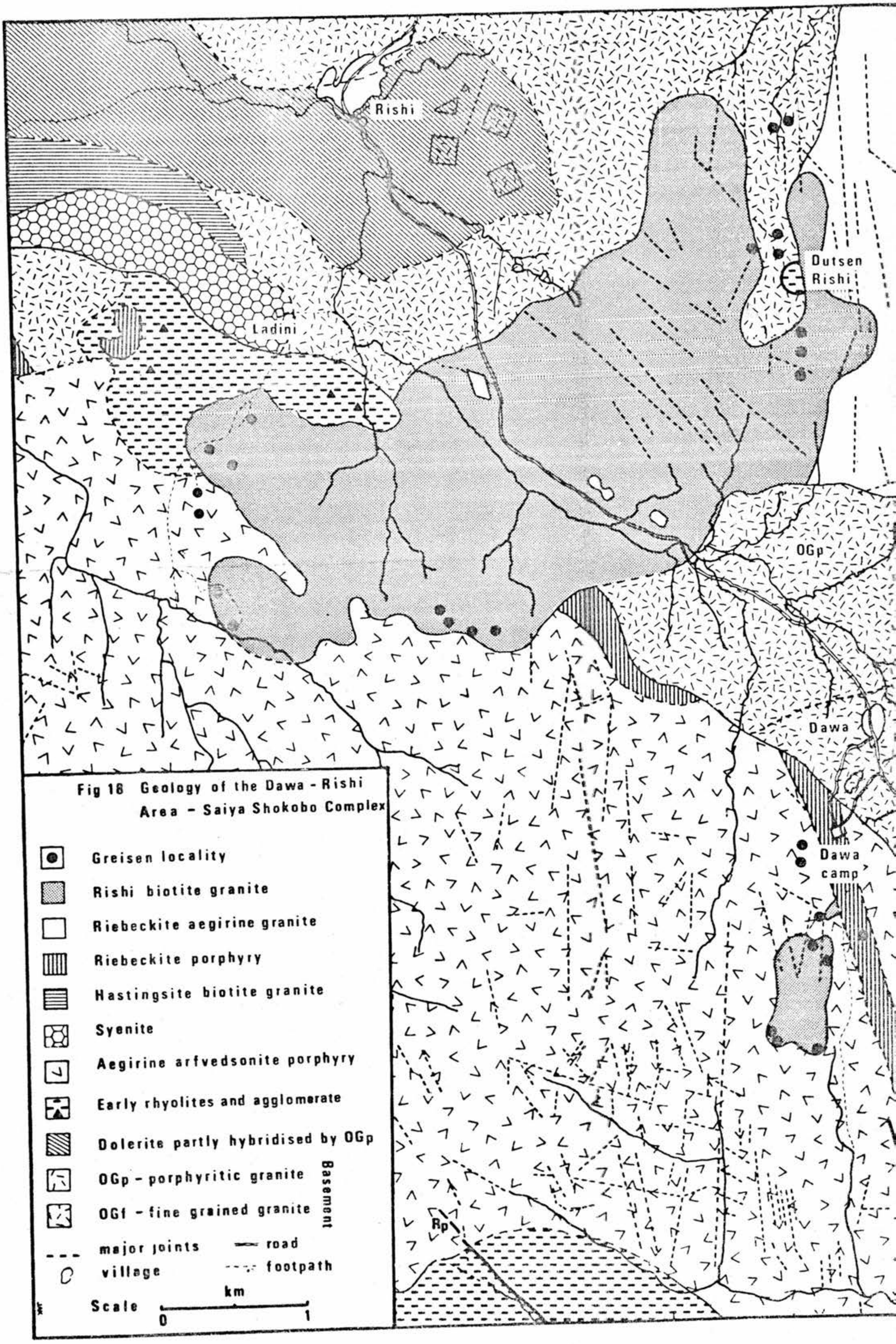


Fig 18 Geology of the Dawa - Rishi Area - Saiya Shokobo Complex

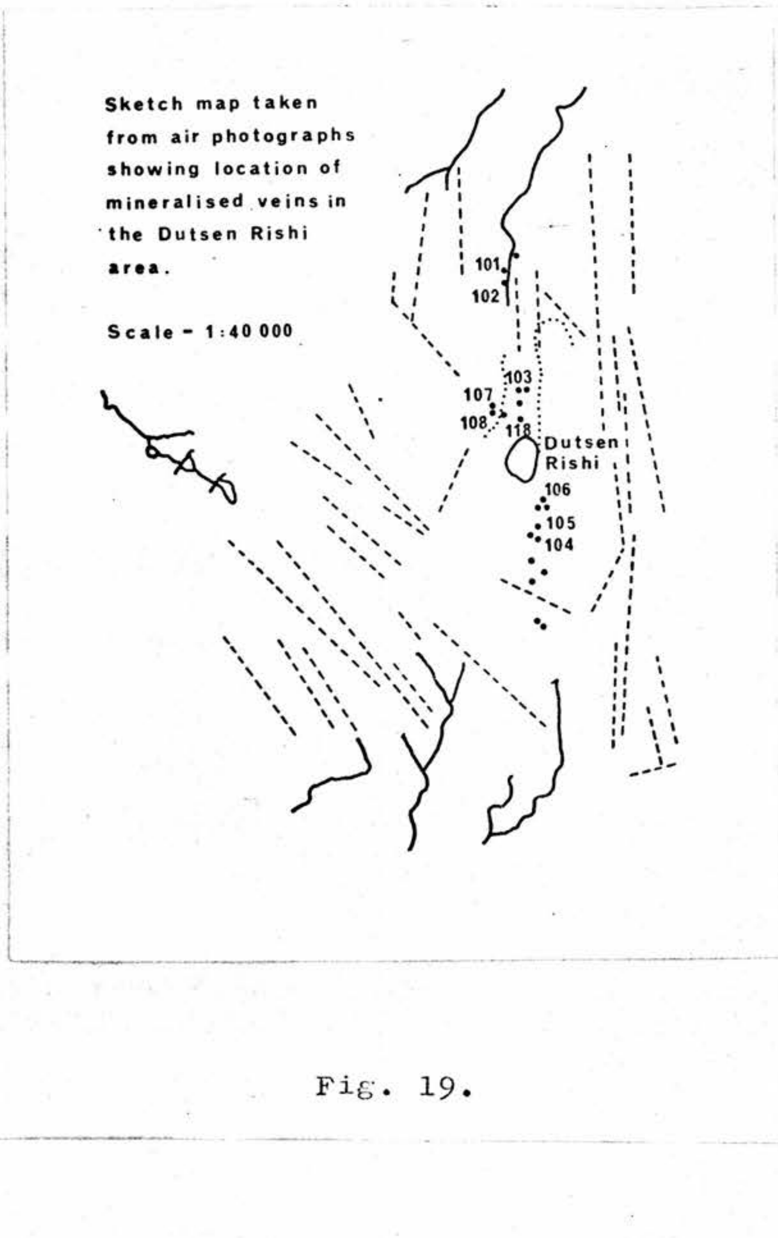

Sketch map taken from air photographs showing location of mineralised veins in the Dutsen Rishi area.
Scale - 1:40 000
101
102
103
107
108
118
Dutsen Rishi
106
105
104

Fig. 19.

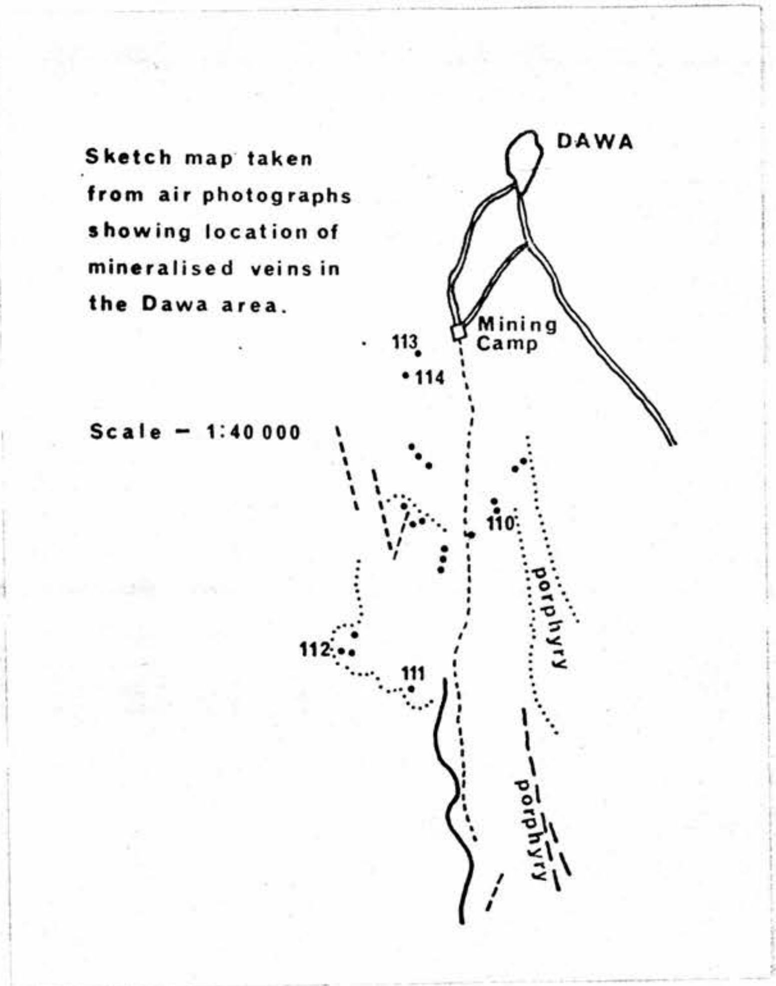

DAWA
Sketch map taken from air photographs showing location of mineralised veins in the Dawa area.
Mining Camp
113
114
Scale – 1:40 000
110
porphyry
112
111
porphyry

Fig. 21.

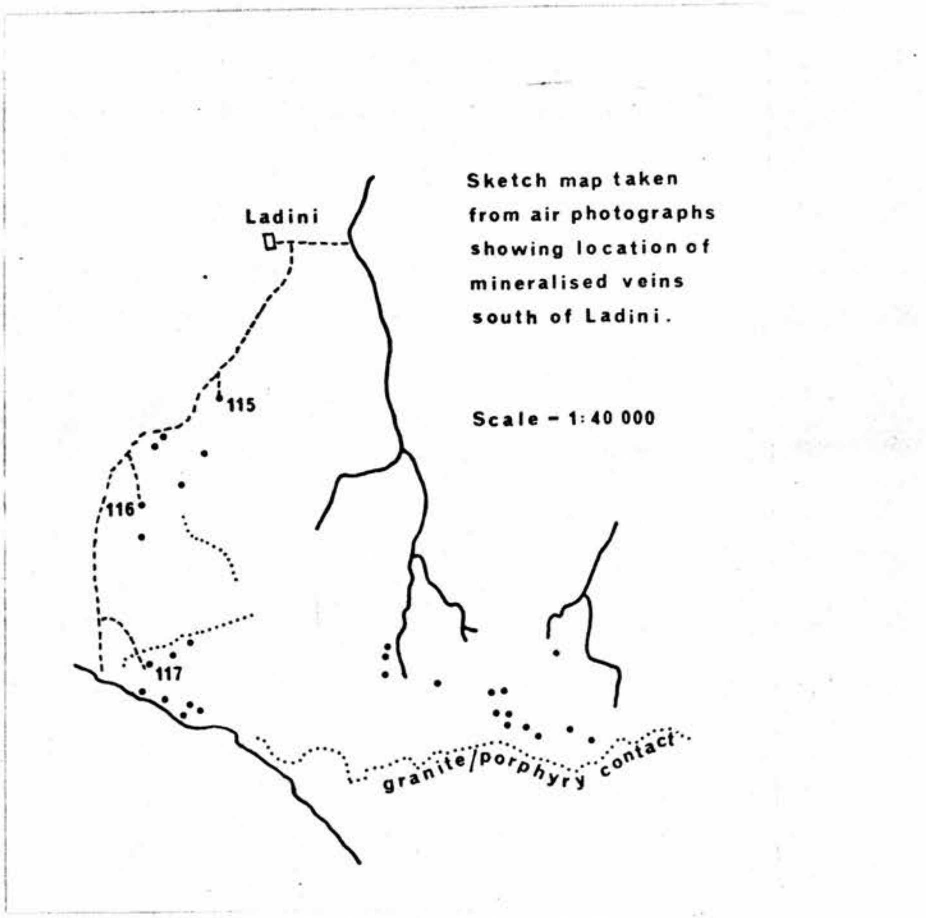
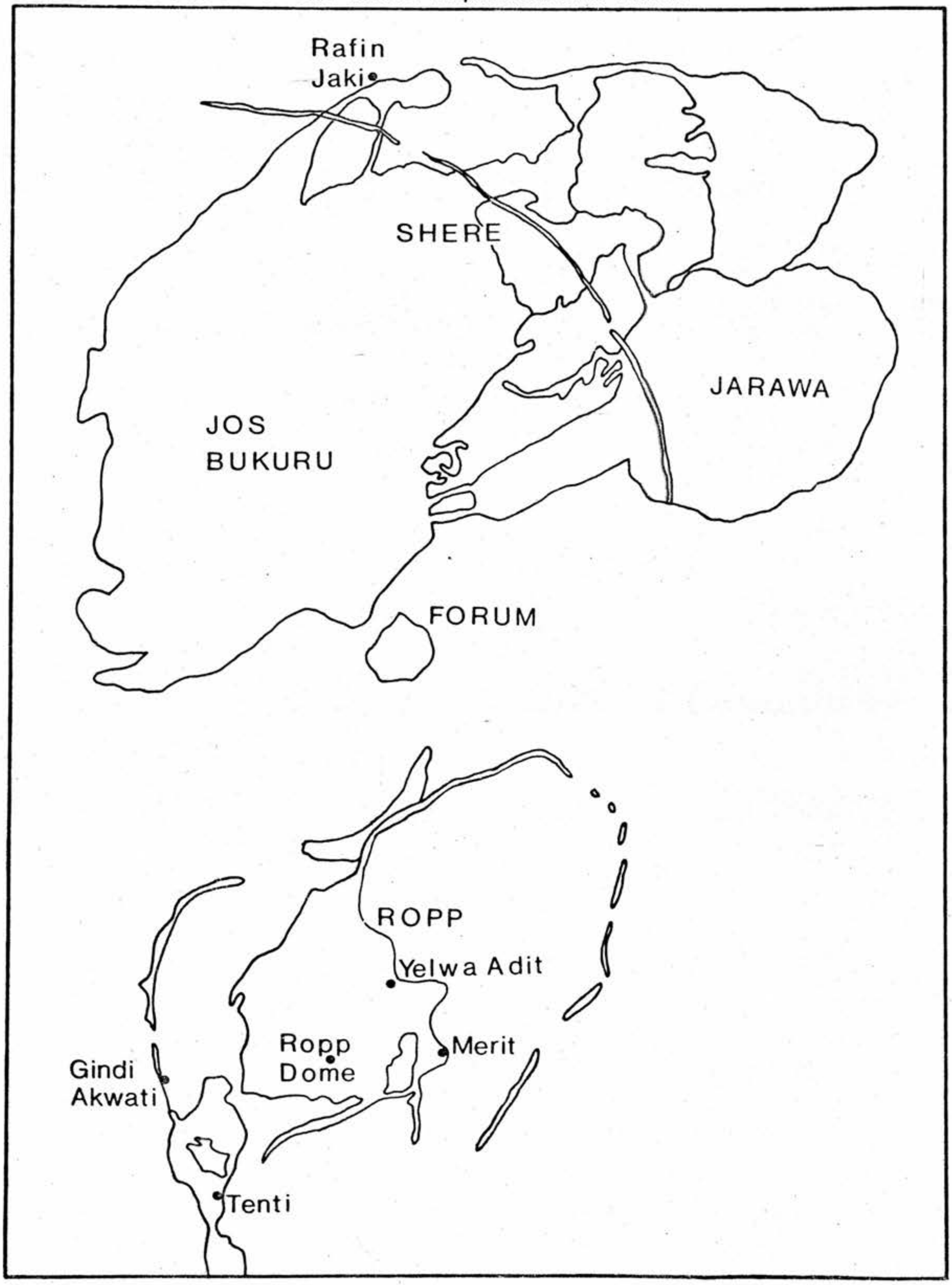

Sketch map taken
from air photographs
showing location of
mineralised veins
south of Ladini.
Scale - 1:40 000
Ladini
115
116
117
granite/porphyry contact

Fig. 22.

Fig 23 Location of the minor replacement veins



MINERALS DESCRIBED

Oxides	Cassiterite
	Columbite
Sulphides	Sphalerite
	Chalcopyrite and copper minerals
	Molybdenite
	Pyrite and arsenopyrite
	Galena
	Greenockite
	Bismuthinite
Fluoride	Fluorite
Fluorosilicate	Topaz
Silicates	Zircon
	Thorite
	Beryl: genthelvite: phenakite: danalite
	Mica
Phosphates	Xenotime
	Monazite
Tungstate	Wolframite

Cassiterite

Nigeria is the world's sixth biggest producer of tin and produces some 4% of the global output. Cassiterite is the only tin mineral as yet recorded from the Jurassic granites although nigerite, a tin-zinc spinel, has been recorded from the basement pegmatites (Jacobson & Webb 1946).

Compositionally, cassiterite contains oxide impurities of Fe, Nb, Ta, Ti, Cu, Zn and Mn. An analysis of cassiterite from the Harwell area of the Jos-Bukuru Complex by ATMN showed the following composition:-

SnO_2	89.5%
Nb_2O_5	4.70
Ta_2O_5	1.60
Fe_2O_3	1.64
TiO_2	0.12
Sc_2O_3	0.01
Loss on ignition	3.30
	100.87

Cassiterite has a much wider primary distribution throughout the Province than columbite. It occurs as small crystals preceding the formation of columbite in albitised granites (Williams et al., 1956), but high values are concentrated into narrow zones, possibly due to incipient veins, and only low values are dispersed through the granite as a whole. Cassiterite occurs as a very minor constituent in many granites and is not confined to albitised variants. The values of cassiterite in a particular granite may vary from nothing to over 350 ppm SnO_2. In addition to these occurrences, abundant cassiterite, varying from small or large anhedral forms to perfect crystals which may exceed 1 cm in size, is found in mineralised veins throughout the province.

Cassiterite varies in colour according to its source, ranging from dark brown to black. Occasionally crystals may show an adamantine lustre but more commonly it displays a sub-metallic lustre or may be brown, friable and hackly. Translucent ruby, yellow and white varieties have been recorded and there is a small amount of colloidal wood tin from Gindi Akwati and south Ropp in the Ropp Complex and from the Gaiya river in the Liruei complex.

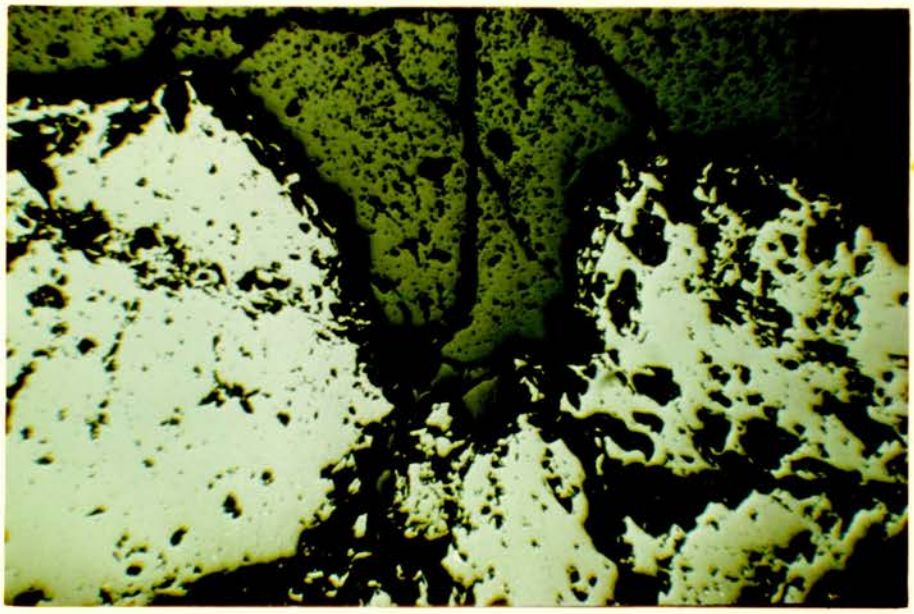
It seems likely that the variations in colour of the cassiterite are related to the temperature of formation. Research at present being undertaken in the chemistry department of St. Andrews University is studying the behaviour of tin deposition. Researchers have observed that above 400°C there is only one phase, i.e. the supercritical fluid, and that any associated cassiterite is very dark green or black and opaque in thin section. This could be equivalent to a pneumatolytic dispersed phase of mineralisation. As the temperature drops to 250°C a liquid and a vapour phase develop and the cassiterite deposited at this stage is brown or yellow green in colour. This could perhaps be the equivalent of the hydrothermal vein stage of mineralisation. Finally it has been observed that at temperatures around 45°C the cassiterite is amber and transparent (Vincent and Weston 1972).

These observations appear to fit known characteristics of Nigerian cassiterite.

Cassiterite occurs in several phases of the mineralised veins. It is present in the sulphide assemblage associated with the chloritic stage of alteration and it also occurs within micaceous clusters in greisens. Cassiterite has also been introduced in addition to wolfram in the silicification stage. In thin section the cassiterite associated with quartz veins or silicified altered veins is pale yellowish, brownish or colourless, whilst the cassiterite found associated with green mica in greisens is dark reddish brown in colour and may show zoning, from dark coloured at the centre to colourless at the margins. Thus the cassiterite found in the later, cooler stages of alteration is lighter than that formed in earlier phases, and even that found in the earlier stages may show colour zoning which may be related to fall in temperature. Some of this darker coloured cassiterite is intensely pleochroic from pale yellow to a dark reddish colour which is attributed by many authors to a high niobium content.

Polished sections of cassiterite show different characteristics depending on which stage of alteration the cassiterite is from. Sections taken from cassiterite formed in an early, presumably high temperature, phase show few if any inclusions, and those so far observed appear to be of pyrite. Inclusions in cassiterite taken from quartz veins (photomicrograph 1) from Ropp Adit are more numerous and so far only quartz has been observed as inclusions. The cassiterite is strongly anisotropic, has very low reflectivity and is easily identifiable in polished sections.

Cassiterite has a density of approximately 7 and a



Photomicrograph 1 shows polished cassiterite, with surface cracks, containing inclusions of quartz. From a quartz-cassiterite vein, the Adit - Ropp.

Photograph 1 shows cassiterite crystals from vugs in the Liruei lode. x 5.

hardness of 6 to 7. Some cassiterite is magnetic, which according to Greaves et al., (1971) is due to the presence of microscopic to submicroscopic inclusions of magnetite exsolving from the crystal lattice. Both Greaves et al., (1971) and Grubb and Hannaford (1966) show that darker cassiterite fractions are more magnetic than lighter coloured ones, but in Nigeria ATMN geologists have found that the magnetic quality does not vary with colour and even transparent varieties may be magnetic. Ramdohr (1961) concluded from a study of polished sections of cassiterite that magnetism may be due to exsolution of columbite/tapiolite from crystal lattices, although he noted that these minerals also occur in non-magnetic cassiterite. However, Hanus and Krs (1965), having examined specimens of pure columbite, found that they had a much lower remnant magnetism than their samples of magnetic cassiterite, showing that columbite alone was not responsible for the magnetism. Grubb and Hannaford (1966) supported this since they had studied magnetic cassiterite that contained no niobium.

Grubb and Hannaford (op. cit.) showed that in the darker more magnetic fractions of cassiterite there is a relatively high Fe^2/Fe^3 ratio but Banerjee (1969) found no correlation between magnetism and Fe^2/Fe^3 ratio. He suggested that the iron impurity was in the form of super paramagnetic Fe_2O_3 or $Fe_{2-x}Sn_xO_3$, which Grubb and Hannaford (op. cit.) also suggested, and later Banerjee et al., (1970) suggested Fe_2SnO_4 or a member of the Fe_2SnO_4-Fe_2O_3 solid solution series. In contrast, Hanus and Krs (1965) suggest that magnetic cassiterite is due to the presence of

$Fe_xSn_{1-x}O_2$.

Unlike the cassiterite from the Australian localities described by Greaves et al., (1971), the Nigerian magnetic tin is neither localised nor apparently restricted to certain rock types.

The bulk of the cassiterite is won by alluvial mining since the accessory cassiterite in granites is not of high enough concentration to justify extraction costs. In the Harwell area of the Jos-Bukuru Complex however, (Fig. 8) cassiterite forms a valuable by-product of columbite extraction from heavily decomposed albitised granites. This dispersed cassiterite is probably related to the supercritical fluid from which black, opaque cassiterite (described by the St. Andrews chemists) is deposited. However this type of cassiterite has not been investigated by the writer.

Locally, groups of miners are extracting tin from mineralised veins; at Yelwa Adit, Ropp (Fig. 23) tin is being extracted by crushing the hard rock and crudely separating the cassiterite in small channels cut in the surface. In the Rishi area the same method is applied but at Dawa and locality 106 the veins are blasted out before treatment by hand. At Liruei, Ririwai Mines Ltd. are planning to extract cassiterite, sphalerite and galena from the Liruei lode by sophisticated underground mining techniques.

The way in which tin is transported in hydrothermal fluids appears to be in doubt although most workers agree that it is transported in fluids rich in chlorine and fluorine. Some advocate a Sn fluoro-hydroxyl complex

(Shcherbina 1963, Barsukov and Kuril'chikova 1966) whilst Hesp and Rigby (1972) more recently have considered stannic chloride complexes to be more prevalent and therefore more stable. Shcherbina believes that Sn, W, Al, Li, Be, Y, Ti and Zr are fluorophile whilst Cu, Ag, Fe and Pb are chlorophile elements. However, in many of the Nigerian mineralised veins it is not uncommon to get cassiterite, sphalerite, galena and chalcopyrite in one specimen. The research chemists in St. Andrews, mentioned earlier, have used tin chlorides in all their experiments. They have found that with stannic chloride there is a change to an unstable compound SnO_3H_2 at temperatures which coincide with the change from a single phase supercritical fluid to a two phase liquid/vapour state. This unstable compound then forms cassiterite and water viz:-

$$SnCl_4 \text{ --- } SnO_3H_2 \text{ --- } H_2O + SnO_2$$

Using stannous chloride as a basis for cassiterite production they have found that it merely involves straightforward oxidation with liberation of chlorine viz:-

$$SnCl_2 + O_2 \text{ --- } SnO_2 + Cl_2$$

In the Nigerian model it is suspected that most tin partitions towards the aqueous chloride phase although this does not preclude the occurrence of some tin in the silicate-fluoride-phase. At the moment no fluid inclusion data is available, so the nature of the ore forming fluids is merely speculative.

There is however one further possibility which has been suggested by Grant (pers. comm.) from his work on Bolivian tin. He believes that the tin may be transported in the form of sodium stannate which is very soluble and can precipitate cassiterite simply by dilution. He believes there is no evidence for fluorine transport since there is no topaz in Bolivia, but in Nigeria, where topaz does occur in some veins, only fluid inclusion data will clearly indicate the transporting medium.

Columbite and associated minerals

Nigeria is the world's leading producer of columbite and whilst there is a small production of pegmatitic columbite from the basement the vast bulk of the material is won from elluvial and alluvial deposits associated with the Jurassic fine-grained biotite granites.

Historically, since columbite was found in alluvials only in association with cassiterite it was assumed that they had a similar source and were thought to be derived from the lodes and greisens that were the source of cassiterite. Since 1945 when Col. Dent-Young found columbite in biotite granite in the Rukuba hills it has been realised that columbite occurs as an accessory constituent in albitised biotite granites and does not occur in greisens or its normal pegmatitic environment.

Columbite is known to occur in varying quantities in all complexes where fine grained biotite granites occur, but none of the complexes, with the possible exception of Afu in the Benue valley (Fig. 2), shows the enrichment that is apparent in the Jos-Bukuru complex (Fig. 8). From an early date it was known that some granites within the Jos-Bukuru complex contained more columbite than others and MacLeod (1956) and Williams _et al._, (1956) analysed all the granites and found that only the Rayfield-Gona contained economically significant values. MacLeod found that each granite, except the Rayfield-Gona, had a fairly well-defined range of values. The Jos granite varied from a content of nil to 19 ppm, the Ngell granite varied from a trace to 95 ppm whilst the Bukuru granite varied from 38 to 150 ppm of columbite. The Rayfield-Gona granite, however, was found to have values ranging from 150 to 2875 ppm of columbite and in two zones east of Rayfield values ranged between 760 ppm and 0.4%. This rich Harwell zone was discovered in 1952 by MacLeod and is at present being worked by Amalgamated Tin Mines (Nigeria). The other columbite ore body in the Jos-Bukuru complex is also in the Rayfield-Gona granite and is located at Passa Kai, being worked by Jantar-Bisichi.

The columbite occurs as small, black opaque crystals which are variable in shape from platy to acicular. Williams _et al._, (1956) believe that crystal shape is related to source granite.

Primary columbite is rarely coarser than 20 mesh, the greater portion lying between 60 and 200 mesh although some figures quote 30% of the columbite as less than 200 mesh. The high proportion of fine-grained fraction represents a major problem in recovery from decomposed bedrock. Alluvial columbite contains a preponderance of small equidimensional crystals generally finer than 60 mesh.

Columbite from the Jurassic granites, in sharp contrast to that from the basement, is very niobium rich and an analysis of columbite from the Harwell area shows 65% of Nb_2O_5 compared with 8% Ta_2O_5, a ratio of 8 : 1. MacLeod _et al._, (1971) state that the Nb_2O_5/Ta_2O_5 ratio in Jurassic granites is always greater than 5: 1 and Williams et al., (op. cit.) suggest that the average is 7 : 1.

Analysis of Columbite from Harwell

Nb_2O_5	64.8%
Ta_2O_5	8.1
FeO	15.1
Sc_2O_3	0.02
TiO_2	0.49
Mn_3O_4	1.95
ZnO	0.15
SnO_2	1.60
U_3O_8	<0.05
Loss on ignition	1.40
	93.66

In contrast, analyses of columbo-tantalite from basement pegmatites show a whole range of the isomorphous series.

Thorite, xenotime and hafnium-bearing zircon are commonly found associated with the columbite as accessory minerals within the granite and MacLeod (1971) also records pyrolusite and anatase in association.

The writer has found that within the Rayfield and Passa Kai areas (Fig. 8) there is a wide range in columbite content and 50 analyses showed the Nb_2O_5 content varying from less than 30 to over 2500 ppm. High columbite content coincides with high thorite content but there was no correlation between high columbite and cassiterite content which proved generally less than 50 ppm in the Passa Kai area and between 100 and 150 in the Harwell area where Nb_2O_5 content was lower. However, in the Passa Kai samples that

Nb_2O_5/SnO_2 results
from Rayfield Gona granite

ATMN

8838 - present paddock	ppm Nb_2O_5	ppm SnO_2
A	90	25
B	770	200
C	510	165
D	460	165
E	470	70
F	610	140
G	55	50
H	470	130
J	770	50
K	520	56
L	1115	50
M	590	120
N	630	120

8838/1127B		
A	100	-
B	1300	1433
C	1140	830
D	1000	650

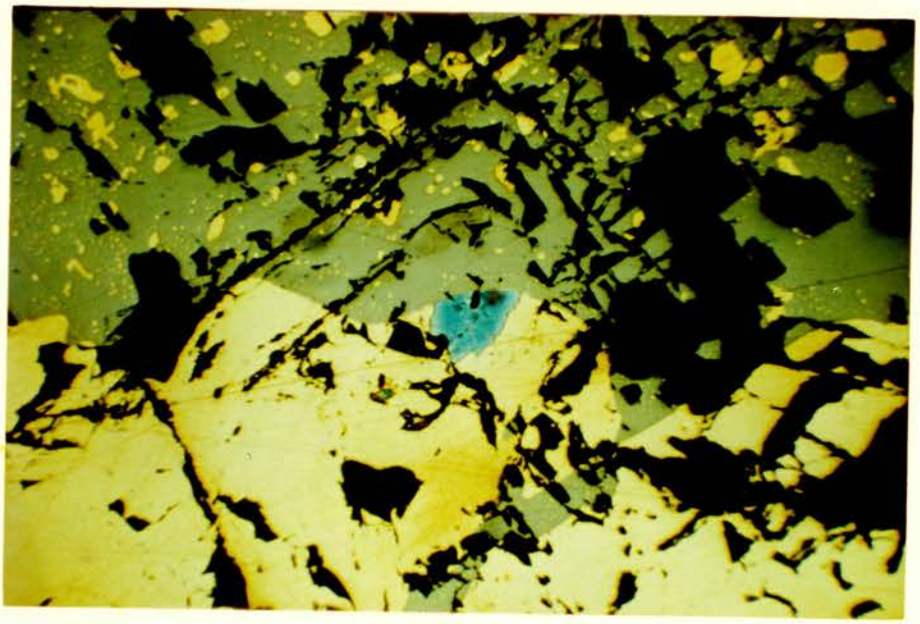
Jantar	Nb_2O_5 ppm	SnO_2 ppm
No. 1 GP		
A	50	50
B	33	
C	33	
D	50	
PCP 10		
A	40	20
B	30	20
C	30	20
D	900	520
E	2290	1450
F	1200	68
G	30	<20
H	1280	350
J	1720	430
K	750	360
L	500	20
M	1050	28
N	820	<20
O	320	<20
P	40	20
Q	40	<20
R	430	<20
S	33	<20
T	33	<20
U	450	<20

had very high Nb_2O_5 values there were also higher than average values of SnO_2 (Table 1).

Sphalerite

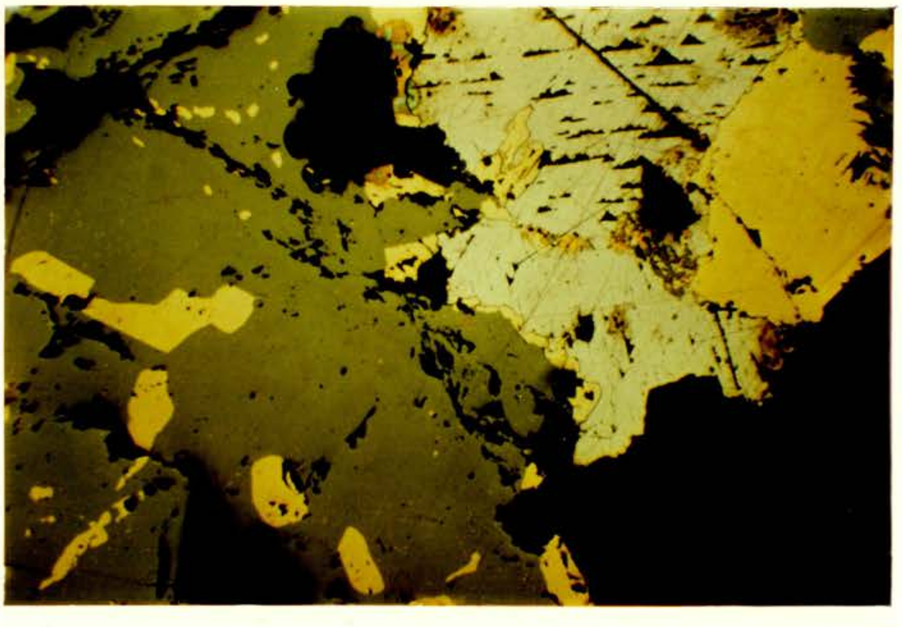
In contrast to previous literature on Nigerian mineralisation it has been found by the writer that sphalerite is the dominant mineral of the hydrothermal mineralisation phase and occurs to a greater or lesser extent in four of the five alteration phases described in Chapter 3, and in addition may occur in small amounts in quartz cassiterite veins. It may occur in masses 30 cm across, especially in the fluorite rich, chloritic phase of alteration. In massive form it varies from reddish brown to almost black with a resinous to sub-metallic lustre.

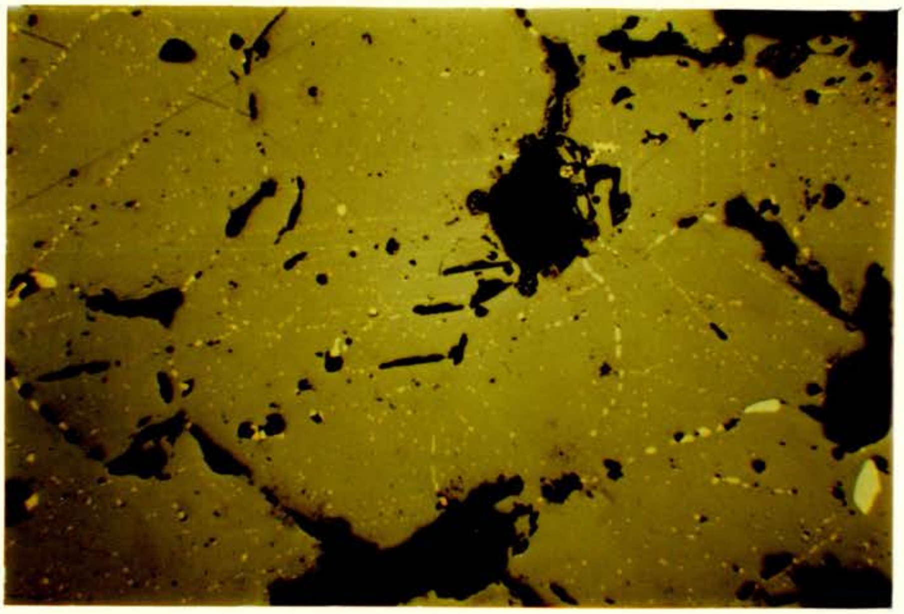
In thin section it shows characteristic dodecahedral cleavage and varies in colour from light yellow to orange or deep blood red. The dark red variety, according to Stanton (1972), is a high temperature variety, rich in Fe and/or Mn and conversely the yellow variety is a low temperature form depleted in these elements. The amount of Fe that can be accommodated in the sphalerite structure increases with increasing temperature, so that, subject to careful consideration of equilibrium conditions, the iron content of sphalerite is supposedly usable as a geological thermometer. In the Nigerian occurrences, however, it would be extremely difficult to establish equilibrium between sphalerite/pyrite/pyrrhotite. Also, Ramdohr (1969) has found that a high sulphur pressure in the fluids from which depositions have taken place results in transparent (i.e. iron poor) sphalerites, regardless of the temperature of



Photomicrograph 2. A polished ore section from locality 103, Rishi shows sphalerite with inclusions of chalcopyrite and gangue. Chalcocite occurs at the margin of the chalcopyrite.

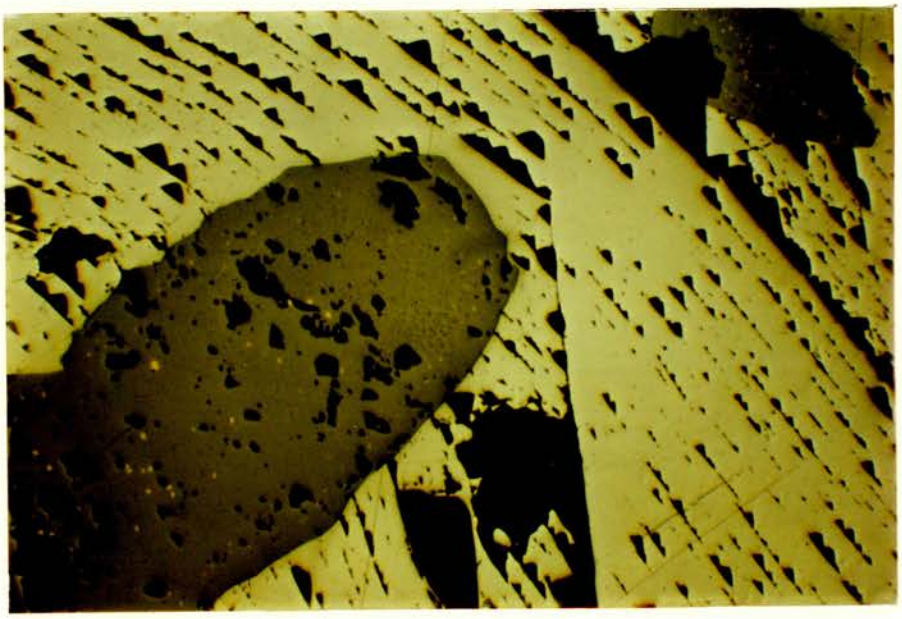
Photomicrograph 3. A polished ore section from locality 103, Rishi showing two generations of sphalerite: an early well crystallised uniform grey sphalerite surrounded by a later phase full of blebs of chalcopyrite.





Photomicrograph 4. A polished ore specimen showing sphalerite containing irregular blebs of arsenopyrite and gangue with trains of chalcopyrite inclusions. Locality 114, Dawa.

Photomicrograph 5. A polished ore specimen showing galena being replaced by sphalerite which contains chalcopyrite inclusions. Locality - the Adit, Liruei lode.



formation, so colour and iron content may not be reliable indicators of temperature of formation.

Deer, Howie and Zussman (1969) suggest that the different colours of sphalerite may be associated with certain elements, in particular that tin may be responsible for the red colouration, but increase of iron may mask this red colouration. In dark coloured sphalerites with a metallic lustre, the iron content varies from 6.5-10% with corresponding zinc values of 52.5 and 69.9%. Cadmium content decreases with increasing iron content. Analyses of two dark metallic looking sphalerites are shown below:

	Rishi	Liruei
Cu	4.21	0.25
Pb	0.14	0.96
Zn	52.5	60.9
Fe	10.2	6.48
Mn	0.02	0.04
Cd	0.19	0.59
Co	137 ppm	$<$16 ppm
Ag	61 ppm	5 ppm

If iron content does reflect temperature changes then the analyses samples from Rishi and Liruei fit the predicted pattern. The Rishi sample has come from the chloritic stage of alteration which is believed to be formed at a higher temperature than the sample from Liruei, which has been affected mainly by greisenisation and low-temperature silicification. The Rishi sphalerite contains 3.5% more Fe than the Liruei sample and contains sufficient iron to warrant the name marmatite.

Occasionally both red and yellow varieties occur in the same thin section, the former occurring as large anhedral patches with exsolved cubes of chalcopyrite along the cleavage, whilst the latter occurs as rims around patches of chalcopyrite. This exsolution phenomenon has also been acclaimed a good geothermometer, but Ramdohr (1969) has shown that some very high temperature sphalerites are only partly exsolved. Despite the presence of large amounts of impurities distributed within the sphalerites he describes, they have not exsolved; certain components, possibly Sn, serve to stabilise the structure and prevent exsolution.

It seems likely therefore from these considerations and those in Part 2 that there are several phases of sphalerite formation. A polished ore specimen of the analysed sphalerite from Rishi (photomicrograph 3) indicates two phases of sphalerite formation: an early well crystallised, uniformly grey phase surrounded by a slightly darker phase full of blebs of chalcopyrite. Other polished sections of sphalerite show inclusions of chalcopyrite, molybdenite (photomicrograph 4) and replacement of galena (photomicrograph 5). The blebs of chalcopyrite are attributed to exsolution on cooling from a higher temperature $ZnS-CuFeS_2$ solid solution.

In sulphide rich veins associated mainly with the chloritic stage of mineralisation, and to a lesser extent the sericitic stage, sphalerite occurs in association with cassiterite, galena, pyrite, chalcopyrite, molybdenite, greenockite, chalcocite, covellite, bornite, monazite and genthelvite. However in greisens it is associated with cassiterite, and occasionally galena and chalcopyrite.

In replacement veins that show some crude zoning, the sulphide-rich portion generally occurs towards the margins of the vein. However, in a section of one of the greisens of the Liruei lode sphalerite occurred marginally.

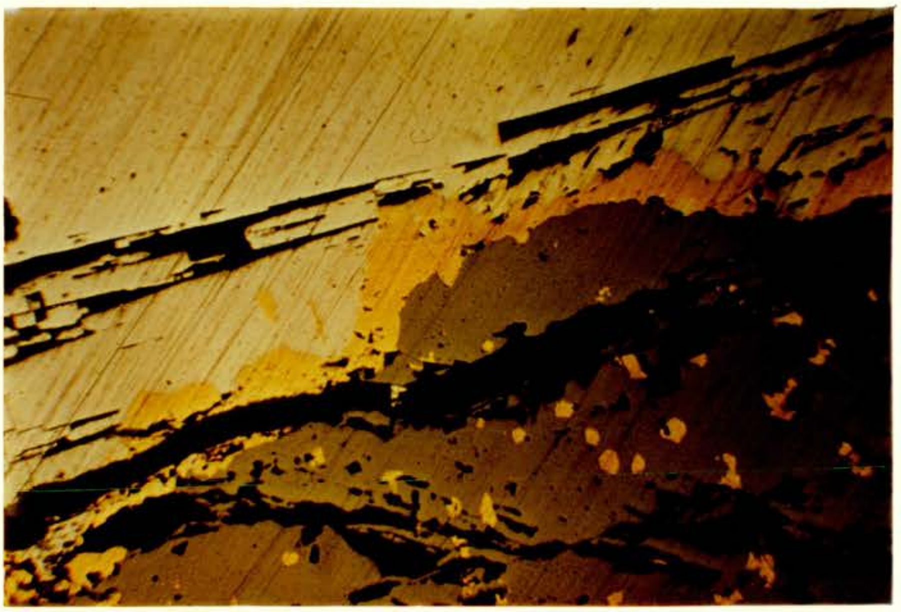
Only recently has sphalerite been identified in large quantities. It does not survive as an alluvial mineral and since the attention paid by the mining companies to primary mineral veins has been small on account of uneconomic tin values, the abundance of sphalerite remained unrecognised. In the Rishi area it has been observed and described by the writer (this volume) whilst at Liruei, Ririwai Mines Ltd. estimate that the production of zinc metal from the mine will be 6000 tonnes a year in comparison with 1,600 tonnes of tin metal. These figures suggest an overall tenor of 1.5-2% Zn and 0.5% Sn. The writer believes that some of the Rishi veins would show a similar Zn:Sn ratio of 3 or 4:1.

Chalcopyrite and other copper minerals

Chalcopyrite is the most common copper mineral and is widely distributed in replacement veins. It may be exsolved along cleavage traces in sphalerite, it may form rims around sphalerite and other minerals, or it may occur in massive form.

Chalcopyrite is not as abundant as some of the other sulphides and is only abundant in the fluorite-rich replacement veins formed in the chloritic stage of alteration although it may be found in minor quantities in some of the later stages.

Very small amounts of other copper minerals may be associated with the chalcopyrite. Bornite has been



Photomicrograph 6. A polished ore section showing two generations of chalcopyrite, one forming a rim around sphalerite the other forming blebs of inclusions within it. A late quartz vein cuts across galena, chalcopyrite and sphalerite. Locality 114, Dawa.

identified in some of the veins in the Rishi area (Fig. 18) and chalcocite and covellite have been observed in polished ores. Native copper was found in altered pyroxene granite at the adit in the Ropp Complex (Fig. 23, photo 15 Vol 1) Azurite, malachite and chalcanthite occur as secondary copper minerals.

In polished sections, chalcopyrite may contain silicate gangue in the form of streaks and blebs and may show minor replacement by chalcocite at its margin (photomicrograph 2). A very characteristic feature observed in the Nigerian polished ores is the blebs of chalcopyrite occurring as trains or in an irregular fashion within sphalerite. (Photomicrographs 2,3,5 & 6). Those from Dawa show that chalcopyrite is most abundant in sphalerite near its margins.

Since chalcopyrite is commonly intergrown with other copper and iron sulphides, analyses give atomic proportions which only approximate the ideal formula. Minor and trace amounts of numerous elements have been reported but some of these elements may be present as admixed impurities.

Molybdenite

Small flakes of molybdenite are common in mineralised veins and altered granite, but the only large scale occurrence is in riebeckite aegirine granite in the Kigom Hills. The molybdenite is scattered through the granite in rich clusters several centimetres across and in small disseminated flakes; it also forms a coating on joint surfaces.

Most commonly small quantities of molybdenite occur in veins, as at Ropp and Banke, or in veins and altered granite at Gyantagere Quarry in the Jos-Bukuru complex and Dawa in the Saiya-Shokobo complex. The molybdenite in the veins is in association with cassiterite, sphalerite, galena and copper minerals at Ropp, and with a similar assemblage, including genthelvite, in the Dawa veins. In altered granite at Dawa, molybdenite is common as quite coarse flakes but is not associated with any other ore mineral. At the Gyantagere Quarry molybdenite is abundant locally both in a very siliceous greisen, accompanied by sphalerite and copper minerals, and in altered Rayfield Gona granite. Molybdenite is not abundant in the Liruei lode although Jacobson (1947) has observed a few coarse crystals in the altered granite at Kerigateri Hill and also in the veins to the west of the Makota path.

In hand specimen it is unmistakable, steel blue in colour with a hardness of 1 and showing perfect cleavage in one direction.

In polished section it appears white in colour, is anisotropic and has a very strong bireflection.

Pyrite and Arsenopyrite

Pyrite and arsenopyrite do not occur in large masses like sphalerite and chalcopyrite although both are widespread in minor amounts, frequently in association, in many of the sulphide rich veins of the chloritic stage of alteration. Only minor amounts are recorded in later stages of alteration. Further study of ore polished sections may show these minerals to be more widespread and abundant.

In polished sections pyrite is usually isotropic. It is lighter in colour than chalcopyrite and has a higher reflectivity. It is also harder. Arsenopyrite is similar to pyrite but its reflectivity is slightly lower than pyrite and it is anisotropic (photomicrograph 4).

In the Liruei lode pyrite is found at the western end of the lode in association with galena and sphalerite. It is found in the Rishi and Dawa greisens and is common in the Ropp greisens especially those from Ropp Dome. Arsenopyrite has so far been identified only in veins from Dawa and Ropp.

Galena

Galena is not as abundant as zinc and copper sulphides in many of the replacement veins although it predominates at the western end of the Liruei lode near the adit.

It is presently being mined in the bed of the Gwame River at the base of the Kigom Hills (Fig. 2) where it occurs in a micaceous vein, cutting gneiss, 800 metres north of the steep Kigom escarpment where the molybdenite deposit occurs. The galena-rich vein extends at least 60 metres along an 035° strike and has been proved to a depth of 20 metres. The vein follows a fine-grained granite porphyry dyke, presumed to be of younger granite age. The galena which contains 0.5% silver has been found at depth in cubes as large as 15 cm across but usually occurs as cubes less than 5 mm in size. The maximum width of the galena-bearing vein is recorded by Buchanan et al., (1971) as 20 cm but the vein rapidly pinches and swells and often dies out altogether further along the strike. It has not yet been located by drilling in the higher ground to the south.

A galena-rich vein is also known to occur in the south Ropp area 1.5 km-west of the Mongu dyke. It is 30 to 45 cm wide and strikes 325°, parallel to the Mongu dyke.

Galena appears to be associated with a slightly later stage of mineralisation than the bulk of the sphalerite, chalcopyrite and pyrite, and should be regarded as predominantly associated with the sericitic phase although inevitably some will occur in other phases. However, in the polished section from the west of the Liruei lode there is evidence to show that galena is being replaced by chalcopyrite and sphalerite (photomicrograph 5) which indicates that one of the phases of sphalerite formation described earlier has formed after the galena in the Liruei lode (Fig. 16).

Greenockite (CdS)

Cadmium sulphide has been identified in one of the replacement veins from the basement locality 103 near Dutsen Rishi (Fig. 19). It was identified on an X ray scan of a thin section and shown to occur as discrete grains and not as a coating on sphalerite, although sphalerite does occur in other parts of the vein. It is associated with chloritised mica, chalcopyrite, monazite, fluorite and cassiterite. An analysis of sample 103 showed a cadmium content of 150 ppm.

There appears to be some confusion in the past literature as to the difference between greenockite and hawleyite. According to Stanton (1972) the β form which is hexagonal and has a wurtzite structure (α ZnS) is the variety greenockite. This changes at a temperature of 700 - 800°C into the α form, which is cubic and more dense with a sphalerite structure (β ZnS). This is the variety hawleyite. The colour of both varieties ranges from bright yellow to orange brown. It is proposed therefore that as the cadmium sulphide is in association with 'medium' temperature minerals it must be the variety greenockite.

Butler and Thompson (1967) record greenockite from the Kaffo valley albite-riebeckite granite at Liruei. It is in the form of thin yellow disseminations and patches on quartz and feldspar and is not associated with sphalerite since the only zinc bearing mineral in the granite is riebeckite. Their analysis of the granite showed a cadmium content of 0.25 ppm. They consider that the greenockite is evidence of a later mineralisation than the albitisation. The writer considers therefore that greenockite has been introduced as a result of the intrusion of the adjacent Liruei biotite granite.

Bismuthinite

As yet bismuthinite has only been identified in the Liruei Complex, where it has been found underground in the mine recently initiated to exploit the Liruei lode. It has been found growing in vugs in association with cassiterite and clay minerals and forms long fragile, slender greyish needles, with a metallic lustre, up to 10 cm long.

Bismuthinite with cassiterite has also been recorded in the earliest lode mineralisation which post-dates the sericitic alteration, at Llallagua in Bolivia (Sillitoe *et al.*, 1975).

Fluorite

Fluorite forms a common accessory mineral in many of the biotite granites and is colourless or pale green. It is also abundant in replacement veins, especially those associated with the chloritic phase of mineralisation (Chapter 3 Vol. 1) and is predominantly colourless with occasional deep purple patches. Rarely, as at locality 106 Rishi (Fig. 19) the fluorite is predominantly purple.

Both topaz and fluorite may occur in the same rock sample although the two minerals are never abundant when co-existing. Abundance of one appears to preclude the other.

There appears to be a massive input of fluorine associated with the chloritic phase of alteration, resulting in fluorite formation. There appears to be a direct correlation between ore concentration and fluorite content. Highest enrichment in sulphide ores, particularly of sphalerite, pyrite, arsenopyrite and chalcopyrite are always associated with fluorite-rich chloritised veins. One such sulphide-rich vein from locality 103 Rishi (Fig. 19) which contained sphalerite, chalcopyrite, greenockite and chalcocite in addition to cassiterite and monazite proved on analysis to contain 11.5% CaO. Although no analyses have been made for fluorine it is almost certain that nearly all the calcium will be present as fluorite.

Topaz

Topaz may occur as a pegmatitic mineral in association with beryl and quartz in biotite granites formed prior to jointing and consolidation of the granite. Crystals 7.5 cm long have been collected from the Tega granite of the

Amo complex (Fig. 2) in the Timber Creek area. They have also been found *in situ* in the Juga area of the Kwandonkaya complex and have been found in the river gravels of the Ganawuri and Jarawa Hills (Fig. 2 and 23).

The topaz is usually colourless but blue-green, yellowish and brownish varieties have been found. It is rarely of gem quality but should prove useful for fluid inclusion techniques.

Topaz also occurs as small grains in replacement veins formed by the breakdown of feldspar in the host granite into sericite, topaz and quartz. Nockolds and Richey (1939) give an equation representing the change from microperthite to sericite and topaz assuming that no alumina is added or removed:-

$$6(K_{.66}Na_{.33})Al_3Si_3O_8 + 3Fe + \overset{\text{added}}{2F_2} + 2(OH) \longrightarrow K_2Fe_3Al_2(AlSi_3O_{10})_2\,(OH_{.5}Fe_{.5})_4 + AlF_2AlSiO_4 + K_2SiO_3 + Na_2SiO_3 + 9SiO_2.$$

Topaz is a constituent of the greisen phase of alteration in addition to forming an accessory in the sericitic phase, although the topaz content is small in comparison with the amount in greisens from Czechoslovakia (Baumann *et al.*, 1974) or Alaska (Sainsbury 1960). The individual topaz grains are small and nowhere does it achieve the size of the pycnite crystals - up to 30 cm in size - from the Altenberg area of the eastern Krusne Hory. In replacement veins it only rarely forms grains greater than 1 mm in size.

The topaz has similar associations to that found in the Chaillats deposit of the Echassieres region of France where topaz may be associated with quartz, mispickel, cassiterite, wolframite, fluorite, pyrite, sphalerite, chalcopyrite, galena and other sulphides (Burnol 1974). Similarly topaz is recorded in cassiterite bearing veins from other tin provinces although it does not seem to occur in ore-bearing veins in Bolivia.

In contrast to the fluorite rich veins however, topaz-bearing veins contain cassiterite with only minor sulphide minerals. In thin section it appears as small colourless anhedral grains associated with either sericitic or siderophyllite mica.

Zircon

Zircon is a common accessory mineral in many of the younger granites. It occurs in two forms:

1). In the metamict state it may be associated with xenotime, thorite, and other minerals in the apogranites and with pyrochlore and other minerals in the albite riebeckite granites. In the apogranites the zircon may contain up to 5% Hf. When Hf is present to this extent the mineral is in the form of almost opaque brown grains and is usually uraniferous - this is the variety described as malacon. Zircon from the Rayfield area of the Jos/Bukuru complex and from Odegi in the Afu hills is Hf rich, and is separated from tin/columbite tailings by float tables and sold for Hf content. Some of the metamict zircon is anomalously magnetic and MacLeod and Jones (1955) showed that this is due to a high proportion of loosely combined iron. The degree of magnetic permeability is thought to be controlled by the relative proportions of non-magnetic Fe_2O_3 and magnetic

Fe_3O_4 in the mineral. Zircons can be demagnetised by leaching in cold HCl, changing from brown to white during the process. It is probable that cyrtolite is also present in the albitised granites and albitites but there is difficulty in recognition of the mineral and in a lack of uniformity of opinion on the difference between cyrtolite and malacon. Both varieties contain uranium and thorium in addition to rare earths, Hf and water. Also, both minerals are metamict which is shown by their partially or completely isotropic character and by their lower indices of refraction, specific gravity and hardness than normal zircons. A.N. Labuntsov (quoted by Petrova 1961) has proposed that U-Th zircon is malacon and that Th-U zircon is cyrtolite. Petrova (1961) describes malacon associated with albite, microcline, riebeckite, fergusonite, xenotime, ilmenite and astrophyllite from metasomatic veins and albitites. Caruba _et al._, (1975) believes that in certain cases metamict zircons arise from normal hydroxyled zircons that have crystallised out of a medium rich in fluorine and radioactive elements and that fluorine leads to the substitution $(SiO_4)^{4-}$ $(OH)^{-}_{4}$. This leads to weaker bondings causing the lattice to be vulnerable to the particles given off during the decay of radioactive elements.

2). In contrast, the zircons from other granite sources are colourless, brownish yellow to amber or grey and are transparent to sub-translucent. In the Jos/Bukuru complex, Williams _et al._, (1956) describe their technique for differentiating various granite types by the zircon colour- e.g. the straw zircons of the Jos granite and the pale brown zircons of the Ngell. This method of granite identification is sometimes useful where the granite is badly weathered and decomposed.

Thorite

Thorite is found in the late-stage albitised granites in close association with columbite. It occurs as anhedral, resinous grains averaging 1 mm in size and they are either a reddish brown or orange (variety orangite) colour. There seems to be a direct proportional relationship between thorite and columbite content and visible thorite is a good indicator of high columbite content.

The thorite collected from the Harwell area of the Jos-Bukuru complex is strongly radioactive as a result of the replacement of some of the thorium by uranium giving the variety uranothorite. Because of the radioactive content the thorite is in a metamict state.

Thorite and zircon appear to form a structural series and it appears that there is a definite trend from zircon, malacon (a uranium-thorium zircon) and cyrtolite (a thorium-uranium zircon) to thorite.

Petrova (1961) records replacement of malacon by thorite in Siberian albitites and evidence from a limited number of Nigerian thin sections indicates that a similar phenomenon takes place. In the zones in malacon that have become isotropic, point-like segregations which discolour the metamict malacon unevenly in shades of brownish red are suggested by Petrova to be ferrithorite. Petrova presumes that the development of isotropic properties in malacon is associated with the activity of thorium during replacement of the mineral by thorite.

Beryl:Genthelvite:Phenakite:Danalite.

Beryllium minerals, although not common, occur in mineralised veins and pegmatites in many areas of the Jurassic granite province. Most occurrences are situated in the northern part of the province where granitic members of the ring complexes are exposed at or near their upper contact with pre-existing rocks. Southward where erosion has proceeded to geologically deeper levels beryllium mineralisation is less conspicuous.

Beryllium occurrences are confined to the contact zones of biotite granites and microgranites; beryl has been recorded in contact facies of biotite granites and other Be minerals are usually restricted to mineralised veins that lie within biotite granites less than 30 metres from their contacts.

Beryl has been recorded from numerous localities, most notably in the pegmatites in the Tega biotite granite of the Amo complex, near the contact with the Teria biotite granite. Aquamarine can occasionally be found there in association with large colourless topaz crystals. Aquamarine has also been found in a pegmatitic vein in the Kulfana biotite granite of the Kwandonkaya complex - again from a contact facies.

The mineral genthelvite appears more common than beryl. It has been noted in the Dawa-Rishi area of the Saiya-Shokobo complex and has also been recorded and described by von Knorring and Dyson (1959) from the Harwell paddock in the Rayfield area of the Jos-Bukuru complex (Fig. 8) and by Berridge in Buchanan et al., (1971) from the Jarawa Hills. (Fig. 23).

Genthelvite, resembling massive almandine, appears as a late stage replacement mineral in the albitised granite at Harwell and the following description is given by von Knorring and Dyson (op cit). "In the locality it occurs as irregular knots and veins up to 18 cm across within an irregular vein of almost pure albite. Commonly, these knots consist of pure genthelvite, but may contain stumpy laths of albite. A selvedge of protolithionite from 0.5-2 cm thick with accessory thorite frequently crystallised as a peripheral growth on euhedral genthelvite". They also describe genthelvite in the microcline pegmatites as anhedral masses up to 5 cm across. In thin section the genthelvite is greyish or very pale pink and isotropic. It may be almost pure genthelvite or may be intimately intergrown with albite. Some triangular sections occur and the mineral is intersected by numerous cracks. It has inclusions of columbite, zircon and cassiterite and occasionally orangite in the specimens studied by von Knorring and Dyson (op cit).

The framework structure of genthelvite is formed by the linkage of SiO_4 and BeO_4 tetrahedra in approximately equal numbers, each corner oxygen being shared by two tetrahedra. Cubo-octohedral units are formed bounded by six rings of four tetrahedra parallel to $\{100\}$ and eight rings of six tetrahedra parallel to $\{111\}$: the six membered rings define a set of channels which intersect to form large cavities. The cavities are occupied by sulphide ions which are tetrahedrally co-ordinated by Zn and Fe (or Mn) ions. A chemical analysis of the mineral from Harwell (von Knorring and Dyson, op. cit.) shows that it is very similar in composition to that from silicified syenites from U.S.S.R. described by Gurvich et al., (1963). The Harwell sample showed 12.9% BeO compared to 11.9% in the genthelvite analysed by Gurvich and 40.56% Zn compared to 41.3% Zn. The formula for the Harwell genthelvite is:

$$Zn_3FeBe_3Si_3O_{12}S$$

whilst Gurvich et al., suggest:

$$(ZnMnFe)_8(BeSiO_4)_6S_2$$

an identical formula except for the inclusion of Mn which in the Harwell analysis was less than 2%. Gurvich does not give a figure for Mn content. He describes the associated minerals as willemite, fluorite, cyrtolite, tantalo-columbite and other minerals.

An analysis of genthelvite from the Ladini area of the Saiya-Shokobo complex showed greater Fe and Mn content than the Harwell sample, and a corresponding decrease in zinc content, although the zinc is still predominant so the name genthelvite still applies.

	Harwell		Ladini
SiO_2	30.70		31.5
TiO_2	n.d.		<0.1
Al_2O_3	0.18		n.d.
FeO	11.73		23.7
MnO	1.72		3.1
BeO	12.39		12.2
ZnO	40.56		25.5
MgO	tr.		<0.04
CaO	tr.		0.08
Na_2O	tr.		0.15
K_2O	n.d.		<0.07
S	5.50		~5.00
	102.78		101.00
O ≡ S	2.74	O ≡ S	2.49
	100.04		98.51

Further occurrences similar to these in Nigeria are also found in Russia. Chistyakova and Moleva (1966) describe idiomorphic crystals of genthelvite from drusy cavities in pegmatites cutting granites of the Kentskii massif in Central Kazakhstan. In this occurrence the genthelvite is in association with phenakite, bertrandite, quartz, haematite, iron-poor sphalerite, fluorite and green mica. Kalenov (1962) also describes helvite minerals from greisens in Mesozoic granites in Central Asia, whilst Gurvich et al., (1962) described occurrences of genthelvite from greisens in metasomatised biotite granites in the U.S.S.R. The quartz-siderophyllite greisens he described contain small quantities of cassiterite, garnet, fluorite and columbite in addition to the genthelvite. However in these environments the crystals are very small (usually <1 mm) in comparison to some Nigerian occurrences where masses 10 cm across have been found.

Gurvich et al., (1963) believe that genthelvite forms in the late stages of mineralisation as a result of pneumatolytic processes leading to the formation of quartz veins and silicification. The circulating solutions were rich in Si, S, Be, Zn and other cations (Fe,Mn,Pb, and Mo) and were poor in alumina; as Kalenkov (1959) has shown, that in the absence of Al genthelvite will form instead of beryl.

Beus (1956, 1962) describes further occurrences of genthelvite similar to those in the younger granite province of Nigeria. He believes that in granites which consolidate at comparatively high levels in the crust and where the formation of mineralised pegmatites is restricted, such Be as is present will precipitate in a hydrothermal pneumatolytic environment. He concludes from the available data that formation of high concentrations of Be in the hydrothermal process coincide in time and space with the formation of high concentrations of tungsten, tin and molybdenum. Some of the veins at Dawa contain genthelvite, cassiterite and molybdenite but no genthelvite-tungsten association has been found here yet. These genthelvite occurrences have been described earlier under locality headings.

Danalite ($Fe_4[\bar{B}e_3Si_3O_{12}]S$) has also been identified by Taylor (1959) from the Dawa area but a mineral collected from this locality by the writer, similar to the one he describes, showed on XRD and chemical analysis (see above) to have zinc predominant and therefore to be genthelvite. The danalite described by Taylor is dark red with a slightly greasy lustre and in thin section is pale pink. He quotes the specific gravity as 3.44 and R.I. as 1.754. X-ray spectroscopic analysis showed Fe as the major constituent with subordinate zinc and minor manganese with a trace of chromium. BeO content is given as 13.0%.

Phenakite (Be_2SiO_4) has been found by Taylor (1961) in small amounts in greisens from the Ladini-Dawa area in association with cassiterite, topaz, fluorite, danalite and sphalerite; it has also been recovered from crushed ore and from alluvials in the Dawa area.

Further investigations of mineralised veins both in hand specimen and thin section will probably show that beryllium minerals are even more widespread than the description above indicates.

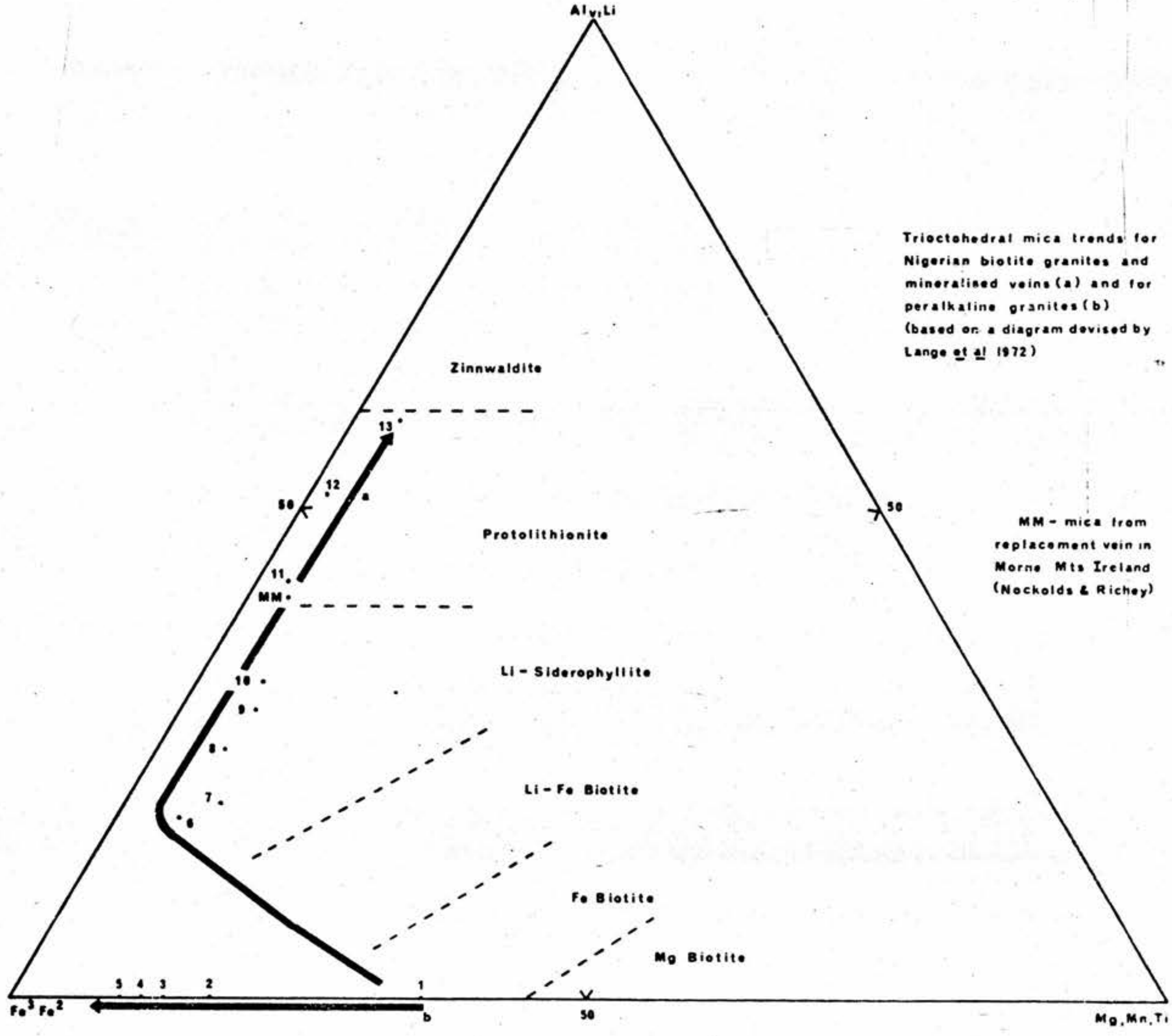
Mica

The micas in the Nigerian Younger Granite Province belong to two related tri-octahedral series. There are only small amounts of dioctohedral micas in the granites and these usually take the form of sericite, derived from the alteration of feldspars during successive stages of replacement vein formation.

Micas have been analysed from biotite granites, albitised granite and replacement veins (Fig. 24). The results have been plotted on a triangular diagram devised by Lange et al., (1972) and the structural formulae have been calculated using the method of Foster (1960) (Table **2**).

The magnesium content of nearly all the micas is extremely low and the biotites are therefore characterised by a high Fe^{2+}/R'' ratio which is greater than 0.94 except for the biotite from Sara Fier (Fig. 24) where the ratio is 0.78. The Fe^{3+}/R''' ratio is also high; ($R'' = Mg + Fe^{2+} + Mn \quad R''' = Al^{vi} + Fe^{3+} + Ti^{4+}$).

In the aluminous granites the micas are iron rich and belong to the phlogopite $\longrightarrow$ annite series. During the processes of replacement vein formation there is a progressive alteration of the micas and they become enriched in alumina and lithium; these micas belong to the siderophyllite $\longrightarrow$ protolithionite $\longrightarrow$ zinnwaldite series (Fig. 24). Thin sections show that during alteration there is a progressive destruction of the brown iron-rich annitic mica of the granite and a replacement by chlorite, with the growth of new blue-green siderophyllite which in turn may be overgrown or partly replaced by pale green, grey or almost colourless protolithionite. Early breakdown of



Al$_{VI}$,Li
Trioctahedral mica trends for Nigerian biotite granites and mineralised veins (a) and for peralkaline granites (b) (based on a diagram devised by Lange et al 1972)
Zinnwaldite
Protolithionite
MM - mica from replacement vein in Morne Mts Ireland (Nockolds & Richey)
Li - Siderophyllite
Li - Fe Biotite
Fe Biotite
Mg Biotite
13
12
a
50
50
11
MM
10
9
8
7
6
5 4 3 2 1
b
$Fe^3 Fe^2$
50
Mg,Mn,Ti

Figure 24

feldspars releases potassium which forms sericite and related minerals. This sericite forms small clustered grains at first marginal to, or within the feldspar and then completely replacing it. The sericite itself may also be altered during the greisenisation stage and break down to give silica with released potassium and aluminium. Perhaps some is transformed to tri-octohedral mica, since in the latest stages of replacement only blue-green siderophyllite or colourless protolithionite is found. Thin section comparisons of mica-rich greisens and host biotite granite reveal that not all the siderophyllite can have formed at the expense of the original annitic mica. Thus, late-stage mica formation, derived from sericite enriched in lithium and iron by volatiles, seems likely.

During the apogranitic phase of mineralisation, the albitisation which affected the perthites is accompanied by a modification of the micas. The biotites become enriched in alumina and lithium and depleted in Fe, and protolithionite appears to be the ultimate composition.

Physical properties

The annitic micas in thin section are pleochroic from dark green, brown or reddish brown to light brown, straw yellow or pale green with Refractive Indices of 1.65 to 1.68.

Micas which plot in the siderophyllite field are very dark green, almost black, in hand specimen, and in thin section are pleochroic from dark blue-green to pale green, straw yellow or almost colourless. Nockolds and Richey (1939) give Refractive Indices of 1.582-1.625 for similar micas. These are low refractive indices for iron-rich micas and the authors believed that this is partly due to the low amount of ferric iron and partly to the presence of relatively abundant fluorine which constitutes 2%.

The micas in the protolithionite field range in hand specimen from a pale blue-green colour (i.e. those near the protolithionite/siderophyllite boundary) to colourless. In thin section they may be pleochroic from very pale green to colourless or they may be grey to colourless with no pleochroic scheme. Von Knorring and Dyson (1959) give a refractive index of 1.612 for protolithionite from Harwell (Fig. 8).

Chemistry.

The annitic micas are rich in both Fe^{3+} and Fe^{2+} and during albitisation or replacement vein formation there is a gradual decrease of Fe^{3+} together with a marked decrease of Fe^{2+} and Ti between siderophyllite and protolithionite. There is also a gradual decrease of Na and a slight decrease of Mg although the Mg content is initially low. Variations in trace element proportions have yet to be investigated although preliminary evidence suggests that along the trend lithium-iron biotite $\longrightarrow$ siderophyllite $\longrightarrow$ protolithionite, there is a gradual increase in Zn, Be and Sn.

Considering the compositions of the iron-rich biotites from non-albitised granites it appears that they are relatively poor in Al_2O_3 since their values are generally less than 12%. In contrast, the micas from the albitised granites and replacement veins have Al_2O_3 values which exceed 12%. This characteristic confirms the evolutionary direction during recrystallisation (Fig. 5). These micas also contain more Al^{3+}, Fe^{3+}, Ti^{4+} ions than those from the non-albitised granites.

It is possible that the relative proportions of TiO_2 and Fe_2O_3 influence the colour. Hayama (1959) has shown that TiO_2, which is responsible for brown or red colour, is in general in very small amounts in greisen biotites. The green colour may also result from a high proportion of Fe_2O_3 to an average value of TiO_2.

Microprobe analysis (C. Abernethy pers. comm.) across a zoned mica, with a brown core and colourless zone followed by a green rim and white overgrowth, showed a progressive decrease, from the centre, in total iron and titanium, with increased aluminium. There was little chemical change between the inner brown core and the colourless zone which separated brown and green mica. This observation suggests that the margin of the biotite was 'bleached' before overgrowth by green siderophyllite and subsequently by protolithionite.

It is concluded therefore that primary biotites from the perthitic granites are rich in "annite" whilst the composition of green or white biotites characterising the albitised granites is comparable to the biotites from mineralised replacement veins and these range between siderophyllite and protolithionite. Fabries and Rocci (1965) have also reached similar conclusions about the biotites from the Tarraouadji massif in the Niger Republic.

Further work on mica composition is intended, Analysis of the micas from greisens and pegmatitic veins

	8	9	10	11	12	13
SiO_2	39.2	36.10	45.50	41.11	42.24	43.60
Al_2O_3	12.24	13.26	10.42	16.59	19.62	19.09
Fe_2O_3	2.98	7.29	2.48	2.00	2.02	2.57
FeO	29.0	25.30	28.10	22.61	18.64	14.80
MgO	0.03	0.05	0.13	0.13	0.08	0.10
CaO	0.15	0.20	0.40	n.d.	0.11	0.21
Na_2O	0.10	0.11	0.10	0.16	0.14	0.18
K_2O	8.15	8.82	6.09	9.92	8.84	9.54
H_2O^+	2.28	1.40	2.50	1.12	2.35	4.58
H_2O^-	1.61	1.27	1.56	0.29	0.48	0.82
TiO_2	2.58	3.07	2.47	0.30	0.18	0.88
F	-	-	-	5.49	5.02	-
S	-	-	-	-	0.02	-
MnO	0.43	0.51	0.40	0.67	0.30	0.84
Li_2O	1.40	2.73	1.96	1.85	1.90	3.34
	99.57	100.27	98.87	102.24	101.94	98.93
Less O				1.85	2.11	
				99.93	99.83	

	8	9	10	11	12	13
Be	6ppm	16ppm	19ppm			32ppm
Cr	10ppm	20ppm	30ppm			10ppm
Zn	1660ppm	2510ppm	3140ppm			1350ppm
Cd	6ppm	10ppm	30ppm			<6ppm

Formula calculated to 24

	8		9		10		11		12		13	
Si	6.36	8.00	5.74		6.96	8.00	6.30		6.22	8.00	6.16	
Al	1.64		2.26		1.04		1.70		1.78		1.84	
Al	0.69		0.22		0.84		1.30		1.62		1.34	
Ti	0.31		0.37		0.28		0.03		0.02		0.09	
Fe'''	0.39	6.30	0.93	6.71	0.30	6.31	0.23	5.72	0.22	5.33	0.29	5.
Fe''	3.93		3.36		3.60		2.90		2.29		1.75	
Mn	0.06		0.07		0.05		0.09		0.04		0.10	
Mg	0.01		0.01		0.03		0.03		0.02		0.02	
Li	0.91		1.75		1.21		1.14		1.12		1.90	
Ca	0.26	1.98	0.03	1.85	0.07	1.29	-	1.97	0.01	1.71	0.03	1.
Na	0.03		0.03		0.03		0.03		0.04		0.05	
K	1.69		1.79		1.19		1.94		1.66		1.72	
OH	2.47		2.80		2.55		1.15	3.81	2.30	4.63	5.09	
F							2.66		2.33			

Analysis of the micas from some of the granites.

	1	2	3	4	5	6	7
SiO_2	35.94	33.10	35.36	30.72	35.14	37.58	37.38
Al_2O_3	11.71	9.77	10.90	11.54	6.44	15.43	11.89
Fe_2O_3	5.00	12.19	3.76	11.62	4.40	4.96	4.38
FeO	23.91	24.48	31.38	26.49	34.92	25.00	28.65
MgO	6.35	1.95	1.06	0.15	0.43	0.32	0.22
CaO	1.65	2.37	n.d.	1.70	0.97	1.15	0.16
Na_2O	0.42	0.41	0.97	0.44	0.74	1.67	0.39
K_2O	6.95	5.43	9.04	4.35	8.92	7.34	8.78
H_2O^+	4.15	5.55	3.74	8.27	3.12	-	1.84
H_2O^-	0.03	1.94	n.d.	0.27	0.06	0.52	0.67
TiO_2	3.33	2.96	3.04	3.04	2.87	1.42	1.84
P_2O_5	nil	nil	nil	0.06	0.03	tr.	n.d.
F	n.d.	n.d.	n.d.	n.d.	n.d.	2.01	4.36
MnO	0.50	0.64	0.65	0.64	0.53	0.20	0.41
Li_2O	n.d.	n.d.	n.d.	n.d.	n.d.	-	0.77
	99.94	100.55	99.90	99.29	101.04	101.85	97.60
Less O					1.04	1.86	
					100.00	99.99	

Formula calculated to 24

	1	2	3	4	5	6	7
Si	5.616	5.282	5.798	4.744	5.984	6.05	6.03
Al	2.156	1.842	2.107	2.106	1.274	1.95	1.97
Fe'''	0.228	0.876	0.095	1.150	0.544	-	-
	8.0		8.0		7.72	8.0	8.0
Al	-	-	-	-	-	0.98	0.29
Ti	0.392	0.354	0.374	0.352	0.362	0.17	0.22
Fe'''	0.360	0.588	0.368	0.202	-	0.64	0.53
Fe''	3.124	3.268	4.303	3.428	4.912	3.36	3.86
Mn	0.066	0.054	0.091	0.084	0.074	0.03	0.06
Mg	1.476	0.464	0.259	0.034	0.104	0.08	0.05
Li	-	-	-	-	-	-	0.50
	4.418	4.728	5.393	4.10	5.452	5.26	5.5
Ca	0.276	0.406	-	0.284	0.172	0.20	0.01
Na	0.128	0.126	0.309	0.128	0.240	0.52	0.12
K	1.286	1.106	1.892	0.856	1.908	1.51	1.81
	1.690	1.638	2.201	1.268	2.320	2.23	1.9
OH	4.328	5.902	4.091	8.544	3.498	3.01	1.98
F	-				1.300		2.22
					4.798		4.2

1. Fe-biotite from Fier hastingsite biotite granite, Sara Fier. Analysis taken from Bull. 32 of Geol. Survey.
2. Lepidomelane (Foster) from Kula hastingsite biotite granite, Pankshin. Analysis taken from Bull. 32 of Geol. Survey.
3. Annite from early hastingsite biotite granite, Amo. Analysis taken from Bull. 32 of Geol. Survey.
4. Lepidomelane taken from Daffo hastingsite biotite granite, Sha Kaleri. Analysis taken from Bull. 32 of Geol. Survey.
5. Annite taken from riebeckite biotite granite, Amo. Analysis taken from Bull. 32 of Geol. Survey.
6. Li-siderophyllite from Kudaru biotite granite. Analysis taken from Bain (Jacobson, Imperial Institute).
7. Li-siderophyllite from Liruei biotite granite. Analysis taken from Bull. 32 of Geol. Survey.
8. Li-siderophyllite from greisen in Rishi biotite granite, Saiya/Shokobo Complex. Analysed by R. Batchelor, St. Andrews.
9. Li-Fe-siderophyllite from pegmatitic vein in Rishi biotite granite. Analysed by R. Batchelor.
10. Li-siderophyllite from greisen in Rishi biotite granite, Saiya/Shokobo Complex. Analysed by R. Batchelor.
11. Protolithionite from Rayfield Gona granite, Harwell area, Jos/Bukuru Complex. Analysed by von Knorring and Dyson (1959).
12. Protolithionite from greisen in biotite granite, Liruei. Analysis taken from Bull. 32 of Geol. Survey.
13. Protolithionite from quartz-mica pegmatitic vein, Sabon Gida South biotite granite - Jos/Bukuru Complex. Analysed by R. Batchelor.

especially using microprobe analyses, to study the trace element distribution between micas from perthitic granites, albitised granites and mineralised veins.

Xenotime/Monazite

These rare earth phosphates have been mistakenly considered in the past to have the same paragenesis. However, the present study has shown that xenotime (yttrium phosphate) belongs to the apogranitic dispersed phase of mineralisation whereas monazite belongs to the postjoint phase of mineralisation.

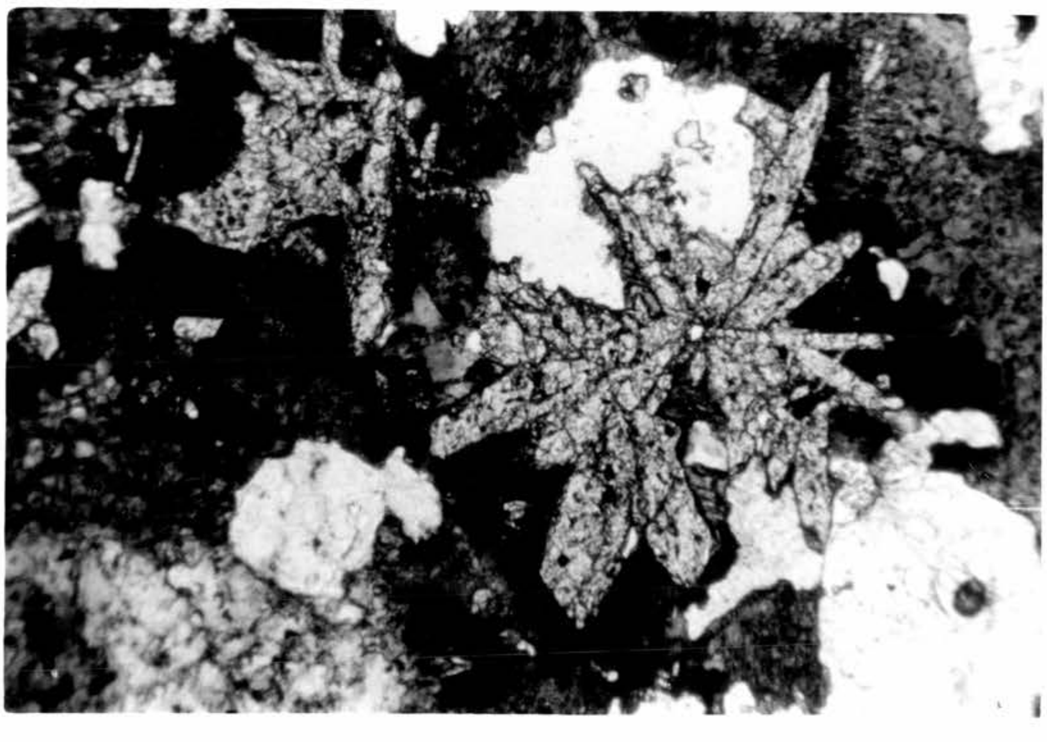
Monazite, a cerium phosphate, has been identified as a euhedral mineral in altered veins predominantly associated with the chloritic stage of alteration in the Rishi area. Analyses of the two minerals for ATMN produced widely differing results at different laboratories - the following analyses are an average of these results.

	Monazite	Xenotime
P_2O_5	26.7	26.9
SiO_2	-	1.5
Fe_2O_3	-	0.48
Y_2O_3	1.45	28.9
La_2O_3	11.8	-
CeO_2	29.6	-
Pr_6O_{11}	4.1	-
ZrO_2	-	1.08
Nd_2O_3	9.4	0.23
Sm_2O_3	0.95	0.64
Gd_2O_3	1.2	1.24
Tb_4O_7	-	0.64
Dy_2O_3	0.39	6.15
Ho_2O_3	-	1.5
Er_2O_3	-	6.55
Tm_2O_3	-	1.55
Yb_2O_3	-	12.7
Lu_2O_3	-	1.55
U_3O_8	0.32	0.2
ThO_2	5.45	0.94
Loss on ignition	4.8	1.7
	96.16	94.45

In thin section, monazite forms colourless to greyish euhedral crystals which are generally less than 0.01

Photomicrograph 7. Cross section of a euhedral monazite crystal under crossed nicols showing weak birefringence. It is set in a matrix of fluorite quartz and chloritised mica with a large anhedral isotropic sphalerite adjacent to the monazite. From locality 103, Rishi. x 20.

Photomicrograph 8. Cross section showing rosettes of monazite crystals, in plane polarised light, set in a matrix of fluorite, quartz and chloritised mica. Locality as above, x 20.



Bibliography.

Alderton, D.H.M. 1976. The Evolution of the Cornubian Metallogenic Province, South-West England. In preparation.
Halliday, A.N.
Jackson, N.J.
Sheppard, S.M.F.

Banerjee, S.K. 1969. Origin of weak ferromagnetism and permanence in natural cassiterite crystals. Journ. of Geoph. Res. 74, no. 15, p. 3789-3795.

Banerjee, S.K. 1970. Mossbauer study to find the origin of weak ferromagnetism in cassiterite. Nature 5228, 225, p. 173-175.
Johnson, C.E.
Krs. M.

Barsukov, V.L. 1966. On the forms in which tin is transported in hydrothermal solutions. Geokhimiya no. 8, p. 943-948.
Kuril'chikova, G. Ye

Baumann, L. 1974. Metallogeny of Tin and Tungsten in the Krusne Hory - Erzgebirge. IGCP Metallization Association with Acid Magmatism Symposium, Karlovy Vary 1974. Published by the Geological Survey Prague.
Stemprok, M.
Tischendorf, G.
Zoubek, V.

Beus, A.A. 1956. Beryllium. The State Publishing Office of Scientific and Technical Literature on Geology and Conservation of Mineral Resources.

Beus, A.A. 1962. Beryllium. Evaluation of Deposits during prospecting and exploratory work. W.H. Freeman and Company.

Buchanan, M.S. 1971. The Geology of the Jos Plateau vol. 2. The Younger Granite Complexes. Bull. Geol. Surv. Nigeria, 32.
MacLeod, W.N.
Turner, D.C.

Burnol, L. 1974. Granites Acides du Nord-Ouest du Massif Central Francais et Mineral-isations Associees. I.G.C.P. Metallization Associated with Acid Magmatism Symposium Karlovy Vary 1974. Published by BRGM Paris.

Butler, J.R. 1967. Cadmium and zinc in some alkali acidic rocks. Geochimica et Cosmochimica Acta, 1967, Vol. 31, p. 97-105.
Thompson, A.J.

Caruba, R. Baumer, A. Mano, J. Turco, G.	1975.	Etude comparative des proprietes respectives de zircons hydroxyles synthetiques et de zircons metamictes naturels; hypothese de genese des malacons. Petrologie 1975, tome 1, no.1 p. 57-70.
Chistyakova, M.B. Moleva, B.A.	1966.	Genthelvite from rock crystal voids in the Kentsk granite massif Central Kazakhstan. Tr. Mineral. Muz. Akad. Nauk, SSSR, No. 17, p. 240-5. (in Russian).
Clark, A.H.	1970.	Manganese-Iron Ratios in Wolframite, South Crofty Mine, Cornwall: A discussion. Econ. Geol. 65, p. 889-892.
Deer, W.A. Howie, R.A. Zussman, J.	1969.	An Introduction to the Rock Forming Minerals. Longmans.
Fabries, J. Rocci, G.	1965.	Le massif granitique du Tarnaouadji (Republique de Niger). Etude et signification petrogenetique des principaux mineraux. Bull. Soc. franc. Miner. Crst (1965) LXXXVIII p. 319-340.
Foster, M.D.	1960.	Interpretation of the Composition of tri-octohedral micas. Prof. Pap. U.S. geol. Surv. 354-B, p.11-49
Greaves, G. Stevenson, B.G. Taylor, R.G.	1971.	Magnetic cassiterites from North Queensland. Econ. Geol. 66, p. 480-487.
Groves, D.I. Baker, W.E.	1972.	The Regional Variation in Compositions of Wolframites from Tasmania. Econ. Geol. 67, p. 362-368.
Grubb, P.L.C. Hannaford, P.	1966.	Magnetism in cassiterites.Mineralium Deposita 2, p. 148-172.
Gurvich, S.I. Brusnitsyna, N.V. Dusyatskii, V.A. Lun'ko, V.F.	1962.	A new type of Beryllium-Zinc Mineralisation Razv. i. okhr. nedr. 8 (In Russian).
Gurvich, S.I. Zubkov, L.B. Galetskiy, L.S.	1963.	Genthelvite from silicified syenite Doklady Akademii Nauk SSSR. 150, No. 5, p. 1123-1124.
Haag, H.L.	1943.	Wolfram in Nigeria: With notes on cassiterite, wolfram and columbite. Trans. Inst. Min. Metall. lii.

Hanus, V.
Krs, M. 1965. Cassiterite as a carrier of palaeomagnetism. Nature 5011, 208, p. 675-677.

Hayama, Y. 1959. Journal Geol. Soc. Japan, 65, 21.

Hesp, W.R.
Rigby, D. 1972. The transport of tin in acid igneous rocks. Pacific Geology, 4, p. 135-152.

Jacobson, R.R.E. 1947. The Younger Granite Complex of the Liruei Hills, Nigeria. Unpubl. thesis Univ. of London.

Jacobson, R.R.E.
Webb, J.S. 1946. The pegmatites of central Nigeria. Bull. geol. Surv. Nigeria, No. 17.

Kalenov, A.D. 1959. A greisen type of helvite mineralisation. Zap. Vses. Min. ob-va, ch.88, vyn. 4.

Von Knorring, O.
Dyson, P. 1959. An occurrence of genthelvite in the Younger Granite Province of Northern Nigeria. Amer. Min. 1959, 44, p. 1294-1298.

Lange, H.L.
Tischendorf, G.
Pälchen, W.
Klenn, I. and Waltraut, O. 1972. Zur petrographie und geochemie der granite des Erzgebirges-Fortschritte der Metallogenie in Erzgebirge, B. Geologie 21 p. 457-493.

MacLeod, W.N. 1956. The Geology of the Jos-Bukuru complex with particular reference to the distribution of columbite. Rec. Geol. Surv. Nig. 1954, p.17-34

MacLeod, W.N.
Jones, M.P. 1955. The effects of heat and hydrochloric acid on the properties of some Nigerian minerals. Colon. Geol. Miner. Resour., 5, p. 166-173

MacLeod, W.N.
Turner, D.C.
Wright, E.P. 1971. The Geology of the Jos Plateau, Vol. 1, General Geology. Bull. Geol. Surv. Nigeria, 32.

Nockolds, S.R.
Richey, J.E. 1939. Replacement veins in the Mourne Mountain granites, Northern Ireland Am. Journ. Sci. 237, No.1, p.27-47.

Petrova, E.A. 1961. Malacon from albitites in Siberia in "New Data on Rare Element Mineralogy" Ed. A.I. Ginzburgh p. 121-129.

Ramdohr, P. 1961. Magnetische Cassiterite Comptes Rendues Soc, Geol. Fin., 33, p.473-480.

Ramdohr, P. 1969. The Ore Minerals and Their Intergrowths. Pergammon Press.

Raulais, M. 1948. Sur la decouverte de wolfram dans le jeune granite a biotite de l'Aïr (Niger) CR. Ac. Sc. No. unknown.

Sainsbury, C.L. 1960. Metallisation and Post Mineral Hypogene Argillisation, Lost River Tin Mine, Alaska. Econ. Geol. 55, p. 1478-1506.

Shcherbina, V.V. 1963. The occurrence of elements as chlorides and fluorides in nature, depending on the position of the elements in the Periodic Table. Geochem. 1963, No. 8, p. 751-764.

Sillitoe, R.H., Halls, C., Grant, J.N. 1975. Porphyry tin deposits of Bolivia. Econ. Geol. 70, No. 5, p. 913-927.

Stanton, R.L. 1972. Ore Petrology. McGraw-Hill, New York.

Studentikova, Z.V., Ivanova, G.F., Bryzgalin, O.V. 1967. On the Possible Source and Transportation of Tungsten in the Formation of Deposits of Greisen Type. in "Problems of Hydrothermal Ore Deposition" Ed. by Z. Pouba and M. Stemprok. E. Schweizerbart'sche Verlagsbuchhandlung - Stuttgart.

Taylor, J. 1959. Occurrences of Beryllium in the Younger Granites of Northern Nigeria. Geol. Surv. of Britain Atomic Energy Division Report No. 221.

Taylor, J. 1961. Investigations of the Economic Potentialities of Danalite-Genthelvite Occurrences in Northern Nigeria. Geol. Surv. of Britain Atomic Energy Division, Report No. 237.

Taylor, R.G., Hosking, K.F.G. 1970. Manganese-Iron Ratios in Wolframite South Crofty Mine, Cornwall. Econ. Geol. 65, No. 1, p. 47-53.

Vincent, C.A., Weston, D.G.C. 1972. Preparation and Properties of Semiconducting Polycrystalline Tin Oxide. Journ. Electrochem. Soc. 119, No. 4.

Williams, F.A., Meehan, J.A., Paulo, K.L., John, T.U., Rushton, H.G. 1956. Economic Geology of the Decomposed Columbite Bearing Granites, Jos Plateau. Econ. Geol. 51, No. 4, p. 303-332.