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Thesis
Submitted for the Degree of Doctor of Philosophy
In the University of Durham.

The Petrology of The Older Granites Around Bauchi, Nigeria,

by

MOSOBALAJE OLALOYE OYAWOYE, B.Sc., F.G.S.

Hatfield College
and
The Department of Geology
Durham Colleges.

Durham.
June, 1959

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THE PETROLOGY OF THE OLDER GRANITE AROUND BAUCHI NIGERIA

ERRATA

Page 10 line 12 for abundance and soon, read abundance and th
the rock soon.

Page 21 line 17 for clacsilicate, read calcslicate.

Page 23 line 8 for grantie, read granite.

Page 150 line 13 for euqilibrium, read equilibrium.

Page 163 line 5 for filed, read field; line 12 for underformed,
redd undeformed.

Page 164 line 12 for discontnuos, read discontinuous.
line 19 for seperated, read separated.

Page 175 line 12 for fluorine, read fluorite.

Page 192 last line for fig 21, read fig 19.

FRONTISPIECE

The Bauchi district is characterised by isolated groups of hills and inselbergs seperated by wide, flat-lying plains which are actually low domes. The picture is taken from one of these domes just south of Gurn hill looking southwards. The hills to the right are the lower members of the Kasuma hills, and on the horizon the Baskin hills are just discernible. The isolated hill in the centre is Runde hill, an inselberg; to the extreme left on the horizon are the Jura hills.

PREFACE

The investigation which is the subject of this thesis was carried out in the Department of Geology, Durham Colleges in the University of Durham, under Professor K. C. Dunham, F.R.S. During the first year the work was supervised by R. Phillips, B. Sc., and subsequently by C. H. Emeleus, D.Phil.

The writer is indebted to Professor Dunham for giving him the opportunity to do this research work under him, and for much assistance and encouragement.

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I am finally much indebted to my mother; my brother, Mr. Banji Oyawoye for financial help, and to my wife for devotion and encouragement which made this work possible.

The Petrology of the Older Granites around Bauchi, Nigeria

Abstract.

The area studied is situated in the North East of Nigeria and consists of a rock complex known as the Older Granites to differentiate it from the granites of the ring - dyke complexes, termed the Younger Granites. The rocks in the district are classified as metasediments, migmatites, Biotite Granite, Biotite Hornblende Granite, Fayalite Quartz Monzonite and Quartz Diorite.

In the field the rocks were examined in detail and a geological map of the area constructed. The contact relationships of the members of the Older Granites are described and results of detailed petrographical examination given. In particular, a study has been made of the microstructures, including perthite amd myrmekite; from various considerations the microstructure appear to indicate a metasomatic origin for large microcline crystals found in these rocks. Various lines of evidence for and against both magmatic and metasomatic origins for the Bauchi rocks are examined; the equivocal nature of much of this evidence is stressed.

The weight of petrographic and field evidence, backed by the plutonic setting and spatial distribution of the different rocks, is thought to indicate a metasomatic origin for the migmatites, the Biotite Granite and the Biotite Hornblende Granite. The Quartz Diorite and the Fayalite Quartz Monzonite are demonstrated to be related the Charnockite series; they originated by a soaking of the Biotite Granite and the Biotite Hornblende Granite respectively with dilute basic magma or solutions under deep seated conditions. It is suggested that the basic solution could have originated from the basic material displaced in the zones of granite and migmatites. The petrology of the Bauchi rocks is considered in the light of problems relating to granites and charnockites in general.

The account includes ten chemical analyses of rocks from the Bauchi area, as well as optical data on the minerals and numerous modal analyses.

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CHAPTER I. INTRODUCTION.

Location and Topography.

Bauchi town, in the centre of the district under study, is situated in the north-east of Nigeria. It is in the middle of one of the extensive outcrops of the Older Granites which, with the Archaean Schists, amphibolites, granulites and calcsilicates are, generally termed the Undifferentiated Basement Complex in the provisional map of Nigeria, (Fig. 1). The area studied lies between longitude $9^{\circ}45'$ and $9^{\circ}55'$ East and latitude $10^{\circ}15'$ and $10^{\circ}23'$ North, immediately East of the central plateau of Nigeria and the Younger Granite ring-dyke complexes.

The district is generally about 2,000 feet above sea level and according to Bain (1926) the general fall of the country is to the East and South. The country appears as a flat plain broken only by inselbergs or island hills, but this plain is actually a number of low domes which is only truly appreciated as the crests are reached and extensive views of the surrounding countryside suddenly emerge (Frontispiece).

The inselbergs occur in seperated clustered groups of various shapes among which whale backs, turtle backs, and cones (much resembling volcanic cones)

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are the most common. (Plates 1 and 2.) Less commonly the Older Granites form jagged chains of hills much resembling the hills of the Younger Granites; the Buli hills being the most prominent example of this (Plate 2 fig. B.)

All the hills, whether whale back, cone, or jagged chain, tend to be elongated in a north-east south-west direction, parallel to the general strike of the foliation of the rocks. (Fig. 2)

Field work and nature of outcrops.

Two field investigations lasting eight and five months respectively were carried out, both during the dry season when the grasses were burnt laying bare the surface and thus enabling the writer to study practically all exposures. The outcrops are very widely seperated and almost entirely limited to the hills and their immediate surroundings. The degree of exposure may be appreciated from the accompanying map (A) on which the principal groups of outcrops are indicated.

Mapping was done on aerial photographs, transferred directly on to a preliminary map of the same scale and subsequently on to a reduced copy of the same map. The aerial photographs were supplied by the Survey

Department of the Northern Region of Nigeria who also prepared and supplied the two maps. The district has many good roads and numerous foot paths (see Map A) all clearly shown on the photographs.

History of Geological Investigation.

The Older Granites of Bauchi district were first investigated by Falconer (1911) who described them during the general economic survey of Northern Nigeria. In 1926 Bain mapped and examined them in some detail. Since that date the granites of this district have not been examined, but some study of Older Granites in other parts of Nigeria has been done, mostly as a subordinate investigation of the Younger Granite masses which they surround. In 1949, the Osi area in Ilorin province was studied by DeSwardt and King (1949), and more recently, the Ilesha district by DeSwardt (1953). Even from this scanty information the great similarity of most of the Older Granites extending over nearly two-thirds, of the country, is very striking. Some of the descriptions of the Older Granites by King and DeSwardt (1949) and DeSwardt (1953) could be used word for word for certain of the granites of the Bauchi district.

Geological Setting.

The gneisses, gneissose granties, granites, granodiorites, diorites and migmatites in this complex are collectively known as the Older Granites. This distinction appears to have been first made by Falconer (1911) to differentiate them from the Plateau Granite ring intrusions known as the Younger Granites. He believed that the Older Granites were collectively an ancient igneous complex. Stratigraphical age determination of both the Younger and the Older Granites is impossible and very little can be said beyond stating that the latter are older than the former. For no stated reason it is commonly believed th that the Older Granites are definitely PreCambrian and the Younger Granite either late PreCambrian or early Paleozoic (Macleod, personal communication).

Apart from the more obvious fact that the Younger Granites are ring-dyke intrusions and the Older Granites are of doubtful mode of emplacement, various distinctions have been made between the two classes. Raeburn (1926) suggested that the Younger Granites are, in contrast, soda-rich and this chemical difference was expanded by Mackay (1949):- "Chemically the older have less soda, somewhat less potash and more lime than the younger". Genetically, the Older Granite, unlike the Younger, is held to be more deep seated and there is considerable doubt that they were ever molten (Mackay, 1949). The Older Granites generally show some foliation (Falconer, 1926) and are less resistant to erosion, weathering to isolated groups of inselbergen, whereas the Younger Granites form a high dissected plateau with steep escarpments (Jacobson and others, 1958).

The oldest member of the basement complex are granulites, amphibolites and calcsilicate rocks. The granulites, associated with subordinate calcsilicate rocks, occur mostly as thin lensoid relics in the gneisses, sometimes sharply demarcated and at other times grading into them. Commonly they form irregular elongated strips intercalated between quartz-feldspathic bands thus forming lit-par-lit gneiss; irregular patches showing microfolding are common but too far apart to be correlated to form any intelligible picture.

The calcsilicate rocks in general appear as narrow elongated bands in the ~~granite~~ granulite. Sometimes they can be followed for a few yards, but in general are rather short and discontinuous. Their contacts with the surrounding granulite are sharp but comformable. North of Miri, the largest calcsilicate body forms a wall-like body about 18 inches wide, standing nearly three feet above its surroundings and almost twenty-five yards long.

The gneisses in which these rocks form patches are of two types, feldspathised and unfeldspathised. The latter was probably that designated "soft gneiss" by Falconer (1911) and the former is termed "hard gneiss". Falconer's statement that no boundary can be definitely placed between these two was confirmed. The "hard gneiss" has developed prominent microcline porphyroblasts from 0.02 sq.cm. to 0.1 sq.cm. in size and the "soft gneisses" form scattered patches within it.

The "soft gneiss" is generally strongly lineated and is more or less always deeply weathered (probably why it is called "soft gneiss" by Falconer, since he gave no reason for so designating it). The "hard gneiss" is much fresher and in most cases it is nearly free of gneissose banding being more homogeneous and granitic. This led Bain (1926) to describe it as the "feldspathic" granite. In the present work it is called Biotite granite (Map A). The rock is characterised by extremely variable distribution of biotite and microcline, the former increasing locally where granulite or amphibolite ghost relics (schlieren) are common.

In some places the rock has been baked along narrow zones by underlying basic dykes becoming brick red in colour, more feldspathic and with decomposition of the biotite.

Quartzo-feldspathic dykes are common and often associated with veins. With increase in the veins and dykes, the rock gradually gives way all along a north-western front to agmatitic gneiss where the gneisses are dissected into angular blocks of various shapes. (Plate 3) Bain described this as brecciation (Bain 1926). In this agmatitic mixture the dyke rocks are as abundant as the gneisses. Several generations of the dykes and veins can be observed and the later ones may appear to displace the earlier ones slightly. They vary considerably in width from a few inches to two feet and in length from a few yards to several tens of yards. These dykes may be pegmatitic, coarsely granitic, or aplitic. When pegmatitic they usually show a zoning from a central line of pegmatite, laterally into granite. Generally they are never sharply demarcated from the gneisses, though the colour contrast gives the contrary impression. The enclosed blocks show no relative displacement as result of being so dissected by the "metatectites" (the dykes and veins, Barth 1951, p. 365) and the foliation in one block is concordant with that of the surrounding blocks. (fig. 3) Large microcline porphyroblasts no doubt of the material of the metatectite are commonly present in these blocks. (fig. 3).

Further north the agmatitic gneiss gradually merges with mixed gneisses and pegmatite dykes. The dykes strike approximately 280° and are concordant with the general lineation of the gneisses. They are chiefly composed of microcline with some quartz, and may contain some muscovite. They vary in width from one to three feet and may be zoned with muscovite and quartz towards the centre and microcline on the outside. Locally, there may be more pegmatite dykes than gneisses.

The feldspathised gneiss, the agmatitic gneiss and the mixed pegmatite dykes and gneisses are collectively regarded as migmatites by the present writer.

Surrounded by an aureole of Biotite Granite, there are the rocks of the "Bauchi Batholith". They consist of three principal members: The Fayalite-Quartz Monzonite, the Biotite-Hornblende Granite and the Charnokitic Quartz Diorites. Between these, local variations occur which do not fall into this broad classification (Map B).

The Fayalite-Quartz Monzonite covers the whole of Bauchi town and extends north-westwards and eastwards into the Kwini and Dumi Hills respectively, an area of nearly twenty square miles. Another exposure covering Baskin Hill and extending southwards for nearly two miles is about two square miles in area. Smaller outcrops occur around Miri and a charnokitic phase appears around Yelwa bridge on Kwalanga river (Map A).

The rock has a somewhat crushed appearance around Bauchi town. Jointing is poorly developed and weathering is largely by exfoliation resulting in whale backs (Plate 1 fig. B), with individual boulders forming large cannon balls due to onion weathering. Lineation, so common a feature of rocks in this district, is weak or totally absent.

Inclusions are common. These are of a dense fine grained granitic rock (Plate 4, Fig. A.) which microscopic examination reveals to be a microcline granite with low mafic (biotite-hornblende) content.

The rock was called Porphyritic Older Granite, "syenitic type" by Bain (1926) and described as a pyroxene syentie - thd fayalite being mistaken for "enstatite" and ferrohedehbergite for "magnesium diopside" Bain 1926 p.47).

In the north-east the rock grades into the Quartz-Diorite, patches of which are to be found inside it all along the east and south margins (Map B). The Quartz-Diorite is extremely variable in texture and sporadic occurrence of large microcline crystals is common. On the east side of Kwini Hill and on Inkil Hill considerable areas can be seen where these large microcline crystals are so abundant the rock approaches the Quartz Monzonite in appearance. From such areas the microcline usually diminishes rapidly in size and abundance and soon regain the appearance of the usual diorite (Fig.4).

The Biotite-Hornblende Granite grades sharply into the Fayalite-Quartz Monzonite which it surrounds like a jacket. No common contact is known between the diorite and the Biotite Hornblende Granite; the two are usually seperated by the Fayalite-Quartz Monzonite. The Biotite-Hornblende Granite is strongly lineated striking about 220^0 except in the North West, where it turns east-west. Generally this lineation is concordant with that of the surrounding gneisses. As in the monzonite, fine grained granitic inclusion are common, principally of quartzo-feldspathic rocks with a scanty amount of biotite. At times the inclusions may appear aplitic, and vary in size from a few square inches to several square feet.

Two other rock types occur in the district. One is a medium grained Biotite-Hornblende Granite which, covering half of Ran Hill and running transgressively southwards, fades out into the gneisses about two miles North of Bauchi. A smaller narrow outcrop near Kundum village strikes east west. The other is a medium grained Biotite Granite and occurs like a roof pendant situated between the diorite and the fayalite quartz monzonite.

Structual Features.

The Fayalite-Quartz Monzonite with the diorite and the Hornblende-Biotite Granite to which it grades form a body of batholithic dimensions. Together they make up an extensive mass with a known surface area of about 80 square miles, while about another 80 square miles may be inferred from the map between Bauchi town and Miri Village. Their southward extent is not known but eastward they appear to continue to Kangeri (Fig. 5). They are of undeterminable depth and deep seared, and show many other batholithic characters such as variable colour and composition, porphyritic texture, and indefinite boundary. This complex could thus be called the "Bauchi Batholith."

No major fault is directly observed, but some may be inferred from possible breccias and from the aerial photographs, (Plate 4, fig. B), these are shown on Map (B). Small fault displacements are frequently found in the migmatites. They are usually short, often less than a yard long with a displacement of from two to eighteen inches. The faults strike in three directions; 10-20°, 340-350° and 310-320°.

Several zones of cataclastic deformation are marked by augen gneisses. They are indicated on Map (B)

Jointing is not prominent in the Bauchi Batholith but rather common in the migmatite, (Plate 5, fig. A), the different sets are represented diagramatically in fig. 6.

The general foliation is north east - south west, but local variations occur, and it is generally concordant with the foliation in the schists and granulites. Shading in Map B shows this foliation, as reconstructed by the writer from information shown on Map A (arrows).

Contact Relationship

Contacts between the rocks of this district are of very indefinite character and poorly exposed. The contacts between the different gneisses and also between the Biotite Granite and the Biotite Gneiss are unquestionably gradational. The nature of the contact between the Biotite Granite and the Biotite-Hornblende Granite is rather more varied: East of the Zungar hills and east of Miri, outcrops showing gradation from one to the other can be seen, but south of the Agricultural Department farm and just east of the Yelwa Bridge a definite line of contact is seen, but this is actually a line of textural contrast.

The contacts between the different members of the Bauchi batholith are gradational. Gradation from the Biotite-Hornblende Granite to the Fayalite-Quartz Monzonite is rapid but can be seen in the Dumi hills just north of the village. The contact between the Quartz Diorite and the Fayalite-Quartz Monzonite is for a large part obscured by Medium-grained Biotite Granite which sits like a roof pendant over both, but in those places where the diorite is within the monzonite, the contact can be seen to be gradational.

The contacts of the medium grained Biotite Granite are sharp all round but unchilled (Plate 5,fig B)

In the Ran hills, the medium grained Biotite-Hornblende Granite has similar contacts with the Biotite Gneiss but towards its southern end, in the neighbourhood of Meriamma Hill, it changes character and the rock merges with the surrounding gneisses.

The Charnockitic Diorite where it occurs within the gneiss, as in the west part of the area around the Jos road, from the closeness of outcrops belonging to the different rocks, appears to have a sharp contact. Here again the contact may be no more than a line of colour contrast.

Dykes.

In the north-west of the area a number of soda-trachyte dykes cut through the migmatite, but none was found in the rocks of the Bauchi Batholith. These dykes are approximately vertical with good rectangular jointing. They are usually two to five feet wide and can in some cases be traced for a mile or more (Plate 6 fig. A).

Dolerite dykes, usually about 18 inches broad, are the most widespread. They cut across all the rocks in the district and strike rather consistently in an east west direction. The larger dykes may carry numerous blocks of the country rocks; the inclusions are altered both texturally and mineralogically. Three such dykes are known and are marked on the accompanying maps. (A and B).

Few granitic dykes are observed. (All the dykes are indicated on map A.)

Sequence of Geological Events.

The earliest rocks, now represented by the amphibolite, granulites and calcsilicate rocks, are believed to be sedimentary in origin and were once widespread (Bain 1926, Falconer 1911). Assuming these to be the ancient sediments, the sequence of geological events leading to the present exposed rocks are summarised in Table 1. The sequence as interpreted by Bain (1926) who regarded all the rocks as intrusive is shown in Table 2, constructed by the present writer from information given by Bain (1926, p. 61-63).

TABLE 1

		Ancient Sediments		Sedimentation
Schist cycle.	1. 2. 3.	Schists Quartzite Meta-limestone lenses.	Folding and faulting of the sediments.	Progressive Metamorphism
		Basic Dykes		
Migmatite cycle	4.	Gneisses	Period of injection and widespread diffusion of Si and K. Faulting on a small scale	Migmatization microclinization.
	5.	Pegmatite dykes		
	6.	Quartz-feldspar veins.		
	7.	Relict rocks: granulites amphibolites (from basic dykes) calcsilicates (from meta lime-stone)		
	8.	Migmatites		
		Basic Dykes		
Granite cycle.	9.	The biotite-hornblende granite.	Period of increasing diffusion of Si, K, Na, Mg, Fe and Ca.	Intense microclinization and recrystallization
	10.	Fayalite quartz-monzonite.		
	11.	Quartz-Diorite		
	12.	Massive quartz-reefs.	Period of alteration	Silification Epidotisation
		Soda Trachyte Dykes, Dolerite Dykes, Granitic Dykes		
Weathering since Precambrian forming Inselbergs and low-lying domed plains.				

For the same district the sequence as visualised by Bain is shown on Table 2 drawn from information given by him. (Bain 1926) He regarded all the rock as definitely intrusive.

TABLE 2

	Ancient Sediments	
Schist cycle	1. Calcic rocks (Calc-silicate rocks). 2. Biotite Schists. 3. Biotite garnet schist (granulites)	Recrystallization from dynamic and to a less extent thermal metamorphism.
Granite cycle (Migmatite cycle.)	4. Primary banded gneiss (lit-par-lit gneiss). 5. Biotitic granite (Biotite gneiss).	Injection of quartz feldspar veins. Intrusion of acid rocks. Injection of massive pegmatites with tourmaline and brecciation of older rocks.
	Period of Quiescence (no evidence given)	
Porphyritic Granite cycle. (Granite cycle).	6. Fine Grained feldspathic granite (feldspathise gneiss; biotite granite). 7. Porphyritic Older Granites with syenitic types (Biotite Hornblende Granite, Fayalite-Quartz Monzonite)	Intrusive activity.
	7a. Syenitic dykes. 8. Granitic and Trachyte dykes. 9. Basic dykes.	Dyke intrusions.

The above table is from information given by Bain (1926 p. 61-63) The lithological classification from Table 1 are shown in brackets against Bain's.

CHAPTER II THE DESCRIPTION OF THE BAUCHI ROCKS.

Classification

The rocks of Bauchi can be classified as shown in table 3. They are arranged in order of probable age, with the oldest at the bottom. (Note: dykes are excluded)

TABLE 3.

7. Quartz Diorite (charnockitic) (Youngest?)

6. Fayalite-Quartz Monzonite (variable within quartz syenite and adamellite)

5. Biotite-Hornblende Granite.

4. Medium Grained Biotite Granite.

3. Medium Grained Biotite-Hornblende Granite

2. Migmatites:
    a. Biotite Granite.
    b. Biotite gneiss.
    c. Mixed gneiss and pegmatites.
    d. Agmatitic gneiss.
    e. Lit-par-lit gneiss.

1. Metasediments:

    a. Arkosic Quartzite.
    b. Calcsilicate Rocks.
    c. Amphibolite.
    d. Hornfelsic granulite.
    e. Granulite. (Oldest)

Description of Metasediments

The Granulite has a salt and pepper greyish colour with reddish spots of disseminated garnet. Pegmatitic knots are common, usually surrounded by a feldspathic halo.

Under the microscope the rock is seen to have a lepidoblastic texture (Plate 7 fig A) and is composed largely of plagioclase, biotite and quartz (Table 4). The biotite is pale brownish green in colour, and the plagioclase is oligoclase. The latter has a crushed appearance and generally shows very poor twinning. The quartz has very strongly undulatory extinction. Garnet porphyroblasts occur in scattered ragged grains with inclusion of, and intergrowth with, quartz vermicules and blebs. The outline of the garnet is amoeboid, and it embays adjacent minerals appearing to be preferentially replacing plagioclase and biotite. It is identified as almandite.

The Hornfelsic Granulite appears to be a granulitic relic which has been locally baked (ME179). Only two small patches are known in the area and these occur in the south-east of Bauchi town and just south of the air strip (Map A). The rock has acquired a purplish hue from the red colour of the biotite and the garnet, and has developed quartzo-feldspathic veins.

Under the microscope the rock is seen to be hornfelsic in texture and to have been recrystallized.

The plagioclase and the quartz show far less marked crush effects. The biotite is reddish in colour. The quartzo-feldspathic veins are seen to be lensoid in shape and composed of coarse aggregates of oligoclase, potash feldspar and biotite. Small areas of myrmekite may occur at the border between plagioclase and potash feldspar (Plate 7 fig. B).

The only occurrence of amphibolite is that about half a mile north of Bauchi town and just inside the road fork. Here the amphibolite has been dissected into blocks and partly digested (Plate 8 fig. A). The rock is dense and black in colour in the central portion of the blocks but towards the borders against the encasing granite it becomes coarsely biotitic.

As seen under the microscope, the rock is granoblastic (Plate 8, fig. B) and composed mainly of hornblende, plagioclase and biotite (Table 4). The hornblende is strongly pleochroic from pale yellowish green to deep bluish green. The biotite is yellowish brown in colour and pleochroic to dark brown.

The plagioclase is of the composition of oligoclase (An80 Ab20) and may show zoning. The biotite zone near the border with granite is seen to be a coarsely recrystallized aggregate of biotite, oligoclase and quartz. It contains more quartz than the amphibolite core and some calcite and sphene appear as accessory minerals.

The Arkosic Quartzite is the least common of the Archaean metasediments and only one exposure,near the air strip (Map A) is known and this is so limited that the structureof the rock cannot be determined. It is, in hand specimen, a grey massive rock with disseminated pyrrhotite.

Under the microscope, the rock has a granoblastic texture (Plate 9, fig. A) and it is composed of microcline (41%), plagioclase (34%) and quartz (25%). Opaque ore, presumably manganous oxide, occur as patchy clots and as an intergranular stains (Plate 9, fig. B).

The Calcsilicate Rocks are usually dense and almost flinty. Commonly, they are banded in tints of green and red, corresponding with alternative zones of pyroxene and garnet, or less frequently in green and white, corresponding to the zones of pyroxene and quartz and feldspar. Massive calcsilicate which is not banded is mottled greenish and reddish due to patchy concentrations of pyroxene and garnet.

The mineralogical assemblages are shown in Table 4.

The pyroxene occurs in large equant grains or in large poikiloblastic masses (Plate 10, fig. A) It is identified (Table 7) as a ferrosalite with $MgSiO_3$ 26%, $FeSiO_3$ 43% amd $CaSiO_3$ 31% corresponding to about 1:1 proportion of diopside and hedenbergite. (Hess 1949)

Scapolite is abundant especially when the plagioclase is not appreciable and presumably has occurred in place of it under some special conditions not fully known (Fyfe 1958 p. 160). The plagioclase is a bytownite (about An_8 Ab_2). In some specimens (ME 237) it may have a checkerboard s~~o~~tructure, containing small cubes of what appears to be a plagioclase of lower refractive indices. The parallel extinction of these cubes suggests Oligoclase (Ab_{75} An_{25}). Many of the crystals show weak zoning. The garnet has a refractive index which varies between 1.752 and 1.768, and it is believed to be grossularite. It occurs in equant grains or irregular poikiloblastic masses which may contain any of groups of the other minerals (Plate 10, fig. B). Quartz and calcite are commonly present in varying proportions and the twominerals may occur contiguously with no reaction zone. For some reason calcite tend to occur mostly in or associated with grossularite.

Sphene is the titaniferous phase in all specimens andoccurs commonly as disseminated grains and, occasionaly, as clotted granular aggregates.

Description of The Migmatites

The Migmatitic rocks of Bauchi had been variously described as gneisses, gneissose grantie, lit-par-lit gneiss and igneous breccia by Bain (1926). The present classification is shown in Table 3.

The lit-par-lit gneiss consists of alternating parallel bands of granulites and granitic rocks with some intercalated quartz veins (Fig. 8). The granulite bands as well as the granitic bands vary in width from fraction of an inch to several inches. Narrow elongated bodies of calcsilicate rocks may be found associated with the granulite. As seen over a wide area, the structure is one of parallel banding, but on close examination, the granulitic bands may exhibit varying degrees of folding.

The granulite component of this gneiss has been previously described. The granitic portion is composed mostly of quartz and microcline. The texture is often irregular due to sporadic development of

TABLE 4

MODAL ANALYSES OF THE METASEDIMENTS

	1	2	3	4	5	6	7	8	9	10
K. Feldspar	-	1	-	-	-	-	-	-	-	-
Plagioclase	38	38	36	5	36	31	28	42	32	2
Pyroxene	-	-	-	31	17	38	21	40	30	15
Hornblende	-	-	35	-	-	-	-	-	-	-
Biotite	36	37	25	-	-	-	-	-	-	-
Garnet	5	6	-	15	33	-	40	-	19	45
Quartz	21	18	2	20	13	25	8	10	11	10
Scapolite	-	-	-	20	-	-	2	1	7	13
Calcite	-	-	-	-	-	-	-	-	-	15
Sphene	-	-	-	4	1	6	1	6	1	Tr.
Epidote	-	-	-	15	-	-	-	-	-	-
Ore	-	-	2	-	-	-	-	1	-	-
	100	100	100	100	100	100	100	100	100	100

1. ME. 220 Granulite inclusion in Migmatite, Ran Hill.
2. ME. 179 Hornfelsic granulite, S. E. Bauchi Town.
3. ME. 206A. Amphibolite, ½ mile north of Bauchi Ran Gate.
4. ME. 171 Calcsilicate rock, Tara Hill.
5. ME. 173 " " , ½ mile south of Kundun Village.
6. ME. 170 " " " " "
7. ME. 172 " " East of Sanfara Village.
8. ME. 237 " " Ran Hill.
9. ME. 240 " " " "
10. ME. 165 " " 1 mile north of Miri.

of pegmatitic phases. A thin band only an inch or less wide may sometimes be traced for nearly a hundred yards and the quartz veins and stringers which are very widespread can be equally persistent over a length quite out of proportion with their breadth.

Th agmatite gneiss has two componnents also, the angular blocks of gneiss and the dissecting granitic dykes. (see Plate 3) The gneissic blocks vary widely in their appearance. Generally they are grey in colour and show foliation which is best appreciated in the field, especially on wet or old surfaces. This foliation is consistent from one block to the other. Large, sparsely distributed microcline porphyroblast about 3 sq. cm. across are frequently present.

Under the microscope the rock is granoblastic and is composed principally of oligoclase, quartz and biotite, (Plate II fig A), and microcline porphyroblast may be present. The oligoclase is about An_{80} Ab_{20} average composition. It is generally very poorly twinned. The quartz is in irregular larger masses and most grains show strong undulatory extinction. The biotite is greenish brown and pleochroic from brown to dark brown. It is more or less arranged along parallel zones and, as seen under the microscope, appears to be the only mineral affecting the foliation structure as observed in hand specimen.

The microcline porphyroblasts, (Plate 11, fig B.) show strong gridiron as well as simple Carlsbad twinning, microperthitic structure is absent but inclusions of quartz, feldspar and biotite, which are presumably relics, are fairly abundant, especially round the margins. Though oblong shaped and rather subhedral looking, its margins can be seen to be sutured with those of the surrounding minerals. Smaller grains of microcline and ragged pieces of muscovite occur in the immediate vicinity of the porphyroblasts though absent in the main portion of the rock.

The metatectite is composed largely of microcline, quartz and a subordinate quantity of plagioclase. Rarely garnet crystals (almandite) may be found and muscovite is not uncommon, especially in the more pegmatitic dykes. The microcline is commonly microperthitic and clear while the plagioclase is often clouded with alteration. Quartz has strong undulatory extinction. When present muscovite occurs in plates with ragged edges.

The contact between the metatectite and the gneissic block is gradational though the strong colour contrast gives a contrary impression, especially when viewed from a distance. When closely examined (ME. 259, plate 12 fig A) there is mutual interpenetration of the metatectite and the gneiss components.

The Mixed Gneiss and pegmatites differ from the agmatite gneiss in that, in the former the dykes have a consistent strike direction, about 280° and are in general concordant with the foliation of the gneisses. Locally a small area may be wholly of pegmatite developed from the union of many dykes.

The gneiss is the same as that described for the agmatite gneiss. The pegmatite often show zonal distribution of its mineral components. Quartz frequently occurs along a central line surrounded outwards by large microcline crystals. Not uncommonly quartz may be completely absent, or nearly so, the dyke consisting almost wholly of microcline. Occasionally muscovite may be oresent, it is localised in the central zone with quartz. In rare instances large crystals of almandite garnet occur. In one locality, a dyke was found consisting entirely of interlocking crystals of quartz and muscovite (MEF 117).

The microcline crystals average about 10 cm. square some crystals may be two or three times larger (Plate 12, fig B). They are generally flesh pink but white crystals are sometimes observed under the microscope, the feldspar is perthitic containing vein type blebs of plagioclase which form a high proportion of the crystal. The blebs have parallel extinction and are believed to be oligoclase. The microcline shows strong gridiron twinning. Few and small inclusions of quartz may be present.

In handspecimen the quartz is crystal white and massive and the muscovite is colourless but usually stained by dirt and limonite. The muscovite is rarely more than 7 cm. long and 4 cm. wide. A book of muscovite is rarely more than 2 cm. thick.

Pegmatite is found widely distributed in the migmatitic rocks though in much less concentration outside this area. In the neighbourhood of Guru, black tourmaline may be associated and some crystals are up to 7 cm. long and 4 sq. cm. in cross section (Plate 13, fig. A). Rarely they are found taking the place of feldspar in a graphic pegmatite (Plate 13, fig. B).

The biotite gneisses are very variable both in the proportion of biotite and in degree of foliation.

Frequently the foliation is strong and the rock shows bending (ME. 185, Plate 14 fig. A). The darker band consists of thin parallel strings of alternating biotitic and quartzo-feldspathic aggregates. The light bands are dominantly aggregates of quartz and feldspar. The different bands are not as regular as the illustration may suggest, being inconsistent in width and rather discontinuous. Occasionally the banding is vague (ME. 188 Plate14, fig. B) and the light and dark areas are irregularly distributed. The gneissose structure in such can readily be appreciated only over large exposures and on an old surface.

Under the microscope the first type is seen to be of xenomorphic granular texture and composed of plagioclase, microcline, biotite, quartz. (Plate 15, fig. A) The plagioclase is an oligoclase, often clouded and altered. The microcline generally shows strong gridiron twinning but a few perthitic untwinned crystals may be observed. The microcline is intergranular and sutured with the surrounding minerals. Quartz occurs in large masses and elongated bodies, and is weakly undulatory extinction. Small blebs and vermicules of quartz occur over most of the plagioclases imparting a corrosion appearance to the rock as a whole. Some myrmekite is present. Biotite plates are arranged along parallel lines and some muscovite is present as ragged plates. In the case where the banding is vague, the rock is composed of plagioclase, biotite and quartz which appears to be much recrystallised. (Plate 15, fig. B) Patchy areas, free of biotite, are observed to have intergranular microcline.

These two rocks are evidently quite different from each other in texture and modal composition, however they are not unrelated but are two extreme local variations within the same group.

The Biotite Granite is, texturally, the most granitic of the migmatites. The rock is less conspicuously foliated, but on wet or fairly old weathered faces a foliation can be discerned. Schlieren or ghost relic are abundant and pegmatitic knots are common. The rock, like most of the other migmatitic rock is widely variable in colour, grain size and modal composition; even in the hand soecimen this variation may be appreciated. Its chief unifying characteristic is the presence of a large number of small porphyroblasts about $\frac{1}{2}$ sq. cm. (Plate 16, fig. A). Occasionally the porphyroblasts may become numerous and larger, attaining 3 sq.cm. in size (Plate 16, fig. B). Then, the groundmass becomes coarser and the resulting rock is hardly distinguishable from the biotite hornblende granite of the Bauchi batholith. Garnet (almandite) may occur as segregated bodies surrounded by quartzo-feldspathic zones free of biotite. (The principal field characters of this rock are summarised in Fig. 8.)

Under the microscope, the rock has a granoblastic texture and is composed of microcline, oligoclase, quartz and biotite (Plate 17, fig. A). The larger microcline porphyroblasts are nearly always poikiloblastic enclosing relic minerals from the groundmass. Gridiron twinning is pronounced and there is some tendency to develop microperthitic texture and myrmekitic fringes. Generally the outline of the porphyroblast is lost in sutured interlobing with the fringing minerals and the development of myrmekite.

The plagioclase is oligoclase (Ab_{80} An_{20}) and is clouded to variable degrees. Quartz occur principally in large irregular masses, and may show strain effects, but quartz vermicules and blebs associated with myrmekitic activity are also abundant.

Biotite is on the average very scanty. Commonly, there may be slight alteration to chlorite and overgrowths of muscovite may sometimes be observed.

The medium grained Biotite granite

The rock is similar to the Biotite granite in most of its features except that it has slightly larger and more closely spaced porphyroblasts. Further it has a darker greyish colour.

Under the microscope, the rock is composed principally of plagioclase, potash feldspar, biotite and quartz, and the texture is granoblastic (Plate 17, fig. B). The plagioclase is in plates of various sizes, many of which show strain by their bent lamellae and wavy extinction, some are clouded with alteration and a few show weak zoning. The average composition is about Ab_{25} An_{75}. The microcline porphyroblasts contain small quartz inclusions and are surrounded by small areas of myrmekite. Biotite is abundant, and arranged along clustered branching lines surrounding the feldspars. It is a brown biotite and may be partly altered to chlorite. Quartz occur in large masses showing varying degrees of strain extinction.

Medium Grained Biotite Hornblende Granite.

The rock is extremely variable. In colour many shades of grey and reddish grey are present; in texture, it is generally about fine to medium grained with microcline porphyroblasts varying from abundant to practically absent and from 2 sq. cm. to ½ sq. cm. in size. In the occurrence to the south of Bauchi very large porphyroblasts about 4 sq. cm. may occur sproadically.

Under the microscope the rock is of granoblastic texture, (Plate 18) and is composed of microcline, plagioclase, biotite, hornblende, quartz, orthite and ore.

The microcline is of two types, one which occurs as small irregular grains in the ground mass, with strong gridiron twinning and no myrmekite or perthite associated with it, and the other, which occurs as porphyroblasts in large irregular grains with poorly developed gridiron twinning but good film and patch perthitic structures. Inclusions of quartz, biotite, hornblende may be present and myrmekite is commonly developed around the fringes.

The plagioclase, an oligoclase, has zero to slight extinction. It may show slight strain and is generally clouded with alterations products. Biotite and hornblende occur in irregular plates with the former generally more abundant and the latter rather variable, sometimes nearly absent. The hornblende is generally as overgrowths on the biotite.

Quartz is common and may show very strong strain extinction.

Orthite and opaque iron ore are other accessory minerals, the former in irregularly coloured brown plates.

Description of the rocks of the Bauchi Batholith.

The outer zone of the Bauchi Batholith is composed of a very coarse granite with large microcline crystals averaging about 4 cm. by 1.5 cm. and set in a coarse matrix of quartz, feldspars and ferromagnesian minerals. These microcline crystals are arranged more or less parallel imparting a slight lineation to the rock. (Plate 19) Locally the rock may appear crushed, becoming strongly gneissoid, and the microcline crystals crowded and elongated. The distribution, size and colour of the microcline is also variable in this rock. This feldspar is generally light coloured, white, pinkish or yellowish brown. The quartz is

TABLE 5

MODAL COMPOSITION OF THE MIGMATITIC ROCKS.

	1	2	3	4	5	6
Microcline Perthite	39	8	23	28.3	23.4	21.1
Plagioclase	23	56	37	27.3	32.1	33.4
	31	17	20	22.3	22.5	21.6
	5	19	17	11.0	13.4	18.7
	-	-	-	7.0	6.3	1.5
	2	Trace	2	1.1	1.0	2.5
	-	-	Trace	1.0	0.9	1.2
	-	-	-	0.6	0.9	Trace
	-	-	-	0.2	Trace	Trace
	-	-	-	0.3	Trace	0.2
	0	100.0	99.0	99.1	100.5	100 .2

University of St Andrews

With the
Librarian's Compliments
and thanks.

Gneiss West of Kasuma Hill.

" Foot of Shadawanke Hill.

ained Biotite Granite,
North of Wombai Hills.

ained Biotite Hornblende Gramite,
Ran Hill.

5. ME. 212 Same as above about 1 mile south of
Ran Hill.

6. ME. 176 " " " Near Gundun Hill.

invariably colourless.

Under the microscope the rock is composed of microcline microperthite, plagioclase, quartz, biotite and hornblende, and it is of allotriomorphic granular texture (Plate 20, fig. A).

The microcline is crystaloblastic: it has amoeboid outlines, interlobing with the surrounding minerals. It is microperthitic, the plagioclase blebs are of stringlet type (Alling 1932) and barely resolved under the low power (X5) objective. In the larger blebs, string and film types of perthite are occasionally observed. The microcline crystals are phenocrystalike being generally much bigger than the other minerals present. They may be fringed by a chain of myrmekite or a garland of a fine mosaic of quartz and feldspar. Inclusions are commonly present but are not abundant. Gridiron twinning is weak to absent. The optic axial angle is negative and generally very large ($2V=84^{o}$), corresponding to a high soda content or maximum lattice structure order. (Laves, 1952)

The plagioclase is oligoclase (Ab_{80} An_{20}). It occurs in large to small plates and generally show some strain effects, most evident of which is the bent twin lamellae. Weak zoning may be noticed in some grains. Along the contact with plagioclase, when myrmekite is not developed, a narrow selvedge of reversed orientation of the twin lamellae may be observed, (ME 233, Plate 20, fig. B).

Quartz occur in large masses. Some show undulatory extinction while others have rather even straight extinction. Vermicules and blebs of quartz occur in myrmekite and as inclusions in the feldspars.

The ferromagnesian minerals are biotite and hornblende. They are of very variable distribution and proportion. The biotite occurs in clusters of flaky plates and may be ragged. Rarely it occurs in large irregular mass that is optically continuous and pleochroic from pale brown to dark brown. Hornblende is commonly associated with the biotite. It is a greenish brown in colour, and Pleochroic X = greenish brown, Y = brownish green, Z = bottle green. From the refractive indices (Table 7), it is identified as an hastingsite.

Other less common accessory minerals are orthite, which are euhedral to subhedral and strongly pleochroic brown to deep brown, and iron ore which is commonly associated with biotite though rather rare. Zircon and apatite may be present.

The gradation to Fayalite-Quartz monzonite is rapid but it is marked by increased abundance of hornblende and to a lesser extent by the sporadic occurence of fayalite.

The Fayalite-Qaurtz Monzonite is the most distinctive of the rocks of Bauchi. It is massive and very coarse, the dominating large microcline crystals averaging 3 cm. by 2 cm. (Plate 21). It is characteristically brownish green with a peculiar resinous lustre. The large microcline crystals are unevenly set in a subordinate matrix of ferromagnesian minerals, quartz and plagioclase.

On oxidised surfaces the rock is dark brown, this is often seen and is what led Bain (1926) to describe them as "dark brown". However, at blasting sites the rock is found to be greenish on fresh surface. A fresh greenish specimen heated strongly for an hour turned to a dark brown colour similar to the oxidised surface in field, an indication that iron impregnation may be responsible for the colour.

The rock is of xenomorphic granular texture, (Plate 22, fig. A) characterised by mutual interlobing of the aggregate minerals. It is composed of microcline, plagioclase, quartz, fayalite, orthopyroxene, hornblende with apatite, zircon and magnetite.

The microcline is microperthitic and the grid twinning is very poor. The microperthite is commonly of stringlet type, just barely resolved by the low powered (X5) objective and giving the crystals a velvety texture. The individual microcline crystal appears to be subhedral to euhedral in hand specimens, but on stained surface and under the microscope they are crystalloblastic, amoeboid in outline, and characterised by lobes and tongues with which they tend to embay other minerals. (Plate 12, fig. B) It may also be sutured by fine mosaic aggregates of quartz and feldspar. Inclusions of quartz blebs, and rounded plagioclases with reaction selvedges of incipient myrmekite are invariably present though not abundant. The 2V is 69° optically negative, smaller than those observed for the microcline in the migmatites and in the Biotite Hornblende Granite and suggesting lower soda content or a lattice structure of lower order.

The plagioclase is oligoclase-andesine (average, Ab_{65} An_{35}) It occurs in various sizes and irregular shapes; some are crystalloblastic. Bent crystals and grains with crush fractures are commonly found (Plate 23), though many crystals show no strain at all. Small equant grains of feldspar may form a band of mosaic aggregate between microcline crystals, and skeletal bodies of optically continuous plagioclase may occur in microcline towards the margin, forming a type of patch perthite similar to those found in the Quartz-Diorite.

Quartz is typically of resinous greenish brown colour in hand specimen and variably distributed. Under the microscope it occurs in large masses, some showing strain undulatory extinction while others are only weakly or not at all so. Quartz also occur in myrmekite as vermicles and as small blebs included in other minerals.

Fayalite is the distinguishing ferromagnesian mineral. The composition is about 95% Fe_2SiO_4. (The optical data are shown in Table 7). It is rarely found as discreet grains but most commonly in clustered aggregates with other ferromagnesian minerals. These clustered aggregate of ferromagnesian minerals are almost always associated with vein-like bodies of quartz and arranged in the following generalised pattern (Fig. 9); Iron oxide, if present occurs along the centre in the quartz, the fayalite crystals then occur as discreet grains arranged round it followed outwards by crystals of pyroxenes, hornblende and plagioclase (Plate 24); but the pyroxene is not always present. The individual minerals occur as detached crystals which appear to be primarily crystallised and not as reaction mantles, except hornblende which may form an outer sheaf round the whole structure, and even these do not appear to be reaction mantle product on either the fayalite or the pyroxene, and may be seperated from them partly by a zone of quartz. They appear to have formed by reaction on the surrounding plagioclase.

Commonly fayalite may occur in a long-rod like body of optically discontinuous grains, wedged in between the large feldspar crystals (Plate 25, fig. A) but such bodies will be seen to be connected to a larger mass associated with other ferromagnesian minerals arranged as described above.

The clinopyroxene is commonly pale greenish with no appreciable pleochroism. It is indentified as ferrohedenbergite (Table 7). Inclusions of parallel needles of magnetite may occur in some grains to form schiller structure. The mineral has rather irregular distribution and it may be absent from some sections, probably because of the coarseness of the rock.

Orthopyroxene is sometimes present and in some sections amounts to a considerable part of the ferromagnesian minerals. It may be found interlocked with the fayalite.

Hornblende is the most abundant of the ferromagnesian minerals. It may be found discreet but is usually associated with fayalite, surrounding the latter like a mantle as previously described. It is identified as ferro-hastingsite. (Table 7). It is greenish brown and strongly pleochroic as for that described earlier. Magnetite is the common inclusion. Biotite may be associated but is rather uncommon in this rock except near the transition zone towards the biotite hornblende granite.

A charnockitic phase of this rock occur around Yelwa bridge, on North band of river Gwalanga south-east of the aerodrome and near the Ran Gate, forming patches in the Marginal zones. This rock, (Plate 25, fig. B) is essentially like the fayalite quartz monzonite in hand specimen but tends to be richer in in ferromagnesian minerals. Under the microscope fayalite is absent and the mafic mineral assemblage fayalite-hedenbergite-hornblende is replaced by orthopyroxene-hornblende-biotite. The orthopyroxene is identified as eulite about, $MgSiO_3$ 20% and $FeSiO_3$ 80% in composition. (Table 7, Wahlstrom 1955 p.160). It is strongly pleochroic X = brownish pink to Z = green and presumably contains appreciable $TiSiO_3$. It may occur in large masses that are optically continuous or in elongated plates. Generally there is a tendency to be localised in linear zones and associated with hornblende (Plate 26, fig. A). Inclusions of clino-pyroxene are sometimes observed.

The hornblende is very abundant and may occur in large masses but usually ragged with associated pyroxene. It is a deep green amphibole. It is also a ferro-hastingsite.

The biotite is abundant and occurs mostly as ragged plates or masses associated with hornblende. It is a brown biotite with inclusions of apatite.

The plagioclase is andesine and slightly less clalcic than that in the fayalite quartz monzonite, (about $Ab_{67}An_{33}$).

The Quartz Diorite, to which the quartz monzonite appears to grade, is a dark blue-black fine grained rock in the fresh hand specimen. It may be of uniform texture but quite commonly poorly defined area of what appears to be a larger crystal of microcline may be seen (Plate 27, fig. A). Stained surfaces show that these areas are of potash and plagioclase feldspars (Plate 27, fig. B). Occasionally, they become larger, numerous and better outlined. The rock is then hardly distinguishable from the Fayalite-Hornblende Granite to which it grades. Some specimens show lineation of these "ghost" microcline crystals.

Under the microscope the rock is seen to be of granoblastic granular texture (Plate 28, fig. A) and to be composed of plagioclase, potash feldspar, microperthite, ortho-/and clino-pyroxenes, hornblende and some quartz with occasional biotite and rare fayalite. The plagioclase is andesine ($Ab_{60}An_{40}$). Zoned crystals are common and these often have an irregular calcic core or cores (Plate 28, fig. B). In one case the outer zone gives $2V = 87^{\circ}$ and the inner zone $2V = 76^{\circ}$; optically negative. Deformed crystals are not common but some crystals may show distinct bending of the lamellae (Plate 29, fig. A). The plagioclase in some specimens is characterised by parallel inclusions of numerous needles of iron oxide (Plate 29, fig. B), but generally they are clear of alterations and sharply twinned on the albite law.

The potash feldspar is invariably microperthitic. The perthite blebs are extremely fine and just barely discerned under the low powered objective (X5) Commonly, irregular patches of optically continuous plagioclase may be observed enclosed within it, and these patches may be found to be optically continuous with a larger plate of plagioclase outside at the border of the potash feldspar (Plate 30, figs, A and B).

The ortho pyroxene is the most common ferromagnesian mineral. It is strongly pleochroic; X = pale reddish pink, Y = reddish green, Z = green. It is identified as ferrohypersthene ((Ti) $FeSiO_3$, 75%; $MgSiO_3$, 25% (Wahlstrom 1955, p. 160))

The clinopyroxene is green with no appreciable pleochroism, and it is identified as ferroaugite ($CaSiO_3$ 40%, $FeSiO_3$ 39% and $MgSiO_3$ 21%, (Hess 1949)) The two pyroxenes always occur together associated with magnetite and amphibole, the former in clots and latter in shreds. Either magnetite or the amphibole may occur in minute needles arranged in parallel zones forming schiller structure (Plate 31, figs. A and B).

The hornblende is ferrohastingsite. It occurs in ragged masses invariably associated with a core of pyroxenes. Biotite is rare in most specimens but locally abundant biotite may occur, associated with the other ferromagnesian minerals.

Some quartz occurs interstitially and rarely myrmekite is developed at the margin of microcline.

Magnetite is usually abundant and associated with the dark minerals.

Chemical Composition of Bauchi Rocks.

The Bauchi rocks are intermediate to acid in composition (Table 6) and only the Quartz Diorite shows normative olivine. Generally they show fairly high potash, average alumina and low magnesia content; and the ferrous iron ratio relative to the total iron plus magnesia, is very high.

The composition of the rocks plotted on Harker diagram (Fig 9) shows some peculiarities: The Alumina shows peculiar fluctuation but the values used are not sufficiently reliable to be regarded as conclusive. The potash has a peak in the Biotite Hornblende

TABLE 6

Chemical Compositions and Norms of Rocks from Bauchi District

	1	2	3	4	5	6	7	8
SiO_2	73.0	71.2	68.4	69.5	66.1	70.1	70.0	52.6
Al_2O_3	13.0	12.8	13.0	12.2	12.5	13.4	13.70	11.7
Fe_2O_3	0.3	0.9	0.6	1.9	1.5	0.8	0.49	0.6
FeO	1.2	1.6	3.4	2.6	4.7	2.5	2.30	14.7
MgO	-	0.8	0.7	0.7	0.7	0.3	0.51	3.1
CaO	2.8	2.1	2.1	2.0	3.2	2.1	3.91	6.7
Na_2O	3.6	3.7	3.5	3.0	3.4	2.9	2.35	2.8
K_2O	4.71	5.4	6.9	6.6	5.7	6.4	7.28	3.1
TiO_2	0.27	0.44	0.47	0.45	0.76	0.38	0.33	3.2
P_2O_5	0.08	0.13	0.11	0.17	0.23	0.07	n.d.	0.57
MnO	0.09	0.07	0.07	0.10	0.12	0.08	n.d.	0.16
H_2O	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Total	99.04	98.84	98.95	98.92	98.91	99.03	99.87	99.23

Norm.

Q	=	26.2	22.6	15.2	20.2	10.7	20.0	20.5	3.8
or	=	28.5	32.5	41.5	40.5	43.0	39.5	43.0	19.5
ab	=	33.0	34.0	30.5	28.0	25.5	27.5	20.5	26.5
an	=	5.5	0.5	-	-	-	4.00	5.8	9.3
di	=	-	-	-	-	-	-	-	20.4
ac	=	)-	-	1.2	-	4.4	-	-	-

wo	=	5.4	3.2	4.2	4.0	6.4	2.6	5.2	-
fs	=	1.6	1.8	5.0	2.6	7.2	3.2	3.2	-
en	=	-	2.2	2.0	2.0	2.0	0.8	1.4	-
fa	=	-	-	-	-	-	-	-	13.5
fo	=	-	-	-	-	-	-	-	3.0
mg	=	0.3	0.9	0.2	2.0	0.0	0.9	0.5	0.6
il	=	0.4	0.6	0.6	0.6	1.0	0.6	0.4	5.6
ap	=	0.3	0.3	0.4	0.4	0.3	-	-	1.-
Total		101.2	98.6	100.8	100.3	100.5	99.1	100.5	103.2

1. ME 11A Biotite Granite, opposite Gurn Hill.
2. ME 136 Biotite Granite (Tara Type) Tara Hill.
3. ME 111 Biotite Hornblende Granite, below Yelwa School Hill.
4. ME 94 Fayalite Quartz Monzonite Baskin Hill.
5. ME 102 " " " Yelwa Bridge.
6. ME 222 " " " south of Kofar Wombai Hill.
7. ME 222A " " " " " "
8. ME 133 Quartz diorite North of Kofar Wombai Hill.

(See also Table 10)

Analyses Nos 1 - 6 and 8 by R. P. Hollingworth, Dept. of Geology, Science Laboratories, Durham.

and No. 7 by J. Cobbing and W. Layton of the Dept. of Geology, Science Laboratories, Durham.

Norm Calculations by the writer, after the method proposed by T. W. F. Barth (1951, p. 76).

granite and then shows decrease with increase silica, while Calcium curve tends to show the reverse trend, both representing some sort of abnormality from the Biotite Hornblende Granite towards the Biotite Granites. Between the Fayalite-Quartz Monzonite and the Biotite-Hornblende Granite, the iron and magnesia curves indicate an abnormal rise in the amount of these oxides in the Biotite-Hornblende Granite over the Fayalite-Quartz Monzonite.

TABLE 7

Optical Data for Fayalite, Pyroxene and Hornblende.

	1	2	3	4	5	6	7	8	9
Z	n.d.	n.d.	1.758	1.742	n.d.	1.709	1.713	1.712	1.712
Y	n.d.	1.731	1.747	1.735	1.716	1.709	1.711	1.712	1.712
X	1.81	n.d.	1.742	1.727	n.d.	1.689	1.692	1.692	1.690
Z-X	n.d.	n.d.	0.016	0.015	n.d.	0.020	0.020	0.020	0.022
2V	-50°	+55°	-83°	-63°	+53	n.d.	n.d.	n.d.	n.d.
EXT (X C)	0	47°	0	0	n.d.	n.d.	20°	26°	14°

1. Fayalite from Fayalite Quartz Monzonite (ME101)
2. Clinopyroxene from the same specimen above.
3. Ortho-pyroxene charnockitic monzonite (ME102)
4. Ortho-pyroxene from quartz diorite (ME133)
5. Clinopyroxene " " " " "
6. Amphibole from Biotite Hornblende Granite (ME124)
7. " " Fayalite Quartz Monzonite (ME101)
8. " " Charnockite variation of "7" (ME102)
9. " " Quartz diorite (ME135)

CHAPTER III. MICRO-STRUCTURE OF THE BAUCHI ROCKS.

Becke, Sederholm, Spencer, Eskola, among many other petrologists, have given a great deal of attention to the problem of petrological structures such as myrmekite and microperthite; since these structures may in many ways hold the key to petrogenetic classification of most rocks of indefinite origin in which they are commonly found. In this work, a special study has been made of these structures because their genesis is intimately tied up with that of the potash feldspar, a very conspicuous and important constituent of the Bauchi rocks.

Myrmekite.

Myrmekite is an intergrowth of quartz and plagioclase. It was first described by Michel Levy about 1874 and the term myrmekite was proposed by Sederholm a few years later (Anderson 1937). Myrmekites are of vermicular structure and when well developed, they strongly resemble coral growth. (Plate 32 fig. A) They commonly appear based on a plagioclase plate, referred to by some authors as the core, with a convex front invading the potash feldspar. (Fig. 10).

Three stages may be observed: early, late and decline. (Fig. 10) The early stage is marked by a narrow albitic selvedge which grades on the plagioclase side to a finely shredded incipient myrmekite invading the potash feldspar. Later, a stage is reached when two or more of the fine quartz vermicules join, rivulet-like, to form more definite ones. At this stage the front towards microcline has achieved a definite convex outline and the typical myrmekite form has emerged. Finally detached blebs of quartz may then appear to mark the decline stage.

Not uncommonly all three stages may be observed on one large myrmekite area but far more common are combinations of either early and late stages (Plate 32, fig. B)., forming "matured" myrmekite, or late and decline (Plate 33, fig. A) forming "old" myrmekite.

Almost invariably, very old myrmekite is associated with marginal quartz, especially when only the decline stage is present. This marginal quartz is "excretory" being forced out of the plagioclase by its higher force of crystallization. Some plagioclase crystals enclosed in potash feldspar may have only this excretory marginal quartz (Plate 33, fig. B) to indicate that they are post-myrmekitic. Thus as it were the growth of the myrmekite is a process of collecting the quarts together for expulsion by a plagioclase clearing itself of inclusions.

Myrmekite is most commonly located at the contact of microcline and plagioclase where it appears as inflated cauliflower-like masses into the former. Nearly all the myrmekite observed in Bauchi rocks is so localized. Plagioclase enclosed in microcline may be wholly or partly myrmekitic; commonly they are not, but post-myrmekitic as shown (Plate 33, fig. B) and with associated excretory quartz.

A narrow rim of a myrmekite-like body is often observed at the border of quartz with microcline, and a chain of myrmekite may be located at the contact of two microcline crystals or fracture line in a crystal. In no case is myrmekite observed on plagioclase which is not contiguous with microcline except where such relationship with a microcline could be inferred. In all cases the size of the myrmekite is subordinate to that of the microcline with which it is associated.

In the Bauchi rocks myrmekite occurs in all rocks in which potash feldspar is present, except the Quartz Diorite and it becomes progressively abundant with increasing microcline content, indicating some quantative relationship with the microcline. (Fig. 19)

There is widespread agreement among petrologists on certain characters of myrmekites some of which the present writer has also observed. As stated by Sederholm (1916), most authors agree that myrmekite is almost always invading microcline and a core or "pedestal" of plagioclase is invariably present or inferrable. (The term "pedestal" is proposed for the plagioclase on which the myrmekite is sitting. This term is more descriptive of the relationship of the myrmekite to the plagioclase, sitting on it as it were. The writer objects to the term "core" because this term may suggest that the plagioclase is of inner or central part of the myrmekite and one with it, whereas the plagioclase on which this structure is rested, as will be shown, is necessarily primarily crystallized before the myrmekitization. Some authors have observed contrary features, for example, Eskola (1914) claimed to have observed myrmekite with a rectilinear boundary against microcline. As was noted by Sederholm (1916), these contrary observations are so rare and easily explained that they do not invalidate the generally accepted characters of myrmekite as stated above. Myrmekite with such rectilinear boundary against microcline is not observed in any of the Bauchi rocks; however, such rectilinear boundaries against microcline could very well be attributed to the later truncation of the myrmekite by the microcline.

Spencer (1945) in agreement with Barth observed that there is commonly a decreasing basicity from the core (pedestal) to the rim and that the plagioclase of the myrmekite is generally more acidic than the primary plagioclase. In the rocks of Bauchi this tendency has been observed but it is not uncommon to find some myrmekite which has plagioclase uniform in composition through to the pedestal.

Spencer (1945) further observed the scarcity of myrmekite in pegmatite microcline and in orthoclase of soda syenites, but in the rocks in which they occur, as Sederholm (1916) observed, myrmekite is usually widespread but is never large enough to replace a whole microcline. The study of myrmekite in Bauchi rocks confirms this.

Origin of Myrmekite.

Becke (1908) who first made an elaborate study of myrmekite concluded that in the ~~pr~~ replacement of potash feldspar by plagioclase, the albite replaced the potash feldspar molecule for molecule, but the anorthite portion, on replacing potash feldspar, yielded four molcules of quartz. He justified this by showing that the proportion of quartz to feldspar in a myrmekite is always within what might be expected from such origin. This has since been the most acceptable explanation of myrmekite and explanations given by Eskola, Sederholm and Spencer given below have used it as the basic assumption. This explanation appeared to satisfy all the different structures and characteristics of myrmekite described above, but in the Bauchi rocks in which myrmekites are most common a late-stage soda-lime metasomatism is most unlikely and does not appear to have occurred. Rather, a late stage potash metasomatism appears to have taken place.

Schwantke in 1909 (Spencer 1945) suggested that some lime feldspar are held in solution in potash-soda feldspar in the form $Ca(AlSi_3O_8)$. He found that analyses of alkali feldspars showed excess silica and deficient feldspar. Schwantke therefore concluded that on seperation the lime feldspar would take its usual form releasing silica. Spencer (1945) examined more recent analyses and showed in support of Schwantke's that potash-soda-feldspars show excess silica. Even though this is a very tempting solution, the localization and distribution of myrmekite in Bauchi rocks cast much doubt on the role of such high silica feldspar in the formation of myrmekites. Myrmekites should, for instance, have been more abundant enclosed in alkali-feldspar, especially in those of pegmatite, rather than invading.

Eskola (1914), agreeing with Becke, maintained that the rectilinear boundaries against microcline he observed associated with the ordinary curved myrmekite was an idiomorphic form which originated during the processes of consolidation. No rectilinear myrmekite was observed in the Bauchi rock and such primary crystallization of myrmekite seems most doubtful.

Sederholm (1916) believed that myrmekites were formed by a late magmatic phenomenon which he termed "deuteric action". Before the final consolidation of the rock, solution and gases circulating from neighbouring or distant parts of the rock caused replacement of potash-soda feldspar by lime on the line postulated by Becke. He maintained that material from without must be available. Applied to the Bauchi rocks, Sederholm's explanation encounters the same difficulty as that of Becke, on which it is based. In addition such late-stage circulation of gases and solution if causing a lime metasomatism, should form a reaction rim of myrmekite round some albitic plagioclase. This explanation will not satisfactorily explain the "pedestal" plagioclase which appears to be essential in the formation of myrmekite.

Anderson (1937) stated that myrmekite appeared to have been formed "as an accompaniment of replacement of potash feldspar by plagioclase" in agreement with Becke's theory which he considered the best substantiated and most widely accepted explanation. He showed by their occurrence "in contact zone in partly re-crystallized rocks, which, beyond question, never were molten," (p. 9) that myrmekite was not invariably due to magmatic crystallization. He did not indicate the source of this replacing plagioclase, but, he first divorced myrmekite from late magmatic activity.

Drescher)Kaden (Bugge 1943) thought that myrmekite was formed by replacement action related to the formation of potash feldspar paving the way for the conclusions of Edelman (1949) that a K - Al metasomatism causes a Ca-Na-Si metasomatism. His equations for these process are given below.

$$\text{I} \quad K^+ + Na\ Al\ Si_3O_8 = K\ Al\ Si_3O_8 + Na^+$$

$$\text{II} \quad K^+ + Si + Ca\ Al_2Si_2O_8 = K\ Al\ Si_3O_8 + Ca^{++} + Al^{+++}$$

$$\text{III} \quad K^+ + Al + 4\ Si\ O_2 = K\ Al\ Si_3O_8 + Si^{++++}$$

The Na^+, Ca^{++}, Al^{+++} and Si^{++++} thus provided caused a reversed reaction in some other parts of the rock thus forming myrmekite according to Becke's theory. He maintained that there was a quantitative relationship between microline and the myrmekite fringing it and concluded that myrmekite was formed by and contemporaneous with granitization.

Most authors as seen from above review, accept Becke's theory in principle but differ over the source of soda-lime necessary to replace potash for the formation myrmekite. In the rocks of Bauchi, the microcline appears to be replacing other minerals, lobing into them and embaying them. Some of these, minerals, especially the plagioclase, show strain, while the microcline show no evidence of such deformation. The order of formation is therefore plagioclase, microcline and finally, the myrmekite. In truly magmatic rocks an alkali-rich phase is the more reasonable end of crystallization. Concentration of soda and lime over potash cannot be widespread in the late magmatic stage to cause large scale myrmekitization. This accounts for the invariable absence of large scale myrmekite association with orthoclase.

The suggestion by Drescher-Kaden (Bugge 1943) that myrmekite was formed by replacement action related to the formation of potash feldspar is more in accordance with the writer's observations of myrmekites in Bauchi rocks. Endelman's hypothesis (1948) and the reaction equations given by him partly explain the myrmekite in these rocks, except that he has not explained the role of the "pedestal" in the formations of myrmekite.

Endelman's (1948) equation should be modified as follows:

IV: $2K^{+} + Ca\,Al_2Si_2O_8 + 4\,SiO_2 = 2K\,Al\,Si_3O_8 + Ca^{++}$

This reversible reaction is controlled by the concentration of cations, since, in whatever phase the reaction is taking place, certain minimum concentration wuould be expected for either Ca^{++} of K^+ before the reaction takes place one way or the other.

In microclinization, soda and lime are being released both of which are soluble to a limited extent in microcline. This generation of Ca^{++} and Na^+ would accelerate rapidly when a plagioclase is being replaced by a microcline and in most cases the critical concentration of Ca^{++} and Na^+ relative to K^+ would be reached and thus the reverse readtion would be initiated with the consequent formation of myrmekites due to simultaneous production of quartz and feldspar. Once this reverse reaction sets in, it attracts more soda and lime from the surroundings where microclinization is in progress and exchanges potash for them according to the concretion principle of Eskola (1932). Thus a potash feldspar may build itself in one direction at its own expense. It is also conceivable that the microcline being now replaced by soda-lime feldspar would seize the opportunity to unload itself of excess soda and lime. Thus the plagioclase initiated the growth of myrmekite, and acted as the pedestal for this "petrological" coral" but does not aid its growth once initiated.

Microclinization may continue on both sides of the growing myrmekite, supplying it with more material for its own growth, and eventually the microcline may enclose the myrmekite as occasionally observed. Less commonly, a fluctuation to a more vigorous microclinization would cause the myrmekite to be replaced, thus may be formed a truncated myrmekite with rectilinear boundary observed by Eskola (1914.)

As soon as the myrmekite is formed and growing the process of "quartz-clearing" by the plagioclase brings the quartz together as described earlier. In prolonged metamorphism, such as is essential for the replacement formation of microcline porphyroblasts, many crystals have successfully cleared themselves of quartz and whether poikilitically enclosed or not the excreted quartz is commonly found in its typical association with the plagioclase which has gone through the complete cycle of myrmekitization, (Plate 33, fig. B).

The myrmekites in Bauchi rocks are formed in this manner, and whether they are subsequent and consequent to microclinization or a late stage action in magmatic crystallization they are essentially a product of subsolidus phenomenon. Their abundant and even distribution through all the members of Bauchi rock complex rich in microcline rules out a late stage magmatic action, and the widespread evidence of decline myrmekitization is suggestive of replacement under the condition of a prolonged dynamo-thermal metamorphism, as the origin for the microcline.

Perthites

Perthite was originally defined in 1843 by Thomas Thomson as the parallel intergrowth of orthoclase and albite, but the term has been since extended to include all sorts of irregularly shaped intergrowths of potash feldspar and plagioclase (Anderson 1937). Various types are now recognised.

Anderson (1928) made a systematic study of perthite and/recognised several textural types;- string type, film type, vein type, and patch type. Alling (1932 and 1938) has proposed many generic types, not favoured by the writer since most of these are already covered by Anderson's (1928) textural types. Two of Alling's (1938) textural types, stringlets and rods, are not covered by Anderson's and are used together with Anderson's to classify the perthites in the Bauchi rocks.

The varieties encountered in Bauchi rocks include the following: The stringlets which are of very fine blebs just barely resolved under the low powered (X5) objective. They are frequently oriented parallel to (100) and often give the host feldspar a velvety texture (Plate 34, fig. A). The perthite in the Quartz-Diorite is finer still and may be called "sub-stringlet".

The string type appears to be formed by the union of two or more stringlets. The blebs are long needles about 0.03 to 0.1 mm. in length and in width average about 0.01 mm. (Plate 34, fig. B). The prientation is as for stringlets.

The film type is of thin lamellae, longer and broader than string type and, contrary to Alling (1938), sharply outlined (Plate 35, fig. A). They are oriented parallel to (001).

The rod perthites (Plate 35, fig. B) are most likely a special section of the film type or the vein perthite. The vein perthites are of coarser and longer blebs and are oriented parallel to (100).

Though maintaining this general orientation they branch irregularly (Plate 36, fig. A) The less coarse type which might be called veinlet (Plate 36, fig. B) is termed "Streak" by Anderson.

The patch perthite (Plate 37, fig. A) is formed by patchy plates of plagioclase in the potash feldspar. These blebs tend to be elongated at right angle to the length of twin lamellae and not uncommonly these optically continuous patches are connected by blebs of the vein or string type. A type of patch perthite in which the blebs are more like inclusions (37 fig. B) may be called "poickiloperthite". The blebs may be optically continuous with a larger grain of plagioclase contiguous and sutured with the host potash feldspar. In this type, it is not unusual to find one of the blebs optically discontinuous, and there is no elongation in the direction perpendicular to the lamellae as in the patch type.

When a plagioclase host contains blebs of potash feldspar it is termed an antiperthite (Plate 38, fig. A). The blebs form irregular patches and are themselves perthitic (Plate 38, fig. B) thus forming a compounded-perthite.

Distribution in Bauchi Rocks.

The stringlets are found mostly in the Fayalite-Quartz Monzonite and the substringlets in the Quartz-Diorite. The string, film and rod perthite are most common in the Biotite-Hornblende Granite and the Biotite Granite. The vein perthites are associated with pegmatites and the patch perthite with strained porphyroblasts. Poikiloperthite and Antiperthite occur almost exclusively in the Quartz Diorite but are rarely observed in the Fayalite-Quartz Monzonite.

Some characteristics of perthites:-

On heating perthite of average bulk composition at about 850^{o} or lower temperature under condition of high (H_2O) pressure, for a few hours the feldspars become gradually homogenized (Spencer 1937 and 1938) possibly passing successively through cryptoperthite and "X-ray" perthite stage. On being slowly cooled the feldspars unmix again to give a perthite feldspar. "Low temperature cryptoperthites having composition near Ab_{50} Or_{50} refused to mix completltly on heating near the liquidus (Tuttle and Bowen 1958). Chayes (1952b) demonstrated the effect of stress on perthite and concluded that shearing stress favour if it did not actually induce unmixing of the feldspars to give perthites. The writer's experience with the cataclastically deformed rocks of Bauchi supports Chayes' suggestion. The "augen" frequently develops much coarser perthitic structures than the microcline of the undeformed rocks, but at an advance stage of cataclastic deformation the effect appear negative.

Alling (1932 and 1938) has variously emphasized the effect of inclusions on the perthite blebs.

In the Bauchi rocks, the perthite blebs may become definitely more abundant around a plagioclase inclusion or any other inclusion in the potash feldspar, but they may also avoid margins of such inclusions creating a barren halo round them, and most frequently they ignore inclusions completely. Perthites of relatively high temperature rocks tend to be very fine with sub-stringlet perthites and cryptoperthites, while perthites associated with low temperature rocks such as simple pegmatites are the coarser, less regular vein type of perthites. However, rocks originally crystallized at high temperature and slowly cooled in the presence of water vapour may develope coarser types of perthite blebs than those in the string type. (Bowen and Tuttle, 1958).

Anderson (1928) recognised this temperature control of perthite and his textural classification used above represents condition of decreasing temperature. The distribution of the various types in Bauchi rocks may thus indicate successively lower temperature condition from the Quartz-Diorite to the Biotite Granite.

The Origin of Perthite.

Four main theories have been proposed to explain the origin of perthites in rocks: exsolutions, simultaneous crystallization, replacement and solution filling.

The exsolution theory has appealed to many petrologists as an explanation of perthite and today it is probably the most accepted and the most substantiated. The principle of exsolution has been the subject of various types of phase diagrams. Those of Bowen and Tuttle (1958) and Laves (1952) (fig. 11) are the most recent. According to these diagrams, when first crystallized, potash feldspar carries in solution an amount of soda feldspar which it could hold at that temperature, and with cooling, it continuously adjusts the amount it holds in solution to the falling temperature by exsolution and thus perthite is formed. All the characteristics of Bauchi perthites discussed earlier can be explained by this theory and it is also justified by the consideration of the mutual solubility of $NaAlSi_3O_8$ and $KAlSi_3O_8$. Most of the perthites in the Bauchi rocks, other than some vein and patch types were most likely formed on this principle. Warren (1915) made a quantitative study of feldspar, and concluded that those perthitic feldspars with more than 28% albitic plagioclase, which could not have been formed by unmixing of a previously homogeneous feldspar, are formed by "original intergrowth". Though he appeared to have changed his opinion later (1945), Spencer (1938) suggested the term cotectic-perthites for vein perthites and claimed that they were formed by simultaneous crystallization. Simultaneous crystallization, limited to perthites in low temperature rocks like pegmatite, seems a valid conception. That the albite component of most perthitic pegmatite is far in excess of what they could previously have held in solution, make this mechanism probable. The Bauchi pegmatites appear to have been emplaced either by direct crystallization from very low temperature solution or by replacement process. In either case, relatively low temperature high pressure condition must have prevailed over a long period. Under such condition, intergrowth by simultaneous crystallization appears a reasonale explanation. Attempt to attain equilibrium must have caused the feldspar to rearrange themselves by diffusion into a form which imposes the least strain on the lattice thus giving the usual vein perthite form. Here there is no limit to the proportion of soda to potash feldspar and the emphasis is on the feldspar being ordered to equlibrium.

A replacement has been claimed by many petrologists for certain perthite (Schaller 1926, Anderson 1937). In the Bauchi rocks the patch perthite, poikilo-perthite and antiperthite could have been formed by pseudomorphic replacement processes, but the augen gneisses in Bauchi district demonstrated that some patch perthite might be formed by exsolution under the influence of stress.

Anderson (1928) suggested that certain perthites are formed by recrystallization in contraction cracks. This is considered an unlikely origin of perthite in general. It is, at least, not supported by the characters of perthites in Bauchi rocks. One would wonder why such cracks are not sometimes filled by other minerals, say quartz.

Perthitic Porphyroblasts.

It appears that the large microcline crystals formed under metamorphic condition by replacement in solid rocks could be perthitic. The solubility of $Na\ Al\ Si_3O_8$ in $K\ Al\ Si_3O_8$ is a function of temperature and the diffusion of Na and K is equally dependent on temperature. As shown in the equations by Endelman (Equations I-II) considerable amounts of soda and lime are released as a result of potash metasomatism during the formation of the porphyroblast, and some of this soda and lime will diffuse through the porphyroblasts and, depending upon the temperature, an amount may be held in solution. On cooling the attempt by the crystal to maintain equilibrium according to the principles explained by Laves (1952) will result in unmixing and consequent formation of perthite. Such perthite would hardly be distinguishable from that formed by phenocrysts crystallized directly from magma. However where the thermal condition has not been maintained over a sufficient period of time the diffusion may not be thorough and the soda and lime content of the potash feldspar would be uneven, higher in the immediate area where a plagioclase has been replaced and low where, say, quartz has been replaced. Such, on cooling, would unmix to give unevenly distributed perthite blebs these being clustered in areas of high soda-lime content and sparse in areas of low soda-lime content. Though one would hesitate to say that such uneven distribution of belbs could not occur in perthites of magmatic origin, it is considered rather unlikely.

Origin of the Perthite in Bauchi Rocks.

Of the various origins proposed for perthites the most acceptable and the best substantiated in Bauchi are those which are based on the principle of "unmixing" (exsolution). Unmixing as a phenomenon is the attempt of soda-potash feldspar to attain equilibrium on the line explained by Laves (1952) (ordering of Al and Si, and the unmixing of K and Na.) This follows from the difference in the atomic sizes of K and Na which renders them only limitedly mutually soluble at the low temperatures. Perthites formed on this principle should be regarded as true perthite.

These, even when irregular as in the vein type or Anderson's streak type, have an overall uniformity of pattern an orientation characteristic of it such being dictated by the rate and length over which exsolution has taken place, the presence or absence of water vapour, the bulk composition and structure of the host feldspar and to a less degree by the magnitude of shearing stress; many of these variables are interdependent.

In deep seated Pre-Cambrian rocks, such as the Bauchi granites, which are of uncertain petrological history, distinction could hardly be made on the basis of the type of perthite, between a rock of direct magmatic origin and one which has been formed by metasomatism and granitization. As shown above a porphyroblast may develope perthitic blebs quite similar to those of phenocrysts crystallized from a magma, since the principle is the same. Where the perthite blebs have a tendency to be irregularly clustered and are of non-uniform proportions from grain to grain, one may begin to suspect, with reservations, that the rock was of replacement origin. Applied to the Bauchi rocks, the Quartz-Diorite would appear to have had relatively a higher temperature origin. The Fayalite-Quartz Monzonite and the Biotite-Hornblende Granite with stringlet and string type of perthites which are irregularly clustered and distributed, the potash feldspars were probably formed by replacement at fairly high temperature, while those of the Biotite Granite, with coarser but irregularly distributed blebs, have possibly been formed by replacement under the conditions of prolonged dynamo-thermal metamorphism, such as must have favoured the development of the pegmatite dykes with bold vein-perthitic blebs.

The Pseudocataclastic Structure.

The term pseudocataclastic structure was proposed by Anderson (1939) to describe a sugary to fine mosaic aggregate of minerals surrounding the large crystals of feldspars and forming a texture which is similar to that of cataclastically deformed rocks.

A similar texture has been observed in some sections of the Bauchi rocks. (Plate 39 fig. A) That they may not be related to true cataclastic structure is shown by the following characters of the texture:- They follow the outline of the larger minerals which frequently are sharply angular, unlike the rounded augen in cataclastic rocks with the granulated material sweeping round them. Their mineral aggregate is quite different from what would be expected if they were ground off from the larger crystals in their immediate vicinity and the quartz grains are not as elongated as would be expected from a cataclastic rock.

The Minerals of the Pseudocataclastic Structure.

In the Bauchi rocks the mineral principally forming this structure are quartz and plagioclase in a fine granular aggregates with the latter the more abundant. Some small amount of microcline may be present. Frequently, the minerals form a very fine sugary-textured mass in which the individual minerals cannot be identified, but which soon grade into a mosaic of larger grains. The plagioclase is oligoclase. The quartz occurs as small grains, vermicules and blebs corroding the feldspars, and masking the granular texture. Microcline is rather variable and is frequently absent in the aggregate. Where the structure adjoins a microcline it may be festooned by a chain of myrmekite.

The Distribution and Origin of the Pseudocataclastic Structure.

The pseudocataclastic structure is most abundant in the Biotite Hornblende Granite, least common in the Fayalite-Quartz Monzonite and not found in the Quartz-Diorite.

Anderson (1937) attributed this structure to late stage solution effects in which secondary material was introduced along the boundary of the larger minerals which were corroded as the vein-like mass widened. This is not the case in the Bauchi rocks. The fringe of myrmekite, along some of the veins, as concluded from the study of myrmekite suggest that the microcline was replacing the minerals of this structure. Such a late-stage solution effect is admittedly possible in the Bauchi rocks.

Where the veinlike aggregate is wider (Plate 39, fig. A) the similarity to the ground mass of a fine grained Biotite Granite is striking. It is therefore probable that the structure is formed by narrow zone of relic mineral remaining between two advancing porphyroblasts. In some instances (ME 140, plate 39, fig. B), the pseudocataclastic structure could represent the relic of what was actually a cataclastic ground mass.

Thus this structure further points to replacement as the probable origin for the large microcline of the Biotite-Hornblende Granite.

Zoning in the Plagioclase.

Normal zoning is commonly observed in the plagioclase of the Quartz-Diorite, and this tendency is also noted in those of the amphibolite. The zoning in the quartz diorite is of an inner core of calcic andesine with an outer zone of more albitic andesine. The crystals are anhedral and are usually lobed into by the surrounding ferromagnesian minerals (Plate 28, fig. B).

Normal zoning is commonly held to be a magmatic phenomenon. In all cases it is interpreted as representing unstable condition in the magma chamber, (e.g. Phemister, 1934).

Dunham (1958) mentioned a case of zoned andesine-oligoclase feldspar in amphibolite from Sierra Leone, "which could not, because of the textural relations, be other than of metamorphic origin" (p. 8.) Through the kindness of Professor K. C. Duhham the writer has been able to compare the zoning in the plagioclase of these Sierra Leone amphibolites with those of the

Quartz-Diorite and the amphibolite from Bauchi. They all have a characteristic vagueness of definition. The zoned feldspar of the Quartz-Diorite show better defined cores which are very irregular and they may have more than one core in a crystal. (Fig. 12) These characteristics of the zoning in the plagioclase of the quartzdiorite are difficult to explain by any theory based on instability or changed conditions in a crystallizing magma but may be explained either by magmatic resorption effect, or else by metamorphism.

Origin of Zoning in the Feldspar of Bauchi Rocks.

Plagioclase zoning commonly accepted as a magmatic phenomenon is not necessarily such. As proved in the plagioclase of the amphibolite from Sierra Leone, zoning can be induced in plagioclase by metamorphism under conditions of amphibolite facies. Magmatic zoning is more sharply defined, frequently oscillatory and are in outline subhedral to euhedral. Those less sharply defined zoning, especially with irregular or disjointed cores, are probably not of magmatic origin. The zoning in the plagioclase of the amphibolite might have originated by exchange of lime for soda, the plagioclase losing the lime to the growing hornblende by ionic diffusion in solid or vapour phase. The zoned plagioclase of the Quartz-Diorite with the disjointed and irregular cores could be due to resorption or otherwise to loss of lime to the pyroxenes and hornblende by metasomatosis.

Checkerboard Structure.

The (?) calcsilicate rock specimen (ME 137) from near the air strip, which may be called a pyroxene granulite ~~granite~~ contains abundant plagioclase with a peculiar checkerboard structure (Plate 40, fig. A). This structure is formed by rectangluar to cubic blebs of a mineral of much lower refractive indices than the host plagioclase. The bleb mineral is believed to be a plagioclase feldspar because the twinning, in some cases, appear to be continuous across it and of oligoclase compostion from its parallel extinction.

This checkerboard structure is believed to originate by exsolution of albite from the host feldspar, resulting from the necessity for the latter to adjust its composition to high temperature and pressure condition of metamorphism.

CHAPTER IV. EVIDENCE FOR THE GENESIS OF BAUCHI ROCKS.

Bain (1926) who was the only person who had previously studied the rocks of Bauchi in great detail concluded, that the Bauchi "granites" were intruded bodies. He suggested three periods of intrusion, as shown in Table 2. He claimed that a long period of quisence prevailed before the last intrusive phase, so that the Bauchi Granite series and the fine grained Biotite Granite series formed two major intrusive cycles. He claimed further that the Bauchi Granites differentiated in place into two types, Pyroxene Syenite and Hornblende Biotite Granite corresponding to the Fayalite-Quartz Monzonite and the Biotite-Hornblende Granite of this account.

Bain did not mention any evidence in support of this view, but those features could have led him to conclude that the Bauchi "granites" are intrusive and differentiated in place can be readily appreciated in these rocks.

Evidence for Magmatic Origin of the Bauchi Granites.

The rocks of the Bauchi Batholith, the later intrusion, are Quartz-Diorite, Fayalite-Quartz and Biotite-Hornblende Granite. They form a gradational series and could have been formed in place by differentiation from a common magma. From the composition of the three principal members of this series, a diagramatic representation of the course of differentiation has been constructed (Fig. 13) In the plagioclase, there is a progressive increase of Ab ratio, and in the pyroxenes there appears to be a progressive increase in theFe/Mg ratio as would be expected of a differentiated body. Such variation in soda and iron is however not necessarily due to differentiation as will be shown subsequently.

The Quartz-Diorite member of the series frequently shows normal/zoning in the plagioclase. As shown in the preceding chapter, this may be regarded as a magmatic phenomenon, even though similar structures may be produced or preserved in metamorphic rocks as demonstrated by the amphibolite from Sierra Leone (Dunham and others 1958, p. 8) and the amphibolite from Bauchi (ME 206).

According to Buddington (1948) the phenocrysts of a porphyritic rock crystallized from a magma are usually well formed. Superficially the large microcline crystals of the Bauchi Granites are strikingly well formed, and their arrangements very regular, so that as seen over a large area they make patterns of wallpaper regularity. Moreover, the linear distribution of these large crystals in the Biotite Granite could suggest the effect of magmatic flow.

The contacts of the Bauchi Batholith series with fine grained biotite granite, rarely seen, are sometimes sharp though not chilled at the margins. The absence of chilled margins could be attributed to the intrusion having taken place at great depth so that the country rocks were hot when they were invaded.

The large inclusions of fine-grained dense rock found in the Bauchi granites (Plate 5, fig. A), could be xenolithic blocks of biotite granite which were immersed in the magma during stoping and subsequently recrystallized.

The Medium-grained Biotite Granite resting partly on the Quartz-Diorite and partly on the Fayalite-Quartz Monzonite resembles a recrystallized roof pendant. The Fayalite-Quartz Monzonite in its western margin contains relict granulite which has been recrystallized and appears hornfelsic.

These and perhaps a few other lines of evidence could be evoked to suggest that the Bauchi granite series was a product of differentiation of a magma in place. If such an origin were assumed, certain features of the rock present considerable difficulties; these are discussed below.

The Possible Nature and Origin of the Magma.

A magma differentiating in place to give the Bauchi Batholith series would not be very basic and at least less basic than the Quartz Diorite, the most basic member of the series, except if there are more basic members of the series still unrevealed. It would also have to be somewhat less acidic than the Biotite-Hornblende Granite, the most acid member. The Fayalite-Quartz Monzonite and the Biotite-Hornblende Granite which made up about 98% of the rocks in the series are composed on the average of microcline perthite 51%, plagioclase 25%, and quartz 16%, the remaining 8% being fayalite, hornblende, biotite, apatite and ore. The magma of the present Bauchi rocks would therefore have had to have been very rich in the constituents of microcline, intermediate plagioclase and quartz at the beginning of differentiation, even if it were originally more basic, and would probably be chemically about the composition of the Fayalite-Hornblende Granite (table 9).

The presence of fayalite suggests that the magma was dry. From the absence of chilled margins, when the contact is a sharp line, it can be inferred that the surrounding rock must have been nearly as hot as the invading magma. By the absence of evidence of partial fusion of this wall rock this temperature could not have exceeded 1025°.

The viscosity of a silicate magma at a given temperature can be estimated from the viscosity which is characteristic of its components (Vogt. 1923). The magma which would give Bauchi granites as shown earlier is very largely of $KAlSi_3O_8$, $NaAlSi_3O_8$, $CaAl_2Si_2O_8$ and SiO_2 components (92%); with the exception of $CaAl_2Si_2O_8$ which is of medium viscosity, these components are extremely viscous even when heated some hundred degrees above their melting temperature, (Vogt. 1923, Bowen and Tuttle 1958 p. 77). Since the magma would be dry as shown earlier it would be more viscous than average granite magma. Granitic melts are extremely viscous even when heated as much as 300° above the temperature of crystallization (Vogt. 1923). According to the same author the effect of pressure would have been to increase this viscosity.

In conclusion, one must assume that the Bauchi Magma if there were one would most likely be potash-rich, of a temperature not above 1025°, poor in volatiles, especially water and extremely viscous. Such dry granitic magma would hardly be fluid (that is it should be crystallized) at the probable temperature and it is therefore doubtful if it could exist. If it could, it would be unlikely to crystallize into rocks of such extreme coarseness as the Bauchi granites even given a considerable length of time; for an efficient diffusion of material is hindered in such dry, viscous material. Hypothetically, the most that could be expected of such magma is intermediate grain size. (Vogt 1923). The coarseness could of course be due to later recrystallization by metamorphism.

There is the additional difficulty of generating such a magma. If it could be derived it Might originate in the following ways:- Differentiation and fractionation of a primary basaltic magma according to Bowen's theory, selective fusion of rocks at depth (Anatexis) according to Eskola and Sederholm, or wholesale fusion of some previously existing rock or rocks of granite composition ----- Palingenesis. (Sederholm and Daly).

Considering Bowen's theory of deriving granitic magma from a primary basalt magma, the argument in its favour and the serious objections to it are too well known and thoroughly discussed to be reiterated. It is sufficient to say that the large extent of Bauchi "granites" and the total absence of basaltic rocks makes that source doubtful for deriving the magma of the Bauchi granites. Bowen and Tuttle (1958 p. 124) suggested the derivation of granitic magma from andesitic liquid derived from partial melting of basalt. In their own words, the process is as follows: " ...... at depths of 35-40 km. basalt could become partially liquid and the liquid would have a composition not far from that of andesitic rocks. If the unmelted portion then settled out, and the andesitic liquid, displaced upward, crystallized in an environment where an opportunity for settling of crystals still prevailed, liquids of granitic composition could result."

This will not yield more granite, possibly less than that from fractional crystallization of basalt magma. It is doubtful whether fractional melting of basalt will yield a liquid in any way near andesite.

Rocks are not molecular but mineral aggregates. Most of the soda, potash and, especially, silica in basalt are locked up in minerals which will not release them until completely melted. Gorasson's experiment (1932) suggests that partial melting of rocks does not mean fractional melting.

The minerals of granites have the lowest melting or crystallization temperature of all igneous rocks (Vogt 1923), as also can be deduced from their eutectic position. Thus granite magma of the composition of the average of the Bauchi Granite series can conceivably be generated by partial fusion of the low melting materials of granitic rocks and the squeezing out of these melted materials during orogenic movements - differential anatexis (Eskola 1932). The various ways in which this couldbe generated were described by Eskola (1932a, 1932b, 1933) and Daly 1933. Such a pore magma if dry would be very viscous, and would require much higher temperature, the necessary amount of water to bring it to reasonable viscosity and temperature of melting is normally sufficient to cause complete fusion of granitic rocks. (Goranson 1932) Thus partial fusion of rocks near granite composition is unnecessary and partial fusion of diorite is open to the same objection as Bowen and Tuttle's Andesitic magma.

Daly (1933), Sederholm (1933), Kennedy and Anderson (1936) have shown the various ways in which granitic magma could be derived by wholesale fusion of part of the granitic layer during orogenic mountain building. According to Daly's hypotheses (1933), during mountain building the Sial is downwarped and founders into the substratum with consequent rising of vitreous basalt, the mountain root being thus invaded by basaltic magma. "The deeply sunken blocks, and slabs of sialic rocks" are melted after a considerable time. This he termed "abyssal palingenesis." Some of this abyssal palingenetic magma is taken into solution by the hot basalt but most rises to the bottom of the mountain where, if it is more basic than granitic composition, there may be differentiation. It is known from Geophysical evidences that the Sima is not a liquid and the foundering of the Sial is improbable. Kennedy and Anderson (1936) with much petrological and geophysical evidence in support of this principle emphasized that such primary fusion of the granitic layer could only take place in orogenic areas. There is hardly any doubt that granite magma could be formed from such abyssal palingenesis, but modern experimental work (Bowen and Tuttle, 1958, Fyfe and other, 1958) indicates that water and fluxing volatiles are needed, and we have no evidence of these in Bauchi rocks other than a little tourmaline, and the dry nature of the Bauchi rock has been demonstrated.

The Differentiation of the Bauchi Magma.

The differentiation of a granitic magma to give rocks of such contrasting composition and texture as the Quartz-Diorite, the Fayalite-Quartz Monzonite and the Biotite Hornblende Granite is another problem. If the magma were, as summed up earlier, viscous, not of exceptionally high temperature and of low water content, its ability to differentiate into such rocks is doubtful.

If it could differentiate, the course of differentiation would be as shown diagramatically (Fig. 13). The abrupt change from crystallization of Ferrohypersthene and Ferroaugite to Fayalite and Ferrohedenbergite is not quite understandable, but is accepted as probable. The main difficulty is the mechanism of effecting such differentiation.

Daly (1933) treated exhaustively all the important mechanisms by which a magma could differentiate. These are, fractional crystallization, resorption, liquid immicibility, diffusion of molecules and ions, pure melting and differentiation. It is not intended to discuss these various mechanisms elaborately but only in so far as they are related to Bauchi rocks.

Bowen's work has established fractional crystallization as one of the most accepted mechanisms by which a magma can differentiate. His well known reaction series summarised this theory of differentiation. Since the magma had presumably differentiated in place seperation had to be by either gravity or convection currents. It is doubtful if the densities and the crystallization temperatures of the different minerals involved are sufficiently different to allow these to be effective in a viscous magma.

According to Daly (1933), as crystallization begins along the walls the early crystals will sink and, if the temperature is suitable, they would be resorbed as they pass through the part of the magma with higher temperature. Thus there would be three different liquids of contrasted densities: "magma yet unaffected by crystallization, magma modified by re-solution of crystals sunken into it and magma residual from partial crystallization". He suggested that the effect of gravity would prevail over their miscibility and they would be arranged according to densities and would be crystallized before diffusion can effect uniformity. This Daly called differentiation by resorption.

Since the early crystallized minerals are those of higher densities and basicity, then the initial magma modified by re-solution of sunken crystals must be more basic and denser than the magma yet unaffected by crystallization and since the former lies above the latter, it must displace the latter gravitatively. Such displacement is doubtful in two very miscible liquids slowly brought together.

It seems more probable that the continued re-solution of early minerals in the deeper part of a magma will cause a gradual lowering of temperature in that part and as soon as the crystallization temperature of these early minerals is again reached they will be reprecipitated to continue their journey towards the bottom of the magma chamber. This will in no practical way be different from gravitative seperation in a fractional crystallization. Thus Daly's "rest magma versus magma of resorption" (1933) is an unnecessary recasting of Bowen's "fractional crystallization" theory, which has been discussed in the preceding paragraphs. It is not considered a probable mechanism.

Bowen (1928) has considered the role of liquid immiscibility and advanced powerful arguments against it. The mechanism as a means of magmatic differentiation is now taken to be a "Speculation" with very "little direct sanction" (Daly 1933). In relation to the magma of the Bauchi Batholith it can completely be ruled out since at the temperatures demonstrated for these rocks, the different members so close in composition would be completely miscible.

Diffusion of molecules and ions can take place under the influence of gravity, a chemical gradient and a temperature gradient according to the Soret principle. Bowen (1921) has shown conclusively that such diffusion can be of no practical value in the differentiation of an individual magma. Molecular diffusion as a means of producing rocks of contrasting composition is considered reasonable, but such differentiation probably falls more within metasomatic field than that of magmatism.

In conclusion, it does not seem proabable that the rocks of the Bauchi Batholith could have attained their varying compositions by magmatic differentiation. If the rocks had any magmatic past, they could possibly have been produced by composite magma. This is highly hypothetical, but certain features of the rocks favour it; the rapidity of gradation, the contrasting colour of the Biotite-Hornblende Granite and the Fayalite-Quartz Monzonite and the occasional independent occurrences of Quartz-Diorite and Biotite-Hornblende Granite in the field. The essential problem in this is in accounting for the source or sources of the different magmas and the mechanism of their emplacement.

The Space Problem.

The large dimensions of the Bauchi Batholith have been described earlier. As an intruded mass, the space problem for a magma of such huge dimensions is formidable; - magmatic stoping (Daly 1933) notwithstanding. This problem disappears only if the magma is considered palingenetic.

Some Petrolgraphic Features against a Magmatic Origin.

Most of the plagioclase showed strain effects characterised by bending of the lamellae and corresponding wavy extinction. Such strain effects are not exhibited by the microcline and some grains of plagioclase. Presumably the rock was solid enough to be deformed before the introduction of some later generation of plagioclase and all of the microcline. This could however be explained as due to deformation of early crystals in a partly crystalline magma. This is unlikely from the occurrence of the microcline as phenocryst-like crystals. So far we have considered the rocks of Bauchi Batholith, the migmatitic rocks can now be examined. Bain (1926) showed that the boundary between the Fine-Grained Biotite Granite (Fine-Grained Feldspathic Older Granite - Bain 1926), and the Biotite Gneisses (Biotite Granite and Gneisses - Bain 1926) is gradational or inderterminable, and yet he recognised three distinct intrusions within them. The same gradation is found by Falconer (1911) and by the present writer. The contrasting aspect of the two rocks is the presence in one of numerous medium sized microcline crystals and their absence in the other, features that can hardly be attributed to magmatic differentiation.

In conclusion, if the Bauchi rocks are of magmatic origin, then the rocks, as far as they are known, do not bear any unequivocal evidence of this.

Some Evidence of a Metasomatic Origin.

That a metasomatic transformation can result in igneous looking rocks of batholithic dimensions has been shown by the work of many geologists for example, Termier, Lacroix, Sederholm, Holmes, Read, Eskola and Reynolds to cite a very few. Most adherents of magmatic theory conceed that such phenomena commonly termed granitization, can take place to a limited extent around an intrusive mass. Such admission of small scale granitization also implies its possibility on a large and intensified scale. Metamorphic transformation of rocks into varieties of igneous character may be accepted as avalid theory in petrogenesis and for the Bauchi rocks in particular it is a probability.

The geological map of Bauchi, (Map B) shows that the Fayalite-Quartz Monzonite forms the core in a plutonic series arranged in an aureole. Such a petrological pattern is typical of granitization as demonstrated in the several writings of Read, Reynolds, Backlund and other authors. The writer thinks it probable that a granitic rock mass surrounded by a zone of migmatization has been made in place as suggested by Read (1940) more especially if the contrary cannot be demonstrated. This spatial relationship is, at least a corroborative evidence of metamorphic origin.

The contact of the Bauchi Batholith is rather indefinite. It is rarely seen, but where exposed it is characterised by development of irregular migmatites. In few localities it is sharp but without a chilled margin. In some places there is complete gradation from one type to the other. Such apparently intrusive contact features are better explained by localised mobilization. The Biotite-Hornblende Granite of the Bauchi Batholith has a lineation structure (from the linear arrangement of its large microcline feldspars), which is invariably concordant with that in the Biotite Granite. (Map B) Some specimens (ME 101, ME 208) showed that this lineation is present in the Fayalite-Quartz Monzonite and the Quartz-Diorite as well. The conclusion seems justifiable that this lineation structure might be inherited from some previous rock.

The study of myrmekite, perthite and pseudo-cataclastic structure in the rocks of Bauchi suggested the probability that the microcline of the rocks is of metasomatic replacement origin (Chaper III).

The microcline crystals look somewhat euhedral and uniformly distributed when viewed casually in ordinary handspecimen or over a wide area in the field, but a stained specimen (Plates 19 and 21) showed that these are crystalloblastic and irregularly distributed. Such textures have been described by King (1943) and Reynold (1943, 1946) and, according to King (1943), by Spurr and Garney (1908) and Anderson (1934) as evidence of a replacement origin for the microcline.

In the angular blocks of the agmatites, large microcline porphyroblasts in all details similar to those of the Bauchi granites are often developed and obviously formed in the solid state. A dyke-like body of cataclastic rock just north of Tiruin village, demonstrates a similar case of microclinization (Plate 41, fig. A): After strong cataclastic deformation the rock, a fine grained Biotite Gneiss, has developed large microcline porphyroblasts simply twinned according to the Carlsbad law, some of the porphyroblasts are about 2 inches by 1 inch and many are set right across the deformation S plane (Plate 41, fig. B). Under the microscope the introduction of the microcline after deformation is further confirmed. It is thus quite clear that these large microcline crystals are developed in solid rock, being so strikingly undeformed and frequently lying across the shear planes. These porphyroblasts are very similar to the microcline of the Bauchi "granites" showing similar myrmekite and perthite structure.

In the Biotite Granite patches are frequently found where these large porphyroblasts have been sufficiently developed so as to look like the Biotite-Hornblende Granites (Fig. 8) and all gradations are to be found. It is significant that at such localities there is often evidence of some previous deformation (where diffusion, permeation or recrystallization are to be expected to be greatest. It is also quite evident that in most cases these microcline porphyroblasts have not participated in the deformation.

Examination under the microscope shows that in all the above cases the microcline porphyroblasts are crystalloblastic. Thus all around the rocks of Bauchi Batholith, are developed, even if only sparsely, microcline porphyroblasts exactly similar to those found in the rocks of the batholith and producing rocks that are hardly distinguishable from the batholithic rocks. Similar evidence for replacement origin for the microcline of batholithic rocks has been cited by Read (1940) and Perrin (1956).

All over the Pre-Cambrian of Nigeria, Older Granite rocks with large microcline porphyroblasts are described by Falconer (1911, 1921), King and deSwardt (1949), deSwardt (1953), Mackay et al (1949) and others. Their descriptions could be used word for word for the rocks of the Bauchi batholith. The writer has seen the rocks of the Ilesha district described by deSwardt (1953) and some granites near Ilorin close to those described by King and deSwardt (1949), these rocks are in no way different from those of the Bauchi Batholith. The granites of Ilesha and Ilorin are stated by these authors to be formed by microclinisation.

Some of the microcline granites from Sierra Leone, described by Marmo (1955) and from Uganda by King (1943) from Portugal by Schemmerhorn (1956) seem to be in no way different from the rocks of the Bauchi Batholith. According to Marmo (1956) such potassic rocks are widespread in the Pre-Cambrian of Finland. Rocks characterised by extreme coarseness due to large porphyroblasts of microcline perthite are probably very widespread in the African Pre-Cambrian, and everywhere it is evident from the work of various authors that the evidence points to metamorphic transformation in place which is essentially a microclinization process.

Turning to the migmatitic series, the Biotite Granite as described earlier is extremely irregular in character, with great variation in colour, mineral content and texture, even within a few yards. The common occurrence of ghost relics of schist and schlieren, (represented by biotitic patches) puts these gneissose granites within the nebulitic granite of Sederholm (1926) and explains the irregularity of the character of this rock. This explains the mystery of the absence in the Bauchi district of schist and quartzite which according to Falconer (1911), are abundant in the surrounding provinces.

It could be argued that such variation could be attributed to varying degree of assimilation by the granitic magma (Bain 1926), but assimilation of so much schist and granulite by a granitic magma presents a serious energy problem, except if the magma be derived in situ by palingenesis.

Generally all the "granites" of Bauchi district show great variation and irregularity in the distribution and development of the microcline crystals which can be noticed even in hand specimen and which is believed to be consistent only with a metasomatic process.

If a metamorphic origin by transformation in place is assumed many of the problems facing a magmatic origin could be solved. The space problem is reduced to accounting for the loss of only some ions (i.e. Fe, Mg.), the texture of the rock becomes easier to explain by microclinization, and the problem of generating such magma is reduced to finding the source of the microlinising "ichor" (Sederholm 1926).

Much of the evidence cited in support of a metasomatic origin is not entirely unequivocal. Just as many lines of evidence pointing to magmatic origin can be equally explained under certain circumstances by metamorphism, so could many of these lines of evidence pointing to metasomatic origin be explained by magmatism under certain conditions.

The general plutonic setting together with other field and petrographic evidence discussed above leads the writer to conclude that metasomatism has played a large part in the evolution of the Bauchi rocks.

However, the Quartz-Diorite and the Fayalite-Quartz Monzonite have some very disturbing features; the distinguishing colour of their feldspars and quartz and their general petrography are strikingly igneous, while the microcline porphyroblasts with continuous lineation through all the rocks and the gradational contacts from the Quartz-Diorite through to the Biotite Gneiss suggest some common history. This could probably be due to all the rocks having metasomatic origin, with these two rocks modified by some near igneous conditions not shared by the other rocks.

The important problems facing a hypothesis of metamorphic origin for Bauchi rocks are; the source of the materials for microclinization, the mechanism by which transformation is effected, the source of energy required to drive the necessary reaction and the disposal of surplus material. It will be shown in the next chapter that these problems can be adequately met.

CHAPTER V. THE GENESIS OF THE BAUCHI ROCKS.

The Archaean Metasediments.

The schists and quartzites which are abundant in the provinces around the Bauchi district were attributed to dynamic metamorphism of an ancient sedimentary series by Falconer (1911). They are represented in the Bauchi district by granulitic relic rocks which occurs as small patches throughout the migmatites. Bain (1926) believed these granulites to be product of dynamic, and to a less extent thermal metamorphism.

The calcsilicate rocks are probably not all derived from limestone but from some basic dykes. Many of them contain enough diopside and garnet to be called calcsilicate rocks, but in some plagioclase feldspar is abundant, garnet is absent and the general texture is granulitic; then, the rocks may be descfibed as ~~claeic~~ pyroxene granulite (ME 237).

Migmatization in the Bauchi District.

The infrequent occurrence of the schists and quartzites around Bauchi, referred to by Falconer (1911) is the direct results of intense migmatization producing biotite gneisses, lit-par-lit gneiss, agmatite gneiss, and mixed gneisses and pegmatite dykes and ultimately granites.

The term migmatite was first proposed by Sederholm (1907) and according to him (1928) they are hybrid rocks originated by mixture of older rocks and a later erupted granitic magna and he has emphasized the intrusive character of the later rock and designated them "arterite". Holmquist (Eskola 1932) on the other hand regarded this later rock as of metamorphic segregation, exuded from the surrounding rock, designating them "venites." A non-genetic term for this injected or segregated portion of a migmatite is "phlebite" (Barth 1951 p. 364) and the older portion of the rock may be called paleosome (Barth 1951 p. 365).

The phlebites in the Bauchi Migmatites could not have been injected foreign granite magma. They constitute about half of the area of the migmalite and the injection of so much granitic material as thin leaves poses a more serious space problem than that of granitic mass of comparable size since stoping cannot be involved. Quite often a narrow phlebite only about one centimetre broad could be traced over several hundreds of centimetre. In agreement with the observation of Currier (1947) and other authors there is no discernible squeezing aside of the paleosome bands of granulite in the lit-par-lit gneiss. In the agmatitic gneiss, the biotite gneiss has been dissected into numerous angular blocks as in the case of the agmatites described by Hsing-Yuan-Ma (1948) from the Shetlands. The angular blocks retain their regional orientation and are not sharply demarcated from the phlebites.

The writer therefore considers injection of granitic magma as suggested by Sederholm quite unlikely. On the other hand, it is considered improbable that these are simple cases of metamorphic segregation as proposed by Holmquist (Eskola 1932). The segregation of so much quartz and microcline would leave a residula rock quite different from the original granulite. From thin section of the gneiss in which the phlebites are closely spaced, one can discern distinct alternating bands of granulite and phlebite and the general impression is one of a mixed rock. The granulite bands appear to be impregnated with microcline andquartz and not secreting these minerals. The phlebite could only have been introduced by metasomatic replacement, the granulite absorbing potash and silica as it were from a solution like a "blotting paper" (Barth 1933), in exchange for surplus material from its own components.

The various migmatitic gneisses in the Bauchi district differ from one another only in the varying degree of development and arrangement of the phlebites. In the Lit-par-lit Gneiss, the phlebites and the bands of granulite alternating with it are relatively broad whereas in the Biotite Gneiss there is intimate and closely spaced inter-leaving of the granulite with the phlebites. In much of the Biotite Gneiss, there are only a faint trail of biotite flakes remaining from the original granulite bands.

The Agmatitic Gneiss on the other hand is of blocks of Biotite Gneiss, in which the phlebites are irregularly introduced as veins, veinlets and sporadic microcline porphyroblasts. The Biotite Gneiss dissected by dykes which are relatively wide and frequently are pegmatitic. In the Biotite Gneiss, some of the phlebites are seen to have branched off from these large dykes, which may be called metatectite (Barth 1951, p. 365), and are therefore genetically related. In the Mixed Gneisses and pegmatites, the metatectites are arranged parallel to each other and concordant with the gneisses. The metatectites in the above two cases consist of granitic and pegmatitic dykes and may be regarded as broad phlebites. Their genesis are discussed later.

Granitization.

"Granitization is broadly defined as a process by which rock formations have been changed into rocks of granitic composition and texture without passing through a magmatic stage". (Currier 1947). It almost always involves the introduction of K-Al-Si and removal of Ca-Fe-Mg (Eskola 1948), at least at the early stage. MacGregor (1938) claimed that the ultimate product of granitization is quartz diorite.

Granitization in the Bauchi district fits more to the broad definition but it is generally a process of microclinization. The granites were formed from the gneiss dominantly in this way. The Biotite Granite which cannot be demarcated from the Biotite Gneiss is distinguished only by numerous small porphyroblasts. Though they tend to grow "with their two, longer axes within the S plane" (Harry 1951), the general tendency is to subdue the foliation, by decrease of biotite, making the rock more granitic looking. The microcline first appears as a number of small intergranular grains that are optically continuous (Plate 42 fig. A) and as these grow towards one another and coalesce they form bigger porphyroblastic grains with inclusions of other minerals (Plate 42 fig. B).

As the microclinization is intensified, presumably directed by the differential distributions of free energy (Perrin 1956), still larger plates of microcline up to 3cm. long are formed. Biotite appears to be partially altered to hornblende, contributing potassium to the growing crystals. The resulting rock is the Biotite-Hornblende Granite. Increasing amount of pore fluid could have contributed to the development of these large porphyroblasts. Petrographic inspections of the plagioclase show that the Biotite-Hornblende Granite had been slightly sheared previous to the introduction of microcline. This is in agreement with the experience of Marmo (1955, 1956) who has observed similar relationships between zones of shearing and shattering and the large potash porphyroblasts in the synkinematic granites of Sierra Leone. Presumably the shearing, apart from facilitating the movement of material, has raised the free energy level thus favouring the crystallization of large microcline porphyroblasts.

The course of granitization of the gneisses through the Biotite-Granite towards the Biotite-Hornblende Granite is reflected in size and proportion of microcline and the consequent textural changes; this was also the experience of King and De Swardt (1949).

The Nature and Origin of Migmatizing and Granitizing Fluid.

Potash metasomatism by which sedimentary and metamorphic formations become granitic is known world wide in the Archaean. (Eskola 1933) It has been described from various parts of the world. (Querke 1927, King 1943, Marmo 1945, 1955 and Schedmerhorn 1956, to mention only a few). The abundance of such potash metasomatism in the earliest rocks in the deeply eroded zones of the earth is significant, suggesting that it is essentially a plutonic process.

The source and nature of the emanation responsible for this potash metasomatism or granitization has puzzled petrologists for many years, as revealed in the excellent reviews of literature of granites by Holmes (1945): In 1824 Ami Bone attributed veins and disseminated crystals to heat and gases coming from the earth's interior. Devile, seventeen years later, introduces the idea of mineralizing agents. French geologists were amongst the earliest to be convinced of the process of feldspathisation and granitization. Following other geologists before him Virlet d'Aoust expressed the idea that igneous materials have soaked into sedimentary and metamorphic rocks and so altered them to granites; and he designated the process "imbitition" which he later spoke of as "granitification".

Michel Levy and Lacroix towards the end of the 19th century proposed a granite magma as the agent effecting granitization designating it "Corteges d'emanations" (Currier 1947). This was later termed "Colonnes Fitrantes" by Fermier (Holmes 1945) who explained that these highly energized emanations only became granite after combining with the existing rocks, and that they originated from the depth.

From these emerge the present-day ideas on the problem, among the leading views are those of Sederholm, Eskola, Backlund and Reynolds.

Both Sederholm and Eskola, appear to favour a magmatic source for the granitizing material. Sederholm (1926)

(1926) proposed the term "Ichor" to denote a magma diluted with water and containing other mineralizers percolating through older rocks like an oil spot and dissolving some of their minerals and replacing them with others. The ichor is derived by melting or refusion of the lower part of granitic crust, a process which he termed anatexis (Sederholm 1928 and 1933). Eskola's ideas are allied to those of Sederholm. He considered granitization and migmatization to be due to granitic magma produced by squeezing out the lowest melting materials of silicate rocks during orogenesis (Eskola 1932 a, b and c, 1933). The granite magma permeates the rocks impregnating them with granite minerals and as a rule rising upwards.

In respect of the rocks of the Bauchi district such granitic magma may be regarded as being essentially a solution of alkali feldspar and quartz. As this solution rises upwards permeating the granulite with its granitic materials, as suggested by Eskola, it would have to receive the surplus femic material, as Sederholm also realised (Sederholm 1926). As the solution "as a rule " (Eskola 1933) continue to rise upward it will have eventually to dispose of the basic material with which it is becoming saturated into the over-lying rocks. There is no evidence for this. Such a solution could hardly be ordinary granitic magma, for it should, presumably, possess superheat and be highly attenuated to be capable of such close impregnation of the granulite; further it should possess an efficient means of disposing of the basic material it has "dissolved" (Sederholm 1926) without itself losing its power of continuous impregnating of the metamorphic rocks with alkali feldspar. So simple a granitic magma as described by Sederholm and Eskola could hardly have been operative in Bauchi.

Reynolds, Backlund and Bugge on the other hand believe that granitization is essentially a process of ionic diffusion in the solid state. According to Reynolds 1947, the transformed rocks, in general, undergo a change "far intimately woven in the rock to be attributed to fluids", and the process of transformation are dependent on some form of physico-chemical control in solid state. Emanations are thus a "migration of ions within solids by way of structural faults, deformation, crystal discontinuities and by means of potential difference of lattice energies". (Backlund 1946) Ionic diffusion in this way has been evoked by Bugge (1945), Marmo (1955), Perrin (1956) and several others to explain large bodies of granitic rocks.

One of the strongest experimental information in support of this process is that published by Adams (1930). Two magnesite bricks of different compositions were heated in an oven and one had softened and bent over to touch the other along a knife edge through which diffusion had taken place with the result shown diagramatically (Fig. 14) by Read (1948). Even in this there is considerable doubt if the diffusion has not been in a fluid phase. (Read 1948) Experimental work has shown that diffusion in solid state do take place but it has not been sufficiently encouraging for the application of such process to extensive migmatization and granitization (Walton 1955) such as that illustrated by the Bauchi rocks; for as pointed out by many authors, dry ionic diffusion is too painfully slow to effect such large scale metasomatism.

On the other hand, dry ionic diffusion as demonstrated by Bugge (1945) might have played an important part in the metasomatic reconstitution of individual minerals; as for example in the pseudomorphic development of hornblende on biotite or pyroxene, but the long distance transportation of material or even of exchange of ions between adjacent minerals seems more probably to be through a fluid medium. In any case, the formation of the pegmatitic and granitic dykes in agmatite, intimately connected in genesis with the impregnation of the surrounding schists and gneisses with microcline and quartz as seen in the Bauchi district are obviously difficult to relate to dry ionic diffusion of the element. The rock pores must constantly be filled with fluid whether in gaseous or liquid state, for the fluid pressure is constantly not far from the load pressure (Fyfe and others, 1958p. 181) ensuring the constant presence of this pore fluid. Exchange of material through this pore fluid is more probable.

Falling between the various views expressed above, many petrologists in discussions on migmatization and granitization, commonly refer to emanations, solutions and gases associated with hypothetical magmas.

It is doubtful if the process of large scale plutonic granitization and migmatization can be attributed to emanating fluids originating from a magma and moving upwards. It has been observed by Lacroix as far back as fifty years ago that the granitizing agent only produces granite after combining with the older rocks; and as commonly accepted, the process involves dominantly the introduction of potash feldspar and silica: In many instances it is quite evident that only potash has been introduced, while in others a limited amount of Al and Si might have been introduced as well. Broadly conceived the process as stated earlier is one of introduction of K-Al-Si and removal of Ca-Fe-Mg. If the agent were simply a fluid emanation, it would itself get progressively cooler and more altered in composition towards a basic one, and it can hardly be expected to effect so deep and extensive an impregnation of the older rocks with microcline and quartz as is observed in the Bauchi district. Bott (1956) has demonstrated from geophysical evidence that such an hypotheses involving upward and sideways disposal of basic surplus material is incompatible with the structure of granite bodies. Thus this solution, gases or emanations like Eskola's granitic magma as a rule ever moving upward must necessarily conflict with Bott's geophysical evidence.

Read (1944, 1946, 1948) classified rocks as Neptunic (the sedimentary rocks, mostly marine), volcanic (the magmatic igneous rocks, dominantly effusive and basic) and Plutonic (the metamorphic, migmatic and granitic rocks) and "saw the granite problem as one closely tied up with migmatization and metamorphism - as a plutonic problem."

The evidence furnished by the Bauchi rocks is more in support of Read's theory of granite genesis. The spatial arrangements of the rocks could be best explained as of a plutonic series. Therefore, the introduction of potash feldspar and quartz and removal of femic components must have been by some plutonic process. Since the transportation of components is presumably not by dry diffusion, it must be through the medium of pore fluid irrespective of the physical state of this fluid.

The writer considers that the hypothesis of Korzhinsky (1936, p. 58) offers a hopeful solution to the problem:

> "Let us conceive the mechanism of metasomatosis as follows: along a network of fissures through rock flow solutions. But the rock does not react with these flowing solutions, it reacts with an immobile solution permeating the submicroscopical pores of the rock and serving as an intermediary between the whole rock mass and

the flowing solutions. The introduction or leaching of rock components are affected by diffusion through this immobile subcapillary medium which we shall name "solution" irrespec- of its liquid or gaseous state."

It is necessary to distinguish two cases -

"The diffusion of certain components may proceed so rapidly that the concentration of these components in subcapillar solutions and in solutions flowing through fissures may remain all the time at the same level, independently of the course of the reaction between the solution of and the rock; in such a case the reaction proceed as if the rock reacted directly with the flowing solution. Such components will be called the "ideally mobile". Slowly diffusing components cannot maintain their concentration in the stationary solution at the same level as that of the concentration of the flowing solution. This concentration will vary depending on the absorption or loss of components by the rocks and the difference between this concentration and that of local solution saturated by the rock mineral will be infinitely small. Such component may be called inert."

Korzhinsky then went on to make two propositions:

"Proposition 1. Let the mineral aggregates be in chemical equilibrium with the solution at arbitrary temperature and pressure. Then:

1) The maximum number of minerals is equal to the number of inert components (and does not depend on the number of ideally mobile components)

2) The mineral composition is fully determined by the quantitative correlation of inert components.

Proposition 2. Let the mineral aggregate remain constantly in chemical equilibrium with the solution at arbitrary temperature and pressure.

> 1) If the existence of several mineral association with the different content of the mobile component is possible at a given correlation of inert component, then with an unlimited increase (or decrease) of the concentration of this mobile component in the solution successive formation of all these mineral associations without exception will be observed to occur, these associations replacing one another with the increasing (or decreasing) content of the mobile component in strict order.
>
> 2) These substitution reactions will occur at singular concentrations of the solution. At intermediate concentrations there may occur only enrichment (or impoverishment) with the mobile component of the minerals of variable composition."

Thus the migration of elements during metamorphism or metasomatism could be through the mobile solution and their reaction with older rock minerals to form new mineral may then be through the immobile solution. At a given temperature and pressure K_2O is relatively "ideally mobile" and SiO_2 and Al_2O_3 are relatively "immobile". (Korzhinsky 1936, pg. 60). During microclinization the concentration of K_2O in both the mobile and immobile solutions should be constantly maintained and that of SiO_2 and Al_2O_3 less so. These last two components, however, are largely supplied by the older rocks being replaced. (The chemical composition of the Bauchi rocks show progressively less silica with advanced granitization while the alumina show little variation). In any case their mobility would also have been influenced by chemical potential and other physico-chemical law, for as pointed out by Korzhinsky (1936, p. 60) the greater the intensity of metasomatism the greater the number of components that are mobile.

During granitization, the resulting rock depends on the replaced rock for the bulk of its inert components, i.e. SiO_2 and Al_2O_3 but not for the mobile component i.e. K_2O. Thus rocks excessively poor in one of SiO_2, Al_2O_3 or both (as for example quartzite and limestone) are relatively resistant to granitization (Reynolds 1948, Eskola 1948). Thus the process of granitization is justifiably described as one of potassium enrichment.

The Source of Potash.

If the process is viewed, as the writer believes it should, as belonging to plutonic metamorphism, the source of potash becomes easier to understand. The mineral assemblage in the amphibolite facies is characterised by the prevalence of amphiboles and mica that of granulite facies among other minerals is characterised by perthite potassium feldspar.

Potassium bearing minerals are not represented in the eclogite facies, and the potassic ion must be relatively unstable at the greater depth.

Viewed in terms of structural layering of the earth, Geophysical evidence points to the stratification being according to density and basicity. This stratified condition of the earth must have been attained early in its history even if imperfectly. If the ideal state had been attained, the distribution of the principle cations of silicate rocks can be hopthetically represented on a diagram (Fig. 15). This ideal stratified condition is constnatly upset by the extrusion of basic magma from depth which on weathering is incorporated in sedimentary rocks of large geosynclines, later to form metamorphic series more basic than the granites they overlie. This relatively basic mantle of metamorphic rocks is now demonstrated by geophysical evidence (Bott, Personal Communication). In terms of the diagram (Fig. 15) the overlying metamorphites may be considered structurally unstable and the femic components would be displaced downwards by potash when the correct thermodynamic condition was reached.

The down warping of the crust during orogenic movement or during sedimentation in large geosynclines could initiate upward migration of potash. The metamorphic aspect of this process can be appreciated by consideration of the metamorphic facies: with depression into deeper part of the earth, the amphibolite passes to granulite facies and the granulite towards eclogite with consequent migration of potash.

In the Bauchi rocks in the transition from granulite to Biotite Granite, most of the early potash feldspar is formed at the expense of biotite, chemically only about a quarter of the potash in the granite came from outside, (Fig. 18) and this appears to have come from the zone of transition to diorite. Consequently when viewed broadly, the process as possibly operative in Bauchi district is one of reorganization under plutonic metamorphism as long maintained by Read.

The view expressed above is summarised by Walton (1955): "The Alkalis are less capable of entering stable solid phases at depth in the earth's crust than ferromagnesian elements, and a potential exists for their relative movement upward.

The Source of the Driving Energy.

Several sources of heat for driving the process ofmetasomatism have been suggested. Most invoked is the geothermal heat, Eskola (1933) Sederholm (1928) and many others. Some authors have suggested radioactive heat, among them, Bugge (1945) who pointed to the possibility of heat emitted by disintegration of K40 to Ca40 especially in the first milliard years of the earth's history.

Backlund (1946) suggested that much energy is not required. According to him: "minor influx of Na and Si associated with suitable thermodysnamic condition seems to be all that is necessary to start a whole chain reaction". This view is more directly expressed by Perrin (1956), that granitization governed by the tendency to lower the level of free energy necessarily involves heat emission, therefore granitization is an exothermic metasomatism.

Radioactivity as a source of energy in migmatization and granitization is highly hypothetical. The spatial arrangement of the Bauchi rocks, at any rate, does not appear to favour this suggestion. On the other hand, the view that granitization is exothermic is doubtful; so much heat would have been generated in the Bauchi area that the rock would eventually have been melted. Conceived as a metamorphic process, the source of heat energy could be essentially geothermal. The spatial arrangement of the Bauchi rocks probably corresponds with increasing temperature inwards; but such need not necessarily be due to a magmatic effect, for the most depressed zone should have likely reached higher temperauture.

The Disposal of Ca-Fe-Mg in Granitization.

Reynolds (1947a) demonstrated the hypothesis of the "basic front" by which he showed that the Ca-Fe-Mg released during granitization was being fixed along the fronts of granitization. The amount of basic materials so fixed is, however, comparatively insignificant when compared with the vast amounts of Ca-Fe-Mg released during granitization of some rocks. As stated earlier, Bott (1956) had shown that such sideways or upward migration of the basic material is in conflict with the available geophysical evidence.

In the Bauchi area the writer has no evidence which could lead him to believe that there had been any substantial migration of basic components outwards at the front of migmatization though this is not disclaimed. Presumably these components have been exchanged for potash; as such it is quite likely that a little quantity has been fixed in the surrounding rock but most have probably migrated down in the mobile solution to the depth from which the potash is originating. In respect of the minerals forming at such depth, CaO, MgO, FeO and Fe_2O_3 are in term of Korzhinsky's hypotheses the mobile components. The writer is thus in agreement with Perrin (1956) that these components "mostly have moved down". This view is in accord witht the geophysical evidence of Bott (1956). Just as a potential exists for the upward migration of alkalis from the depth where they are unstable (Walton 1955), there must be some such potential for the downward migration of the femic elements even though this has not been as convincingly substantiated as that of the upward movement of the alkali.

The Origin of Pegmatites and Metatectites.

A large number of pegmatite dykes are to be found throughout the migmatite area. They are particularly concentrated in the north of the area where they form nearly half of the total exposed rock surface. In the agmatitic gneiss, the granitic and pegmatite metaectite are also of as much surface area as the gneiss blocks. Despite this, no squeezing or crumpling is to be observed in the surrounding rocks. This is especially striking in the agmatites where the blocks retain their orientation as demonstrated by the continuity of lineation. The contact is usually indefinite and it is gradation into the gneisses which are themselves impregnated with quartz and microcline.

Eskola (1932) regarded the metatectites as being left behind after granitic magma formed by differential fusion had been squeezed out along these passages during orogenesis. Generally this suite of granitic and pegmatite dykes appear to overlie and surround the large granitic bodies, not underlie them as implied by Eskola's hypothesis. These dykes are obviously not injected bodies if only for the great overall volume involved. They most probably have been formed by peaceful reconstitution or replacement of the gneisses. Simple magmatic soaking, as suggested by Kemp (1924) will not satisfactorily explain the structure of all pegmatites. As pointed out by Hess (1925) a long continued flow of solution must be assumed and this must have been concentrated along certain zones.

The dykes might have been formed by the same processes of metasomatism as was discussed earlier under granitization, and based on Korzhinsky's hypotheses and Hess's long-continued-flowing solution might be identical with the mobile solution of Korzhinsky's (1936). The concentration of metasomatism along certain channels to form dyke bodies may be due to the effect of distribution of mechanical pressure or free energy on the diffusing components. The process of granitization involving introduction of some K in place of Ca, Fe and Mg could have resulted in some volume increase contrary to the conclusion of Currier (1947). This volume increase might have caused slight doming of the overlying rock, and the distribution of stress in the overlying rocks could have resulted in the creation of numerous zones of low mechanical pressure (Fig. 16) which may not be actual open fissure. Towards such zones, diffusion of components in the solution should tend to be concentrated to form pegmatite and granite dykes and veins including quartz veins. By some such process so much dyke rocks could form without in any way disturbigg the surrounding rocks.

The Evolution of the Bauchi Rocks (Summafy of Discussion)

Most of Nigeria was probably once covered by sedimentary rocks which were metamorphosed to schists, quartzites, amphibolite, and calcsilicates in the normal cycle of regional metamorphism during the Pre-Cambrian times. These are still found over most of the country where not obscured by Cretaceous sedimentary rock or completely granitized, as in the Bauchi district.

In the Bauchi district the metasedimentary rocks appear to have been converted to granulites with irregular masses of clacsilicate rocks. From these granulites, the evolution of the present Bauchi rocks began with the interstitial development of microcline and a corresponding decrease in the proportion of biotite. Most of the early components for the microcline are taken from the biotite and the downward migration of the basic material must have started very early. This process, if it could be called granitization, was controlled by the planes of schistosity and differential rates of development lead to the development of the lit-par-lit gneiss. As the process advanced, the intervening bands of granulite also succumbed to granitization and only short parallel streaks of biotite and few schlieren were left to indicate their former presence. Thus the biotite gneiss was evolved.

From here on, the course of granitization is reflected in the field mainly by textural changes. There is a marked and progressive, thought not entirely gradual, disappearance of the original fine grained granular texture and the emergence of medium to coarse porphyroblastic aggregates. King and de Swardt (1949) remarked on a similar trend of development in the Osi area of Nigeria. Although themicrocline porphyroblasts tend to grow with their longer axes in the plane of foliation of the original rock, the general effect of their development is to obliterate the gneissose appearance and alter the rock progressively towards one of granitic aspect.

These transformation are believed to fall within the normal cycle of regional metamorphism and to have been under the temperature and pressure condition equivalent to the amphibolite-granulite facies. The intensity appears to be normally a function of depth (fig. 17) though subject to many variables whose influences are not well known, among them: extraneous heat from consolidating abyssal magma, fluid emanation affecting change of temperature and or fluid pressure, stress and the bulk composition of the metamorphites. (Fyfe and others 1958)

Acting seperately or in concert, these would tend to make the intensity of granitization complexly varied, at a given plane in a plutonic series. Thus in Bauchi one is still able to observe the various stages of development from Lit-par-lit Gneiss to the Biotite-Hornblende Granite despite the deep erosion.

The principal stages in the development represented in the diagram (Fig. 17) form aureoles around the core of Quartz-Diorite (Map B) from where, it would appear to emanate heat and solutions.

The mineralogical changes (Fig 18) show that the entire process is a metamorphic redistribution of rock components in an effort to reach a state of equilibrium under plutonic conditions.

CHAPTER VI. THE QUARTZ-DIORITE AND THE FAYALITE QUARTZ MONZONITE

The Similarity of the Quartz-Diorite to Charnockite.

The Quartz-Diorite which has been described earlier, (p43-46) is a member of a series of charnockitic rock which are now known to be fairly widespread in the Pre-Cambrian rocks in Africa. In the Bauchi area it comprises a small part of the batholith.

The term "charnockite" was proposed by Holland (1900) for an Indian rock, composed of quartz, microcline, hypersthene and iron ore; "A rock which would have been ordinarily called hypersthene granite", (Pichamuthu 1953). It is now customary to classify hypersthene bearing rocks of plutonic association with greenish to bluish brown colour as acid charnockite (about the composition of a granite), intermediate charnockite (about Quartz diorite to diorite in composition, basic charnockite (of basic composition) and those of ultrabasic composition as ultrabasic charnockite.

In addition, a number of special varieties are described in the literature though not all of these have been generally accepted; among these varieties are Arendalite described by Bugge (1943) as a series of rocks of "noritic charnockite" character, and Enderbite described by Tilley (1936) as a type with distinctly low K_2O and high Cao and SiO_2 and composed "of anti-perthite (53%), quartz (42.5%), hypersthene (3%) and magnetite (1%)".

The specimens from Bauchi, though of fairly variable composition, fall into the intermediate charnockitic norite division except for a few specimens (i.e. ME102) which correspond more with the acid division. The similarity may be appreciated by a comparison of the Bauchi rocks (Table 8) and some intermediate Charnockites from India (Table 9).

Comparison of the Charnockite Rocks from Bauchi with Intermediate Charnockite from India.

The Bauchi Quartz-Diorite rocks generally have less free quartz but slightly more potash feldspar and less plagioclase than the Indian intermediate charnockites. Hypersthene is about equally abundant in both groups but the Bauchi rocks have a much higher percentage of hornblende and biotite. Ore and apatite are present in approximately the same proportions but

TABLE 8

The Modal Compositions of Quartz-Diorite from the Bauchi District.

	1	2	3	4	5	6	7	8
Quartz	0.9	1.0	2.1	3.4	3.4	3.6	4.9	8.6
Myrmekite	0.6	0.0	0.7	0.0	0.3	0.0	0.0	0.8
Microperthite	11.1	8.7	12.2	0.0	11.6	16.1	0.9	31.9
Plagioclase	57.1	50.1	45.0	45.0	53.3	57.2	39.0	31.6
Ferrohypersthene	20.3	19.2	25.6	17.6	16.1	8.5	23.9	5.3
Clinopyroxene	2.9	0.5	0.6	14.0	2.1	2.2	10.8	0.0
Hornblende	2.9	12.3	6.2	4.0	8.8	8.0	10.6	11.6
Biotite	0.	2.2	2.1	12.0	0.2	1.2	9.9	9.4
Magnetite Ilmenite	4.1	6.0	4.5	4.4	3.8	2.2	0.3	1.5
Zircon/Apatite	trace	trace	0.9	trace	0.5	0.9	trace	0.5
	99.9	100.0	99.9	100.4	100.1	99.9	100.3	101.2

1. ME113 Central Valley, North Kofar Wombai Hills, Bauchi, N. Nigeria.
2. ME207 South of Tiruin Village, Bauchi.
3. ME224 East of Yelwa Road, S. of Agricultural farm, Bauchi.
4. ME226 Near Gundun Hill. S. of Bauchi Wall.
5. ME208 S.W. side of Kwimmi hill. Bauchi.
6. ME209 North end of Kofar Wombai Hill, Bauchi.
7. ME225 S. of Jos Road, Village about 8 miles W. of Bauchi.
8. ME About 100-150 yards W. of Yelwas Bridge, Bauchi.

TABLE 9 *

The Modal Compositions of Some Intermediate Charnockites from India.

	1	2	3	4	5
Quartz	8.7	5.0	6.1	15.5	4
K. feldspar	7.4	26.2	3.8	55.5	4
Plagioclase	61.2	49.7	52.9		2
Hornblende	0.1	-	1.4	-	-
Biotite	0.1	-	7.9	-	-
Hypersthene	17.6	8.3	5.5	23.6	18
Augite	-	6.2	13.7	-	15
Garnet	-	-	-	-	-
Ores	4.6	4.4	4.6	5.4	15
Green Spinel	-	-	-	-	-
Apatite	0.3	0.2	1.1	-	1

* From Howie (1955) p. 98 Nos. 18-21 and 27.

1. Shevaroy Hills, Madras. Anal. J.H. Scoon.
2. Intermediate Rock, Tinnevelly district, Anal. R.A. Howie.
3. Intermediate Rock, Salem, Madras. Anal. J.H. Scoon.
4. Intermediate Rock, Shevaroy Hills, Madras. Anal. H.S. Washinton.
5. "Norite" St. Thomas Mount, Madras.

but there are small amounts of zircon in Bauchi rocks.

Both the Indian charnockites and the Bauchi dioritic rocks are generally dark greenish to bluish in hand specimen and the quartz is of greasy brownish green colour, but the Indian rocks have yellowish tinge (Howie, private communication). In section the quartz in the Bauchi rocks is clear but show strong undulatory extinction. Those of the Indian charnockites are of xenomorphic granular texture. Pichamuthu (1953 p. 9) mentioned that the quartz in Indian charnockite, in general, contain dusty or acicular inclusion, but according to Howie (1955 pg. 759) this is only occasionally so. Their plagioclase ranges from oligoclase to andesine and it is frequently antiperthitic. The potash feldspar is invariably perthitic (Pichamuthu 1953, Howie 1955). These characters are observed in the Bauchi rocks, except that the plagioclase is only occasionally antiperthitic. Thin hair-like inclusions like closely spaced dashes were observed in the plagioclase crystals of one specimen (ME226) while the quartz is usually clear. The orthopyroxene in the Bauchi rocks is ferrohypersthene and the clinopyroxene is ferroaugite, so it appears that the pyroxenes of the Bauchi rocks have a higher proportion of iron to magnesia than those of Indian charnockite. In one specimen (ME226) the orthopyroxene is generally clouded with brownish acicular inclusions which Howie (1958) recorded from Indian rocks. As in the type charnockites, the hornbelnde of the Bauchi rocks is usually pale greenish and pleochroic with X = pale greenish, Y ≠ dark brownish green, Z = brownish green.

Occurrence and Distribution.

Nigeria:- The first note of a rock of charnockitic affinity in Nigeria was made by Falconer (1911) in Toro about 50 miles west of the district at present under study. King and DeSwardt (1949) described a norite from Osi in Ilorin province which is very similar to the Bauchi rocks. Apart from these no other occurrence of charnockite rocks is known in Nigeria, with the exception of the rocks at present under investigation in the Bauchi district. It seems not unlikely that further examples may come to light with increased geological knowledge of the country.

In the Bauchi occurrences, their relationship to the Pre-Cambrian gneisses in which they occur is usually indefinite since the contacts are not directly observed, but it appears that this must be sharp from the suddenness from which one may pass from outcrops of charnockitic rock to those of the country rocks; but it is doubtful if they have intrusive character for they are usually elongated bodies generally concordant with the foliation of the surrounding gneisses.

Africa:- Charnockites and charnockitic rocks are becoming increasingly known in the Pre-Cambrian areas of Africa. Pichamuthu (1953) gave an impressive list of African charnockites and recently Howie (1958) gave petrographic details of some African occurrences. They tend to have the same indefinite relationship to the surrounding gneisses, but Groves (1935) mentioned some intrusive characters in the charnockites of Uganda.

Others

Pichamuthu (1953) gave a list of world occurrences of charnockite and related rocks which need not be repeated here.

In general charnockites appear to be most abundant in the Pre-Cambrian terrains, thus falling into the Read's (1948) plutonic group of rocks.

The Fayalite Quartz Monzonite

This rock would also be classified as a Charnockite except that hypersthene is generally absent. In many of its other petrological characters it resembles Charnockite, for example; the greenish to yellowish brown colour of the rock, the resinous greenish brown colour of its quartz, microstructure such as perthite and the mineral aggregate texture. In contrast to charnockites proper, this rock has fayalite as its characteristic ferromagnesian mineral. The associated pyroxene is ferrohedenbergite; orthopyroxene is not common but occasionally it may be locally abundant.

The rock is variable in modal composition; this is difficult to determine because of the coarse grain size. From a consideration of the potash feldspar: plagioclase: quartz ratio, the rock normally belongs to the monzonitic series and varies from quartz syenite to adamellite. This variation is rather sporadic and may be observed in hand specimens (Plate 21 fig. B). Thus the rock would ordinarily be described as a Fayalite-Hedenbergite-Quartz-Monzonitic Rock.

The rock has certain distinctive chemical feature. The chemical peculiarity of fayalite bearing rocks in general was summarised by Tomkeieff (1939 p. 246); accoding to him the average and range of composition, of 10 analyses by Hawkes and 12 by himself, of fayalite bearing rock was as follows:-

SiO_2 ...... 65.20 (56.59 - 75.55)
Na_2O ...... 5.42 (3.21 - 6.59)
K_2O ...... 4.53 (1.59 - 6.63)
$FeO\ (Fe_2O_3) : FeO\ (Fe_2O_3) + MgO$ 0.95:1

This, he concluded "shows that fayalite bearing rocks are alkalic and range from intermediate to acid and in the majority of cases are quartz bearing". The composition of the Bauchi fayalite-bearing rock supports this conclusion, but in this rock there is a higher proportion of potash to soda. Most of the British Tertiary rocks containing fayalite have relatively higher potash than soda (Emeleus Oral Communication). The most distinctive chemical aspect of fayalite bearing rocks appear to be the high $FeO:MgO$ ratio. Both the Bauchi rocks and the fayalite bearing rocks of the Younger Granites are characterised in addition by high $FeO:Fe_2O_3$ (Table 10)

In many of the occurrences of fayalite-bearing rocks, hedenbergite is often the typical clinopyroxene and the colour of the rock is almost invariably green to greenish brown. Thus the rock has distinguishing peculiarities quite as bold as and differing from, those of a charnockite. The rock cannot be described as a charnockite without transgressing the usual definition of the type; the descriptive term Fayalite-Hedenbergite-Quartz Monzonitic rock is more explicit and will be used although cumbersome and not fully conveying the special peculiarities of the rock. If there is any justification for naming rock varieties however, this rock ought to be a Pseudo-charnockite, from its close resemblance to the normal charnockite in all characters except in the presence of fayalite.

Occurrence of Fayalite bearing rocks in Nigeria

Fayalite-bearing granitic rocks are a common member of the ring intrusion series of the Plateau Younger Granites. Since Bain described them from Kudaru in 1934, they have been described, by Mackay (1949) and more recently most of the occurrences in the Younger Granite Complex have been described, with petrographic and chemical details, by Jacobson and others (1958). Occurrences within the Older Granite Complex outside Bauchi are not known, but the Older

TABLE 10

CHEMICAL COMPOSITION OF THE FAYALITE ROCKS FROM THE YOUNGER AND THE OLDER GRANITES.

	1	2	3	4
SiO_2	67.96	70.59	68.65	71.51
Al_2O_3	14.77	13.90	13.50	12.91
Fe_2O_3	0.98	1.17	0.93	1.14
FeO	2.88	2.30	3.97	2.87
MgO	0.41	0.30	0.55	0.15
CaO	2.37	2.08	2.14	1.16
Na_2O	3.25	3.30	4.18	4.17
K_2O	5.75	5.55	4.85	5.12
H_2O+	0.36	0.33	0.57	0.16
H_2O-	0.16	0.14	0.09	n.d.
TiO_2	0.38	0.33	0.54	0.30
P_2O_5	0.12	0.15	0.17	0.04
MgO	0.04	0.05	0.10	0.09
BaO	0.44	0.13	-	-
Cl	n.d.	n.d.	0.03	0.02
F	n.d.	n.d.	0.22	0.09

1. ME 101 Kobi Hill, by water concrete tank, Bauchi.
2. ME 223 Foot of Kofar Wombai Hill by the Slaughter House, Bauchi.
3. L.1623 (see Jacobson and others 1958, pg. 20)
3. B. 851 (" " " " " ")

Analyses 1 and 2 are by kindness of the Principal, Mineral Resources Division, Oversea Geological Survey, London.

granite areas have not been investigated in any detail so further examples may well appear.

Occurrences of Fayalite-bearing Rocks in the World:-

AFRICA (Outside Nigera)

Howie (1958) mentioned occasional occurrences of fayalite in charnockitic rocks in the Sudan.

AMERICA

Buddington (1952 pg. 58) gave the chemical petrology of a Fayalite-Hedenbergite Granite and a Fayalite Granite pegmatite from the Adirondack complexes and Chapman (1935) described fayalite-bearing syenite from the Percy Ring Dyke Complex of New Hampshire. Murdock and Webb (1940) noted the occurrence of fayalite crystals in lithophysae in/rhyolite in California (Inyo County) and, more recently

Palache (1950) described fayalite at Rockport, Massachusetts and mentioned four occurrences of fayalite granite on Cape Ann, near Boston, in nordmarkite xenoliths within a later granite.

AUSTRALIA

Fayalite Gabbro with hedenbergite was described from Australia by Simpson (1938)

EUROPE

Finland: Savolakti (1956 p. 56) described a greenish yellow granitic rock with fayalite (5.1%) from the Ahvenists Massif.

Great Britain: Professor F. H. Stewart (Private Communication) mentioned several occurrences of fayalite in the Tertiary acid rocks of Scotland among them the well known fayalite-bearing pitchstones from Arran (Tyrell, 1928)

Greenland: Fayalite occur in later basic and acid rocks of the Skaergaard intrusions.

Iceland: Noe-Nygaard has reported fayalite in liparite (Professor Campbell, personal communication) and Hawkes (1924) described fayalite dacite from the Tertiary Volcanic Series of Eastern Iceland.

Ireland: Dr Emeleus also mentioned (oral communication) the occurrence of fayalite in the Porphyritic

Granophyre and Felsite on the Slieve Gullion ring-complex originally described by J. E. Richey and H. H. Thomas. (1932)

JAPAN:

Kurio (1940) described the occurrence of fayalite in some dacites from North Izu and adjacent areas.

Most of these occurrences of fayalite-bearing rock will be seen to belong to high level intrusion, and as mentioned by Professor Campbell (Private Communication) many of them occur in ring-dyke complexes. The Bauchi rock with a deep seated plutonic setting is therefore peculiar.

Petrogenetic Discussion

The spatial position of the charnockitic diorite and the fayalite-bearing rock in the core of a migmatitic aureole is such as to suggest them as being the centre of activity, occupying as it were a position from which energy and substances emanated to transform the metamorphites to migmatitic granites. They fit better into this role conceived as a zone of relative higher temperature and pressure. To any one seeing them casually in hand specimen or in section the two rocks would suggest an origin by direct crystallization from a magma, yet they have some very disturbing features which make one cautious to assign to them such a genesis. These features have been earlier reviewed.

The dominating feature of these rocks is the equivocal character of the petrogenetic evidence furnished by their structure, much of which could individually, be cited for magmatic or metamorphic origin. This could be due to the rock having a mixed origin.

Two possibilities suggest themselves: The diorite was crystallized from a magma and the Fayalite-Quartz Monzonite was formed by microclinization of the diorite at a later date just as the Biotite-Hornblende Granite was formed from the Biotite Granite. Some aspect of the rocks indicate the probability of such origin, for example: The diorite, as described earlier (fig. 4) may develop locally large phenocryst-like crystals of potash feldspar and then the rock resembles the fayalite-bearing rock, in the same way that rocks resembling the Biotite-Hornblende Granite occur as sporadic patches within the Biotite Granite.

The rapid gradation between the Biotite-Hornblende Granite and the Fayalite-Quartz Monzonite observed by

Bain (1926) and the present writer could be explained as being due to microclinization of two sharply different rocks like the Biotite Granite and the Quartz-Diorite.

It is, however, difficult to see why, if such were the origin, there should be so much difference in the colour of the microcline crystals from the Biotite-Hornblende Granite and that from fayalite-bearing rock in spite of their great similarity under the microscope. Further, the contact between the medium grained Biotite Granite and the Fayalite-Quartz Monzonite shows that the latter had behaved intrusively towards the former: and this suggests a second possibility, namely: that the fayalite-bearing rock was formed by hybridisation of the Biotite-Hornblende Granite with a solution rich in ferrous iron. This is supported by many features of the rocks. The microcline of the fayalite rock is very similar to that of the Biotite-Hornblende Granite and a stained specimen (Plate 21, figs. A & B) shows that in both the crystals are arranged in approximately parallel lines, though this is less marked in the Fayalite-Quartz Monzonite. This suggests that the rock when soaked with the diluted basic solution remained as solid crystals in a mush not mobile enough to disturb the orientation of the feldspars. The plagioclase with bent lamellae could have been deformed at this stage and the small clustered mosaic aggregate of equant plagioclase are possibly formed at the same time.

The arrangement of the ferromagnesian minerals of the Fayalite-Quartz Monzonite suggested crystallization or recrystallization in limited spaces bounded by quartz and feldspar (Plate 24).

The green colour which, as suggested earlier, was due to ferrous iron staining the feldspar and quartz could be the result of long impregnation by a pore fluid rich in ferrous iron.

The diorite is thus either crystallized directly from a magma or by an admixture of basic material with the surrounding rocks. At the great depth at which solidification took place, a great problem of volume is involved except if the magma were of small amount. It is therefore conceived that the magma from which the quartz diorite was crystallized might have gradually worked itself into some pre-existing rocks, displacing unwanted minerals such as the alkali feldspars and quartz and incorporating others that are more stable in itself, for example the plagioclase and ferromagnesian minerals. This incorporation would involve partial or whole recrystallization. The irregular zoning described from this rock could be the result of this as might the presence of bent and deformed plagioclase crystals. The large porphyroblast-like ghost microcline crystals described from the rock may be relic skeletal crystals; and such pseudomorphic preservation of their original outline by plagioclase is believed a corroborative evidence of this. Further some of the diorite retained the gneissose structure of the Biotite Granite or Gneiss which was displaced by basic material (ME 208, Plate 43 f. A).

MacGregor and Wilson (1939) made a study of many areas of granitization and demonstrated that the general trend in this process is the transformation from pelitic and metamorphites through granite towards the composition of diorite. They concluded that granitization is effected by this upwards, advancing diorite magma. The petrogenesis of the Bauchi rocks is in accordance with this view and the writer is partly in agreement with it.

The source of the dilute magma itself is not quite understood, but while this can not be conclusively substantiated the hypothetical representation of the evolution of these rocks (Fig. 19) showed that it is quite conceivable that the basic material released in granitization has largely contributed this basic material. Thus further suggesting that the whole process is one of reorganization of components in an attempt to gain equilibrium. This view is partly in agreement with Ramberg (1951), but it appears that these rocks have some pore fluid imparting to them a degree of mobility. This increased pore fluid may originate from rocks undergoing transformation to eclogite in the deeper zone and such a solution may carry excess ferrous iron since eclogite is characterised by high MgO/FeO ratio and very low water.

Metamorphic Facies Control of the Fayalite Rock and the Charnockitic Quartz Diorite.

The metamorphic facies concept is not restricted to metamorphic rocks but is equally applicable to rock crystallizing from magma or "migma". The Charnockitic suite has been held as belonging to granulite facies and characteristic of such an environment.

The calcsilicate rocks commonly intercalated with the schists within the migmatites area gave an indication of the grade of regional metamorphic facies by their assemblage. The modal composition of these rocks is shown in Table 4. From this the characteristic assemblage is: Ferrosalite - grossularite - scapolite - plagioclase (bytownite) - quartz. Ferrosalite has crystallized in place of diopside possibly due to high Fe/Mg ratio. In some specimens scapolite appears in place of some plagioclase. The genesis of scapolite is still little understood but its occurrence in place of anorthite is common under condition of granulite facies (Fyfe et al, 1958). The above assemblage is analogous with the assemblage diopside - grossularite - bytownite - quartz which is characteristic of the sillimanite almandine facies, (Fyfe eta al 1958). The presence of subordinate scapolite partly representing the plagioclase however, suggests a transition into granulite facies perhaps not completely attained. Again, the quartzo-feldspathic assemblage, microcline - oligoclase - biotite -quartz almandite also represent the almandine amphibolite - granulite facies and the feeble development of some perthites points to transition towards granulite facies.

The assemblage in the charnockitic Quartz-Diorite is microperthite - plagioclase - ferrohypersthene - ferro-augite - hornblende - biotite and is to a degree analogous with the quartz - orthoclase - Hypersthene (garnet - plagioclase) assemblage of granulite facies and corresponding to charnockite (Turner and Verhoogen 1951), but complicated by the presence of hornblende and biotite. "Charnockites, however are not always associated with rocks of the granulite facies" (Pichamuthu 1953 p. 147) but are nevertheless products of the highest grades of metamorphism. Apart from their mineralogy, their colour distinguishes them from the surrounding rock which are usually claimed as belonging to the same general metamorphic facies and this may indicate that they have undergone some special conditions not experienced by the surrounding rocks.

The assemblage in the fayalite-bearing rock is andesine - fayalite - hedenbergite - hornblende - microperthite - quartz. This has no analogy in the assemblages listed by Turner and Verhoogen (1951) and in those given by Fyfe, Turner and Verhoogen (1958), but the presence of microperthite, normally associated with rocks of charnockitic affinity, and its colour suggests conditions not far from granulite facies.

Stability of Fayalite - Hedenbergite - Quartz.

Bowen and others (1933) made a study of the system

CaO - FeO - SiO_2 and show that hedenbergite is stable at temperature below 965°, "Above this temperature it inverts to a homogenious solid phase" which is one of the Wollastonite solid solutions. This inversion temperature can be expected to be lowered by water vapour under pressure, but it is significant that hedenbergite is formed as a solid phase from Wollastonite solid solution. The inversion temperature under natural conditions, especially with the presence of water, could be expected to be lowered, coming within the range of temperatures attainable in the pyroxene hornfel facies. (fig. 21)

Let a suite of rocks be in euqilibrium at amphibolite-granulite facies, the removal of load pressure, and the introduction of fluid from the dehydration process in the transition zone towards eclogite will tend to bring the rock suite in to the broad transition field between amphibolite-granulite and the two hornfelses. (The exchange of Ca -Fe-Mg for K-Al-Si in the overlying rocks to form migmatites and granites might have resulted in a lowering of load pressure in this way.) During the formation of the Fayalite-Quartz Monzonite and the Quartz-Diorite both of the above conditions are probable, and it may be suggested that the charnockitic assemblage represent such superpostition of hornfels facies on amphibolite-granulite facies and that the stippled area (Fig. 21) may represent the field of charnockites and the Fayalite-Hedenbergite suite. The exact relationship between the two is unknown.

The Medium-Grained Biotite Granite.

This rock has all the characteristics of the Biotite Granite in the migmatitic series: microcline porphyroblasts, lineation structure, and numerous narrow granitic dykes, sometimes agmatitic. Unlike those of the Biotite Granite, the porphyroblasts are slightly larger and the rock to a certain extent approaches the greenish colour of the Fayalite-Quartz Monzonite and the Quartz-Diorite on which it appears to sit as a roof pendant. Generally it is much richer in biotite than the fine-grained Biotite Granite.

The rock was described by Bain (1926, p. 46) as a hybrid rock resulting from part absorption of "the magma" by the country rock and he described it as hornblende rock. Actually the hornblende occurs only locally and biotite is the most abundant and most persistent ferromagnesian mineral.

The Fayalite-Quartz Monzonite ends in an unchilled sharp contact against this rock. It is therefore suggested that at the margin with the Quartz-Diorite where the Fayalite-Quartz Monzonite was sufficiently soaked with water to become locally mobilised it behaved intrusively towards the Biotite Granite, impregnating it with some of the fluid though not enough to achieve complete homogenization but sufficient to alter its general appearance and texture. Under the conditions of soaking abundant biotite has crystallized.

The Medium-Grained Biotite Hornblende Granite.

This rock does not feature in the map or classification of the rocks of Bauchi district by Bain (1926). Its position in the rocks of Bauchi is uncertain, but from the variable texture and colour, and from the nature of the contacts which in some places are sharp and unchiled and in others indefinite, it is thought this rock could represent the result of local mobilization of the Biotite Gneisses and Granites in which they occur.

Under the conditions of Amphibolite-Granulite facies in which these rocks are formed, the addition of sufficient water and volatiles might cause local mobilization. There is no evidence in the rocks that these conditions are met; the suggestion is only tentatively advanced.

CHAPTER VII THE PETROLOGY OF DYKE ROCKS.

General Statment

The age relationships of the dykes in the Bauchi district are difficult to establish due to lack of definite stratigraphic horizon. No dependable age classification was thus possible. The principal dykes include dolerites, gabbros, and trachytes.

The Dolerite Dykes.

The dolerite dykes are probably the youngest rocks in the area (Bain 1926) with the possible exception of the Soda-Trachyte dykes. They are found cross-cutting all members of the Older Granites. They rarely exceed one foot in width, the majority is about 10 inches wide. Frequently a displacement of about the width of the dyke occur (Fig. 20a) Commonly some of the larger dykes branch, embay the country rock, reuniting again to form a single intrusion (Bain 1926). The best example of this is north of the Zungar hills where they fan out into cataclastic blocks and then re-unite (Fig. 20b) Some of the larger dykes are shown on Map (A).

Three of the larger dolerite dykes contain large xenolith of the country rock. One is immediately south-east of Tiruin, another is 2 miles north-west of Tiruin and the third is about 1½ miles west of the Baskin Hill. These dykes are indicated as xenolithic dykes (Map A). They show baking effects on the enclosed rocks; these are described below.

Petrography of the Dolerite Dykes.

In hand specimen the rocks are dark, dense, very fine grained and frequently porphyritic. Under the microscope diabasic texture is seen. When porphyritic, phenocrysts of plagioclase, pyroxene and olivine (commonly altered to antigorite) occur in clusters. The diabasic ground mass is composed of small laths of plagioclase, scales of brown biotite, fibrous flakes of antigorite and small grains of pyroxene.

The plagioclase is andesine ($Ab_{47}An_{53}$). It occurs in small laths in the ground mass and as elongated plates, frequently with combined Carlsbad and Albite twinning. The pyroxene is identified as ferro-augite (Table 8), of composition $MgSio_3$ 32.0%, $CaSiO_3$ 23.0% and (FeTi) SiO_3 45% (determined on Hess's (1949) diagram). Olivine is almost always altered to antigorite in part or completely.

The xenolithic dolerite dykes contain fragments of the surrounding biotite gneiss. These inclusions vary from about 25sq. inches to microscopic xenocrysts. Under the microscope the diabasic groundmass remains the same but in addition to the usual phenocrysts there are numerous xenocrysts of quartz and feldspar. The quartz xenocrysts are remarkably clear. Thye are resorbed into rounded grains and are invariably surrounded by felted mass of biotite, sericite and possibly chlorite. The xenocrysts of feldspar on the other hand are not so sheathed but are more or less always clouded with alteration products.

The xenoliths are composed of quartz and feldspar, both with amoeboid outline. Intergranular corrosion is indicated by sugar-textured veins of quartz between the grains and by the reaction mantle around the feldspars. Biotite was scanty and has been decomposed into unidentified mass. All the feldspars in the inclusions show some clouding and cracking and the plagioclase near the contact is recrystallized into a feathery aggregate.

The Trachyte Dykes.

There is a system of striking trachyte dykes occupying a narrow belt in the north-west of the district (see Map A).

The dykes vary in width from one foot to ten feet, and in length from twenty yards to over one mile. They are generally vertical with pronounced block-jointing. The jointing and their beautiful greyish-green colour makes them the most valuable building rock in the area, the most worked dyke being that running past the Bauchi administration building and crossing the Jos road towards the village of Shadawanke. (see Map A)

The rock is very fine-grained, dense and of greyish green colour. It may show xenoblastic structure. Under the microscope it is seen to be composed of alkali feldspar, aegirine, riebeckite and a small amount of quartz. The rock generally has trachytic texture and may show flow structure (Plate 44 f. A).

The feldspar is in small subhedral plates twinned according to Carlsbad law. It has parallel extinction. It is the only feldspar present except when the rock contains xenocrysts of other feldspars clouded with alteration. The pyroxene is aegirine and the amphibolite riebeckite; these are the only ferromagnesian minerals observed. Quartz occur in small pools, sometimes, with a fringing cluster of epidote. A small amount of green biotite was also observed.

This rock is evidently sodic, and is unusual in the Bauchi district where the rocks tend to be more potassic. MacLeod thought that they might be related to the Tertiary volcanic rocks of Benue Valley i.e. Wase rock (private communication). The writer is more inclined to classify them as being related to the rocks of the Younger Granite cycle, some members of which are very sodic. The nearest intrusion of Younger Granite is only about fifty miles to the west of Bauchi.

The Gabbroic Dykes.

Two dykes of gabbro were found. They are of interest partly because of the profound alteration of the adjacent gneiss and partly because of their petrography. In hand specimen the rock is medium grained. The feldspar has been altered and is coloured greyish or reddish. Under the microscope the rock is composed of clouded feldspars, titaniferous clino-pyroxene, red-brown amphibole, brown biotite and olivine altering to antigorite. Accessory amounts of apatite and iron ores are present.

The feldspars are orthoclase and plagioclase.

The latter are completely sausuritized and the composition cannot be determined; the intense alteration of the feldspar indicate a high water content of the magma. The presence of orthoclase in association with the assemblage biotite - olivine - clinopyroxene makes the rock closely related to kentallenite the only recorded occurrence of which are known in Scotland and Siberia.

The pyroxene is weakly pleochroic from lavender or pinkish colour to pale yellowish-green. It has the same optical character as the pyroxene of the dolerite dykes (Table 8) but is of deeper pink colour and is therefore titaniferous ferro-augite of the composition $MgSiO_3$, 32.0%, $CaSiO_3$, 23.0% and (FeTi) SiO_3, 45% (Hess (1949) diagram). It is partly altered to chlorite giving it a ragged outline.

The olivine is in equant grains and may be partly altered to antigorite and is more or less always enclosed by pyroxene. Biotite is reddish brown and occurs in large elongated plates, partly altered to chlorite.

The amphibole is deep reddish brown and commonly pleochroic to a pale yellowish colour. This unusual colouration is especially marked in one specimen

(ME 219) It is believed to be a lambprobolite produced by the oxidation of the iron of common hornblende probably through the action of hot gases. (Rogers and Kerr 1942 p. 289). It may, like the pyroxene, be of ragged outline with alteration to chlorite.

Apatite is a common accessory mineral and occurs in long narrow rods cutting across or contained within the other minerals.

The immediately overlying gneiss is baked brick red and the potash feldspar recrystallized into irregular pegmatitic masses. Further out, on both sides of the dyke sporadic porphyroblasts of microcline are developed. Under the microscope the overlying rock was found to be greatly altered. The feldspars are turbid and are rimmed by a felsitic selvedge at their contacts with quartz (Plate 44 f. B). The biotite is decomposeddto chloritic patches and ore. Quartz appears to have been recrystallized. Some sections show strong development of micrographic texture (Plate 44, f. B) indicating the action of hot solutions. These textures are very much similar to those described by Reynolds (1948) from a granophyre on Slieve Gullion, Ireland.

Other Dykes.

Some granitic dykes are found just outside the mapped area. One is a fine grained biotite granite, similar in appearance to some of the Biotite Granite of the Younger Granites Complexes, especially in its paper-white feldspar. The other is a porphyritic granite closely resembling some of the porphyritic Younger Granites.

TABLE 11

Optical Characters of the Pyroxenes and Amphibole from Dykes.

Z	n. d.	n. d	1. 713
Y	1. 710	1. 710	1. 695
X	n. d	n. d	1. 693
Z-X	n. d	n. d	0. 020
2V	+46°	+46°	-72°
EXT X C	37°	38°	14°
X	Light green	Light green	-
Y	yellowish green	yellowish green	-
Z	lavender pink	light pink	-

1. Pyroxene from Gabbroic dyke (ME 164)
2. " " Dolerite dyke (ME 166)
3. Amphibole from Gabbroic dyke (ME 219)

CHAPTER VIII THE CATACLASTIC AND ALTERED ROCKS.

Cataclastic Rocks.

Several zones of cataclastic deformation representing various degrees of crushing are observed in the field (Map A). One such zone at the west of the Zungar Hills and about a mile south of Rugar Ju inselberg, falls outside the maps (A and B) but lies within the Bauchi Batholith. It is described here because it represents an early stage of crushing not found in the area covered by the map and thus fills a gap which would otherwise be missing between the intensively deformed and the underformed rocks.

This cataclastic rock (Plate 45) shows large pinkish lenses of feldspar visibly crushed, surrounded by strands of quartz and dark minerals which appears to flow round the feldspars. Under the microscope the rocks has a groundmass of cataclastic texture with seriate augen of feldspars. The larger of the augen are of potash feldspar and are coarsely perthitic with patch perthite developed. The smaller augen are of plagioclase; these are more rounded, frequently untwinned or poorly twinned, and are slightly clouded by alteration product.

The groundmass is of rather granular texture and is composed of quartz and feldspars. In the microcline of the groundmass gridiron twinning is often very conspicuous. Sparse, finely-shredded greenish flakes of biotite are disposed in parallel lines, and occasional clustered plates of biotite and hornblende may be found. There has been some recrystallization and the augen and the groundmass are commonly so mutually intergrown that it is difficult to say whether the groundmass invades the augen or vice versa.

The groundmass is divided up by elongated, optically discontinuos aggregate of quartz. These rod-like aggregates of quartz often show sharp truncated borders against the groundmass, contrasting with relationship between the augen and the groundmass. The quartz exhibits some slight wavy extinction.

The specimen from Miri village (ME 159, Plate 46 f. A) represent a more advanced degree of crushing. The augen are small, more uniform and seperated by wider area of crushed groundmass. The eye-like feldspars project along their longer axes into tail-like trails of crushed fěldspar. Large irregularly scattered patches of hornblende can be seen and the groundmass is dark with biotite. Under the microscope, the augen are less coarsely perthitic, being mostly of string type. They show similar replacement structures towards the groundmass. The groundmass is as described for the earlier specimen but strewn with fine plates of biotite with parallel orientation. Biotite also occur in large clustered masses associated with rounded knots of hornblende. It may also occur in narrow, ragged linear clusters.

The quartz rods are shorter and are much more undulatory than in the previous specimen; they are also not quite as sharply demarcated from the surrounding groundmass. An idiomorphic mineral with strong relief, believed to be zircon is present.

East of Tiruin village a more intensely deformed zone involving the biotite gneiss is found (ME162). The rock has become banded and consists of alternating dark and light (pinkish) zones. No augen is discernible in hand specimen but under the microscope, they could be seen and are mostly plagioclase of almost an oval shape. Fine plates of biotite lie flat around them forming a thin discontinuous mantle. The plagioclase shows marked strain extinction.

The groundmass is lepidoblastic and consists of alternating biotite-poor and biotite-rich bands. In the biotite-rich part, fine plates of biotite with parallel orientation are generously strewn over the groundmass. In the leucocratic zones spare ragged lines of muscovite are present. The quartz is elongated and arranged in parallel lines forming disjointed rods. The crystals show very strongly undulatory extinction.

Near this zone is a still more intensely deformed rock, nearly a mylonite (ME 163). The crushed groundmass is of a very fine sugary texture with the individual minerals difficult to distinguish. Long rod-like aggregates of optically discontinuous quartz have strong undulatory extinction and show a parallel arrangement. A few augen remain and these have attained the perfect oval shape (Plate 47, f. A) by which they are able to resist shearing stress.

As in the preceding zone, dark biotite-rich zones alternate with light bands containing muscovite.

The other deformation areas indicated on the map (A and B) are examples of one or the other of the varieties described above.

Discussion of the Cataclastic Deformation.

Quartz is the most freely soluble mineral in non-calcareous igneous rocks of the types described above. (Harker 1932 pg. 170) In the early stages of stress it is therefore not surprising that it is the earliest mineral to become re-oriented, lying in the position of least strain in elongated rod-like shape. This recrystallization has probably been effected by solution at points of greatest pressure and redeposition along points of lowest mechanical stress. This may account for the sharp truncating contact with the rest of the groundmass. Such a process may necessarily involve displacement of other minerals and their recrystallization until perfect adjustment to the strain is achieved.

Intergranular fluids might be very important to rock adjustment during cataclasism, not only for the solution and redeposition of the more soluble minerals but as a medium for diffusion of the components of the less soluble material during reconstitution.

Turner and Verhoogen (1951 p. 373) attributed cataclastic rocks, augen gneisses and mylonites to kinetic metamorphism in the strictest sense and emphasized that their cataclastic structure is "determined by crushing and differential movement of the component grains without important recrystallization of old, or growth of new, minerals". Such crushing and differential movement necessarily involves recrystallization; this is demonstrated not only by the elongated rods of quartz but also by redistribution and orientation of biotite flakes. Fyfe and Turner (Fyfe et al, 1958 p. 180) have suggested that the influence of stress-pressure may be considerable though it cannot yet be evaluated and suggested that "increase in stress at constant load and water pressure and constant temperature" could cause the transition of amphibolite to granulite facies, such a transition if really achieved would necessarily involve the breaking down on one set of minerals and the crystallization of others. The development of muscovite in the more seriously deformed zones is the Bauchi cataclasites is evidence of this as is the development of sericite and chlorite in some others. Harker (1932, ps. 172-176), mentioned several types of such mineralogical changes. It is considered that cataclastic deformation is likely to be attended by recrystallization.

The Altered Rocks.

Apart from the altered gneisses overlying basic dykes already described, some altered rocks are found locally. The most extensive of these is the area of silicification near the Jos road to the south-west of Miri village (Map A).

A small conical hill marks the centre of this alteration zone. Quartz bearing solution appear to have been injected into the Biotite-Hornblende Granite. The alkali feldspar porphyroblasts are closely injected with thin strands of quartz (ME149) and are themselves altered into a yellowish powdery mineral which thermal analysis (Fig. 25) shows to be sericite. Open cavities are filled with quartz crystals.

Under the microscope the altered rock (ME149) is seen to be made up of euhedral to subhedral crystals of quartz (Plate 48, Fig. A) which are free of inclusion, fractures or strain extinction. Some euhedral crystals may have a narrow turbid selvedge of altered appearance along and just inside its margin. Felty patches of sericite are dusted over the large quartz masses.

Lower down on the side of the hill the quartz was injected as branching veins about ½ - 1½ inches wide into the granite embaying, impregnating and altering it (ME 148). The original feldspar crystals are marked by reddish oblong areas, found to be sericite impregnated with haematite. Under the microscope it is seen to be much similar to the first specimen (ME 149).

This alteration is continuous in a south-westward direction marked by a number of low hills. Towards the edge, the large alkali feldspar porphyroblast appear to be still intact but altered to a brick red colour (ME 150). Small bodies of purplish-red haematite and yellowish patches of sericite can be seen giving the rock a veriegated appearance. Under the microscope large masses and microveins of quartz are found surrounding the altered feldspars. The microcline is still recognisable and is clouded with haematite-impregnated alteration masses (giving the brick red colour) and injected with thin microveins of quartz. Dark patches of haematite can be seen within it. As in the other examples no trace of the original ferro-magnesian minerals is found except rare patches of limonite and haematite staining. A similar zone of siliceous alteration was found between the aerodrome and the south end of the Bauchi city wall, and smaller areas occur south of Kasuna hill.

In general they are quite similar to the above alteration and are therefore not described seperately.

Epidotization.

This alteration covers about 100 sq. yards at the west end of Buli hill (Map B). In hand specimen, the Biotite Hornblende granite is altered to a handsome rock coloured pink and green. The pink corresponds to feldspars and the green to epidote crystals, while quartz is colourless (ME 151).

Under the microscope, the altered rock is seen to be composed of microcline, plagioclase, quartz and abundant epidote. The microcline porphyroblasts are perthitic and clouded by alteration products, possibly sericite. The plagioclase, in grains of various sizes, is also so turbid with altered material that the outline of the grains may often be indefinite.

Quartz occurring as clear pool-like grain, is within itself optically continuous and shows no strain shadows.

From the surrounding feldspars swarms of long plates of epidote project into the pools of quartz as though into a cavity (Plate 47, f.B) whiles clustered plates may form "islands" within the quartz.

Sericite is present in bent fibrous to felty material on the feldspars. There is no iron ore and no trace of any original ferromagnesian minerals.

Tourmalinization.

Tourmaline crystals are occasionally found in the pegmatite dykes (Plate 48, f. A) and some graphic granite dykes show complete replacement of feldspar by tourmaline (Plate 48, f. B) These are probably not alteration in the strict sense, but about half a mile north-west of Guru hill, in the Biotite Granite, tourmaline is observed replacing the plagioclase of this rock.

Chloritization.

Zones of hot solution alteration are occasionally found in small narrow patches in the area. These probably reflect the intrusion of dykes below the present level of erosion. One specimen (ME 246) from west of Magumma hill (Map A) is the original Biotie Gneiss altered to a greyish colour. Under the microscope all the feldspars are seen to be deeply altered to an unidentifiable sieve-textured mass. Quartz occur as veinlike bodies of granular mosaic. Surrounding the feldspar broad rims of micrographic texture are developed.

The ferromagnesian minerals are altered to chloritic masses with segregations of iron ore. Some vermiculite is formed after biotite.

Another specimen (253) from the eastern foot of the Inkil hills is very similar to the above except in the absence of the micrographic selvedge round the feldspars. Shreds of vermiculite may alternate with biotite.

Discussion on the Alteration in Bauchi District.

In the silicification, the biotite and hornblende are decomposed and reduced to haematite in the early stage to give the partly altered feldspars a reddish colour, but in the more intensely silcified specimen, there is no trace of the original ferromagnesian minerals. Though the metamorphic conditions are not definitely known, it can be inferred from the decomposition of ferromagnesian minerals to haematite that the silicification is a high temperature, while the epidotization possibly indicates low temperature alteration.

CHAPTER IX CONTRIBUTION TO PETROGENESIS.

The Relationship between the Older and the Younger Granites.

The absence of definite stratigraphic horizons makes age determinations of the Older and the Younger Granites difficult. Dating by radioactive methods has been attempted on the Younger Granite; so far the results are not satisfactory. (Jacobson and others, 1956, p. 6.) No age radioactive determination has yet been attempted on the Older Granites.

Jacobson and others (1958) mentioned that the Younger Granites cannot be related to any orogenic cycle; the Older Granites are not known to belong to any. On basis of the intrusive and disconcordant contacts between the Younger and the Older Granites it is commonly held that the later are older and belong to an entirely different petrogenic cycle, the usual assumption being that the two complexes have nothing in common. The present investigation showed that the Bauchi older granites are most likely evolved by a progressive metasomatic transformation of metasedimentary rocks, and that there are certain similarities between the members in one complex and those in another; the most striking being the occurrence of Fayalite-Hedenbergite-amphibole acid rocks in both.

Under the high temperature and pressure condition of metamorphism corresponding to amphibolite-granulite facies in which the Bauchi rocks are believed to have been formed by metasomatism, granitic rocks are not far from melting if enough flux and water were present. (Fyfe and other 1958, Goranson 1932). One distinctive feature of the Younger Granites is the high content of volatile in their magma, some of the granites have as high as 1.69 per cent content of fluorine, many show normative fluorine, and the mica from the biotie granites have as high as 5.02 per cent fluorine, (Jacobson eta al, 1958 p. 14-16). They are also associated with abundant topaz tourmaline and some cryolite. From the common occurrence of greisen zones, and other features, the magma giving rise to the Younger Granites most probably contained much water and other volatiles.

The areal proportions of the different rock groups of the Younger Granites can be summarised as follows: (Data by Jacobson and other (1958, p.7))

Biotite Granite	56%
Rhyolite	19%
Riebeckite granite	12%

Amphibole-fayalite granite 8%

Basic and intermediate rocks 6%

This order of abundance, excepting the Riebeckite Granite, is comparable with the order of abundance of similar rocks in the Older Granites, especially in the abundance of Biotite granites in the Younger Granites corresponding to the vast amount of migmatitic Biotite Gneisses and granites.

Through the kindness of Dr. Jacobson, the writer has been able to see some sections of the Amphibole Fayalite Granite and porphry from the Younger Granites. They have structures which the writer is inclined to believe might mean that they were crystallized from magmas derived by incomplete melting of the basement complex:

In the hornblende fayalite granite (Ll.1623) from Sha, the plagioclase occur mostly as oblong cores with irregular rounded outline, and surrounded by microperthite with dusty brown staining. (Plate 48 f.B). The irregular shape of the ferromagnesian minerals and that of the plagioclase is typical of resorption effects. All minerals show intense corrosion with quartz developing large areas of micrographic texture (Plate 48, f. B).

According to Bowen (1928 p. 229-230) such mantling with orthoclase indicates a reaction relationship between basic plagioclase but such relationship "must disappear before a sodic plagioclase is reached". This Bowen explained by a ternary diagram (1928 p. 231) of the system, orthoclase - anorthite-albite. The orthoclase mantling in this rock of the Younger Granite is at variance with the deductions of Bowen. For one thing the magma of this rock was obviously not potash rich and for another the core plagioclase is sodic and not basic, most being oligoclase (Ab80) This mantling might be interpreted as due to some plagioclase crystals, only partly resorbed in a potash rich magma which could be expected to result if all minerals but the plagioclase of such a rock as the Fayalite Quartz Monzonite were completely melted.

Of the Younger Granites members, the Riebeckite Granite has no counterpart in the Older Granites. Both the Older and Younger Granites have low magnesia and the essential chemical difference between the two is that the Younger Granites tend to be soda-rich. (Table 10). This does not alter the probability that the magma of the Younger Granites were derived from the rocks of the Older Granites. There appears to be a condition inthe nature of the mechanism leading to the generation and emplacement of ring-dyke complexes which favours the accumulation of soda and with few exceptions, ring-dyke complexes of granites or carbonatites have soda-rich phases; and this may be due to high relative mobility of soda which favours its concentration in volatiles and water.

The sequence of petrological events leading to the development of the present rock series in Bauchi, described in this work must have occurred over a wide extent of Nigeria as demonstrated by the similarity of rocks and petrology evident from the works of King and deSwardt (1949) and deSwardt (1953). In areas now containing Younger Granites, the metasomatic processes might have been complicated by the accumulation of large amount of water, fluorine and other volatiles, fluxing the rock with consequent partial to complete melting. The resulting magmas would develop high internal (F, H_2O, CO_2) pressure, resulting in a series of explosions, subsequent subsidences and emplacement of the magmas as cone sheets and ring-dykes in higher level as described by Jacobson and Others (1958).

Thus the magma of the Younger Granites could have been derived from some Older Granite rock series similar to those of Bauchi. The nature of the contacts of the Younger and the Older Granites, sharp but without contact metamorphism suggest that the magma was intruded into preheated rocks and it is possible that the magma might be the culmination of a metamorphic process which had heated the rocks.

The occurrence in the Younger and Older Granites, of rocks of similar mineralogy, though different texture and structural setting becomes understandable if the magmas of the Younger Granites were derived from the rocks of the Older Granites as suggested.

Granites and Granites.

Read (1948) discussed the problem of granites of different genesis and recently it has been more closely examined by Walton (1955), Perrin (1956) and Marmo (1956). Most geologists are now agreed that there are granites and granites, some formed "one way", others by some different "ways". The points of disagreement are essentially two; the extent to which the different "ways" are operative, and the relationship between the different processes by which rocks of granitic composition are believed to be formed.

During the discussion on the genesis of the Bauchi rocks, it is suggested the increasing degree of metamorphism with depth should ultimately involve upward migration of the alkalis into rock of granulite and amphibolite degree of metamorphism. The stability of the alkalis presumably become sharply limited at some point beyond the granulite. This alkali metasomatism, especially of potash, is the dominant process in granitization and migmatization in Bauchi and throughout the Nigerian Pre-Cambrian plutonic granite areas, and produces rocks that are strikingly alike. Similar processes are belived to have produced large bodies of granite in other parts of the world where Pre-Cambrian plutonic granites are exposed. Therefore, in agreement with Read, these large bodies of granite are considered to be the products of regional metamorphism.

Under the metamorphic conditions of Amphibolite-Granulite facies in which the Bauchi "Granites" were formed, rocks of granitic composition are not far from melting in the presence of abundant water and volatiles. Many of the high level granites, termed disharmonious granites by Walton (1955) often show evidence that their magmas are rich in volatiles; and these magmas might have resulted from the complication of the regional metamorphism by local concentrations of water and/or other volatiles.

Thus though "experimental study" (Bowen and Tuttle 1958) confirms the relationship between magmatism and metamorphism, contrary to the implication of Bowen and Tuttle (1958, p. 126), magmatism might be the product of regional metamorphism which has been complicated by accumulation of volatiles.

Bowen believed that magmas rarely contain amount of super-heat and actual measurement and various other determinations (Larsen 1929) supports this view and showed that temperature of granite magmas are of the general order of what could be expected if they mostly have originated from highest degrees of regional metamorphism. The writer is thus readily in agreement with Read (1948) that most granites "may likely be of one connected origin", and finds it difficult to imagine the generation of large quantity of granitic magma or any magma except by melting of related rock.

The process leading to the melting of granites in the upper crust, depending on local accumulation of water and volatiles appear to be much more limited, and granites of undisputable magmatic origin (i.e.

the Younger Granites) are of much smaller extent than the plutonic granites of metamorphic origin. This is true of African "Later Granites" which are generally of much smaller area than the plutonic series in which they may occur (Map C).

Emplacement of Granite.

One of the problems of petrogenesis is the room factor in the emplacement of large masses of granites. The present study showed that Bauchi Batholith has most probably been emplaced by metasomatic processes under conditions that were not far removed from a magmatic state, so that until closely examined and studied in relation to the migmatite, its metasomatic aspects are not revealed and several of the rock types could readily be interpreted as having crystallized directly from a magma.

There has possibly been a slight volume increase, but this could have been relieved by doming of the overlying rocks with consequent development of zones of tensional fractures.

In the Bauchi area such tensional zones probably occurred, though were not as open fractures; these have controlled and induced the development of pegmatites. The constant association of outlying swarms of pegmatites with large granite batholiths showed that similar operations may well have been in force in the emplacement of many granite bodies.

Under the conditions of large concentration of volatiles and water the internal pressure is possibly sufficiently high not only to fracture the overlying rocks (being higher than load pressure) but also to move the magma upwards by stoping of fractured fragments. Thus there may be inherent in the forces which generate granitic magmas a mechanism for the emplacement of the magma.

Large bodies of granite could be formed in place in a condition sufficiently near magmatism to possess some mobility but the writer does not consider that such rocks have been sufficently molten to be called a magma and they could never have moved far from the place where they were made, if at all. The undisputable magmatic types could only be of comparatively small bodies; ring dykes, stocks, pipes and lacoliths, they could attain a batholithic size only by coalescence of such small bodies.

Granitic Rock of Contrasting Composition.

The contrasting composition of Bauchi rock is believed due metamorphic rearrangement of rock components. The writer believes that many bodies of granites of contrasting composition, normally regarded as differentiated bodies might be similarly explained. The writer questions the possibility of granitic magma differentiating to produce three or more granites of different composition, mainly from the cotectic nature of its mineral aggregates, if possible it must be under some rare and unusual conditions.

The Nigerian Ring-Dyke Complexes might be cited as an example of differentiated granitic magma, Jacobson and others (1958) appeared to favour this, (see variation diagrams, Jacobson and others 1958, p. 27). The repetition of the same series of rocks present in the volcanic cycle during the intrusive cycle might equally well be accounted for by composite magmas derived from the melting of rocks of contrasting compositions, similar to the Bauchi rock series.

Classification and Nomenclatures of Granites.

Granitic rocks are generally classified according to the proportions of plagioclase, alkali feldspar and quartz, and sub-divided on basis of ferromagnesian minerals (e.g. acid charnockite). Rocks are often described and discussed under the nomenclature of "granite" rocks which classified properly would be called granodiorite, adamellite, or even diorite and monzonite.

The writer's view is in sympathy with Chayes (1954) who suggested the need for a review of the classification of granitic rocks, but could not wholly share his view that "no classification or naming of granites should be attempted without abundant and reliable modal data". Not only are modal compositions only approximations, they vary, using the same specimen, from one thin section to another. When rocks are unusually coarse, as with the Bauchi rocks, one would need for each rock some hundreds of sections spaced over all outcrops, in order to have a reliable average modal composition and the coarser or more foliated the rock becomes, the more difficult becomes the problem of getting "reliable modal data".

The petrology of the Bauchi rocks suggests to the writer the need, in the classification of granitic rocks, for a nomenclature which represents easily determined rock characters and which can be usefully employed in the field mapping of granite complexes. Such a classification calls for the simplification and clearing of the present "confused" system. (Chayes 1954). Thus a rock could be classified as granite when alkali feldspar is the dominant mineral, except when quartz is scanty and it can be called a syenite; diorite when plagioclase is the dominant mineral except when quartz is very abundant and the rock is a granodiorite. Rocks with roughly equal proportions of plagioclase and alkali feldspar may be called adamellite as is currently used.

Unusual mineralogical, textural or colour varieties may then be indicated by prefixing the special point of peculiarity. The above names are very well established in the literature and recognised as described above; what is being proposed is the elimination of straight line boundary and such terms as alaskite, charnockite, arendalite, endebite, shonkinite and several others which may be considered superfluous. Where granitic rock is abnormally dark coloured and with significant genetic implication as in the case of charnockites and the Fayalite-Quartz Monzonite, the term "melanic" or some other term may be subfixed. Thus acid charnockite will be Melanic Hypersthene Granite and the Bauchi Fayalite-Hornblende Quartz Monzonite simply Melanic Fayalite Adamellite.

These may usefully be employed in mapping and petrological descriptions.

Criteria in Petrogenesis of Granite.

Grout (1944) gave an impressive list of criteria that must be confirmed before the petrogenesis of a rock could be established. As Currier (1947) has remarked, Grout is not being realistic about the problem of granite genesis. The petrology of Bauchi showed how frustratingly equivocal the evidences available in a rock complex can be. As in most cases neither magmatic nor metamorphic origin of a granite can be absolutely proved, what could only be done is to weigh the various evidence in relation to more or less established Physico-Chemical facts.

The problem arises from the fact that most of the characters often observed in rocks of either genesis are functions of temperature and pressure, indirectly of depth, and only to a less degree, of the physical state of the rock mass at the time of formation. The knowledge that with only a little pore fluid, rock mass may be mobilized to have intrusive character has further complicated the problem.

The use of experimental data as criteria in petrogensis may be misleading. Experimental studies only serves to confirm or explain what has been observed in Petrology but do not rule out Petrological phenomena which it cannot explain. That there is a close genetic relaionship between magmatism and metamorphism is well appreciated and there is good evidence for this in the field, recognised before experimental studies, but contrary to the suggestion of Bowen and Tuttle experimental studies, has not established which gave rise to the other. While regional metamorphism has stopped at the threshhold of magmatism in Bauchi, it may well have transcended to this field in the central part of Nigeria leading to intrusive activity and what has made the difference is the abundance of volatile concentration in one and lack of it in the other. Thus magmatism may be different from metamorphism only by degree of mobility.

These phenomena are functions of many variables which are imperfectly known (Fyfe et al, 1958 p. 202-203) and therefore could not be accuratly taken account of in the experimental studies of Bowen and Tuttle (1958).

A set of criteria such as that assembled by Grout (1944) could be applied as reliable guide to study granites, but individual body of granite must be studied by itself and the criteria for its genesis derived from field studies and careful mapping and lastly from petrographical and chemical studies.

Granites in general, like the Bauchi rocks do not give absolute evidences of their origin and in the discussion of their petrogenesis, even with experimental studies, they do not give room for absolute assertions.

The Origin of Charnockites.

The origin of Charnockites is as controversial as that of granite, again because of the lack of unequivocal characters. Holland (1900) who first described charnockites, concluded that they are igneous rocks, but conceded that some features of the rocks were disturbing.

The problem of charnockite are recently reviewed by Ramberg (1951), Pichamuthu (1953) and Howie (1955). Ramberg (1951) suggests that charnockite are products of degranitization, they are left behind after the rise of the granitizing fluid, and further basified by materials migrating downwards from zone of migmatization. Pichamuthu (1953), studying the Mysore charnockitic rocks made an extensive review of charnockite problem which led him to conclude that charnockites are products of high-grade metamorphism, "the basic bands and lenses in the gneisses were converted into basic charnockite and the accompanying gneisses received a charnockitic impress," a process he termed charnockitization. Howie's conclusions (1955) are closely allied to that of Pichamuthu believing "that these rocks represent plutonic igneous rocks which have undergone slow recrystallization in the solid state on being subjected to conditions of plutonic metamorphism."

The exclusive association of charnockite rocks with rocks of granulite (Ramberg, 1952) and Almandine Amphibolite facies, (Pichamuthu, 1953, and Bauchi charnockitic diorites), suggest that the rocks are not simple igneous types as proposed by Holland (1900). If they have had igneous origin they must have been later subjected to metamorphism under high temperature and pressure condition as suggested by Howie (1955). The occurrence of acid Charnockites which can be described as hypersthene granite makes it improbable that Ramberg's degranitization hypotheses is the dominant process in the production of charnockites.

The origin of the Quartz Diorite and the Fayalite Quartz Monzonite is related to the general problem of charnockite genesis. It was suggested earlier that these rocks originated by infiltration into granites and gneisses of basic components under a high temperature and pressure conditions of metamorphism. The greenish or bluish yellow-brown colour of the feldspar and quartz is an invariable character of charnockitic-norite rocks and presumably bears some relation to their genesis. (From the piece of the rock which when subjected to heat turns brownish red, it had been earlier concluded in agreement with Howie (1955,1958) that the colour is most probably due to impregnation with ferrous iron.) In any case, the colour shows that they have undergone some conditions not shared by the surrounding rocks. Thus some charnockites might have originated through the infiltration into gneisses of basic materials rich in ferrous-iron with consequent migration of the alkalis which effected granitization at the higher levels, and so produce more basic components. Obviously, such rock will bear a mixture of metamorphic and igneous characters and could with equal credibility be interpreted as originating from metamorphic recrystallization of igneous rocks (Pichamuthu 1953, Howie 1955), but the general conformable shapes of charnockite bodies (Pichamuthu 1953) shows that the charnockite might be originally part of the surrounding gneisses.

Metamorphic facies of Charnockites.

Charnockites are generally regarded as belonging to granulite facies of metamorphism (Ramberg 1951). Pichamuthu (1953) has demonstrated that Charnockites are not invariably associated with rocks of Granulite facies but may also be associated with those of Amphibolite facies. The Charnockitic rocks of Bauchi support the observation of Pichamuthu.

Though the rocks of Bauchi belong to the Almandine Amphibolite facies (in transition to granulite) if the charnockitic members of the rocks of the district have originated by infiltration of solution from below, it is unlikely that the charnockitic rocks themselves represent this metamorphic facies but would have been formed under a metamorphic condition to be found in the transition field between the Amphibolite-granulite facies on one side and Pyroxene horfels on the other as discussed earlier. (Fig. 21); This suggestion is not considered proved and is only tentative, but it appears probable and follows from consideration of the independent variables in metamorphism as presented by Fyfe and others (1958, p. 180-185).

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X

APPENDIX

DETERMINATION OF MODAL COMPOSITION OF EXTREMELY COARSE GRANITE ROCKS.

The Biotite-Hornblende Granite and the Fayalite-Quartz Monzonites are extremely coarse, some of the large microcline porphyroblasts measuring nearly 4cm. in length. To get a reliable modal perecntage of the microcline in this rock, large hand specimens measuring about 6 x 4 inches were ground until flat and fairly smooth, and the smooth faces were then hetched for about 1 minute with hydrofluoric acid fume at about 30°. The specimens were stained by Keith method with sodium cobalti-nitrite solution (Keith 1939, Chayes 1952). The potash feldspar was stained yellow colour, the decomposed plagioclase was white, quartz was not affected and the ferromagnesian minerals are of greenish colour due to the biotite clustered with them. The stained surfaces were photographed and the results printed on 8 x 10 papers; the potash areas, stained yellow, appeared black, due to filtering effect of the yellow colour, and thus enhanced the contrast. The plagioclase appeared as white areas and the quartz as grey while the ferromagnesians were of a slightly darker grey. With the aid of the hand-specimen and a magnifying glass, the contact lines of the constituent minerals were traced in ink.

The modal proportions of the different minerals were calculated from the results of point counting on the photographs using a ruler at ⅛ square per point.

In addition, some structures of the rock not previously noticed in ordinary handspen and difficult to appreciate in thin section were brought out strongly; as for example, the lineation and crystaloblastic structures of the microcline.

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