THE PETROLOGY, MAJOR ELEMENT GEOCHEMISTRY AND MINERALIZATION OF THE GANAWURI YOUNGER GRANITE COMPLEX, NIGERIA

BY

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A Thesis submitted to the Postgraduate School, Ahmadu Bello University, Zaria in partial fulfillment of the requirements for the Degree of Masters of Science in Geology (Mineral Exploration)

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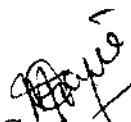Ahmadu Bello University, Zaria

NOVEMBER, 1996

CERTIFICATION

This thesis entitled: "The Petrology, Major Element Geochemistry and Mineralization of the Ganawuri Younger Granite Complex, Nigeria" by Emmanuel Mfongang Effiom Tarh meets the regulations governing the award of the degree of M.Sc. Geology (Mineral Exploration) of Ahmadu Bello University, Zaria and is approved for its contribution to knowledge and literary presentation.
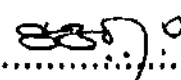
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DECLARATION

I hereby declare that this thesis is a product of my own research work and it has not been submitted elsewhere for the award of any degree. All sources of information have been duly acknowledged by means of references.

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DEDICATION

This work is dedicated to the memories of my two grandmothers, Late Susanna Mbokung Tarh and Late Mama Celina Akem Enoh.

ACKNOWLEDGEMENTS

ABSTRACT

The Ganawuri Complex, mapped on a scale of 1:25,000, is one of the anorogenic granite plutons occurring within the central axis of the Nigerian Younger Granite Province. This complex comprises several granites of biotite, hornblende and fayalite composition, with the biotite - bearing ones being predominant. The granites have near vertical contacts at their boundaries with the rocks of the Basement Complex, while being of lower angle to near-horizontal with successive granite phases.

Joints follow a generally WNW-ESE pattern, which is also the dominant regional trend. Their combined action on the rocks has resulted into rectangular slabs covering a good portion of the entire area.

The litho-units show a certain consistency in their mineralogy, with their major constituent minerals and accessory minerals varying only slightly.

Perthitic microcline and albite occur, alongside quartz, biotite and hornblende in the earlier phases, while orthoclase and fayalite occur in the later phases.

Geochemically, the rocks are silica-rich, and their alkali content increases with the sequence of emplacement. There is a general trend of a decrease in SiO_2 with an accompanying enrichment in alkali content. Also evident is a depletion in Fe_2O_3 in favour of MgO, an abundance of soda over potash and a consistent excess of alumina over the alkalis. The original magma must have been peraluminous, and derived from partial melting of Basement rocks. Three separate phases of magmatic activity have occured:

the first initiating the hornblende - biotite - granite; the second starting with the hornblende-fayalite-granite and the final phase being the intrusion of dykes.

Tin mineralization in the Ganawuri Complex is in the form of Cassiterite, now exploited as secondary deposits in river sediments, which have resulted from erosion of quartz-rich veins. The latter constitute the primary mineralization and resulted from fracture-controlled, epigenetic processes.

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LIST OF ABBREVIATIONS

g: grammes

ml: millilitres

m.y.:   million years

I.U.G.S: International Union of Geological Scientists

p.p.m: parts per million

CHAPTER ONE

INTRODUCTION

1.1   AIMS AND OBJECTIVES

Biotite-granites constitute the most abundant and widespread rocks of the Nigerian Younger Granite Province, and are known to host most of the tin mineralization in this country. It is for this reason that the Ganawuri complex, comprising several varieties of biotite-granites, was selected for this project.

The project involved geological mappping of the study area, with emphasis on the structural relationships between the various rock-types, the petrology, geochemistry and mineralization. This will then bring out details on the geology and economic importance of the complex.

1.2   LOCATION AND ACCESSIBILITY

The area covered by the Ganawuri Complex is approximately 200 Km^2 and it falls between latitudes 9°35' 50" and 9° 45' N, and longitudes 8° 39' 10" and 8° 45 E (See fig. 1.1) It is highly accessible due to the numerous secondary roads (such as the Vom-Heita and Vom-Kinshesho roads), a network of footpaths traversing the entire complex and the major road between Bukuru and Akwanga. Besides, the area was mapped during the dry season when the vegetation cover was not very thick.

1.3   CLIMATE AND VEGETATION

Two distinct seasons characterise the region. A marked rainy season lasts from May to October, followed by a dry season from November to April. In the rainy season, rainfall ranges from 879 to

1500mm, with an annual mean of 1350 mm (Pugh, 1955). During the dry season, weather conditions are characterized by cold, dry north-east trade winds. Temperature ranges from 21° to 30°C with an annual mean of 25°C in the rainy season, while it may fall as low as 8°C in the dry season. (Pugh, 1955).

The vegetation falls within the Northern Guinea Savanna Belt (Keay, 1959), with scattered areas of trees, herbs, shrubs, and grasses. The original vegetation has been highly modified by agricultural and mining activities. Due to the latter, problems of soil erosion have resulted in many areas of the plateau, as also pointed out by Hall (1971).

1.4 TOPOGRAPHY AND DRAINAGE

The topography of the area is one of highly variable terrain, ranging from steep-sided granitic hills to flat or gently undulating areas of either Newer Basalt or laterites from Older Basalts. The main character of the surface relief results from the resistant cores of granitic rocks along with, in places, areas of Newer Basalt flows (Macleod et al, 1971). The most rugged portions are, however, limited to the western and southern parts of the study area.

The drainage pattern is both trellis and dendritic, with the latter being more dominant. An example of a stream display such as pattern is the River Kamara (a tributary of the River Kaduna), which takes its rise from the imposing cliffs on the western boundary of the area. The Ganawuri hills themselves constitute a main watershed, with streams flowing in both north-western and south-eastern directions, often coinciding with the general ENE-WSW structural trend (Turner, 1972) of the area. The north-west-flowing streams join the River Uria (Ourée), while the south-east –

flowing streams form tributaries of the Assob and Werram rivers (Fig. 1.1).

1.5   METHOD AND SCOPE OF STUDY

The field work was carried out in two stages: a preliminary survey lasting for ten days between May 2nd and 11th, 1993, and a second confirmatory trip lasting for one week. Thus the overall period of mapping was seventeen days altogether.

The first trip was during the beginning of the rainy season, and the vegetation cover obliterated some of the contacts between different rock types. However, the second field trip was held during the dry season, and it helped to dispell any doubts over these contacts and other geological features.

A base map was obtained by enlarging a Geological Survey of Nigeria Topographic map from a scale of 1:50,000 to 1:25,000. The mapping was done by compass-traverse method. A traverse was carried out from Wuria through Heita to Ra-Hoss, so as to pass through the various rock types to ascertain their general mutual relationships (see sections A-B and C-D on figure 1.1).

Outcrops were observed on the field, their locations identified and inserted on the map. Samples were also collected according to rock types. These samples later served for petrographic and geochemical studies.

Joints were also examined and recorded (see Table 2.1).

1.6   PREVIOUS WORKS

Falconer (1911) noted the difference between the "Older Granites" and "Younger Granites"; the former, which are part of the Basement Complex, being less alkaline and more concordant

than the latter. Other characteristic differences he noted included the chilled margins of the Younger Granites against their country rocks, their underformed post tectonic nature and their lower calcic content as compared to the Older Granites (Falconer, 1921).

The Younger Granite Province of Nigeria is situated on an extension of an ancient rift structure, on a zone of incipient faulting along which crustal separation failed to occur during the Jurassic to Cretaceous (Black, 1965). It provides a classic example of intraplate, rift-related magmatism, unrelated to any orogeny (Martin and Bowden, 1981). The Younger Granites resulted from epeirogenic uplift and lack associated sediments. They belong to the group of anorogenic ring complexes (Agrawal, 1995) which are generally metaluminous and commonly occur in the centres of alkali ring complexes.

The ages of individual complexes have been shown to decrease from north to south (Karche and Vachette, 1976; Bowden and Van Breeman, 1972; Rahaman et al, 1984). These ages obtained from isotopic dating ranged from 165 $\pm$ 3 m.y. for the northern complexes to 144 $\pm$ 2 m.y for the most southerly Afu Complex (Rahaman et al., 1984). Further correlations of the ages of Nigerian Younger Granites with those of Air Province in Niger and another group of granites in Rio de Janeiro, Brazil was carried out. Ordovician ages of 470 $\pm$ 5 m.y. were attributed to the Air granites, while the Brazilian granites were placed in the late Cretaceous (Karche and Vachette, 1976).

The composition of the Nigerian Younger Granites has been experimentally proved to be significantly close to the magma from which they crystallized (Olade, 1978(a)). This magma has been

concluded to be of an alkaline source (Bowden and Turner, 1974; Martin and Bowden, 1981; Black et al., 1985).

The magma from which the Younger Granite crystallized is generally believed to have been derived from the crust by partial melting (Badejoko, 1976, Creaser et al., 1991). Magmatic differentiation based on crystal fractionation could also explain the perfect chemical and mineralogical differentiation of the Younger Granites. As such two different and divergent trends could result to either biotite-granites or riebeckite – granites, the first being a peraluminous series, while the second is a peralkaline series (Black et al., 1985). In anorogenic settings, peraluminous granites are spatially associated with (and petrogeneticaly related to) peralkaline granites (Agrawal, 1995). In the case of a peraluminous granite associated with anorogenic magmatism, rock-fluid interaction would be pronounced to a great extent (Ike, 1979, Ike et al., 1984). The extent to which autometasomatic reaction may occur depends critically the on amount, composition and provenance of the circulating fluid phase (Martin and Bowden, 1981).

In spite of the alkaline nature of most of the Younger Granites, Bowden and Turner (1974) considered their soda and potash content to be moderate (not high as earlier estimated). It was therefore concluded that the peralkaline nature of the Younger Granites is due to a deficiency of alumina relative to soda and potash. The development of a peraluminous trend alongside a peralkaline one could be explained by incongreuent dissolution of felspars (Smith, 1974; Currie et al., 1986, Dickin and Exley, 1981).

The structure and tectonic pattern of the Younger Granite ring complexes were described by Turner (1972, 1973). The main

stages included a volcanic phase and the formation of a caldera by the collapse of the central block. Intrusion of magma around the latter gave rise to a marginal ring dyke, within which subsequent granite ring intrusions were emplaced (Turner, 1972). Cupola structures such as in Mada (Abaa, 1985 (a), (b)) marked the terminal phases of magmatic activity, together with acid metasomatism. Such structures are commonly found in the southern part of the Younger Granite Province, as in the case in Afu (Imeokparia, 1981).

Extensive geophysical work has been carried out on the Younger Granites, especially gravity measurements over the Ririwai and adjacent complexes (Ajakaiye, 1968, 1970). Recently, a paleomagnetic survey was also conducted on the associated basaltic rocks in the Ganawuri District, confirming a Pleistocene age of 0.9 $\pm$ 0.2m.y. for the Newer Basalts (Ayeni, 1994). Large negative Bouguer anomalies characterise the richest sources of mineralization in the Younger Granite Province (Ajakaiye, 1970; Bowden and Kinnaird, 1978), suggesting some correlation between the mineralized zones and district gravity trends. Most of the mineralized zones correspond to greizens or disseminations located in the roof zones of biotite-granites (Kinnaird, 1977), and are related to hydrothermal alteration (Kinnaird, 1985; Kinnaird et al., 1985).

Tin mineralization in the Younger Granite Complexes, can likely be associated with acid magmatism (Bowden, 1982). Black et al (1985) proposed that tin had already been redistributed and concentrated in crustally-derived granitoids cut by the Younger Granite rocks.

Possible late stage metasomatism in the Younger Granite rocks, along with albitization and greisenization have also been considered responsible for the presence of tin along with Li-Fe rich micas like in Ririwari (Abaa, 1976, 1978). This model of late stage metasomatism is supported by experimental, fluid-inclusion studies (Taylor and Wall, 1992).

The Ganawuri Complex bears a marked similarity with the Jos-Bukuru Complex, both of which belong to the central axis of the Younger Granite Province (Macleod et al., 1971; Buchanan et al., 1971; Kinnaird et al., 1981). The rock units of the Ganawuri Complex are predominantly made up of hornblende-biotite-rich granites, as opposed to the alkaline series of riebeckite-rich granites, such as found in the adjacent Kigom Complex (Omada, 1992).

Mineralization in the Ganawuri Complex, is predominantly tin in its oxide form cassiterite (Buchanan et al., 1971). Another mineral of economic importance in the area is the molybdenite mineralization in the adjacent Kigom Complex, which has been worked upon (Omada, 1992).

CHAPTER TWO

GENERAL GEOLOGY OF THE GANAWURI COMPLEX

2.1 INTRODUCTION

The Ganawuri Complex is part of the well-defined cycles of intrusion called the Ganawuri - Kigom Complex by Macleod et al. (1971). It is centrally located within the Younger Granite Province, to the South -West of the Jos - Bukuru Complex.

The Ganawuri Complex has a diameter of about 16 km, with imposing cliffs and deep gorges on the western side.

This complex consists of varieties of biotite hornblende-fayalite-granites, the biotite-bearing phases being more dominant. The outer parts of the granites are near vertical at their contacts with the Basement Complex. However, the central parts of the Ganawuri Complex have gentle to near-horizontal contacts between the successive granite phases. Good exposures of granitic roof structures are present, together with a series of dykes.

Apart from the rocks of the Younger Granite petrographic suite, other rock types occur within the area studied. These include Older Basalts, laterites derived from them, and Newer Basalts spreading over the rocks of the south-western and western parts.

The biotite-granites and other rocks of the Ganawuri Younger Granite petrographic suite each presented a generally consistent texture and mineralogy over the majority of its area. However, alteration of some primary minerals in certain areas of the rocks had resulted in variations in texture. This caused some adjacent portions within the same rock to appear like different

rock types rather than portions of the same rock types which presented some problems in the course of mapping.

On the other hand, adjacent rock types could merge so uniformly at their point of contact as to appear continuous, so that they could both be identified as a single rock type on first examination. The porphyritic biotite microgranite (see Section 2.3 below) and the fine-grained biotite - granite (2.4) represent a case in point.

The varieties of Younger Granite rocks identified in the course of the field work were as follows:

- the Daw biotite-granite
- the fayalite - biotite - granite;
- the hornblende fayalite - granite;
- the Ganawuri biotite-granite
- the fine-grained biotite - granite
- the porphyritic biotite-microgranite
- the hornblende-biotite-granite

The emplacement of these granitic rocks has resulted from the segmentation and foundering of large, adjacent blocks of the basement, with accompanying rise of the magma. This process has continued intermittently, allowing individual phases to consolidate before the next stage of intrusion. As such, the hornblende-biotite-granite, with its steep, near vertical contacts with the basement rocks would be the earliest of the Younger Ganite rocks. The Daw biotite-granite, which cuts across the others and even bears of some of them is the youngest in the series, and a normal trend is maintained in between these two extremes. This trend coincides with the peraluminous or "normal" series (Black et al, 1985), which is represented below as follows:

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- hornblende – fayalite – granites (later)

- hornblende – biotite – granites

- biotite – granites and porphyries (earlier)

2.2   HORNBLENDE-BIOTITE-GRANITE

The hornblende-biotite-granite covers about two-thirds of the entire area mapped, and presents an almost semi-circular outline.

In the northern part of the study area, the hornblende-biotite-granite is in contact with the Basement migmatites, making very steep angles of 88–90°. The former is also associated with more recent granites, being always cut across by them, thereby establishing the earlier appearance of the hornblende – biotite-granite with respect to other litho-units of the Ganawuri complex. It is also cut across by quartz veins traversing it in an east-west direction (See Plate 2.1).

As concerns the joint pattern, it is predominantly WNW-ESE, following the general structural trend in the central area of the country. Some joint readings recorded on the field appear in Table 2.1.

Silicification follows the joint trend, but the siliceous zones following the joint trend have been worked upon by mining companies, leaving easily eroded, deep, steep-sided valleys.

A good number of outcrops of the hornblende-biotite-granite have been weathered into prominent domes and tors composed of large angular blocks (Buchanan et al., 1971). The Hoss Peak (see Plate 2.2) is a typical example of such a dome and occurs in the southern part of the study area, where it is in contact with the Newer Basalt.

In hand specimens, the hornblende-biotite-granite is coarse-grained. Minerals discernable with the naked eye are feldspars, quartz and also mafic minerals which include biotite and hornblende.
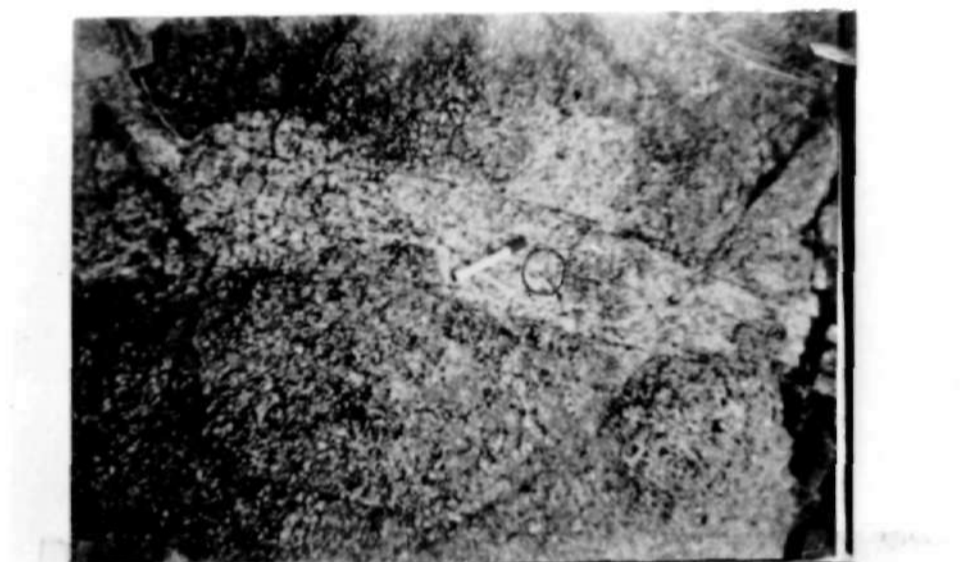
Pate 2.1   Hornblende-biotite – granite bearing Quartz-feldspathic (Q) vein running north-east to south-west. Note the weathered joint at right edge of photogrpah.

Plate 2.2: Hoss Peak (in the background), a prominent landmark of the Ganawuri Complex. Note lighter brown Newer Basalt at left and centre of the picture.

2.3   PORPHYRITIC BIOTITE - MICROGRANITE

The porphyritic biotite-microgranite forms a crescent shaped body in the central part of the study area i.e. east of Vwang village. The outcrops it occur as elliptical hills or as an elongated narrow selvedge along the southern part of the crescent.

The porphyritic biotite-microgranite makes contact with the hornblende-biotite-granite in many places, enclosing xenoliths of the latter, and thereby establishing its own more recent appearance (See Plate 2.3).

In the field, the porphyritic biotite-microgranite occurs as angular blocks left standing on top and around the outcrops. Weathering is aided by the network of both vertical and horizontal joints running WNW - ESE, following the major structural trend.

Macroscopically, the rock is very fine-grained, with the grain size varying between 1 and 3mm in diameter. It is pale-gray in colour in fresh specimens, while weathered specimens are yellowish-brown.

The distinctive property of this mic granite is its porphyritic texture, showing an abundance of feldspar phenocrysts.

Plate 2.3: Porphyritic Biotite-microgranite showing quartzo-feldspattic
xenolith (X).

Plate 2.4. The Ganawuri Biotite-granite (left and foreground)
occuring as jagged and scattered outcrops. At the
right is the Basement plain, while the hornblende-
biotite-granite forms imposing hills in the background.

FINE-GRAINED BIOTITE-GRANITE

The fine-grained biotite-granite occurs in the central part of the study area, east of Vwang Village. It is also elliptical in shape. On the field it makes contact with the hornblende-biotite – granite on the one hand, and the porphyritic biotite-microgranite on the other. The latter, which occurs to the southern part of it, is so intimately associated to the fine-grained biotite-granite that it is often difficult to distinguish between them. This is further compounded by the fact that the fine-grained biotite-granite exhibits a wide range of textures, some portions of it being more or less identical to the microgranite.

Structurally, the fine-grained biotite-granite is traversed by a network of joints running WNW-ESE as measured on the field. This network of joints has further aided weathering, resulting in angular blocks and perched boulders.

Hand specimens of the fine-grained biotite-granite are lightgrey to pink in colour in fresh samples, while appearing yellow-brown when weathered.

Observed minerals are feldspars, quartz and biotite flakes. The minerals are arranged so as to give the entire rock a mottled appearance.

2.5 **GANAWURI BIOTITE-GRANITE**

The Ganawuri biotite-granite occurs in and around the village of Heita, formerly called Tudun Ganawuri, hence, its name.

The Ganawuri biotite-granite also intersects the northern periphery of the hornblende-biotite-granite, suggesting a probable northward displacement of the centre of the earlier intrusion.

Some other of the Ganawuri-biotite-granite are surrounded by the later formed Daw biotite-grantite (section 2.8), which has reacted with the Ganawuri biotite-granite to give zones of hybridization. The manner in which these are distributed within the Daw biotite-granite (see fig. 1.1) suggests that the original intrusion of the Ganawuri biotite-granite must have had a diameter of about 7Km (Buchanan et al, 1971).

In hand specimens, the granite is medium-grained with grain sizes of about 4mm. Occasional phenocysts of quartz and feldspar can be observed, the feldspar forming patchy zones.

Plate 2.5:   The hornblende-fayalite-granite around Barkin-Momo Dogo. Note the weathering into steep boulders.

2.6   HORNBLENDE-FAYALITE-GRANITE

The hornblende-fayalite-granite occurs in the central portion of the study area. It is represented as a flattened sheet some 5 kilometres in diameter and estimated to be about 120m thick (Buchanan et al, 1971). It appears to have displaced some of the previously occurring Younger Granite members.

Unlike the biotite-granites this granite often weathers into small, steep boulder-covered hills (see plate 2.5).

Along the road to Barkin Momo Dogo, the hornblende-fayalite granite is in close association with the Daw biotite- granite, appearing finer-grained at their points of contact.

Hand specimens of the hornblende-fayalite granite are dark in colour, a mixture of blue and green. The texture is porphyritic, with phenocrysts of blue-green feldspars set in a finer-grained matrix also containing chains of quartz. Irregular plates of hornblende and biotite can be seen, the latter easily flaking off on scraping. Fayalite forms dark spots all over the rock.

2.7   FAYALITE-BIOTITE-MICROGRANITE

This rock is situated along the road between the villages of Danwal and Heita. It is semi-circular in outline and dips gently beneath the hornblende-biotite granite. It may also be observed as a small dyke-like structure cutting across the hornblende-fayalite-granite along the road to Barkin Momo Dogo in the western part of the study area.

The joint pattern in the fayalite-biotite-microgranite is a network of both horizontal and vertical joints following the general structural trend of the area i.e. WNW-ESE. These joints have

facilitated weathering processes resulting in small rounded boulders with smooth, slippery surfaces.

In hand specimens the rock is bluish-green in colour and very fine-grained. Occassional phenocrysts of quartz and feldspar occur in a groundmass also composed of quartz and feldpars. Biotite is highly dispersed throughout the rock and some patches of metallic minerals can be observed. Fayalite appears as black spots, giving the rock a mottled apprearance in some places.
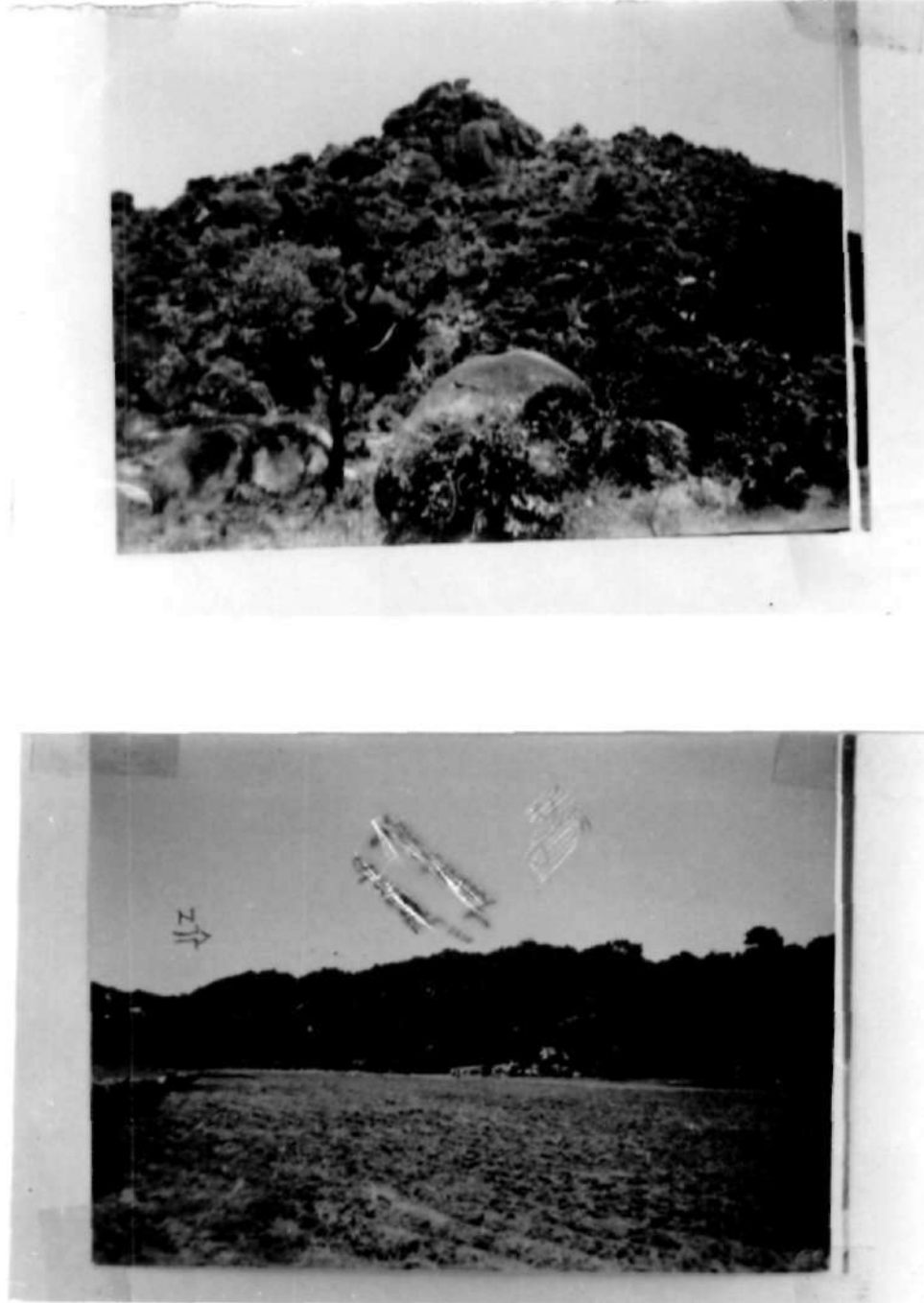
Plate 2.6 and 2.7   Daw biotite-granite close to Bum in near
vertical contact with the Basement Complex
(overlaid by farmland).

2.8 THE DAW BIOTITE-GRANITE

This biotite-granite appears around the village of Danwal (formerly Daw) and spreads westwards to Chuggi village. It occupies a good portion of the northern part of the area studied, also making contact with the adjacent Kigom Hills.

A considerable portion of the Daw biotite-granite is now obliterated by relics of earlier intrusions, such as the highly concordant and steep-sided Older Granites along the road to Kigom.

In the *southern part* of the Daw *biotite-granite, the contact with the migmatites of the Basement is very steep, with angles of about 85-88°* (see *plates 2.6 and 2.7*). On the other hand, the contact between the Daw biotite - granite and the hornblende-biotite - granite as *observed a few kilometres south of Danwal, is just 45°, showing the irregularity in the roof of the former. There is thus a general steepening of the roof of the Daw biotite-granite on going southwards* (Buchanan et al., 1971).

About 1km east of Chuggi, the Daw biotite-granite has reacted *with the earlier hornblende-fayalite-granites, giving rise to a zone of hybridization. The outcrops here are mostly of hornblende fayalite-granite, and a few of the Ganawuri biotite-granite.*

In hand specimens, the Daw biotite-granite is grey-white in colour and medium to fine-grained in texture. It is spotty in appearance, due to a perthite composed of albite and microcline. Red patches occur, dispersed all over the rock. They are due to iron compounds which have undergone oxidation.

Where the Daw biotite-granite has undergone metasomatic reaction with the hornblende-fayalite-granite, there are dispersed

phenocrysts of orthoclase, often exceeding 1cm, probably the result of recrystallization.

2.9 MINOR STRUCTURES

2.9.1 Quartz Veins

Although quartz veins occur within a good number of the rock types, they are best developed in the hornblende - biotite-granite. Large crystals of quartz can be observed, some measuring up to 3 cm in diameter.

The veins generally run in an east-west direction, not following the general structural trend which is WNW-ESE.

2.9.2 Pegmatite Veins

Pegmatite veins occur within the hornblende-biotite-granite, running in a general north-south direction. They measure close to a meter in width, but have been highly weathered. Most of them have been mined for tin sometime in the past, leaving channels bordered by large crystals of quartz and feldspars. The pegmatitite veins used to be very rich in tin, evidence of this being the tiny granules of cassiterite found along these river channels.

2.9.3 Dykes

A number of dykes occur throughout the study area, but the major one is along the road between Heita and Danwal, east of the abandoned mining camp. This dyke cuts discordantly across the hornblende biotite - granite and the porphyritic biotite-microgranite, with a gentle slope of 23° under the latter.

The rock itself is very hard, blue in colour and fine-grained. Its mineralogy ressembles that of the hornblende-biotite- granite, except for recrystallised quartz and iron oxide. Its hard nature and the similarity of its mineralogy to that of hornblende-biotite granite shows that the late magma that entered the fissure must have reabsorbed a lot of the country rock i.e. the hornblende biotite-granite before crystallization. The dyke can therefore be called a quartz-rich biotite-granite or moyite.

2.10   JOINTS

A very high number of joints were observed in the study area, mostly occurring as joint sets. The majority of the joints were either flat-lying or gently dipping.

The joints followed a general WNW - ESE direction as observed by some measurements over different rocks types within the area (see Table 2.1). The joints were plotted on a rosette diagramme (Fig. 2.1) and showed that the dominant direction is WNW-ESE, for all the rocks taken together.

The joints have acted so extensively on the rocks that their combined action have resulted in rectangular slabs covering a good portion of the area (see plate 2.5).

TABLE 2.1: Joint Readings which the Study area. (all values are in degrees)

276	274	007	333	065
315	050	025	120	020
010	222	330	320	290
332	255	010	115	120
360	103	190	310	160
275	267	155	196	145
290	310	250	295	167
255	200	137	137	050
244	353	120	020	010
245	285	270	310	300
275	300	283	291	265

FREQUENCY 1 READING : 1/2 CM
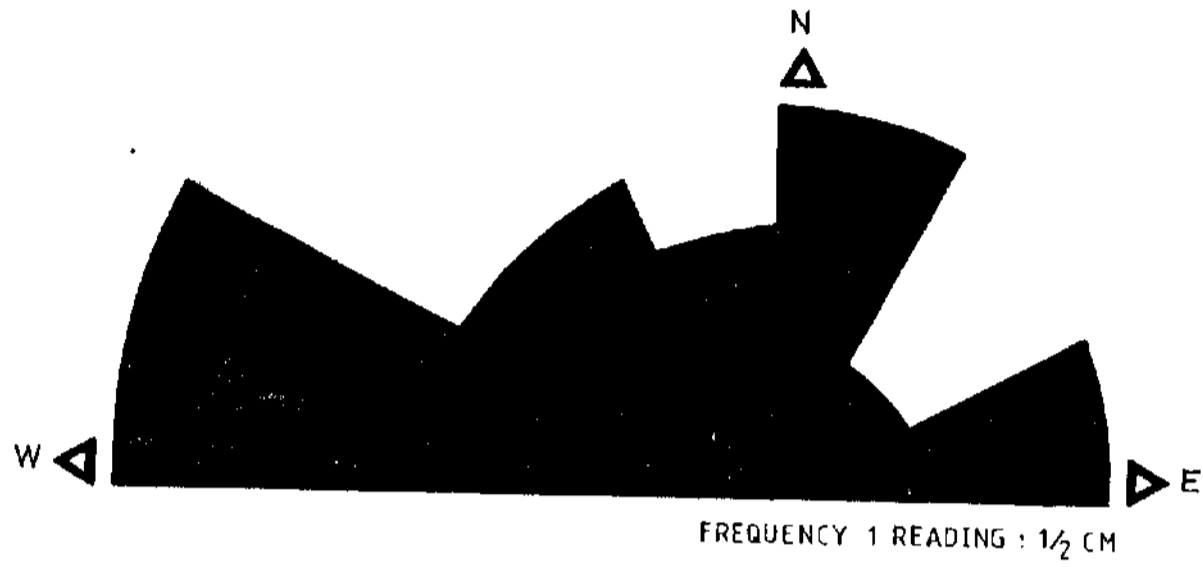
Fig. 2.1. Rosette diagram of joints in the rocks of the Ganawuri Complex .

2.11 OTHER ROCKS

2.11.1 Older Basalts

The Older Basalts are Paleocene or Lower Cenozoic (Grant et al., 1972) often occuring on lava flow of basaltic composition, or as large basalt lava and trachyte-phonolite plugs (Ayeni, 1994).

In the Ganawuri area, the Older Basalts are found in the north Western portion of the study area, often occuring as small outcrops. They dip gently towards the rocks of the basement complex at angles between 10° and 15°. The outcrops are often eroded and partially decomposed, and separated from one another by a substantial barrier of Younger Granite.

When weathered, the Older Basalts turn into friable material that easily detaches into rectangular blocks, aided by the pervading vertical and horizontal joints.

Hand specimens are smooth, dark -grey in colour and fine-grained in texture. The constituent mafic minerals are not easily identifiable with the naked eye.

2.11.2 Newer Basalts

The Newer Basalt is a more recent basalt of Pleistocene age (0.9 ± 0.2 m.y.) (Ayeni, 1994) spread across a considerable portion of the southwest and western part of the study area, around Hoss and Makera villages.

At Hoss village, the north-western part is dominated by a vent about 1000m high, with a flattened top several hundred metres in diameter. It is composed of coarse-grained vesicular basalt as observed in hand specimens.

Both columnar jointing and vertical hexagonal jointing have occurred to split the rock into regular horizontal slabs.

2.11.3   Laterites

The laterites are derived from the Older Basalts and normally overlie them. They are residual, resulting from the leaching action of combined weathering and erosion of the primary minerals of the basalts. The resistant minerals are then concentrated in iron caps and cemented together by iron minerals.

Most of the laterites occur within the central and northern part of the study area, generally at low altitudes, A few, however, may be observed at higher attitudes, but are believed to be associated with the hornblende-fayalite-granites.

On the field, the lateritic profile observed consisted mainly of a pisolithic iron cap of variable thickness between 2m and 10m enclosing nodules of about 5mm in diameter overlying a much thicker clayey layer. The latter is white to greyish-white and bearing some dark granules, probably relics of iron minerals. The intact parent rock could not be seen from the observed profiles (Ayeni, 1994).

The absence of laterites in most of the lithological units of the study area implies that not all of these rock types can serve as parent materials for lateritization under the prevailing weathering regime.

CHAPTER THREE

PETROGRAPHY

3.1 INTRODUCTION

Two thin sections each of representative samples of the litho-units of the Ganawuri Younger Granite petrographic suite were examined. Modal analysis by point counter technique and the mineralogy of these units were studied. Emphasis was laid on the major component minerals and the two thin sections averaged as shown in Table 3.1. Individual modal analyses for the various thin sections are shown in Appendix I

The average modal compositions of all the rock types were then plotted together on a Q-A-P diagram of the I.U.G.S. classification (See Fig. 3.1). (Le Maitre at al., 1989; Le Bas and Streckeisen, 1991).

Accessory minerals could, however, only be quantified by visual estimation.

3.2 HORNBLENDE-BIOTITE-GRANITE

In thin section, the hornblende-biotite-granite presents a granular texture, with various crystals set in a matrix of microperthite. This microperthite is very abundant, and is composed of microcline and albite (See plates 3.1 and 3.2).

Major component minerals of this rock include microcline and albite, as already listed above, together with quartz, biotite, hornblende and orthoclase.

Microcline (55% by volume) occurs as patchy microperthite together with albite. The structure of microcline is lamellar, with two sets of lamellae at right angles to one another. At higher magnifications, the crystals are subhedral in form.

Albite (5% by volume) occurs as two distinct sets of crystals. The greater part of the albite (about 3%) is intimately linked with microcline in the microperthite, or it forms phenocrysts showing indistinct twinning. The second generation of albite is developed at interfaces between the microcline and other minerals, and exhibits perfect polysynthetic twinning (see plate 3.1).

Quartz is abundant (27%) as xenomorphic crystals and granular aggregates, often filling the interstices between other minerals. Quartz is yellow-brown with straight extinction.

Hornblende occurs as ragged and highly altered plates. It is quite abundant (6% by volume) and subhedral in form. It displays green to brown pleochroism.

Biotite (2.5%) occurs as euhedral crystals, often bearing numerous pleochroic haloes due to inclusions of probably magnetite and zircon. A few other crystals of biotite are ragged and highly altered, the secondary product being chlorite.

Orthoclase (4%) occurs as turbid, grey phenocrysts, showing sharp boundaries against the quartz crystals.

Accessory, minerals of the hornblende-biotite-granites include magnetite and chlorite.

Zircon is very rare and occurs as grey, wedge- shaped crystals. Its proportion is less than 1%.

Chlorite is the product of biotite alteration and its relative proportion is also less than 1%.

Magnetite (0.5%) occurs both within and adjacent to the biotite crystals.
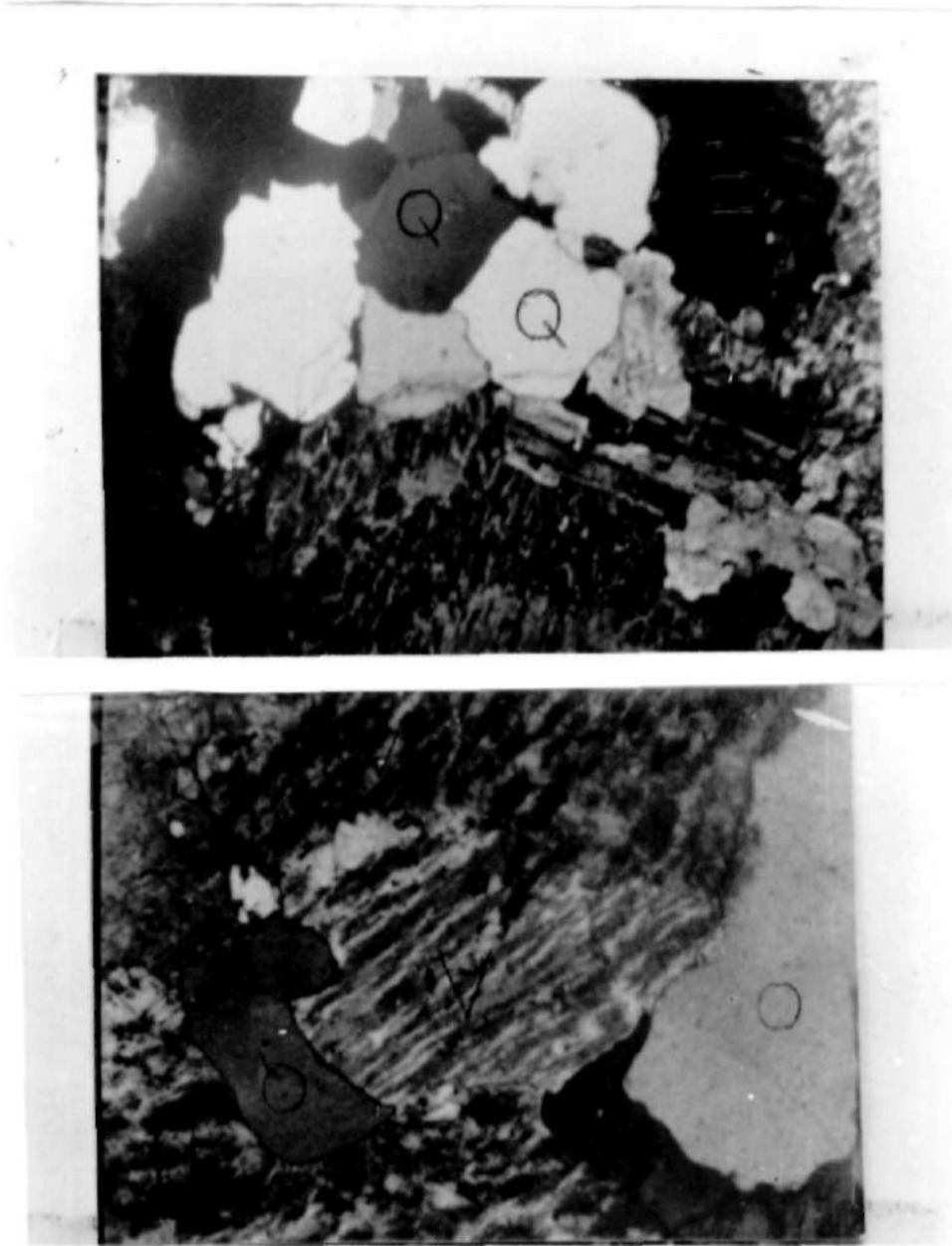
Plate 3.1 & 3.2   Photomicrograph of hornblende-biotite granite showing abundant microcline microperthite (M) surrounding phenocrysts of biotite (B) under extinction, euhedral quartz (Q), albite (A) in polysynthetic twininng and turbid orthoclase (O). Note the dispersed flecks of hornblende (H). Also note the more defined form of second generation albite crystals. (Crossed polars. Magnification x25).

Table 3.1 shows the results of the average of modal analyses for all the rock types examined.

3.3   DAW BIOTITE-GRANITE

In thin section, the Daw biotite-granite is equigranular in texture. There is an abundance of microperthite, quartz and minor occurrences of orthoclase, biotite and hornblende. The above mentioned minerals are the major constituents of the rock. Accessory minerals include zircon, chlorite and magnetite. The microperthite comprises microcline and albite. A second generation of albite thus forms laths enclosed within the microperthite (See Plate 3.3). The proportion of microcline is about 55% while that of albite is about 3%.

Quartz is highly abundant (30%) and occurs as two distinct generations in the rock. The first phase crystallised initially as clusters (See plate 3.4) while in the second phase, quartz occurs as replacement crystals in the microcline of the microperthite. The clear distinction between these two phases was highlighted by Kinnaird et al. (1985).

Orthoclase (6%) is cloudy and visible within the interstices of the other minerals. Its low relief and straight exhinction serve in distinguishing it from untwinned albite, which occurs in similar manner in the sections.

Biotite (4%) ranges from green to yellow-brown in colour. Considerable zoning can be observed, with the outer edges being highly altered, while the inner core is more or less intact. Numerous pleochroic haloes can be observed in the biotite crystals. Abaa (1976) suggested such haloes could have been caused by minute radioactive cores within the biotite, or by bombardment from small zircon crystals bearing alpha particles. Meanwhile the zoning of the biotite (See plate 3.4) could have resulted from variation in the contents of iron and/or titanium (Buchanan et al., 1971; Hall, 1987).

Hornblende occurs in very small amounts in the Daw biotite-granite (approximately 1%). It is the brown variety that can be seen and the cystals are euhedral.

Zircon is relatively abundant for an accessory mineral (about 1%). It is regularly distributed within the crystals of orthochase as prisms showing parallel extinction.

Chlorite and magnetite are both alteration products of the biotite crystals. They both occur in low proportions (0.2%).
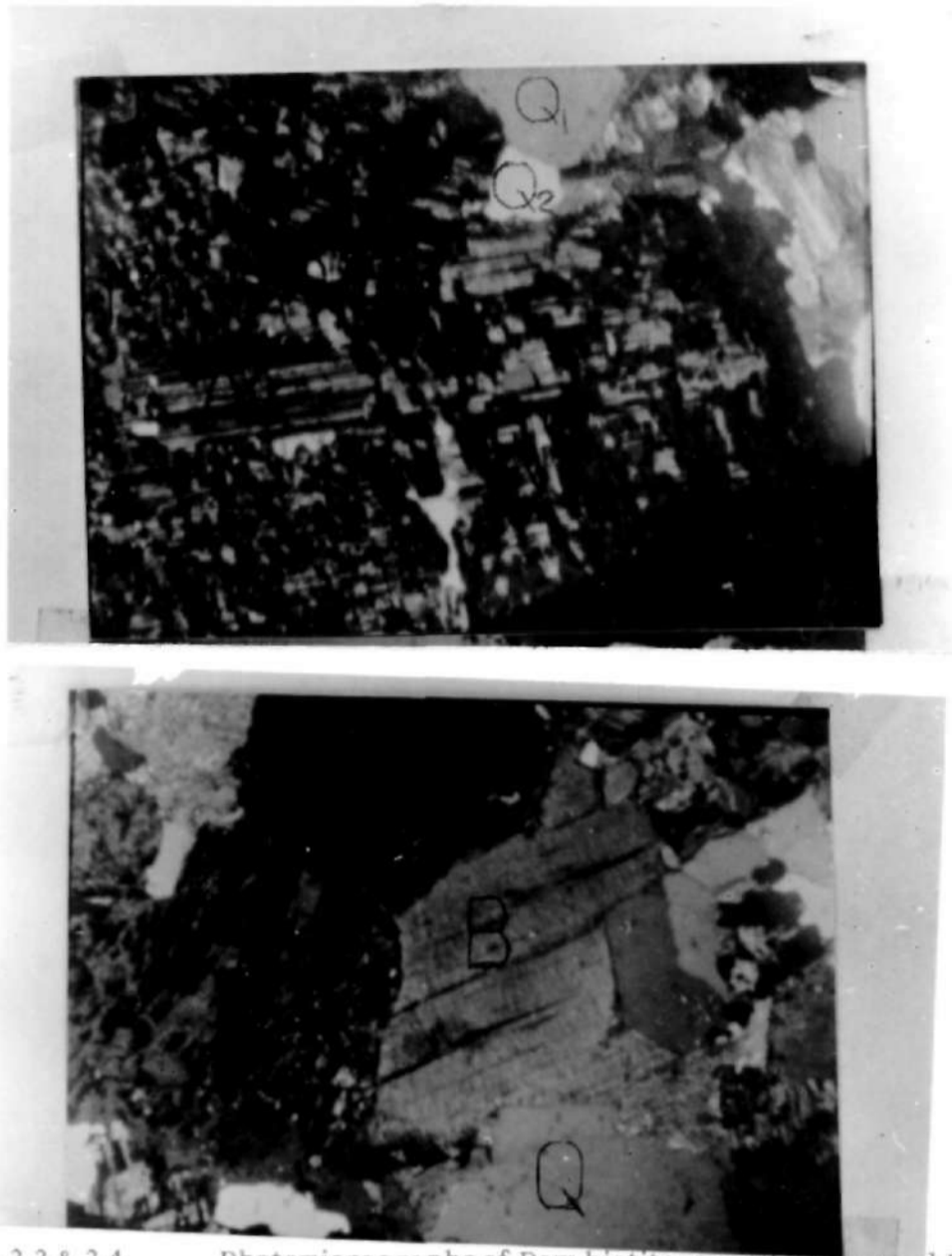
Plate 3.3 & 3.4   Photomicrographs of Daw biotite–granite. (Crossed Polars.
Magnification X25), showing widespread matrix consisting
of microcline microperthite (M) with exsolved crystals of
albite (A) showing polysynthetic twinning (3.3). Quartz is
in two generations (Q_1 and Q_2). The crystals of biotite (B)
are highly altered to Magnetite (Mg) and also show
replacement by patchy albite (second generation?). Intense
alteration of biotite phenocryst (in lower photograph)
interlocking with euhedral quartz crystals (3.4).

3.4 GANAWURI BIOTITE-GRANITE

The Ganawuri biotite-granite shows a graphic texture due to an intergrowth of quartz and orthoclase microperthite (See Plate 3.5). Albite and biotite constitute the other major component minerals.

Quartz (29% in proportion) occurs as large subhedral to euhedral crystals. It appears to have been formed subsequent to the other minerals, so that the quartz forms small knots and chains around the other minerals. The quartz crystals have resisted weathering and alteration.

Orthoclase is abundant as microperthite (40%) which appears patchy due to the replacement of orthoclase by albite. The latter is much more abundant in the Ganawuri biotite-granite than in the other granites, (up to 10%), having replaced a considerable portion of orthoclase in the microperthite. Other albite crystals occur as laths within the microperthite (See Plate 3.5).

Biotite is also very predominant in this rock, as compared to other rock types. Comprising up to 18% of the rock (in average), it is the main mafic mineral, with a variety of large, ragged, shredded or corroded crystals. Some of them have to a great extent been altered to chlorite. (Plate 3.6). Other biotite crystals contain numerous pleochroic haloes, bearing inclusions of magnetite or zircon. The pleochroism is from yellow-brown to dark brown.

Accessory minerals include abundant crystals of zircon, magnitite and chlorite.
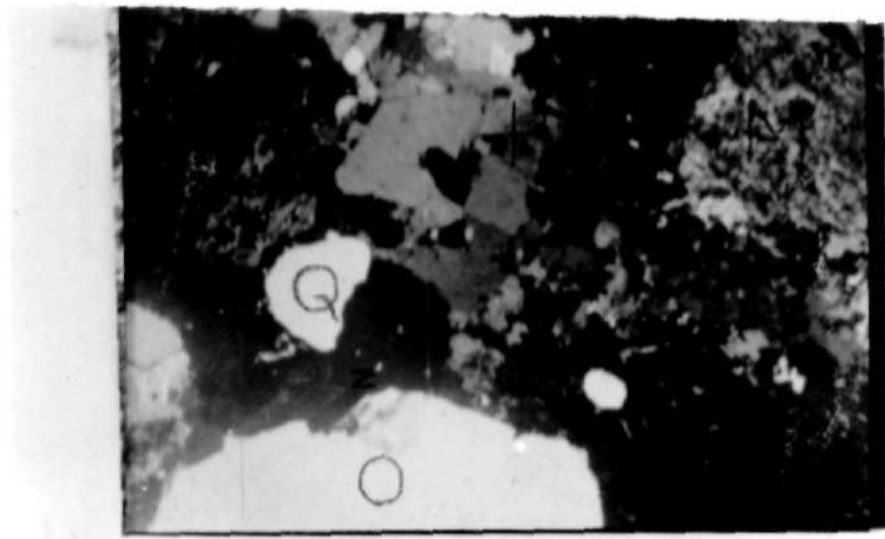
Plates 3.5 & 3.6:   Photomicrographs of Ganawuri biotite–granite.   3.5
shows extensive microperthite (M), portions of which
are being exsolved into orthclase (O) and albite (A).
Note   dispersed   biotite   plates   (B).   3.6   shows
intergrowth of quartz (Q), hornblende (H), strained
biotite (B) being replaced by magnetite (Mg). Also note
tiny wedge-shaped crystals of zircon (Z) within
quartz crystals.

(Crossed Polars. Magnification X25).

different orientations of the crystals in the thin sections rather

than compositional changes. The quartz crystals are dispersed

throughout the microperthitic groundmass (Plate 3.7).

Zircon occurs mostly as euhedral crystals included in the biotite. Its proportion is quite high (0.7%).

Magnitite is in very small proportions (₹0.1%) and occurs as inclusions in the pleochroic haloes of the biotite crystals. Chlorite, slightly more abundant (0.3%), occurs at the edge of biotite crystals, where it is an alteration product.

The average modal composition of the Ganawuri biotite-granite appears in Table 3.1

3.5 PORPHYRITIC BIOTITE-MICROGRANITE

This rock is porphyritic in texture, with phenocrysts of quartz and albite in a groundmass made up of biotite and microperthite consisting of orthoclase and albite. All the above minerals are the major component minerals. The accessory mineral that can be identified is magnetite.

Orthoclase is abundant (48%), existing as pale grey, euhedral crystals with pinkish borders (See Plates 3.7 and 3.8). It displays pale grey to yellow-brown pleochroism.

Albite occurs in two distinct forms: as integrowths with orthoclase in the microperthite or as euhedral, lath-shaped crystals showing good twinning. The latter often forms interstitial crystals. Albite (up to 8%) is fairly abundant in the rock.

Quartz occurs in high proportion (33%), existing as phenocrysts with corroded borders showing colours varying from white to greyish shades. These variations are, however, due to different orientations of the crystals in the thin sections rather than compositional changes. The quartz crystals are dispersed throughout the microperthitic groundmass (Plate 3.7).
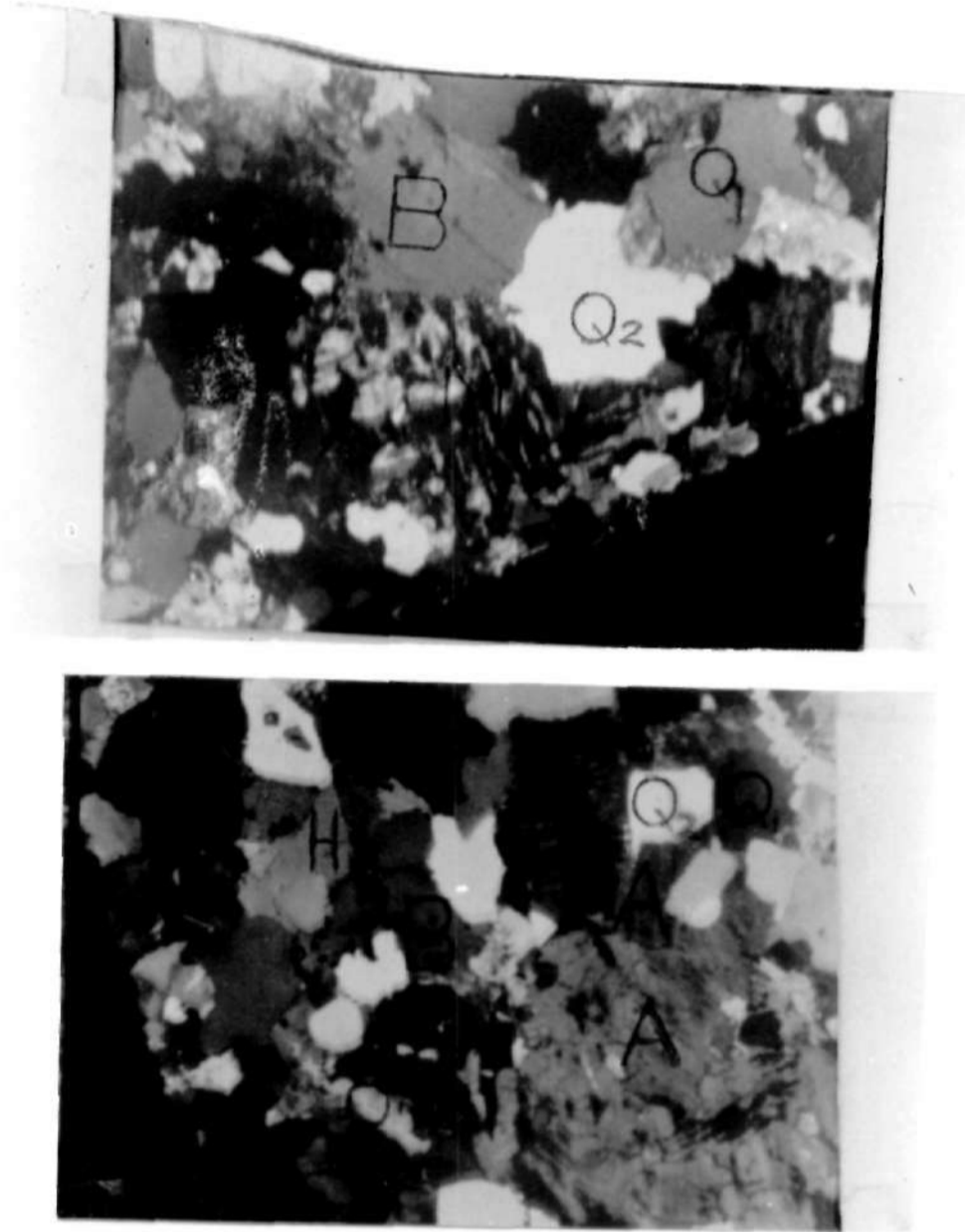
Plate 3.7 & 3.8:   Photomicrographs of the porphyritic biotite-
microgranite showing phenocrysts of microdine
(M), albite (A), Quartz (Q) and biotite (B).
Hornblende (H) interlocks with biotite crystals.
Orthoclase is cloudy-grey and interstitial. Both
albite and quartz appear in two generations each,
the second having better-formed crystals.

(Crossed Polars. Magnification X25).

Biotite occurs both as euhedral (Plate 3.7) and anhedral crystals (plate 3.8). Its pleochroic haloes and yellow-brown colour aid in its easy identification. Some of the biotite crystals have been completely altered. The proportion of biotite in the rock is relatively high (7.5%).

Magnetite is the only accessory mineral and results from the alteration of biotite. The relatively high proportion of magnetite (1%) is due to the fact that some biotite crystals have almost entirely undergone alteration.

3.6   FINE-GRAINED BIOTITE – GRANITE

The fine-grained biotite-granite bears a certain ressemblance to the groundmass of the porphyritic biotite-microgranite. The phenocrysts are considerably fewer in number, and consist of quartz, orthoclase feldspar and biotite.

Orthoclase appears as numerous pale grey crystals showing pink pleochroism. It is abundant, with an occurrence of around 50% in the rock.

Quartz, (about 33%) consists of widely dispersed phenocrysts of various colours from dirty white to grey. The boundaries of quartz crystals are not distinct, implying an overlap of crystallization periods with the adjacent minerals.

Albite (8% in proportion) can be observed as lath-shaped euhedral crystals most often occurring within the interstices of other minerals.

Plate 3.9   Photomicrograph of fine-grained biotite-granite showing phenocryst of biotite (B) interlocking with orthoclase (O) and strained quartz (Q). Note the extensive replacement of biotite by Chlorite (C) and the magnetite rim (Mg) around it.

(Crossed Polars. Magnification X25).

Biotite (approximately 8% in proportion) occurs as large, shredded and corroded crystals, possessing numerous pleochroic haloes.

Magnetite (0.5% relative proportion) is the prominent accessory mineral. It is most commonly observed as alterations within biotite crystals.

3.7 FAYALITE-BIOTITE MICROGRANITE

The texture of the fayalite-biotite microgranite is porphyritic with phenocrysts of quartz and albite existing within a groundmass of quartz and plagioclase feldspas of sodic composition (See Plate 3.10). The other major component minerals are biotite, hornblende and fayalite.
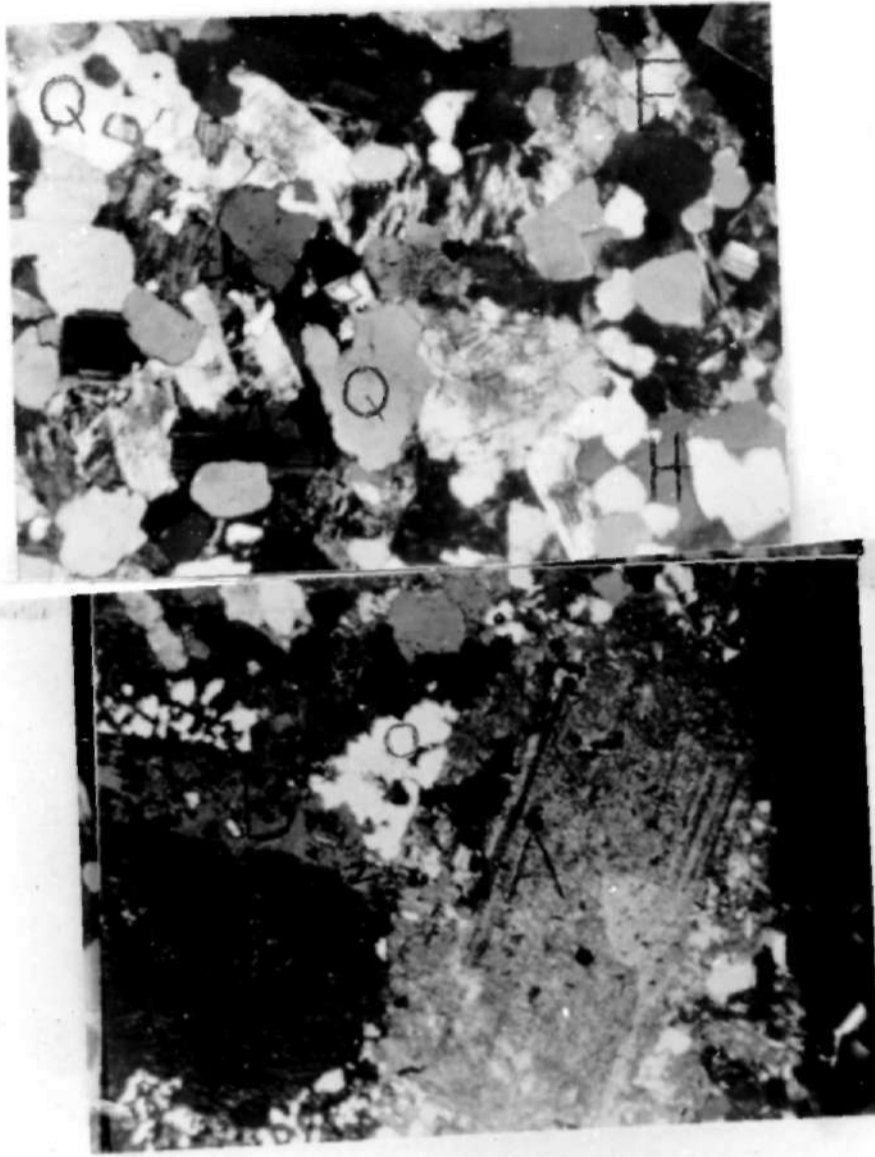
Plates 3.10 and 3.11: Photomicrographs of the fayalite-biotite-
microgranite.
Plate 3.10 shows interlocking crystals subhedral to euhedral
quartz (Q), microcline (M) and finely-twinned albite (A). Fayalite
(F) appears as ragged elongated crystals and hornblende (H)
encloses wedge-shaped zircon crystal. Plate 3.11 shows a large
phenocryst of albite partially replaced by iron oxides and cloudy
oligoclase (O). The biotite (B) phenocrsyt is highly altered to
magnetite (Mg), and also shows small crystals of Zircon (Z).

(Crossed Polars. Magnification X25).

Quartz makes up to 20% of the total area of the rock observed. It exists as euhedral crystals with colours ranging from dirty white to pale brown, which are often cracked and embayed by other minerals such as zircon and sphene (See Plate 3.10).

Oligoclase (12% in proportion) occurs as large anhedral crystals. The crystals do not have any prevailing direction.

Albite is quite abundant (25%). It is intimately linked to the Oligoclase crystals, or forms large phenocrysts (plate 3.11). None of them portrays any prevailing orientation of its crystals. This implies the absence of flow or secondary replacement (Hall, 1987).

Biotite occurs as large, anhedral and highly altered crystals. Pleochroic haloes are abundant and many crystals have been altered into magnetite.

Hornblende forms euhedral crystals interlocked with those of quartz. It is the brown variety of hornblende that can be observed, implying a richness in iron (Moorhouse, 1959). Hornblende makes up 5% of the constituent minerals. Fayalite occurs as pale yellow, subhedral crystals without any cleavage direction. They show light yellow to yellow brown pleochroism.

Accessory minerals include zircon, sphene and magnetite. Zircon appears as well-shaped crystals within the pleochroic haloes of the biotite crystals (see plate 3.11).
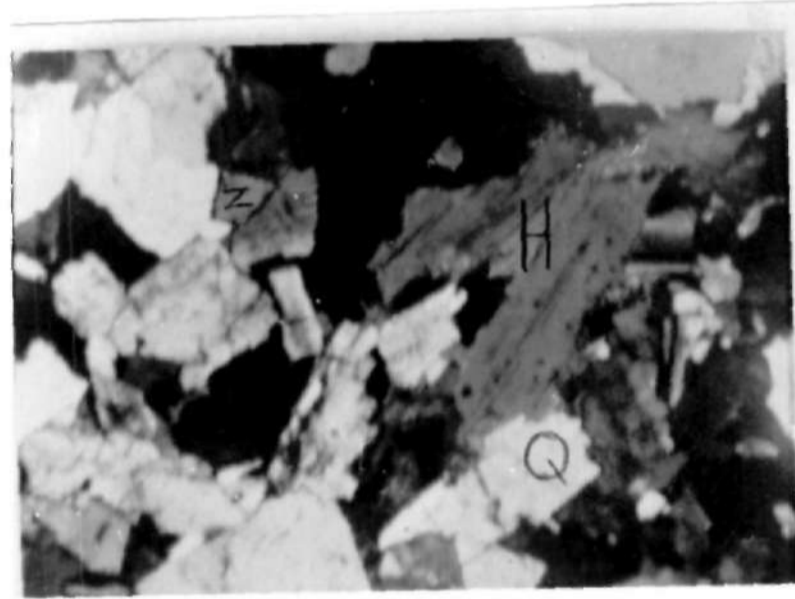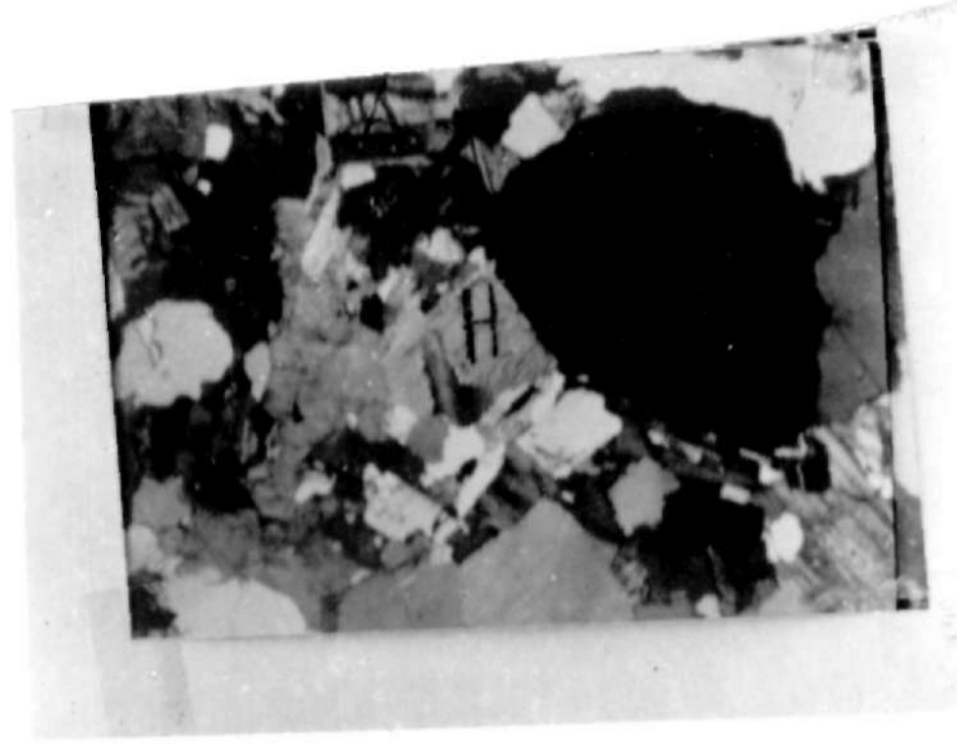
Plates 3.12 and 3.13 Photomicrographs of the hornblende-fayalite-granite showing zoned hornblende (H), biotite phenocrysts (B) enclosing zircon (Z) and subhedral quartz (Q) phenocrysts. Also note the exsolved crystals of well twinned albite (A) and microcline (M).

Sphene occurs as wedge-shaped octahedral crystals within the cracks in quartz. This implies a late stage development of sphene with respect to quartz. There is the possibility of its having been emplaced mechanically by the action of hot percolating fluids.

Magnetite is relatively abundant (1%), resulting from the alteration of biotite crystals.

3.8 HORNBLENDE-FAYALITE-GRANITE

The major constituent minerals of the hornblende-fayalite-granite include quartz, microcline, fayalite, hornblende and biotite.

Quartz is very abundant (22%), occurring as anhedral crystals often cracked and embayed by feldspar (see Plate 3.12). The feldspar is microcline, appearing as twinned, anhedral crystals intergrown with quartz crystals to form a matrix. It also occurs as smaller crystals and makes up 40% of the rock.

Fayalite crystals are small and euhedral, constituting up to 16% of the total composition. They are pale yellow without any cleavage direction, exhibiting straight extinction and high birefringence. Their pleochroism is from pale-yellow to yellow-brown.

Hornblende's occurrence is high (11%) but very irregular throughout the rock. Both varieties of hornblende (green and brown) can be seen together sometimes.

Biotite appears as dark brown plates under extinction (plate 3.13), often interlocked with hornblende crystals. Its proportion in the rock is 8%.

The accessory minerals of the rock is zircon.

Zircon is euhedral, with wedge – shaped crystals most of which occur within cracks and interstices of the larger crystals of quartz and microcline. (See table 3.13).

3.9 HORNBLENDE–BIOTITE MOYITE DYKE

In thin sections some portions of the dyke are almost identical with the hornblende–biotite–granite, hence the assumption that reaction must have occured between the intrusive dyke and its host rock the biotite–granite.

Other portion of the dyke are equigranular, and probably represent the remaining part of the magma that did not react with the host rock.

The first case represents the contact between host rock and intrusion, and exhibits a preferred orientation of laths of quartz and feldspars (see plate 3.14).

In the dyke proper, microcline and albite have exsolved and form crystals interlocking with quartz (see plate 3.15). Their percentages in the rock are 34% and 4% for microcline and albite respectively.

Quartz forms large phenocrysts which are often cracked and embayed by the microcline and albite crystals. Quartz constitutes more than half of the total composition (about 55%). This is evidence of recrystallization, as observed by the differences in size and form of the different quartz crystals. (See plate 3.15). Furthermore, the smaller quartz crystals which were later introduced are intergrown with both the larger quartz and microcline crystals.

Biotite (2.5%) and hornblende (1.5%) are both very rare in the rock and occur as euhedral crystals. However, the former is often highly altered at the edges to magnetite (Plate 3.14).

Accessory minerals include zircon (1%), and magnetite (1%). Possibly half of the original biotite might have been altered to magnetite.
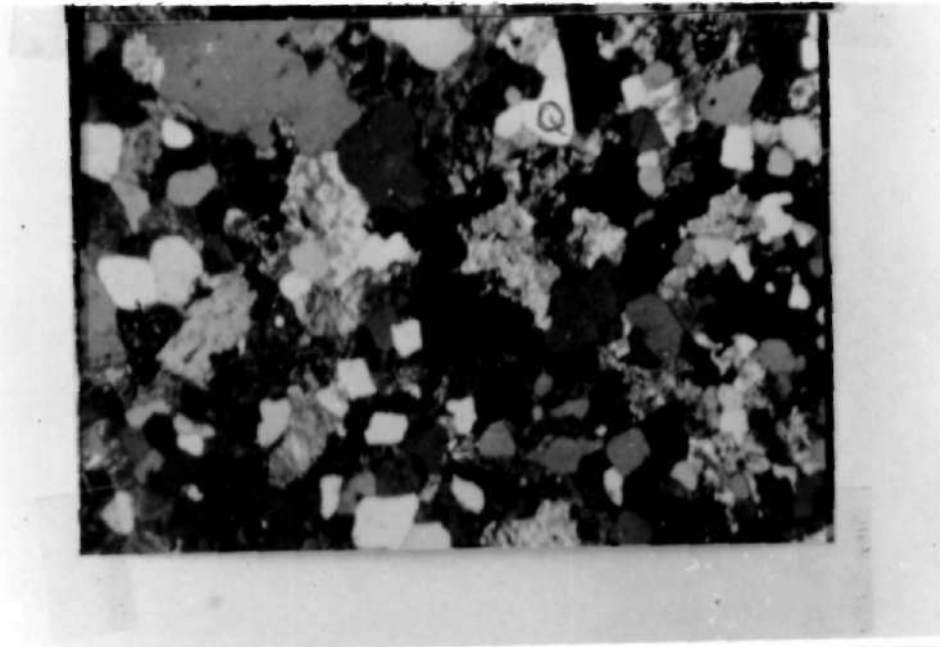
Plates 3.14 and 3.15: Photomicrographs of the dyke. 3.14 represents the contact with the host hornblende-biotite-granite, and shows a certain preferential orientation of the laths of quartz (Q) and feldspars. Note the strain and replacement of biotite (B) crystals, and zoning in the left crystals.

3.15 shows the main body of the dyke with interlocking quartz (Q), microcline (M), albite (A) and biotite (B). Also note magnetite (Mg) partially replacing biotite, and wedge shaped zircon crystals under extinction.

(Crossed Polars. Magnification X25).

3.10 REMARKS

Table 3.1 shows the modal values of all the different rock types. It is the average values from various thin section that are represented here, the actual values for all the thin sections are in Appendix I.

The values were then used in determining the positions of each rock type which were plotted on a Q.A.P diagram of I.U.G.S. classification (Fig. 3.1).

From this plot, it can be seen that most of the rocks fall within the same sector of the triangle, supporting the earlier stated low variation in their mineralogy. They are all close to the Q.A compositional line, with a generally low content in plagioclase feldspar and high alkali feldspar content.

TABLE 3.1   AVERAGE MODAL COMPOSITION FOR ALL THE ROCK TYPES OF THE GANAWURI YOUNGER GRANITEX COMPLEX

	1	2	3	4	5	6	7	8
Microcline	55	55	–	–	–	–	40	34
Quartz	27	30	29	33	33	20	22	55
Albite	5	3	10	8	8	25	–	4
Biotite	2.5	4	18	7.5	8	20	8	2.5
Hornblende		6	1 –	–	–	5	12	1.5
Fayalite	–	–	–	–	–	15	16	–
Orthoclase	4	6	40	48	50	–	–	–
Oligoclase	–	–	–	–	–	12	–	–
Zircon	0.1	0.7	1	–	0.2	1	1	1
Magnetite	0.5	0.2	0.1	1.0	0.5	1	–	1
Chlorite	0.2	0.2	0.3	–	–	–	–	–
Sphene	–	–	–	–	–	0.3	–	–

Total	100.3	99.1	97.4	97.5	99.7	99.3	99.7	99.0
Q	29.1	34.5	35.9	37.1	36.3	35.1	35.5	59.5
A	68.8	63.2	51.3	53.9	55.5	43.9	64.5	36.2
P	2.1	2.3	12.8	9.0	8.2	21.1	–	4.3

KEY

(1)   Average of two hornblende-biotite-granite samples

(2)   Average of two Daw   "   "   "

(3)   Average of two Ganawuri   "   "   "

(4)   Average of two porphyritic biotite-microgranite samples

(5)   Single section of the fine-grained biotite-granite

(6)   Average of two fayalite-biotite-microgranite samples

(7)   Average of two hornblende-fayalite-granite samples

(8)   Average of two hornblende-biotite-moyite dyke samples

NB.   All figures quoted above are in percentage.
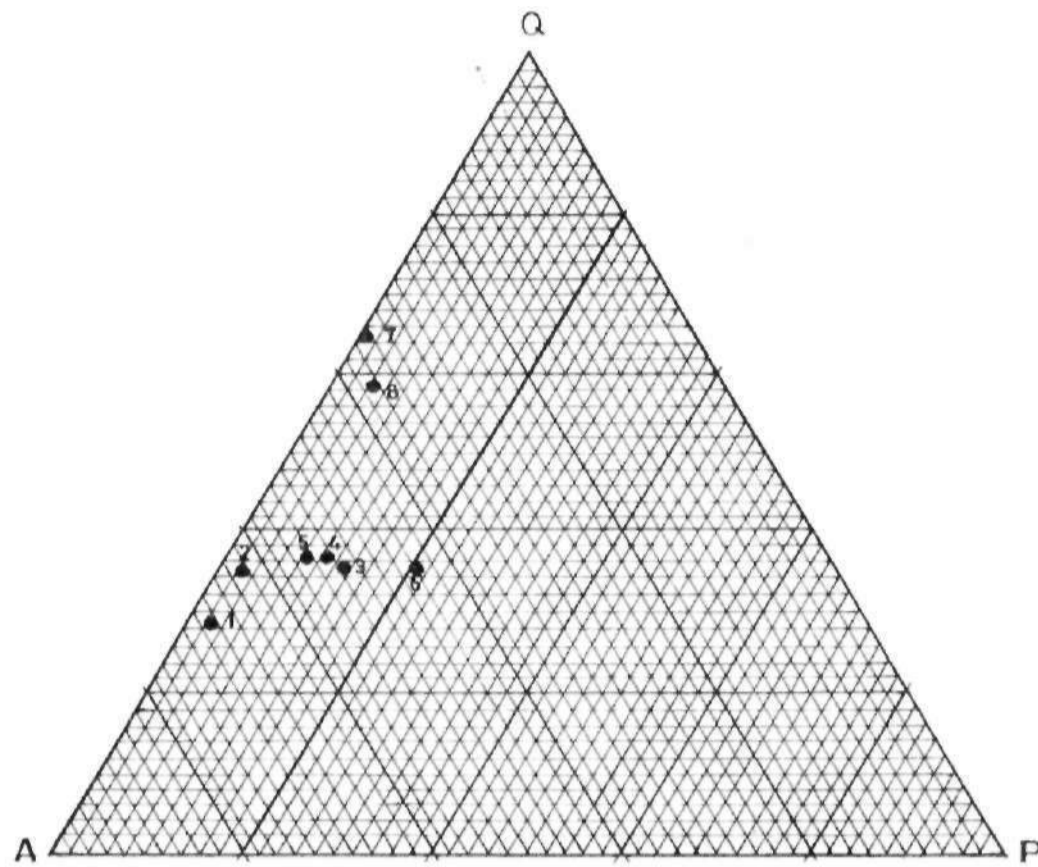
Fig. 3.1. Q-A-P diagram (I.U.G.S. classification)
showing the positions of the rock units
of the Ganawuri Younger Granite Complex.
(Legend same as in Table 3.1)
(After: Le Maitre et al., 1989 ; Le Bas and Streckeisen, 1991).

CHAPTER FOUR

GEOCHEMISTRY

4.1 INTRODUCTION

Whole rock geochemical analysis was carried out on eleven samples of granites from the Ganawuri Complex to serve as monitors for comparison with analytical data on similar rocks elsewhere. In order to enhance representativeness of the samples, grain size and colour index were used.

Crushing, grinding, sieving and mixing were done following the procedures of Potts (1987), after which 0.5g of each sample were subjected to complete digestion by hydrofluoric acid.

Major elements were analysed by the three different methods, these being: atomic absorption spectrometry (A.A.S.), flame photometry and colorimetry. (See Appendix II for the complete procedures and methods of analysis).

4.2 DISTRIBUTION, AND CHEMICAL VARIATIONS OF THE OXIDES

Table 4.1 shows the proportions of the major oxides (expressed in weight percentage) of the litho-units of the Ganawuri Younger Granite units as determined by different analytical methods.

TABLE 4.1   CHEMICAL ANALYSES OF YOUNGER GRANITES
                 FROM THE GANAWURI COMPLEX.

	HO6	H16	P08	P09	G03	G13	H12	F05	D01	D02	H19
SiO_2	75.79	73.93	72.16	75.16	73.62	72.69	75.79	70.35	75.18	75.49	79.08
Al_2O_3	12.92	12.60	12.23	12.33	13.26	12.55	12.27	13.39	12.01	12.13	13.75
TiO_2	0.27	0.18	0.37	0.43	0.18	0.30	0.34	0.18	0.11	0.23	0.50
Fe_2O_3	2.33	2.52	1.61	1.66	1.29	2.39	2.75	2.79	2.86	0.64	0.37
MnO	0.16	0.02	0.12	0.04	0.01	0.08	0.06	0.03	0.05	0.01	0.003
MgO	0.44	0.01	0.54	0.40	0.22	0.65	0.17	0.76	0.29	0.23	0.41
CaO	1.61	0.66	1.39	1.25	1.09	1.39	0.81	1.79	1.26	0.81	0.88
Na_2O	5.06	4.00	5.29	5.00	4.92	5.69	4.45	5.39	4.72	4.65	3.94
K_2O	2.32	4.50	3.47	3.58	3.10	3.70	3.28	3.70	3.10	3.92	0.09
P_2O_5	0.06	0.02	0.03	0.03	0.05	0.05	0.04	0.82	0.27	0.02	0.16
	100.94	98.44	97.21	99.82	97.74	99.49	99.96	99.18	99.85	98.13	99.18

LEGEND

HO6 –   Hornblende–biotite – granite

H16 –   ,,   ,,   ,,

P08 –   Porphyritic biotite–microgranite

PO9 –   ,,   ,,   ,,

G03 –   Ganawuri biotite –granite

G13 –   ,,   ,,   ,,

H12 –   Hornblende–fayalite – granite

FO5 –   Fayalite–biotite – microgranite

D01 –   Daw biotite – granite

D02 –   ,,   ,,   ,,

H19 –   Dyke Sample (Hornblende–biotite–moyite)

ANALYSTS

(1)   BASHIRU, Y. (N.M.D.C. JOS), Al_2O_3, TiO_2

(2)   KAJAKO, P. (,,   ,,) – SiO_2

(3)   LAWAL, A. (I.A.R., SAMARU – ZARIA) – The rest of the analysis.

All the rocks of the Ganawuri complex analysed have compositions that compare closely with those of biotite-granites elsewhere within the Younger Granite Province. Table 4.2 (below) shows the result of analyses carried out on other biotite-rich Younger Granites from the Jos Plateau area.

TABLE 4.2 CHEMICAL ANALYSES OF BIOTITE-GRANITES FROM OTHER YOUNGER GRANITE COMPLEXES (From Macleod et al, 1971, Jacobson and Macleod, 1977).

	1	2	3	4
SiO_2	73.19	76.50	76.15	75.10
AlO_3	13.03	12.03	12.48	12.47
Fe_2O_3	0.50	0.77	0.50	0.47
FeO	2.22	0.98	0.73	1.35
MgO	0.25	0.01	0.19	0.35
CaO	1.25	0.22	0.51	1.00
Na_2O	3.70	4.17	4.06	3.75
K_2O	5.05	4.80	4.43	4.46
H_2O^+	0.22	0.20	0.33	0.35
H_2O^-	Tr	0.12	0.20	0.25
CO_2	nd	nd	0.06	---
TiO_2	0.32	0.09	0.04	0.47
ZrO_2	nd	nd	Tr	0.18
P_2O_5	0.12	0.04	0.01	0.03
Cl	0.03	Tr	0.35	0.02
F	0.05	0.04	0.02	nd
S	0.03	0.03	0.01	--
MnO	0.05	0.02		
	99.98	100.02	100.09	100.14
Less O	0.04	0.03	0.15	0.04
	99.94	99.99	99.94	100.10

LEGEND

(1)   Teria biotite – granite, Amo.

(2)   Rough Range biotite–granite, Amo.

(3)   Biotite–granite, Ririwai.

(4)   Biotite–granite, Kudaru.

TABLE 4.3 STEPS IN THE CALCULATION OF THE AFM DIAGRAM
(Legend Same as in Table 4.1).

Sample Numbers	H19	D01	D02	F05	H12	G03	G13	P08	P09	H06	H16
Na_2O	3.94	4.72	4.65	5.39	4.45	4.92	5.69	5.29	5.00	5.06	4.00
TotalAlkali($Na_2O + K_2O$)	4.03	7.82	8.57	9.09	7.73	8.02	9.39	8.76	8.58	7.38	8.50
Na_2O+K_2O Fe_2O_3+MgO	4.81	10.97	9.44	11.64	10.65	9.53	12.42	10.91	10.64	10.15	11.03
$A = \frac{Na_2O+K_2O \times 100\%}{Na_2O+K_2O + Fe_2O_3+MgO}$	83.78	71.28	90.78	78.03	72.58	84.16	75.60	80.29	80.64	72.71	77.06
$F = \frac{Fe_2O_3+100\%}{Na_2O+K_2O + Fe_2O_3+MgO}$	7.69	26.07	6.78	15.38	25.82	13.54	19.24	14.76	15.60	22.96	22.85
$M = \frac{MgO+100\%}{Na_2O+K_2O+Fe_2O_3+MgO}$	8.52	2.64	2.33	6.53	1.59	2.31	5.23	4.95	3.76	4.33	0.098

TABLE 4.4 DIFFERENTIATION PARAMETERS FOR ALL THE ROCKS
ANALYSED (Legend Same as in Table 4.1).

	H19	D01	D02	F05	H12	G03	G13	P08	P09	H06	H16
$SiO_2(\%)$	79.08	75.18	75.49	70.35	71.74	73.62	72.69	72.16	72.80	75.79	73.93
$Al_2O_3(\%)$	13.75	11.89	12.13	13.38	11.62	13.26	12.55	12.33	11.95	12.92	12.60
$CNK(2CaO+Na_2O+K_2O)$	5.79	10.34	9.19	12.67	8.86	10.10	12.57	11.54	10.83	10.60	9.82
TotalAlkali(Na_2O+K_2O)	4.03	7.82	8.57	9.09	7.73	8.02	9.39	8.76	8.58	7.38	8.50
$MgO(\%)$	0.41	0.29	0.23	0.76	0.16	0.22	0.65	0.54	0.39	0.44	0.01
$Fe_2O_3(\%)$	0.37	2.86	0.64	1.79	2.61	1.29	2.39	1.61	1.61	2.33	2.52
SiO_2/Al_2O_3	5.75	6.32	6.22	5.62	6.69	5.56	5.79	6.09	6.09	5.87	5.86
Al_2O_3/CNK	2.38	1.15	1.32	1.06	1.31	1.31	1.03	1.10	1.10	1.22	1.28
MgO/Fe_2O_3	1.11	0.10	0.50	0.43	0.06	0.17	0.27	0.24	0.24	0.19	0.004
SiO_2/CNK	13.66	7.23	8.21	5.55	8.09	7.29	5.97	6.72	6.72	7.15	7.53
$SiO_2/TotalAlkali$	19.62	9.61	9.97	7.74	9.28	9.18	7.74	8.24	8.67	10.27	8.70

TABLE 4.5 DIFFERENTIATION PARAMETERS OF THE MAIN ROCK
TYPES

	1	2	3	4	5	6	7
SiO_2 (%)	74.86	72.48	73.16	71.74	70.35	75.33	79.08
Al_2O_3 (%)	12.76	12.14	12.91	11.62	13.38	12.01	13.75
Na_2O (%)	5.43	5.14	5.31	4.45	5.39	4.69	3.94
K_2O (%)	3.41	3.51	3.40	3.28	3.76	3.51	0.09
CaO (%)	1.14	1.32	1.24	0.81	1.79	1.04	0.88
MgO (%)	0.23	0.46	0.44	0.17	0.76	0.27	0.41
Fe_2O_3 (%)	2.43	1.61	1.84	2.75	1.79	1.75	0.37
Total Alkali (Na_2O+K_2O)	8.84	8.65	8.71	7.73	9.05	8.20	4.03
CNK ($2CaO+Na_2O+K_2O$)	10.21	11.19	11.33	12.67	8.86	9.76	5.79
SiO_2/Al_2O_3	5.86	6.00	5.67	5.62	6.69	6.27	5.79
$Al_2O_3/$Total Alkali	1.62	1.41	1.49	1.47	1.50	1.56	3.41
$Al_2O_3/$CNK	1.25	1.08	1.17	1.06	1.31	1.24	2.38
$SiO_2/$Total Alkali	9.48	8.45	8.46	7.74	9.28	9.78	19.62
$SiO_2/$CNK	7.34	6.33	6.63	5.55	8.09	7.72	13.66
MgO/Fe_2O_3 (%)	0.09	0.27	0.22	0.43	0.06	0.30	1.11

LEGEND

(1)   Average of hornblende- biotite – granite

(2)   ,,   ,,   porphyritic biotite – microgranite

(3)   ,,   ,,   Ganawuri biotite – granite

(4)   Single sample of hornblende-fayalite-granite

(5)   Single Sample of fayalite-biotite-microgranite

(6)   Average of Daw biotite-granite

(7)   Single sample of dyke (hornblemde-biotite-moyite).

4.2.1 SILICA

The litho-units have SiO_2-rich compositions with a range
percentage varying from 70.35% (in the fayalite-biotite-granite) to
79.08% (in the dyke). Apart from the Daw biotite-granite and the
dyke, with their relatively higher silica content, the other rocks
portray a more or less general decrease in SiO_2 content with the
sequence of emplacement earlier established. (See Fig. 4.1).

4.2.2 ALUMINA

The *range in alumina percentage in the granites lies between* 12.01% (in the Daw biotite-granite) and 13.75% (in the dyke), both of which represent the terminal phase in the sequence of emplacement. However, the general pattern in the variation of alumina with the sequence of emplacement is haphazard (Fig. 4.1).

4.2.3 Fe_2O_3

The percentage of iron oxide ranges between 0.37% (in the dyke) and 2.61% (in the hornblende-fayalite-granite). The appearance of fayalite in the mineralogy of the rocks is accompanied by an increase in iron oxide content, as is the case with biotite-granites occurring elsewhere in the Jos Plateau (Macleod et al., 1971). In Fig. 4.1, $Fe2O_3$ shows a general increase with the sequence of emplacement, but decreases in value at the Daw biotite-granite and the moyite dyke, both being the final units emplaced.

4.2.4 Alkalis (Na_2O and K_2O)

Na_2O ranges from 3.94% (in the moyite dyke) to 5.39% (in the fayalite-biotite-micro-granite), while K_2O ranges from 0.09% (in the dyke) to 3.76% (in the fayalite-biotite-microgranite). The pattern of variation for both Na_2O and K_2O is observed as a general increase with the sequence of emplacement. This increase coincides with a general decrease in SiO_2 inverse correlation between SiO_2 and the alkalis. Furthermore, the highest values for the alkalis occur in the fayalite-biotite-microgranite while their lowest values occur in the moyite dyke, which also have the lowest and highest values of SiO_2

respectively. An enrichment in alkalis is therefore accompanied by a depletion in SiO_2 (see figs. 4.1 and 4.2).

4.2.5 MgO and CaO

MgO ranges from 0.23% (in the hornblende-biotite-granite) to 0.76% (in the fayalite-biotite-microgranite) and CaO ranges from 0.81% (in the hornblende-fayalite-granite) to 1.79% (in the fayalite-biotite-microgranite) (see table 4.5). Both MgO and CaO show similary variation patterns with the sequence if emplacement (see Fig. 4.2). Each shows a gradual increase with the sequence of emplacement from the hornblende-biotite-granite to the Ganawuri biotite-granite, then a trough, followed by a peak at the fayalite-bearing granites.

Both oxides have their lowest values in the hornblende-fayalite-granite, and their highest values in the fayalite-biotite-microgranite. Like the alkalis, they show an inverse correlation with SiO_2.
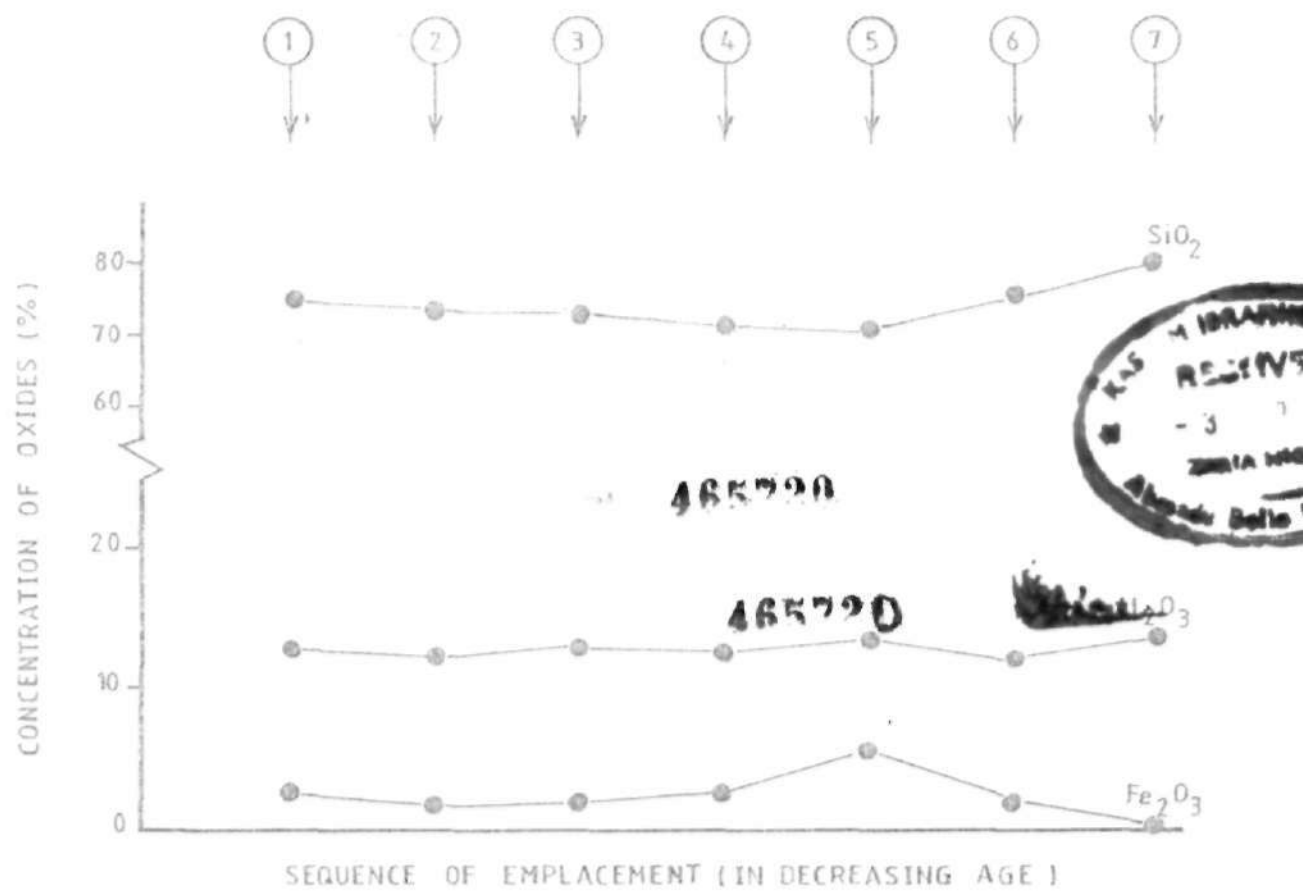
Fig. 4.1 : Chemical variation of SiO_2, Al_2O_3 and Fe_2O_3 in relation to sequence of emplacement. (Legend same as in Table 4.5)
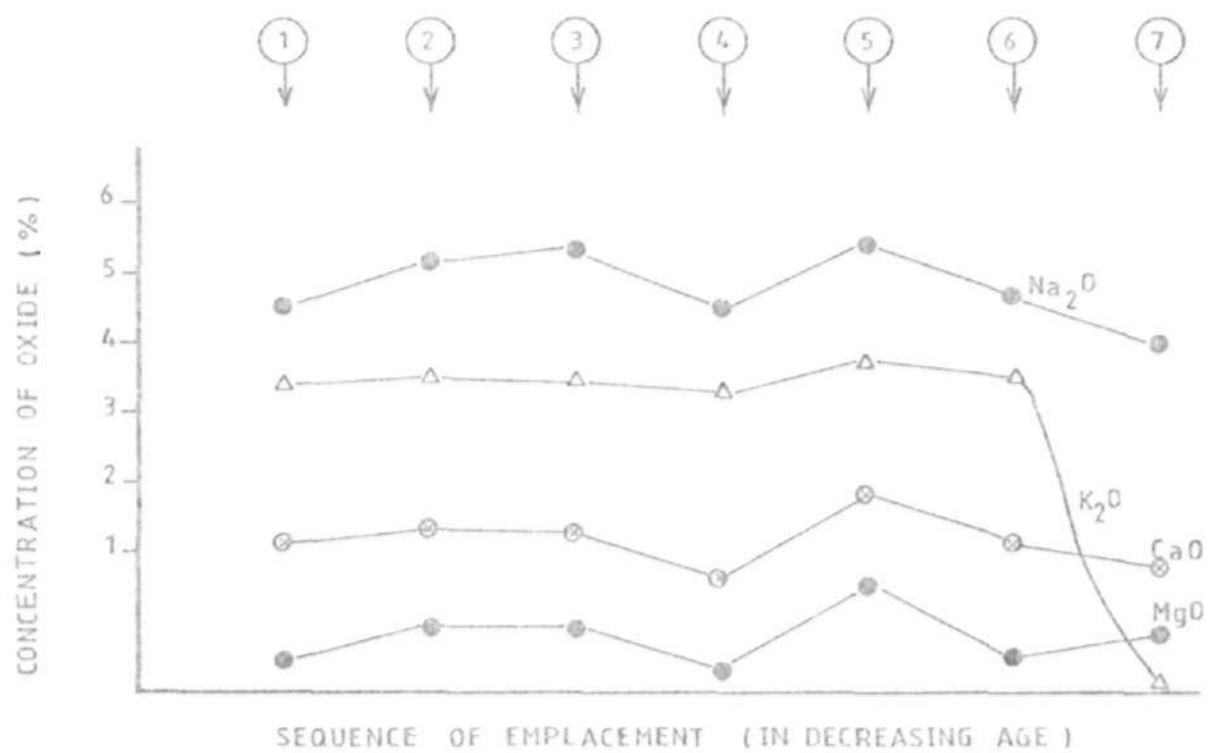
Fig. 4.2: Chemical variation of Na_2O, K_2O, CaO and MgO in relation to sequence of emplacement. (Legend same as in Table 4.5)
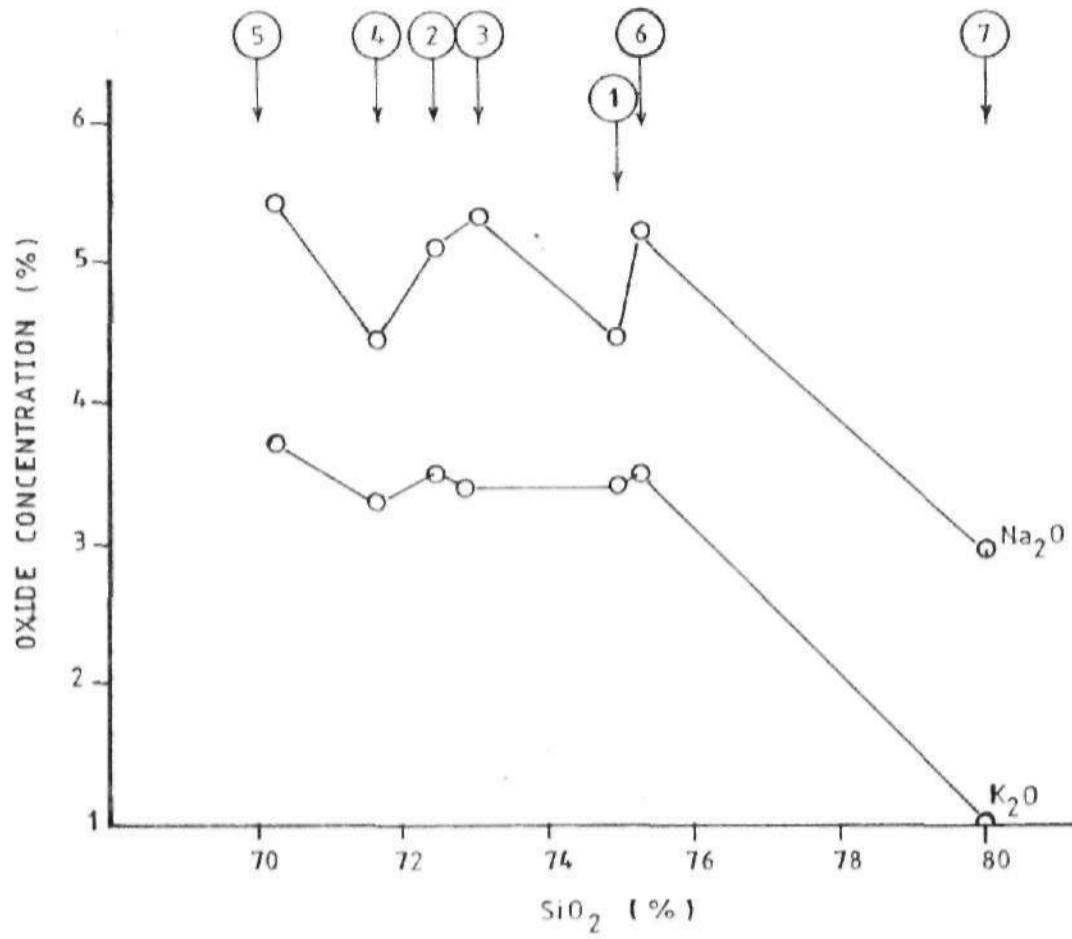
Fig.4.3: Oxide variation diagram for SiO_2 against Na_2O and K_2O. (Legend same as in Table 4.5)
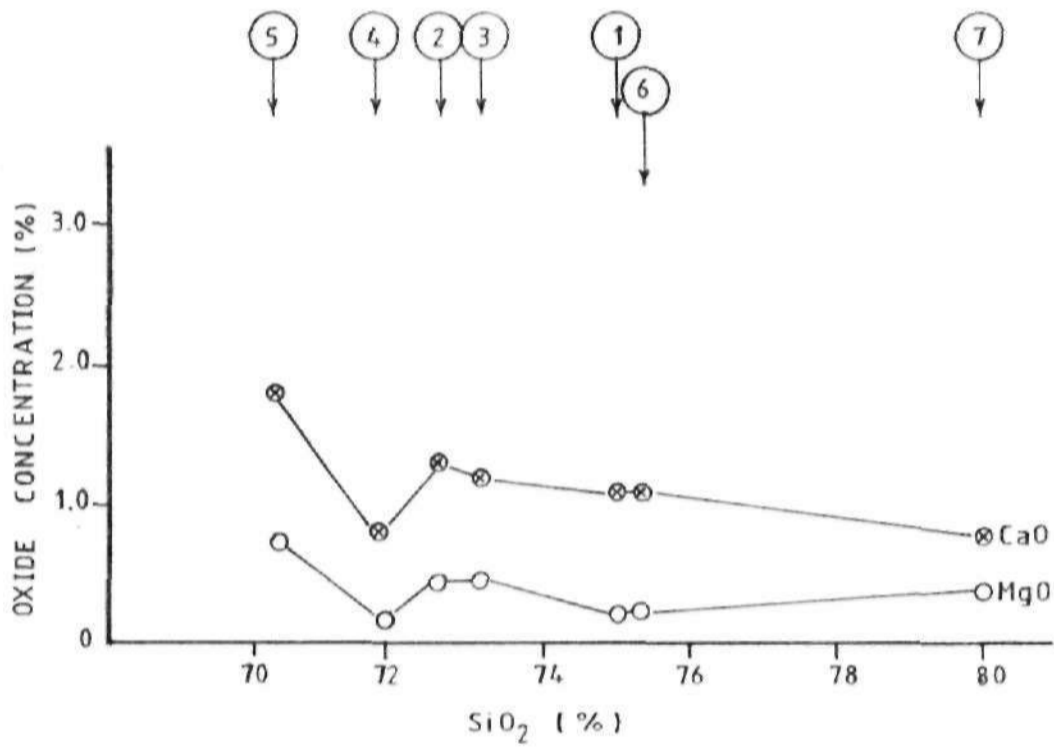
Fig 4.4: Oxide variation diagram for SiO_2 against CaO and MgO. (Legend same as in Table 4.5)
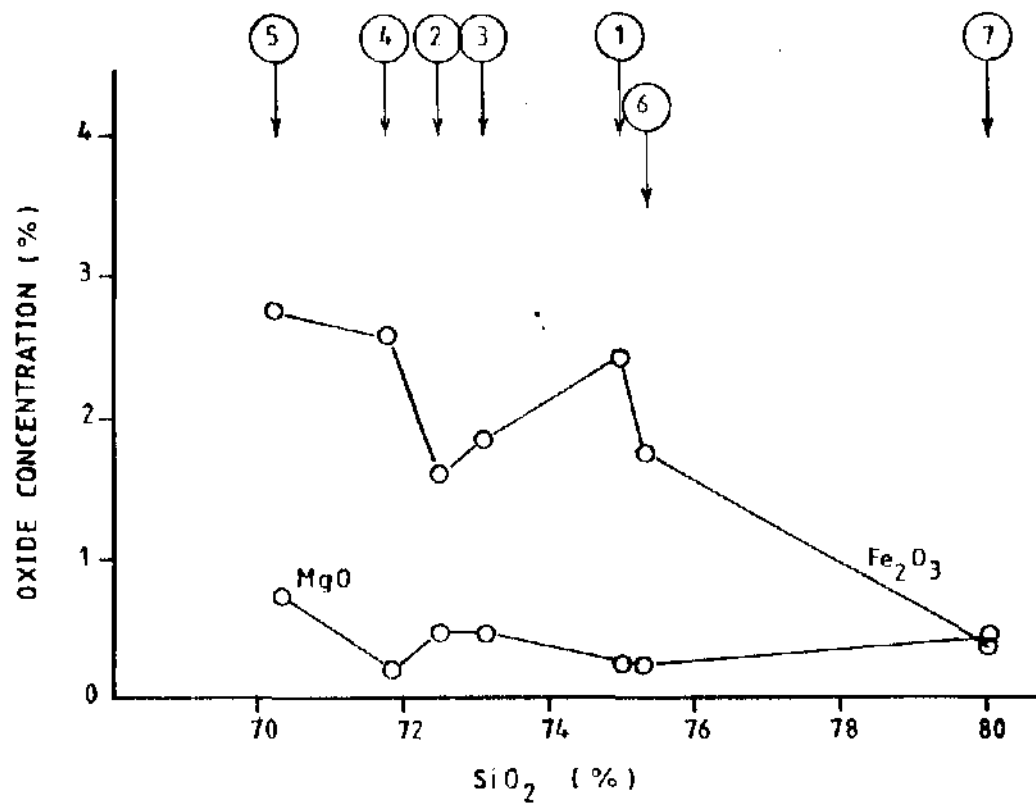
Fig. 4.5 : Oxide variation diagram for SiO_2 against MgO and Fe_2O_3 . (Legend same as in Table 4.5)
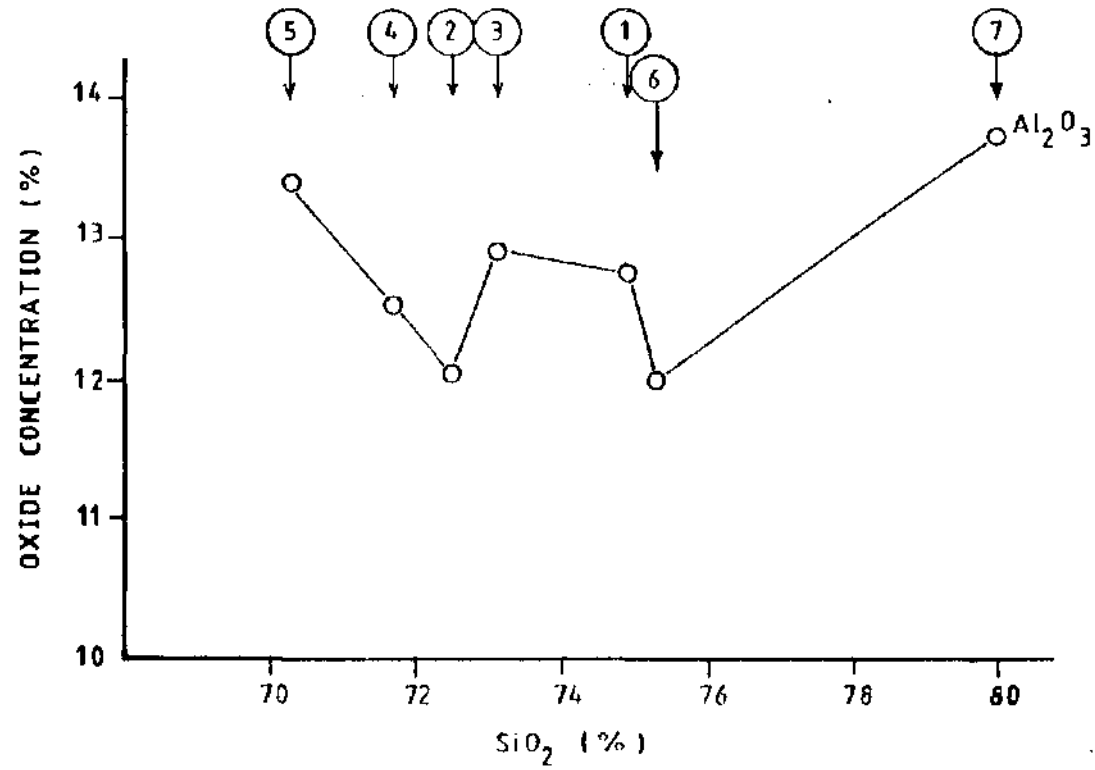
Fig. 4.6: Oxide variation of SiO_2 against Al_2O_3 (Legend same as in Table 4.5)
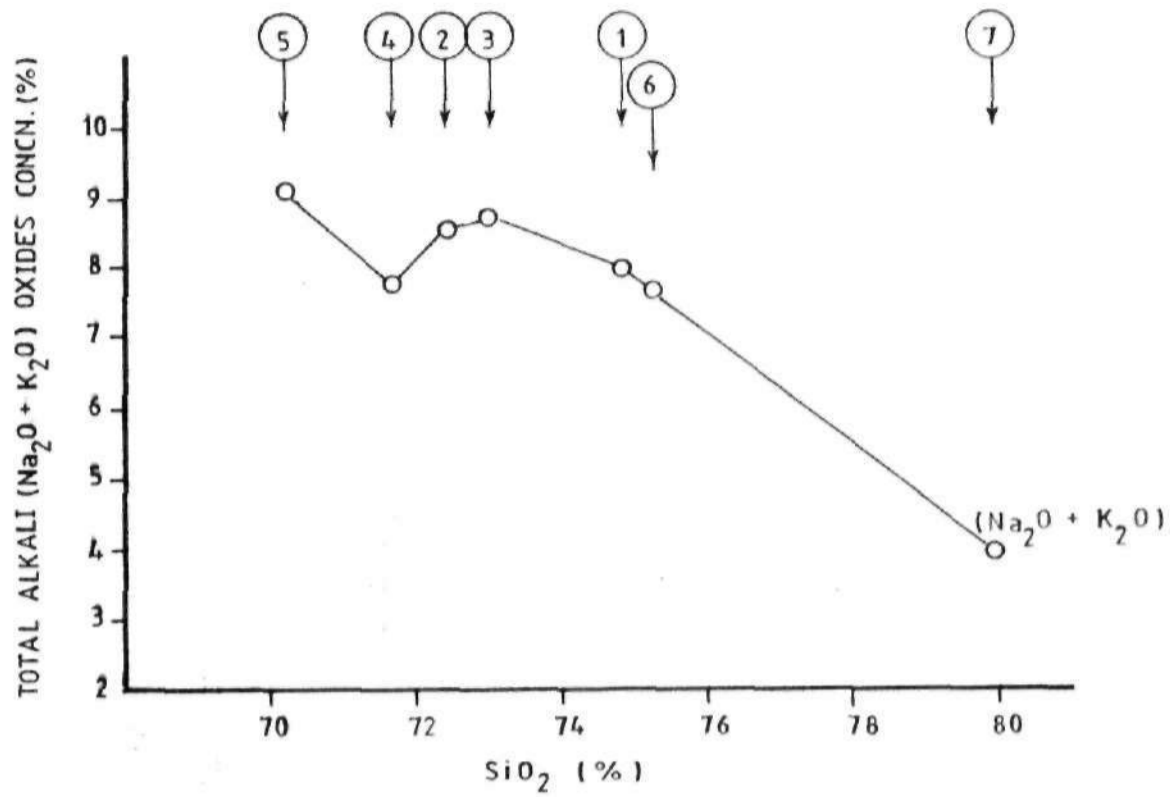
Fig. 4.7 : Oxide variation of SiO$_2$ against total alkali .(Legend same as in Table 4.5)
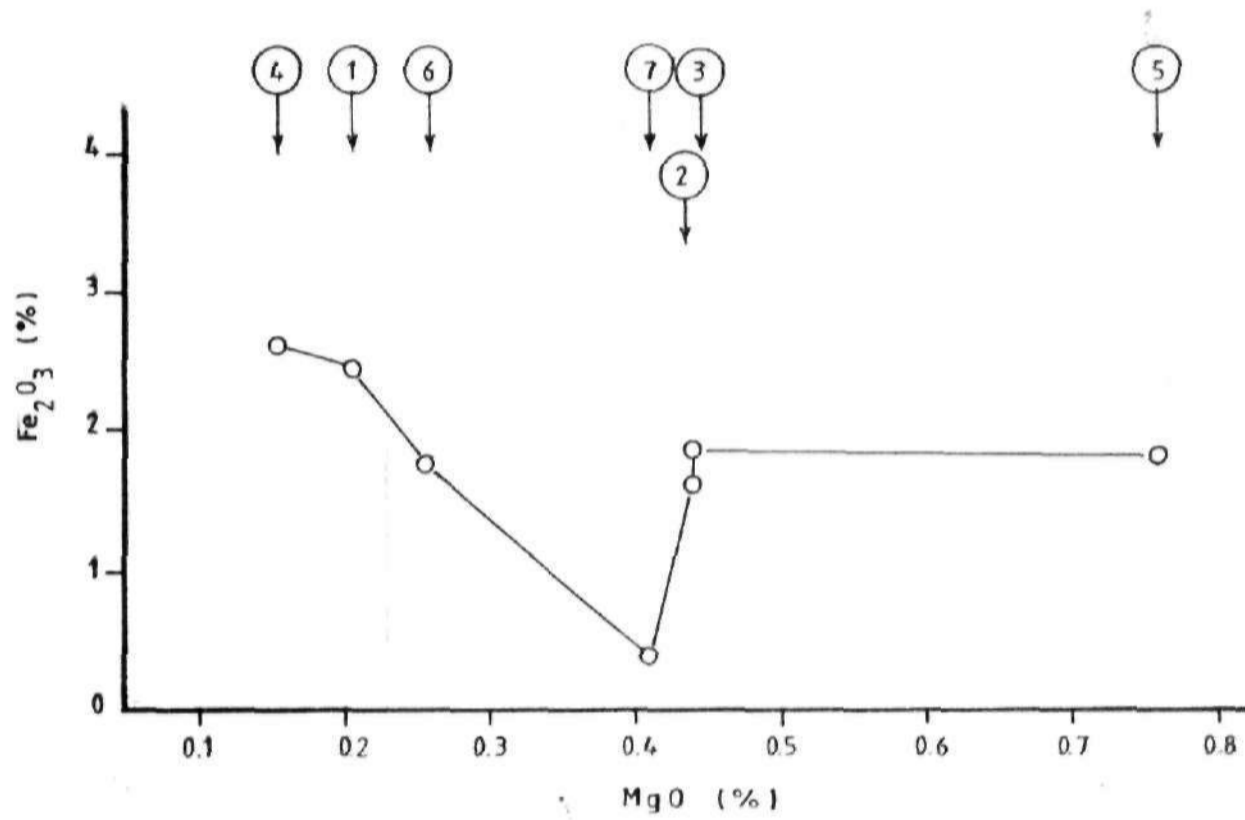
Fig. 4.8 : Oxide variation of MgO against Fe$_2$O$_3$. (Legend same as in Table 4.5)
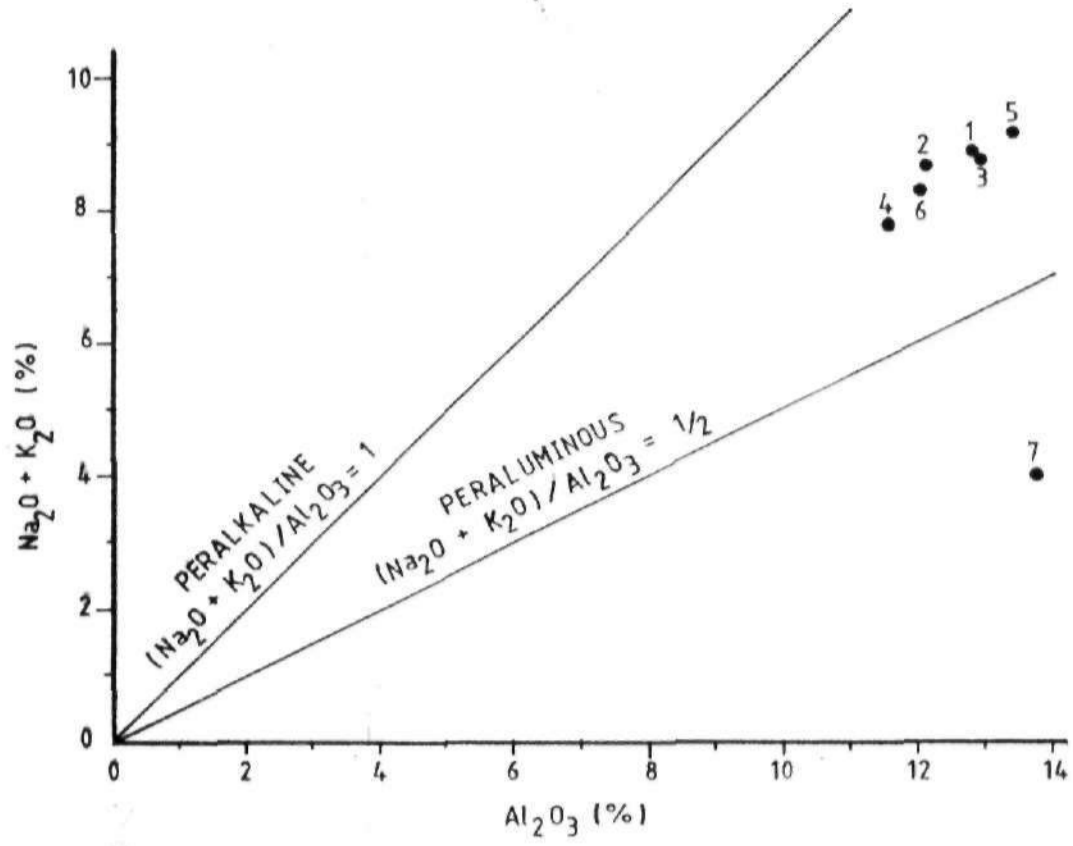
Fig. 4.9. Oxide variation diagram of Al_2O_3 against total alkali (Legend same as in Table 4.5). Dividing lines after Kuno , 1968.
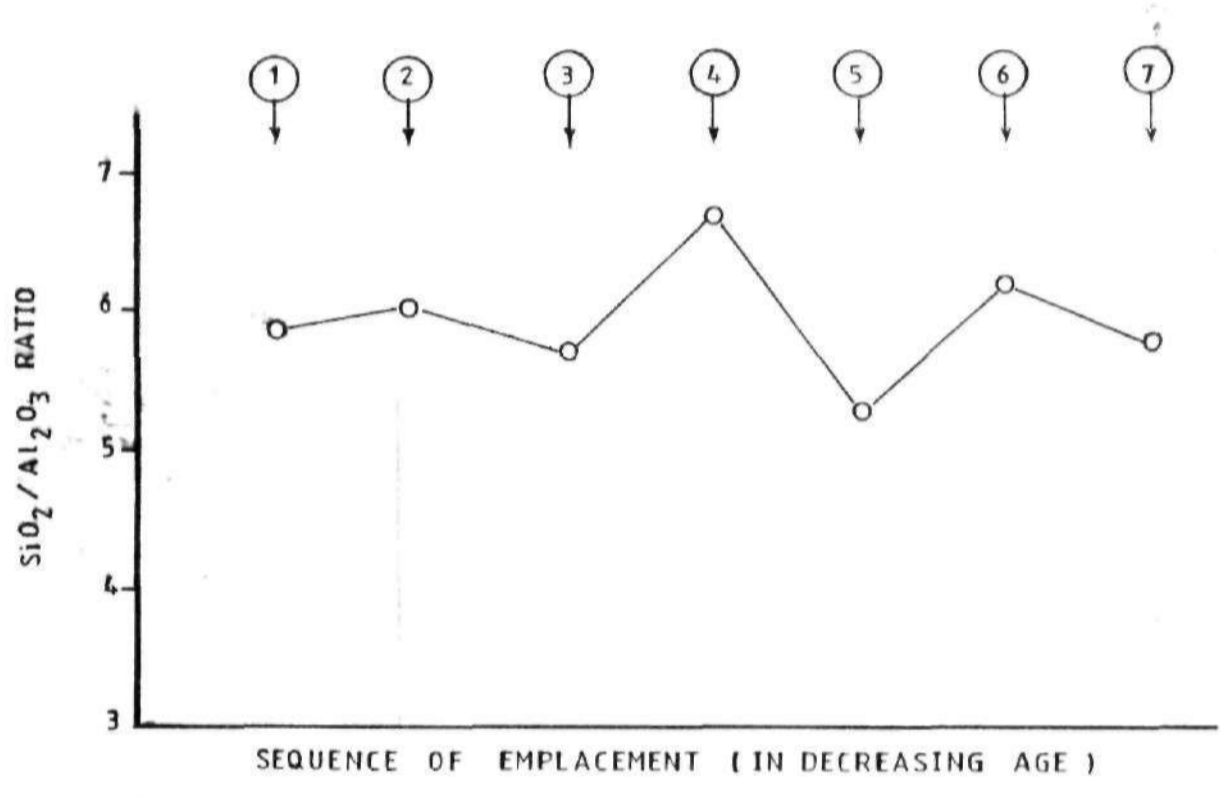
Fig. 4.10: Sequence of emplacement against SiO_2/Al_2O_3 ratio .(Legend same as in Table 4.5)
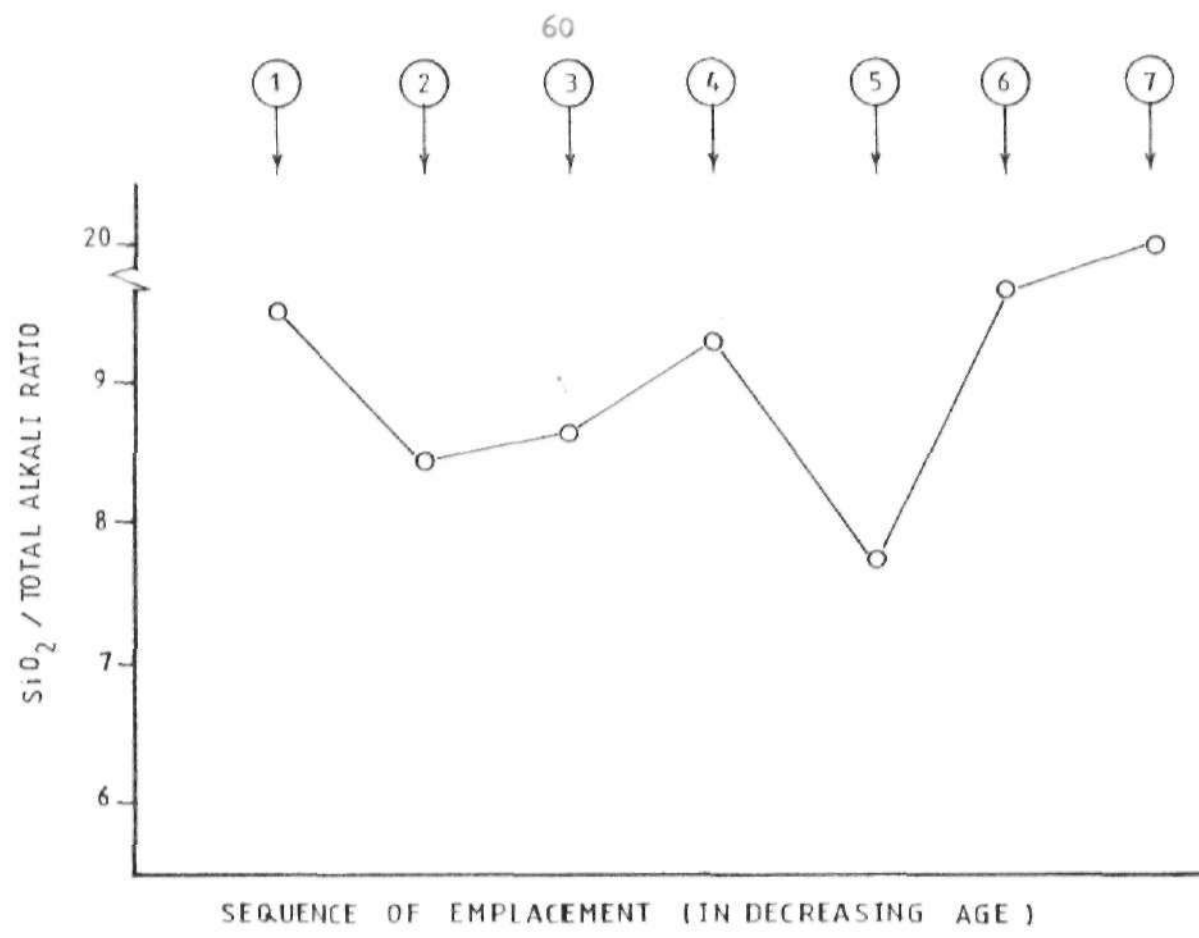
Fig. 4.11: Sequence of emplacement against SiO_2/total alkali ratio. (Legend same as in Table 4.5)
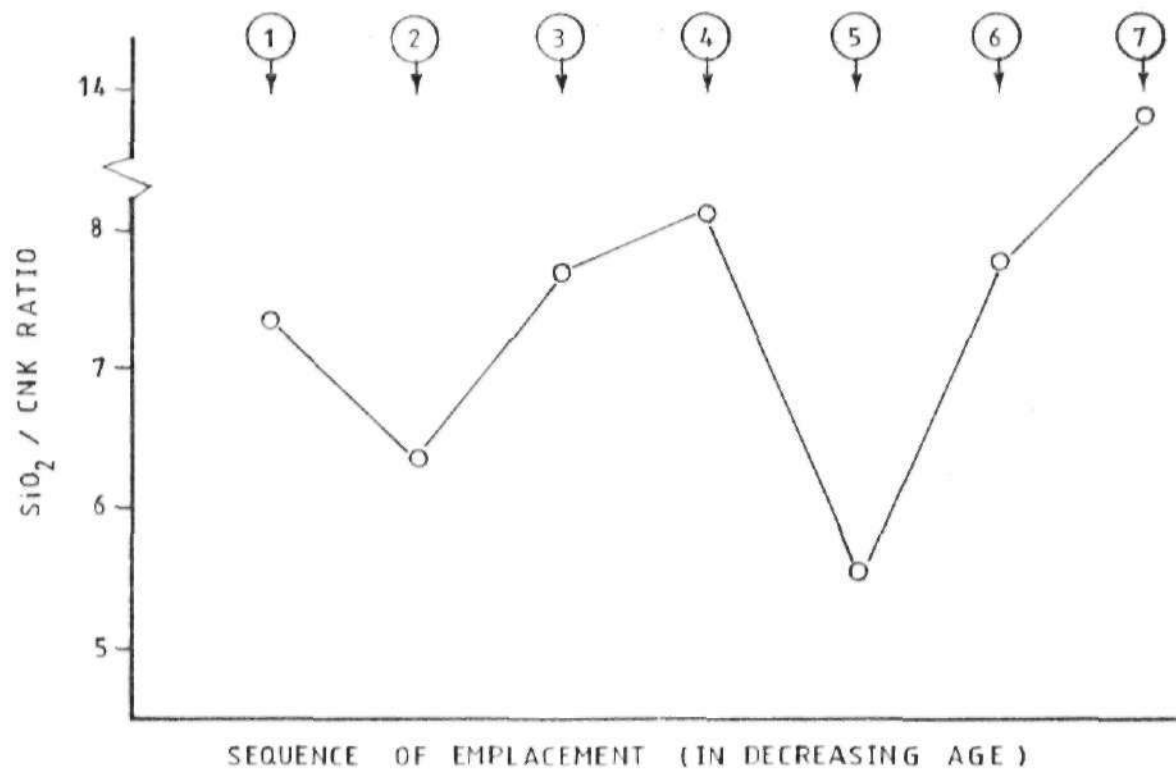
Fig. 4.12: Sequence of emplacement against SiO_2/CNK ratio. (Legend same as in Table 4.5)
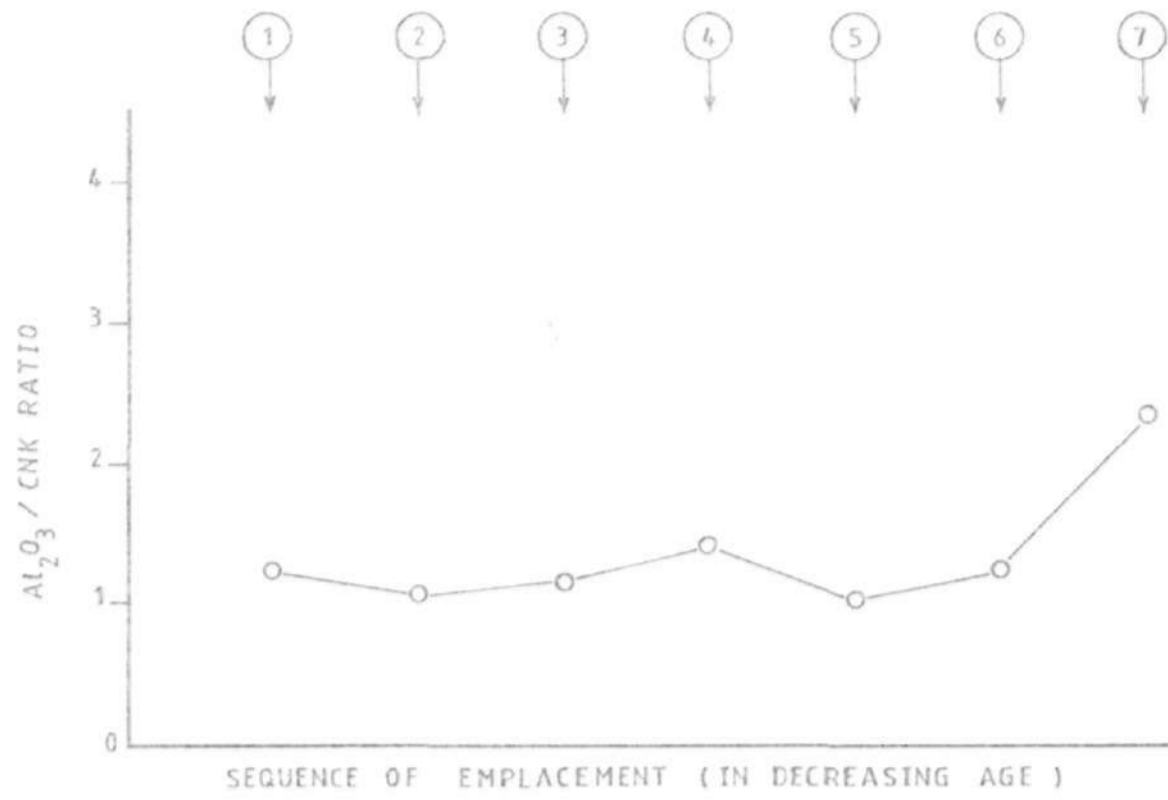
Fig. 4.13: Sequence of emplacement against Al_2O_3/CNK ratio .(Legend same as in Table 4.5)
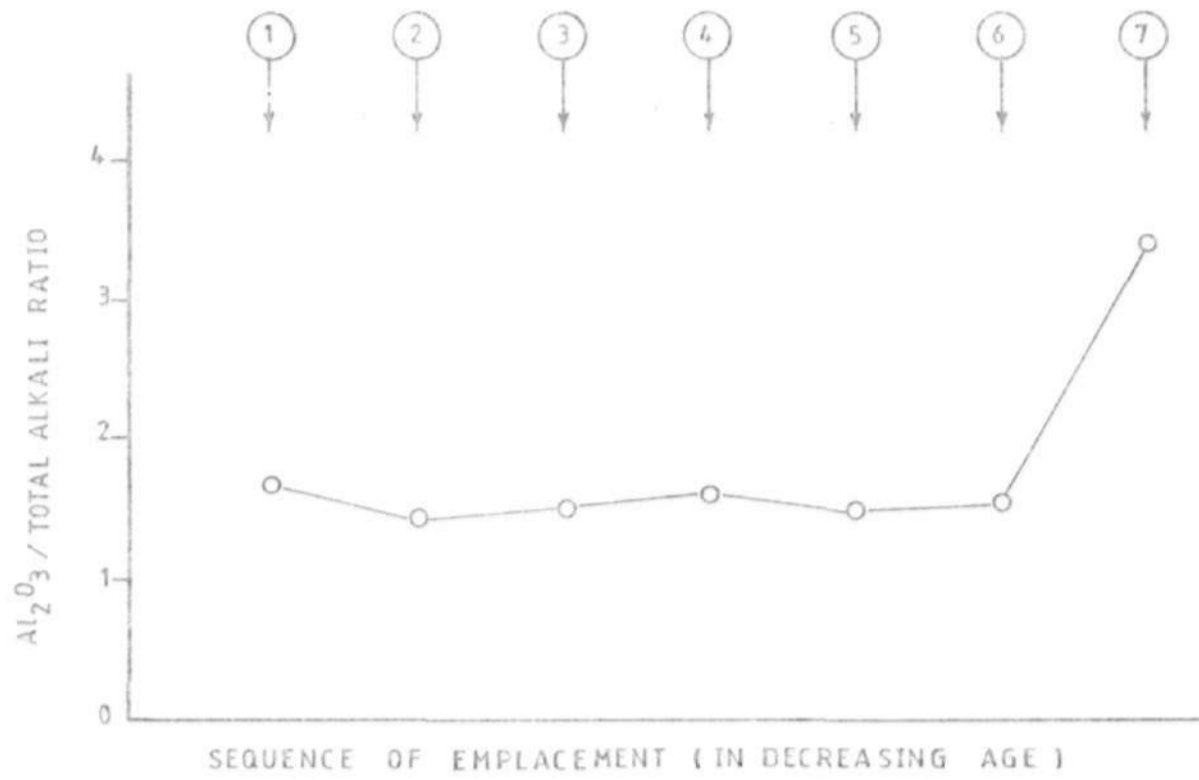
Fig. 4.14: Sequence of emplacement against Al_2O_3/total alkali ratio .(Legend same as in Table 4.5)
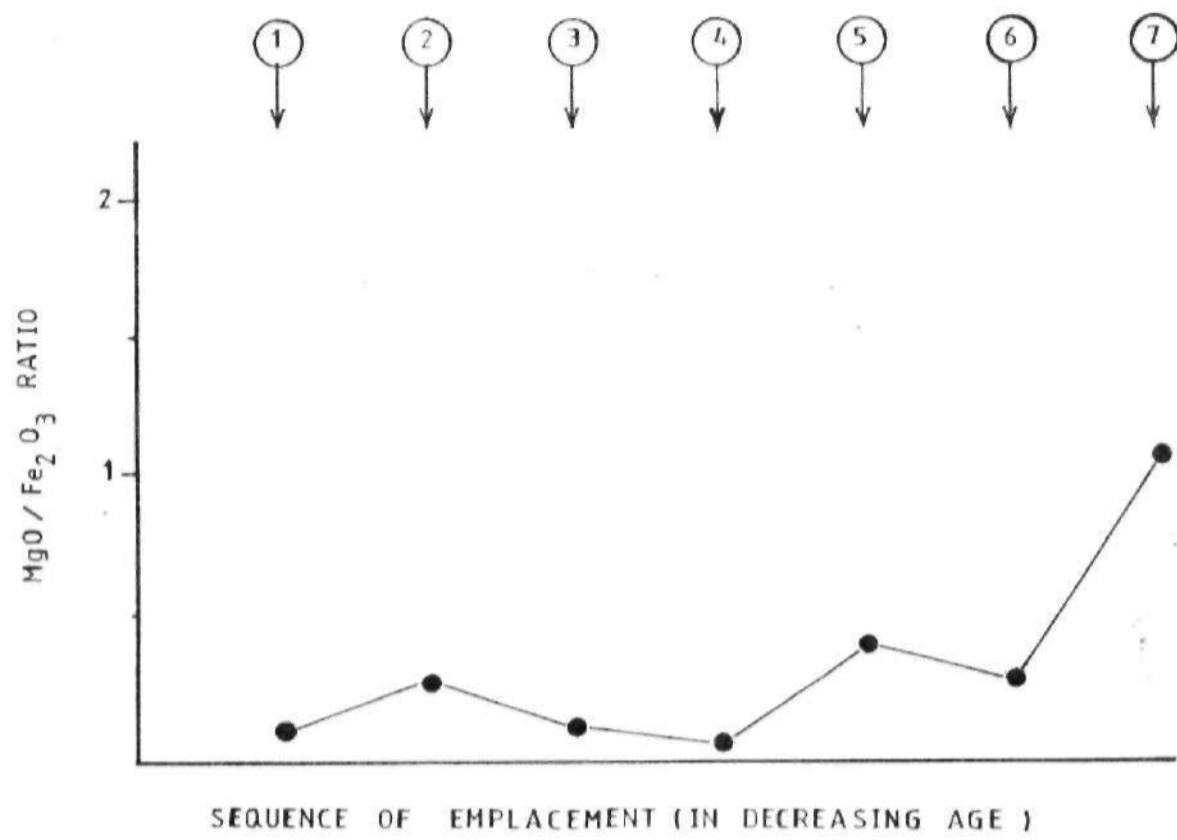
Fig. 4.15 : Sequence of emplacement against MgO/Fe_2O_3 ratio (Legend same as in Table 4.5).
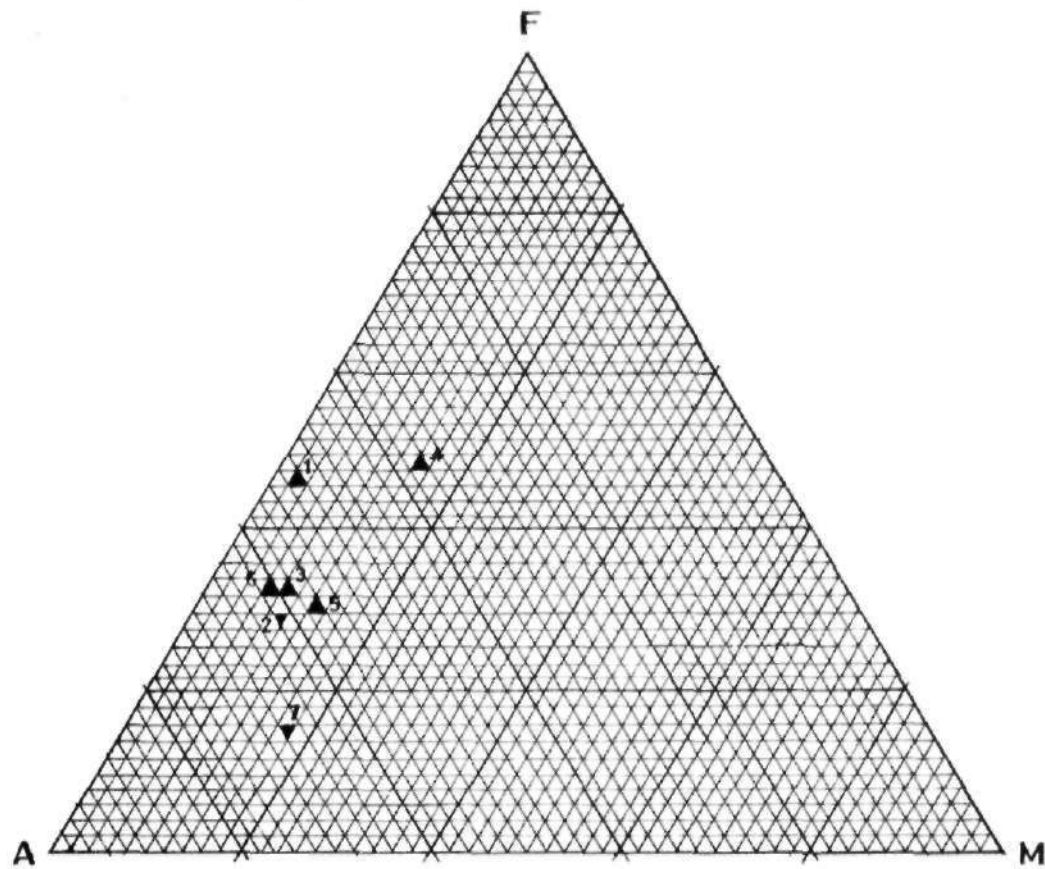
Fig. 4.16: A-F-M diagram showing the position of the Younger Granite rocks of the the Ganawuri Complex.
(Legend same as in Table 4.5)

4.3 DIFFERENTIATION PARAMETERS.

From figure 4.2, the high proportion of Na_2O to CaO can be discerned in all the rock types. This is reflected in their petrography by large amounts of non-perthitic albite.

Concerning the relationship between SiO_2 and the alkalis, there is a general trend of a depletion in SiO_2 accompanied by an enrichment in alkali content. This trend is similar for both Na_2O and K_2O. (See Fig. 4.3). The same variation trend occurs for MgO and CaO, which both decrease with increasing SiO_2 content (Fig. 4.4). The reverse is the case for Fe_2O_3, which increases with an accompanying increase in SiO_2 content. Only the dyke shows an exception, whereby high SiO_2 content is accompanied by very low Fe_2O_3. Furthermore, Fig. 4.5 shows that the varying of Fe_2O_3 with SiO_2 is the reverse of that of MgO, implying that in the rock units, there is a paucity of MgO in favour of Fe_2O_3 (Figs 4.8; 4.15).

The variation of SiO_2 with alumina is plotted in fig. 4.6. The general trend is an inverse correlation between alumina and SiO_2, the former decreasing with an increase in the latter. This coincides with the patterns of variation observed in fig. 4.1.

Total alkalis vary with SiO_2 in the same way as the individual alkalis (Fig 4.7), decreasing with increasing SiO_2 content.

The variation of Al_2O_3 with total alkali can be observed from Table 4.5. It can be noted that an increase in Al_2O_3 content is accompanied by a similar increase in alkali content. From figures 4.13 and 4.14, where the ratios Al_2O_3/CNK and Al_2O_3/Total alkali are plotted against the sequence of emplacement, one can observe a certain consistency in the values of Al_2O_3/CNK ratio and Al_2O_3/Total alkali ratio in most rock types of the Ganawuri Complex. The predominance of Al_2O_3 over the sum total of CaO and alkalis (See fig

4.9) places the rock types of this complex within the peraluminous sector of Shand's (1954) classification.

The plot of sequence of emplacement against the MgO/Fe_2O_3 ratio reveals an enrichment in MgO relative to Fe_2O_3 in the later occurring rocks. A depletion in iron content consequent to the formation of iron-rich minerals would result in a relative enrichment in MgO, which would then form the minerals of the later occurring rocks.

There are similar variations in the plots of SiO_2/total alkali (Fig. 4.11) and SiO_2/CNK ratio (Fig.4.12). They both show a high preponderence at the hornblende-biotite-granite and hornblende-fayalite-granite. These same rocks are isolated on the AFM diagram (Fig. 4.16) and may represent the initial products of intermittent magmatic phases or "pulses" (Olade, 1978).

The same rock units portray the highest values for peraluminous character on the plots of Al_2O_3/CNK and Al_2O_3/total alkali (See Figs. 4.13 and 4.14 respectively). The strongly peraluminous character of the hornblende biotite-granite, hornblende-fayalite-granite and even the moyite dyke (see Fig. 4.9), all three being initial phases of magmatic intrusions, must therefore imply that the parent magma was peraluminous.

CHAPTER FIVE

MINERALIZATION

5.1 INTRODUCTION

Tin occurs in its oxide form as cassiterite with columbite as a by-product of its exploitation. The mineralization is predominantly confined to the roof zones or cupolas of biotite-granites. The type of occurrence is in the form of disseminations, veins and lodes of cassiterite in association with hydrothermally altered rock (greisens).

In the 1950s and 1960s tin was exploited as its primary deposits by the Lang Sign Mining Company in the village of Tudun-Ganawuri (now Heita). It worked on the quartz veins which were fracture-controlled and folded up when these were exhausted, leaving a great number of gullies and pits that presently assist in enhancing erosion.

Presently, tin is exploited in its secondary deposits by panning working on old or contemporary river sediments. An earth dam is built in order to create a water supply for the monitor (a high pressure hose used to evacuate and slurry the cassiterite-bearing sediments) and sluice boxes (in which the dense cassiterite is concentrated). Paddocks are then dug, the overburden being removed by the dragline and piled along the edge of the paddock. These piles are called spoil mounds. The tin-bearing sediments are then removed as slurry, and after passing through the sluice boxes where the tin is concentrated, the waste tailings are pumped back into the orginal pond.

Smaller scale exploitation of the deposits is by panning of alluvium in rivers and streams.

Primary mineralization in the Ganawuri area can only be observed as relics of siliceous veins left after exploitation and abandonment by mining companies. Only secondary mineralization can be discerned along river channels and under old sediments.

5.2 SOURCE AND EMPLACEMENT OF THE MINERALIZATION

The cassiterite deposits are genetically related to the emplacement of Younger Granite magmas derived by partial melting of the sialic crust above the mantle plume system.

Olatunji (1981) suggested that, in such deposits, the hydrothermal ore-bearing fluid is a late-stage collinear derivative of the magmatic processes that produced the host granites. Many granites have been known to have become tin-mineralized following fracture-controlled, epigenetic, hydrothermal processes.

Howerver, the most popular concept of the source of deposits is that of hydrothermal fluids of essentially felsic magmatic origin related to a surrounding acid phase (Taylor and Wall, 1993). Such fluids are enriched in SnO_2, acidic in nature and are of low oxygen fugacity and also enriched in volatile components. Areas of high fracture have often acted as conduits for such fluids in their ascent (Rozendaal et al., 1995).

Taylor and Wall (1993) have shown that there is a strong partitioning of iron and maganese and also tin into the aqueous phase. Then the residual melt and any aqueous phase from it may introduce such components into the host rock systems especially in areas adjacent to such permeable zones as joints and fractures

Enrichment may have resulted from the release from the host rock by postmagmatic solutions. Hence the hydrothermal fluid acted partly as a catalyst to effect leaching of the host rock through hydrolysis reactions.

Enrichment of tin could also be connected to altitization and trace element overprinting by postmagmatic fluids (Macleod et al, 1971).

In the Ganawuri complex which is a peraluminous series, early crystallization of mafic minerals would limit the amount of volatiles removable during the magmatic stage. Hence a gaseous or hydrothermal phase would separate from the magma to give mineralized veins which are almost entirely associated here with the hornblende-biotite-granites.

The primary mineralization is associated with joint systems in the roofs of the granitic intrusions (Jacobson and Macleod, 1977). During the early pneumatolytic stage of the magma, the ore fluids responsible for mineralization were rich in Sn, Fe, Li and water. The central siliceous veins were, however, probably deposited from hydrothermal solutions rich in silicon, tin and tungsten.

Flat or sheet joints of the complex do not show any mineralization. They are post-tectonic stress-relaxation joints attributed to relief associated with erosion and unroofing of the granite. The granites are therefore considered to have become tin-mineralized by fracture-controlled, epigenetic, hydrothermal processes.

In the late Jurassic, much tin-bearing rock was eroded and deposited into the river valleys surrounding the Ganawuri Complex, giving rise to detrital alluvial deposits.

5.3 MECHANISM OF EROSION AND DISPERSION.

The secondary deposits presently being exploited are sedimentary alluvial deposits. They became detrital after undergoing weathering and were concentrated into river valleys by gravity. Most of the erosion of the primary deposits took place in the late Jurassic period.

The resulting alluvial deposits are widely dispersed in old and recent drainage systems due to fast unroofing of the granitic cupolas. The most recent abundant concentrations are related to the fluvial deposits, especially the recent alluvium found along Bum river, Uria, etc.

The erosion following unroofing of the granites was by purely mechanical agencies of stream action. Aided by the relief of the area, which consists of very steep hills for the Younger Granite and flat, undulating plains for the Basement rocks, and high rainfall, the weathered roofs of the granite would slide downwards under simple gravity movement. Solifluction due to the high water content inherent in these regions could also be an important erosion factor.

Mafic rocks are generally more readily worn away by running water than felsic rocks. Many primary minerals would be disintegrated by the abrasive action of flowing water. Cassiterite, being a moderately resistant mineral and a highly stable mineral species would thus be transported by fluviatile means. Erosion and transportation would be greater in the upper part of the river, which could be steep and fast - flowing following the general relief of the area.

The dispersion here is thus by exclusively mechanical means, in this case river action. In the Ganawuri Complex, seasonal

variations in the level and flow of the rivers cause the sediment to be resorted and redistributed, and gravity sorting tends to concentrate some of the tin at critical points along the stream bed. Such areas are usually those where panning is most intensively carried out by the locals.

5.4   ECONOMIC IMPORTANCE

At present tin exploitation in the Ganawuri complex can only be done on very small – scale by artisanal methods such as panning and paddocks. Also, wells are dug randomly to get through the overburden down to the granite cupolas in order to tap the primary deposits.

However, such endeavours are cost ineffective, because the tenor of tin left does not warrant any intensive exploitation. The veins and greisens which were exposed and easily accessible have been completely exhausted by the former mining companies.

At the moment, only the oldest alluvial deposits of tin are left, covered by the Tertiary basalt flows. Such deposits can only be recovered at very great cost which might not warrant their tenor in tin, but improving technology might enable this to be done in future.

Other minerals of the Ganawuri complex include columbite, a by-product of cassiterite exploitation; quartz, as very well formed crystals up to 3cm in length, which could be of interest to the glass industry; alluvial sands for construction purposes and laterite which serves in the construction of secondary roads around the area.

CHAPTER SIX

DISCUSSION AND CONCLUSION

6.1 FIELD RELATION AND PETROGRAPHY

The Ganawuri complex displays an abundance of biotite-granites of diverse types. It is generally accepted that biotite – granites are the host rocks for tin mineralization in the Younger Granites of Nigeria,and this provided the impetus for the present study. Daily panning for tin in the stream sands in the area also added to this incentive, in the hope that the last vestiges of primary mineralization there could be studied in greater detail.

A scale of 1:25.000 was ideally suited for the mapping in order to incorporate enough details on a single framework. The area showed contrasting seasons during the two periods of observation of the complex on the field, and it was noticed that the severe dry season with depleted vegetation would be ideal for field work. The rugged relief, ranging from steep-sided high granitic hills to flat and gently undulating areas, gave rise to a dendritic drainage pattern of the numerous rivers and streams, the major ones being the Rivers Kaduna, Uria (Ouree) and Werram, all of which bear many tributaries.

The associated basic volcanic rocks usually existing in most of the other Younger Granite complexes are absent in this complex. This leaves an exclusively acidic suite of intrusive, gigantic plutons, many of which have undergone severe weathering and erosion following the high rainfall of the area, thus modifying their original distribution.

These plutons make sharp contact with the Basement Complex and even with other members of the same complex. However, in the

central portions, horizontal contacts exist between successive granite phases. Dykes are common in the area.

Joints follow a WNW-ESE trend and are considered to be post – kinematic joints occurring by stress relaxation after lithostatic pressure was restored. Other horizontal or slightly dipping joints cause the granites to be broken up into blocks and tors.

The hornblende-biotite-granite was found to make up about two-thirds of the entire complex and also to be the host rock for most of the mineralization.

The porphyritic biotite-microgranite showed local variations within it in terms of grain size and textures, and one of these was considered as a different rock type, i.e. the fine-grained biotite-granite.

Fayalite-biotite-granite is the least widespread of all the rocks in the series.

Metasomatism had occurred between the Daw biotite-granite and the rocks it intruded, especially the older members such as the hornblende-biotite-granite, the Ganawuri biotite-granite and the hornblende-fayalite-granite. The result was intense albitization and recrystallization, especially in the hornblende-biotite-granites.

Petrographically and mineralogically, the Younger Granite rocks of the complex show a certain variation in terms of their mineral constituents. The essential minerals are basically the same, with quartz being the silica mineral, while microcline and orthoclase are the alkali feldspars. Plagioclase is strongly sodic in composition, being mostly albite which occurs in two generations, one being an exsolution product with the alkali feldspars as perthite, while the other is discrete and resulting from unmixing of the two feldspars beyond the perthtic stage. The plagioclase content is
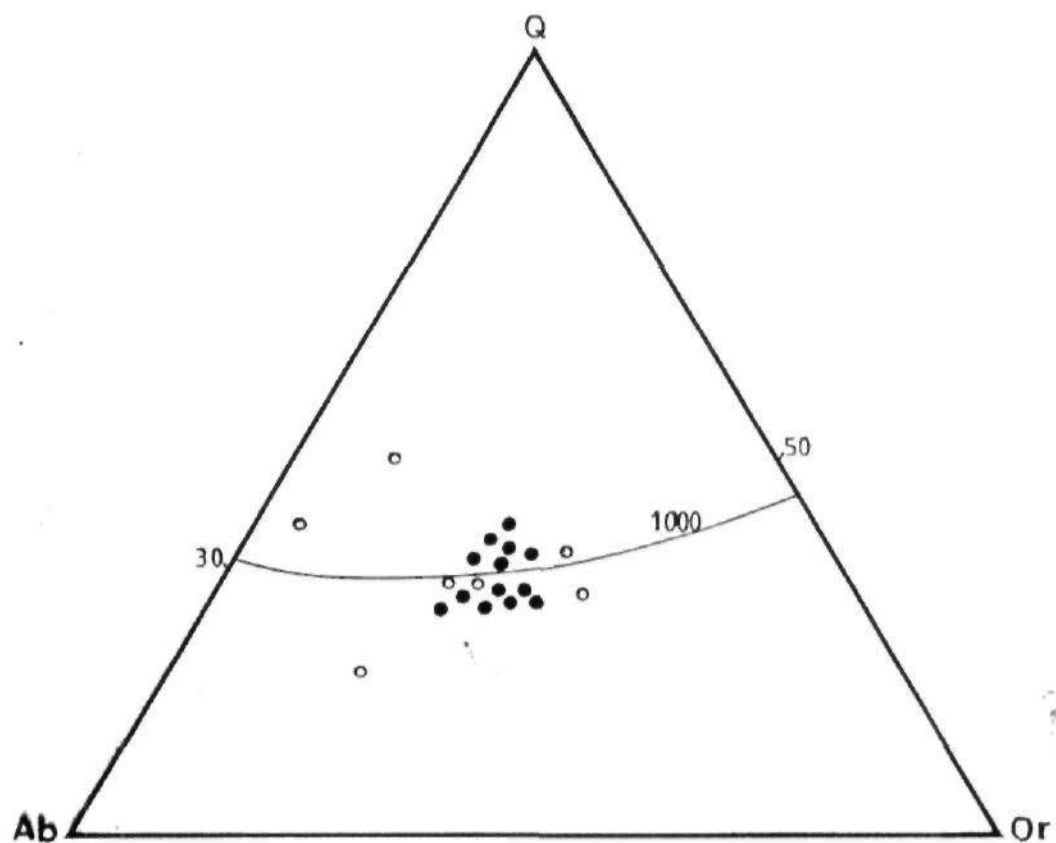
Fig. 6.1 . Position of Younger Granite on the
Ternary system Q - Ab - Or at 1Kb
(from Tuttle and Bowen , 1958) .

(Ganawuri rocks are open circles)

very low compared to the alkali feldspar in most of the rocks, except in the hornblende-fayalite – granite.

The accessory minerals did not vary much, zircon, magnetite and chlorite being the most frequently recurring in the mineralogy.

Geochemically, the rocks of the complex ressemble other Younger Ganite rocks. They show an overall enrichment in silica, and alumina is consistently in excess of total alkali while and soda is also more abundant than potash. Therefore, the litho-units of the Ganawuri complex are all peraluminous.

6.2 ORIGIN OF THE MAGMA

The nature of the source materials of the Younger Granites has been controversial. A sialic origin (Oyawoye, 1976; Bowden, 1982) is now generally accepted, and it is backed by extensive isotopic data (Bowden et al., 1975). Another possible source of magma is by partial melting of the crustal SIMA, an origin supported, by the high basic xenolith content of the earliest ring-dykes (Martin and Bowden, 1981). A further proposed source was by differentiation from basic magmas, a possibility widely discounted because it was neither consistent with geophysical evidence (Ajakaiye, 1970), nor with the relative volumes of acid to basic and/or intermediate rocks in the entire Younger Granite Province (Macleod et al., 1971). However, the geochemical data presented in this study points towards the rocks having crystallized from acidic magmas of granitic composition. From tables 4.1 and 4.2, their chemical composition compare closely with those of other peraluminous granites elsewhere.

The litho-units of the Ganawuri Complex have compositions lying near the ternary minimum on the low temperature trough in

the water-saturated system Q-Or-Ab-H₂O of Tuttle and Bowen (1958) (see Fig. 6.1). Thus their composition is not significantly different from that of the magma from which they crystallized (Olade, 1978(a)).

Chemical variation diagram indicate that the various phases of granites within the study area are not products of differentiation from a single parent magma. Instead, they probably belong to separate phases of magmatic intrusion or 'pulses' produced by progressive melting of the source rocks. These source rocks are migmatite-greisses of the Basement Complex.

The source of heat required to generate the melting of the basement rocks is related to the break-up of the Gonwanaland. The initiation of contact metamorphism around the Younger Granite ring complexes is suggestive of an emplacement into pre-heated country rock e.g. (Martin and Bowden, 1981). Furthermore, Oyawoye (1976) showed that the Younger Granites lie within a north easterly trend of granulites associated with high heat flow. This confirms the culmination of heat flow due to stresses from continental separation accounting for the generation of Younger Granite magmas from Basement Complex rocks.

6.3 EVOLUTION OF THE MAGMA

According to Macleod et al (1971) and Ike et al (1984), two distinct differential processes could have occurred in the magma that gave rise to the Nigerian Younger Granites. These two trends are divergent and depend on the type of products that crystallize first from the magma. If the first minerals consist of mafic minerals, then a peraluminous series would result. On the other hand, an alkaline series would result if the early minerals to crystallize and precipitate are plagioclase feddspars.

Badejoko (1975) postulated that the parent magma of Younger Granite was close to the composition of hornblende-fayalite-granite. Therefore the earliest members of the series in the Ganawuri Complex should be expected to have a composition close to this parent magma. But field evidence and chemical variation diagrams show that this is not the case. Instead, hornblende-biotite-granite is clearly seen to be oldest unit in the complex, and is in near vertical contact with the Basement Complex.

The model of intermittent magmatic phases or 'pulses' (Olade, 1978 (b)) could be applicable here. In such a situation, three separate 'pulses' would have occurred. The first would have initiated the hornblende-biotite-granite; a second phase would have started with the hornblende-fayalite-biotite being the first products, while the third and final phase was the intrusion of the dyke.

The initial products of the first magmatic pulse is the hornblende-biotite-granite, with constituent minerals biotite, hornblende, quartz and microperthitic alkali/plagioclase feldspar. The conditions favouring such an assemblage include high pressures around 5Kb and saturation of the magma with water vapour (Hall, 1987).

Since the first formed minerals are the mafic minerals biotite and hornblende, there is an enrichment in alkalis that is reflected by the formation of phenocrysts of alkalis and sodic plagioclase feldspar in the porphyritic biotite-microgranite. The presence of microcline microperthite implies temperatures of formation below 450°C (Smith, 1974), corresponding to the lowest liquidus temperatures for alkali-rich compositions to crystallize.

The next litho-units in the sequence are the fine-grained biotite-granite and the Ganawuri biotite-granite. The former is intimately associated to the earlier microgranite while the latter is the product of the residual melt, and concludes the emplacement of the first magmatic 'pulse'.

The second magmatic phase emplaced the hornblende-fayalite-granite first. Its composition is close to that of the parent magma (Badejoko, 1975), implying that no anomalous pressures were operating in this case. The relative paucity is SiO_2 and high fayalite content place the hornblende-fayalite-granite high up in Bowen's reaction series. Fayalite bearing granites probably formed at temperatures close to the upper stability limit of fayalite around 900°C (Bea, 1991). The fayalite-biotite-microgranite would be expected to follow suit, and this is confirmed by its field relationship with the hornblende-fayalite-granite.

The Daw biotite-grantie, which occurs last in the sequence of emplacement, is the product of the residual melt fraction, as evidenced by extensive autometasomatic reactions (e.g. Buchanan et al., 1971). The extent of these reactions depended critically on the amount and composition of a circulating fluid phase. If the fluid phase was alkaline in character, it would have been a potent solvent, inducing postmagmatic reactions such as recrystallization. This is supported by the two generations of quartz and albite in the Daw biotite-granite.

The third and final phase of intrusive activity in the complex occurred in the emplacement of the dyke across the hornblende-biotite-granite. The absence of a contact metamorphic implies it must have been emplaced in pre-heated country rock. The moyite dyke is not derived from the same parent magma as the

hornblende-biotite-granite, for it would have been emplaced as a ring dyke.

Furthermore, there would have been envidence of mineralization, which is not evident in the dyke. Finally, the chemical character of the moyite dyke, (as observed in Figs 4.1-4.15), depict a totally different chemistry from the hornblende-biotite-granite. Hence the third magmatic 'pulse' was simply a fracture-controlled intrusion localised within the hornblende-biotite-granite.

The intrusive sequence in the Ganawuri complex can therefore be represented as below.

−	Moyite dyke	} 3rd magmatic pulse
−	Daw biotite-granite	}
−	fayalite-biotite microgranite	}2nd magmatic pulse
−	hornblende-fayalite-granite	}
−	Ganawuri biotite-granite	}
−	fine-grained biotite-granite-	}1st magmatic pulse
−	porphyritic biotite microgranite	}
−	hornblende-biotite-granite	}

The rocks are considered to have been formed from an initially granitoid magma which resulted from partial melting of the sialic crust.This magma could have been emplaced into preheated country rocks, hence the absence of contact metamorphic aureoles.

Thus, the central region of the Pan-African belt in which the Younger Granites occur corresponds to a zone in which heat rose to levels in the crust high enough for partial melting to take place.

The granites were formed during the intrusive stage of the ring complex formation, correlated with cooling conditions in the magma reservoir. Solidification from the margins after cauldron subsidence would control the decreasing sizes of subsequent ring

intrusions. This can be seen in the quasi-concentric patterns of the Younger Granite suite rocks of the Ganawuri complex.

6.4 CONCLUSION

The Ganawuri complex, in spite of the present uneconomic nature of its remaining mineral deposits due to the high cost of exploiting the primary deposits, presents an interesting case whereby the source of the Younger Granite mineralization could be studied, together with its mechanics.

As tin deposits are structurally controlled by joints and zones of weakness, the model of Moore and Jackson (1977) could well apply here, and later extrapolated in other areas in the search for mineralization.

The existing post-kinematic joints suggest a point dilation in the roof zones of granitic intrusions which fail by shear or extension as the roof is lifted (Moore and Jackson, 1977). Residual hydrothermal fluids would cause rapid increase in pressure during the rise of a pluton to the surface.

When fluid presure exceeds the tensile strength of the boundary, cell flanks rupture and expel fluids upward along extensional joints and fractures. Low viscosity magma and hydrothermal fluids would leave a cupola through one or both weak sectors as the boundary of the fluid pressure cell fails, giving rise to a pair of mineral belts, one of which would receive a much greater share of mineralizing fluids flanking a core devoid of economically interesting minerals.

At Ganawuri, an analogous situation would be the case with cassiterite and columbite with galena which can be studied by further researchers.

6.5 RECOMMENDATIONS

A detailed geophysical survey of the area is recommended for a project since the existing data is of regional nature for the entire Jos Plateau (Central) area, and not for the particular complexes involved.

Intensive geochemical analysis of trace elements is also recommended, using ultramodern analytical techniques like Neutron Activation Analysis. Examination and analysis of the constituent essential minerals using electron microprobe is also another research envisaged for future workers. Intensive structural geology is also advised so as to carry out a joint-fracture analysis and correlate the data with country/host rock alterations.

A secondary road through the area is already in the making, which would bring the village of Heita into the limelight. As such, research should be done to clear environmental hazards such as the gullies; pits and wells resulting from tin exploitation in the area. Reclamation schemes could be undertaken to put these into better use.

Finally, topographic maps should be updated to take into account the migration of minor roads and footpaths of the area with the passing years, in order to avoid confusing future workers on the area.

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APPENDIX I

MODAL ANALYSIS OF ALL THIN SECTIONS OF YOUNGER GRANITES OF THE GANAWURI COMPLEX.

1.1   Hornblende-Biotite-Granites

	HO6	H16	AVERAGE
Microcline	58.0	58.5	58
Quartz	26.5	27	27
Albite	5.2	5.4	5
Orthoclase	4.0	4.0	4.0
Biotite	2.6	2.5	2.5
Hornblende	6.0	6.0	6
Zircon	0.1	0.0	0.1
Magnetite	0.4	0.5	0.5
Chlorite	0.1	0.2	0.2
Total			99.3

1.2   Daw Biotite – Granites

	D01	D02	AVERAGE
Microcline	58.0	53.8	55
Quartz	28.3	31.4	30
Albite	2.6	2.9	3
Biotite	3.9	4.3	4
Hornblende	1.0	1.2	1
Orthoclase	4.6	7.2	6
Zircon	0.5	0.8	0.7
Magnetite	0.1	0.2	0.2
Chlorite	0.2	0.1	0.2
Total			99.1

1.3   Ganawuri Biotite-granite

	G03	G13	AVERAGE
Orthoclase	38.0	40.5	40
Quartz	30.0	27.0	29
Albite	10.10	10.8	10
Biotite	19.0	16.7	18
Zircon	0.5	2.0	1
Magnetite	1.0	0.1	0.1
Chlorite	0.5	0.2	0.3
Total			98.4

1.4   Porphyritic biotite - microgranite

	PO8	PO9	AVERAGE
Orthoclase	46.5	49.7	48
Quartz	34.6	30.5	33
Albite	7.8	9.0	8
Biotite	8	7	7.5
Magnetite	1	1	1
Total			97.5

1.5   Fine-grained biotite-granite

	P10
Orthoclase	50
Albite	8
Quartz	33
Biotite	8
Zircon	0.2
Magnetite	0.5
Total	99.7

1.6   Fayalite – biotite – microgranite

	F05	F15	AVERAGE
Quartz	20.5	20.3	20
Oligoclase	11.0	14.0	12
Albite	22.0	27.7	25
Biotite	22.4	16.3	20
Hornblende	8.1	2.8	5
Fayalite	13.6	15.5	15
Zircon	1.2	1.0	1
Magnetite	1.2	1.0	1
Sphene	0.1	0.4	0.3
Total			99.3

1.7   Hornblende-fayalite-granite

	H12	H02	AVERAGE
Microcline	38.5	40.0	40
Quartz	24.1	20.5	22
Biotite	8.6	8.3	8
Hornblende	12.7	11.8	12
Fayalite	15.9	17.0	16
Ziron	1.0	1.0	1
Total			99.0

1.8   Dyke (Hornblende-Biotite moyite)

	H19A	H19B	AVERAGE
Microcline	35	33.5	34
Quartz	51.5	58.0	55
Albite	6.0	1.6	4
Biotite	2.5	2.5	2.5
Hornblende	1.5	1.5	1.5
Zircon	1.0	1.0	1
Magnetite	1.0	1.5	1
Total			99.0

NB :   All figures quoted above are in percentage. In averaging the relative percentages for each mineral in the various rock types, the figures for major constituent minerals were almost always rounded up to the nearest whole number except in cases where this would considerably alter the relative porportion. For accessory minerals, the percentages were also rounded up to one signficant figure.

APPENDIX II

METHODS OF ANALYSIS

II.1 Preparation of Samples

0.5g of each of the powdered rock samples was weighed into a platinum crucible. 2ml of hydrofluoric acid and 6ml of nitric acid were then added and the whole set-up was heated in a sand bath for 45 minutes, until a whitish residue was formed. This residue was then cracked up and dissolved with 20ml of dilute hydrochloric acid, and made up to 50ml with distilled water.

The samples were then put into plastic sample holders, ready for analysis.

II.2 Determination of Alkali Metals

Standards of 5 and 10 PPM were prepared and their percentage emission read on the gauge of the flame photometer. A blank was prepared and its % emission also read.

Solutions of the rock samples were then passed one after the other through the flame and their % emissions obtained and recorded.

The concentration of each was obtained by the following formula:

$$\text{Element Conc (PPM)} = \frac{(a-b)}{(x+y)} \times \frac{(R-B)}{} \times \frac{Vs \times df}{Ws}$$

where

a: Concentration of higher standard

b: ,,   lower   ,,

x: % emission of higher   ,,

y: %   ,,   ,, Lower   ,,

R: %   ,,   ,, Sample

B: %   ,,   ,, Blank

Vs: Volume of sample in ml

Ws: Weight ,,   ,, g

df: dilution factor

II. 3 Determination of Phosphorus

Phosphorus was determined by colorimetry using a Spectronic 20.

Standards of 0,3,6 and 0 p.p.m. were prepared and their % transmittance read on the gauge of the Spectronic. The corresponding percentages of transmittance were then converted to percentages absorbance using logarithm tables, and a curve of concentration against absorbance plotted.

5 c.c. of each sample were then pipetted and to each was added 2 c.c. of nitro-vanado – molybdenic acid colour –developing agent.

The % transmittance of each sample was obtained on the Spectronic 20 and converted into % absorbance. The concentration of each sample was then obtained from the standard curve.

II.   Determination of Silica

1g of each sample was weighed into a platinum crucible, fused with 5g of NaHCO$_3$ (anhydrous) in a furnace for about 1 hour at a temperature of 950°C.

Using 1:1 hydrochloric acid, the fused sample mass was transferred from the crucible into a beaker.

The crucible was washed thoroughly with water, while the beaker with the solution was placed on a hot plate until the precipitates were baked. Using 3ml of 1:1 HCl, the fused material was broken up and the beaker rinsed. Repeating this process three times, the material was baked three times. The baked material was then treated with 5ml of 1:1 HCl and 100 ml of water and filtered into a 200 ml volumetric flask. The residue was washed with 2% HCl and put into a platinum crucible whose weight had already been noted. It was then heated in a furnace. The crucible containing the residue was then allowed to cool in a dessicator and its weight noted.

This residue was next treated with three drops of concentrated sulphuric acid and 10ml of hydrofuoic acid. It was then placed on a hot plate for 20 minutes until all the fumes were expelled. The whole set-up was allowed to cool and weighed again. The % silica in each sample was calculated as follows:

$$\% \text{ silica} = \frac{(y - x) - (z - x) \times 100}{\text{wt in g}}$$

Where:

x = weight of platinum crucible

y = weight of crucible + content before reaction
with hydrofluoric acid

z = weight of crucible + content after reaction with
hydrofluoric acid.

II. 5   Determination of Other Major Oxides

The already digested samples in solution were aspirated into an atomic absorption spectrometer in order to determine the other major elements. These included Al, Ti, Mg, Ca, Mn, and Fe, for which Fe (III) was determined as total iron.

A blank was prepared and its percentage absorbance noted. Three standards and their percentage absorbances were also prepared and their % read on the gauge of the spectrometer.

For the determination of each of the elements, the sample solution was aspirated into the flame of the spectrometer, and the resultant deflection of the needle of the gauge gave the absorbance.

The concentration of the major element was calculated following the formula below:

$$\% \ element = \frac{(a+b) \ * \ (R-B) \ * \ V_s \ * \ D}{(x+y) \ * \ W_s}$$

Where:

a: Concentration of the highest standard

b: Concentration of the lowest standard

x: % absorbance of the highest standard

y: % absorbance of the lowest standard

R: % absorbance of the sample

B: % absorbance of the blank

Vs: Volume of sample (in ml)

Ws: Weight of sample (in g)

D: Dilution factor

The major elements determined by the above formula were next expressed in their percentage oxides by the following conversion.

$$\% \ Oxide = \frac{M.O \ * \ C.E}{A.M \ * \ N}$$

Where:

M.O =   Molecular weight of the Oxide

A.M =   Atomic mass of the major element

N =   Number of atoms of the major element occurring in the oxide.